## UNIVERSIDADE DE LISBOA

## INSTITUTO SUPERIOR TÉCNICO


# A Green Composite as a Hood Part of a Buggy Vehicle


Georgios Koronis

**Supervisor :** Doctor Arlindo José de Pinho Figueiredo e Silva


**Thesis approved in public session to obtain the PhD Degree in**

**Leaders for Technical Industries**

**Jury final classification: Pass**

**Jury**

**Chairperson: Chairman of the IST Scientific Board**

**Members of the Committee:**

**Doctor** Carlos António Alves Bernardo
**Doctor** José Luis Soares Esteves
**Doctor** Arlindo José de Pinho Figueiredo e Silva
**Doctor** Marco Alexandre de Oliveira Leite


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"For the things we have to learn before we can do, we learn by doing."— Aristotle [348 – 322 BC]

Nicomachean Ethics, II03a, 32-3. In Jonathan Barnes (ed.), The Complete Works of Aristotle (1984), Vol. 2, 1743.

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# ABSTRACT

It is a recent tendency followed by glowing support in the technical and scientific literature that green composites can provide mechanical properties analogous to the synthetic composites and therefore they will gradually replace their traditional counterparts in future automotive applications [1-5]. Supplementary studies are demonstrating convenient manufacturing techniques and mechanical performance of equivalent composites intended for the automotive parts while at the same time acknowledge the potential of future composites of higher renewable percentage or biodegradables to be introduced in the automobile industry [1, 6, 7].

Following that trend the current thesis will investigate the possibility of developing a novel green composite by the use of bio-polymer (aliphatic polyester with recycled vegetable oils) and ramie fiber fabrics in the hood of a buggy vehicle. The vehicle will comprise a mean of transport intended for urban use (typically along the coastal areas) and therefore be presumably addressed to a congruent target group. In addition to this limitation, the latter will be produced by manufacturers focused on this niche market forasmuch as the batch size shall be limited. Being essentially concentrated on "green composites" which translates thereupon to sustainables; the range of all constituent materials comprising the composite is narrowed to those of renewable substance that are compatible with current manufacturing capacity.

The appropriateness of these composites will be asserted from a mechanical, economic and environmental perspective.

**Keywords**: constituents material screening, ramie fibers, bio-resins, green composites manufacturing, resin transfer molding, experimental characterization, process cost modeling, environmental degradation, environmental performance.

# RESUMO

Tendo em conta que as propriedades mecânicas dos compósitos verdes são análogas às propriedades dos compósitos sintéticos actualmente utilizados na indústria automóvel, de acordo com a tendência actual sustentada tanto na literatura técnica como na científica, prevê-se que a utilização dos compósitos verdes venha substituir de forma gradual o uso dos compósitos sintéticos [1-5]. Estudos complementares têm demonstrado convenientes técnicas de fabricação e performances mecânicas de compósitos equivalentes destinados a peças da indústria automóvel e, em simultâneo, reconhece as potencialidades dos futuros compósitos com uma maior percentagem de renováveis, ou biodegradáveis, a serem introduzidos nesta indústria [1, 6, 7].

Com base nesta tendência, a presente tese irá investigar a possibilidade de desenvolver um compósito verde inovador, recorrendo à utilização de biopolímeros (poliéster alifático com óleos vegetais reciclados) e tecidos fibrosos de fibra de rami na parte exterior do capô de um buggy. Este veículo será concebido para uso em áreas urbanas (tipicamente junto a zonas costeiras) e, por isso, é supostamente dirigido a um público-alvo. Além desta limitação, o veículo será produzido por fabricantes interessados e conhecedores deste nicho de mercado mas em quantidades limitadas. Estando essencialmente focado nos "compósitos verdes", cuja designação se traduz em materiais sustentáveis, a gama dos materiais usados neste compósito está limitada aqueles de conteúdo renovável.

A pertinência do conteúdo acima descrito é avaliada por três métodos distintos, tendo em conta o desempenho mecânico, económico e ambiental.



**Palavras-chave:** Triagem dos constituintes renováveis, fibras de rami, bio-resinas fabrico dos compósitos verdes, moldagem por transferência de resina, caracterização experimental, modelo de custo do processo, degradação ambiental, desempenho ambiental.

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The present thesis has been performed at the Instituto Superior Técnico, school of engineering, part of the Universidade Técnica de Lisboa (Technical University of Lisbon) at the Alameda Campus. I would like at first to gratefully acknowledge the support of the Portuguese FCT foundation - Fundação para a Ciência e a Tecnologia; for granting me with a Ph.D. scholarship under reference number: SFRH/BD/33971/2009. I would like to thank especially my supervisor Arlindo Silva and co-supervisor Elsa Henriques for their guidance, support and encouragement throughout the accomplishment of this work. I owe gratitude to Daniel Whitney for his practical advice, assistance of technical details and fruitful feedback during the completion of this thesis. Additionally I want to thank Jeremy Gregory for hosting me at the MIT and providing me all the useful documentation and practical advice on the cost modeling for the period of my visit at the United States.

Moreover, I want to thank the owner, internship supervisor and helpful personnel of Ancel Ltda in Rio Claro - Brazil, for receiving me and providing me with all assistance I needed back then. I am very grateful to all of the academia people that had helped me throughout my thesis deployment: Ana Soares, Alexandra Rodrigues, Mihail Fontul, Manuel Freitas, Samuel Furtado, Ana Povoa, Carlos Bernardo, Cristiano Alves and Bruno Soares. I really appreciate all the rest professors, colleagues and personnel of IST University whom I had to ask help from and which I was bounteously given. I must give my ultimate thanks to the rest of colleagues of Portugal that accepted me as a friend and contributed in making my 4 years stay in Lisbon pleasant and memorable.

*Σας ευχαριστώ όλους για αυτό το υπέροχο ταξίδι γνώσης!!!*

Translation from Greek:

*Thank you all for this amazing journey of knowledge!!!*

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# Chapter 1. Thesis Context

## 1.1 Introduction

It has nowadays emerged as a compulsory necessity that we stop developing materials which pose an environmental hazard. As a result novel substitutive solutions based on the concept of bio-based materials have now become of key importance. Added to that, the increasing environmental consciousness among societies has led the composite's industry to search for new ways of producing environmentally friendly materials into a greater extent.

A major concern for automotive manufacturers is the trade-off between cost and sustainability. One way to balance sustainability and manufacturing cost in automotive panels is by the use of composites with renewable materials as already explored by a number of automakers. Analogous components have been applied on trim parts in dashboards, door panels, parcel shelves, seat cushions, backrests and cabin linings. In recent years there has been noted an increasing interest on replacing fiberglass in reinforced composites by introducing natural plant fibers such as jute, flax, hemp, sisal and ramie [8-10]. Recent advances in composite development have often attached the term "green materials"; setting it a buzzword in every construction that incorporates renewable constituents. In order to moderate this misinterpretation; inside this research scope, the term of "**green**" shall be used with the intention of describing materials of considerable renewable content in both matrix and reinforcement.

Broadly speaking, a natural based material can be defined as a product made from renewable agricultural and forestry feedstock, including crops and crop by-products and its residues. A green composite in its turn is another product being manufactured entirely by renewables or a mix of synthetic and natural based products at a discretionary percentage. By the addition of **annually renewable** materials in the composite's constitution; the overall composite itself can be rendered **"green"** and therefore to a certain extent will contribute to a more sustainable application in terms of material usage and energy savings. On the other hand, reduced dependence on petroleum products provides value added opportunities for agricultural industries as the swift natural and

renewable products will increase the demand on crops and/or raw materials intended for green composites.

All this goes to show that by bringing sustainable products to the market provided that their constituents derive from renewable resources they may well show very promising potential and benefits to companies, the natural environment and end-customers when compared to materials made of dwindling petroleum resources.

### 1.1.1 Motivation

The shift to more sustainable constructions in automotive industry is not only a continuous upward trend towards a more viable environment and cost efficiency but also a demand of European regulations. The latter are playing an important role as a driving force toward sustainable materials' usage. According to the European Guideline 2000/53/EG issued by the European Commission, 85% of the weight of a vehicle had to be recyclable by the year 2005. This recyclable percentage will be increased to 95% by 2015 [11]. On the other hand, the increment of consumer awareness regarding recycling and the impact of these materials on the environment have also played a key role in their adoption from both society and industry. All this has definitely led to greater impetus for the development of commercially viable biodegradable composites [2].

From the perspective of society, the informed customers may be willing to pay more as they also become more ecologically conscious of green products [12]. As a result they are seeking to purchase eco-friendly products and services, preferring firms that are in favor of environmental practices.

From the automotive standpoint composites reinforced by renewable natural fibers have enhanced environmental performance as well as added benefits regarding weight-savings when compared with conventional glass fibers reinforcements. On top of that, higher profits margin may be generated by the use of the natural fibers since these are generally less expensive than the synthetics for a new breed of manufacturers. When Mercedes-Benz released the Travego travel coach model reported to have 5% of cost reduction whereas around 10% weight decrease accomplished with a flax-reinforced engine/transmission cover [7]. In another example, by incorporating abaca fibers on composites panels, up to 60% of the energy was saved from the manufacturing phase for the exterior of the Mercedes-Benz A-Class [13, 14]. Daimler Chrysler also reported to have 10% weight savings and 5% of cost reduction just like in the Travego success story [13]. All the above successful industrial applications may be considered as efficacious

instances, and rendering confidence in analogous improvements/benefits when natural fibers are applied on a hood for this particular research.

### 1.1.2 Approach

The analytical methods employed in this investigation are according to the engineering systems perspective and also aligned to the methodological tools and approaches implemented during the MIT-Portugal Engineering Design and Advanced Manufacturing curriculum.

**a. Materials Selection and experimental testing**

The first task is to identify possible body parts to be manufactured with renewable materials. For these applications, screening of candidate materials and processes will be employed to assess whether they meet certain primary goals of performance/cost. The way to do that is using an integrated tool as the Life Cycle Engineering (LCE) methodology [15]. As an output of this screening, a set of promising materials to be applied in a bio-composite production was identified. Thereafter a number of composite sheets were produced and tested for obtaining their fundamental mechanical properties and durability performance to be compared against traditional baseline concepts.

**b. Application of Cost Models**

As a second step, a process cost model is implemented, a tool that was adopted and further modified during the thesis' author visit at MIT in the Materials System Labs. There will be identified the major cost drivers via the use of a process cost modeling technique. This type of cost projection also provides cost and pricing information so the decision makers can make better choices when aligning their companies to the future challenges of technology and increased competitive pressure. This economic analysis examines how the choice of materials and processing technology affects production costs. A cost model is composed of three interrelated and interdependent models: a technical process model, a production operations model, and a financial accounting model [16]. Accordingly two optional manufacturing processes will be economically ranked against each other while different materials combinations and manufacturing settings will be altered accordingly in order to identify key-factors of the cost change.

**c. Environmental Performance**

The last step of this analysis is comprised of an intermediary environmental assessment. The environmental performance of the composite will be quantified with the data and the aid of software, so as to identify traits and areas that need improvement regarding its overall manufacturing/energy footprint. The tool to be used here is the software of CES Selector by Granda Designs [17]. This is an appropriate tool that assists its user to identify the most significant environmental costs. The objective is to get an approximate product's environmental performance during the early stages and thus focus attention on the areas which can lead to the biggest improvements. Through that assessment the several forthcoming scenarios will be compared with each other in an attempt to draw out some conclusion as regards their environmental footprint.

## 1.2 Objectives

The preliminary objective of this research is to adequately substitute the material in a composite construction intended to be fabricated by a Brazilian composites manufacturer using unsaturated polyester and fiberglass mats. A proposed solution will be explored through the proper use of constituents that derive from natural renewable resources at the maximum achievable percentage. The results will be advisedly compared with the findings of another green composite proposed by Alves [18] which was correspondingly intended for the very same application, although comprised of different substance, namely by unsaturated polyester and jute fiber fabrics.

The present proposal is expected to contribute on partially reducing the weight of the vehicle and contribute in higher maximum range with reference to fuel economy. Above all, the effort is to bring up a sufficiently designed "green composite" which will best balance performance, manufacturability and affordable production cost. Succinctly stated the objectives of this study are the following:

1. Investigate the prospective replacement of the traditional composite which derive from synthetic sources with a composite of increased renewable substance.
2. Incorporate the proposed "green" part accordingly into the manufacturing process.
3. Assess its cost and environmental performance.

## 1.3 Research Questions

With the abovementioned objectives a set of linked research questions arise which are branching out into this study area regarding to the green composites production and cost aspects.

1) Which constituent materials may concurrently substitute the buggy hood in terms of performance/cost for the matrix and the reinforcement on the suitable green composite application?
   a) Does this selection satisfy current industry's standards?
   b) How promising is the mechanical performance of the proposed composite?

2) How will the manufacturing of this composite be introduced into the automotive industry's current production facilities?
   a) Can the resulting process be cost effective? In what extend?
   b) Is it possible for the composite to be massively industrialized?

3) What is the impact of the new constituents on the environment?
   a) Where do the greatest improvements or harms can be identified?
   b) Which factors make the greatest contribution on that?

## 1.4 Scholarly and Practical Significance

The bio-polymers have already penetrated a great number of consumer's industries such as the automotive; in which they typically target the eco-minded consumers. In parallel, remarkable academic research has been conducted in recent years on the field of novel green composites development, as long as positive environmental impact and performance (from cradle to grave) are being considered. As a result, bio-plastics have begun to fragment in a greater than ever number of market segments — from packaging, consumer electrical/electronics, automotive and agriculture, to a number of other subdivisions of the global plastics market.

Fundamentally, for automotive applications, several industrialized green solutions have been launched making use of renewable natural based materials in exterior parts. Major car makers such as Toyota [19], Mercedes [14] , Lotus [20] are striving to combine the optimum materials for a light weight green composite production. Despite that, their products either contain renewables in very small volume fractions, or are parts of high renewable volume faction but applied in a small surface of the vehicle's body. As a

consequence the resulting composite parts are not considered green solutions of high renewable content or by the nature of their embedment cannot contribute to noteworthy synthetic/exhaustible material's saving.

On the side of the academic research; a number of studies are aiming for automotive composites applications taking advantage of the renewable natural fibers as reinforcements in polypropylene (PP) matrices [9, 21-26] or just renewable resins as matrices [27-31]; but thereafter the addressed applications are intended for interior or nonstructural parts. Some other researchers have investigated the potential of incorporating chopped ramie mats and kenaf fibers in acrylic composites targeting the automotive industry [32]. Particular research has been accomplished up to date for producing polylactic acid (PLA) resins with the addition of natural fiber reinforcement as flax [33, 34] or short ramie fibers [35, 36]. However, to the best of the author's knowledge there is no recent or past study which uses bio-thermosets with the addition of long ramie fibers and specifically biaxial woven fabrics for the automotive industry. In fact, no other researcher that tested composites exclusively for exterior parts of a vehicle and with the use of the former constituent combination or similar composite constructions has been identified.

This thesis will tackle all the aforesaid gaps by the development of a green composite of high renewable content and for an exterior part of considerable volume. The matrix system to be evaluated is a bio-polymer that contains a percentage of renewable vegetable oils in its constitution. The reinforcement is a totally natural and renewable product; namely a vegetable bast fiber.

In practical terms, it shall be attempted to shed some light on aspects that ordinarily are not investigated by former researchers. It will be not deliberated a particularized assessment of the manufacturing conditions and determination of mechanical performance as customarily comes about. The intension is to additionally characterize composites performance when coated and aged in lab's environmental chamber. Regularly, numerous studies are making use of accelerated aging on their specimens in order to test their exposure to environmental conditions. However, few of the studies test them when coated/painted and less than few follow all the foregoing steps together (aging samples of painted and non-painted specimens).

In due course, the proposed research is expected to provide significant contributions to the scholarly understanding of mechanical and environmental performance for an extra set of material choices regarding ramie woven fabrics and a

novel bio-resin that up to now have not been investigated in combination with each other.

## 1.5 Hypothesis

As it has often been observed in the current industrial setting, several firms are looking favorably at incorporating greener materials in their products, both as a step of reducing the environmental burden and also as a way of appealing to a growing environmentally conscious market. The car makers in particular are constantly in search of chassis components that are lighter, more eco-friendly, and are still adequate for low cost mass production. Following that principle, Ancel Ltda -Rio Claro, Brazil (composite manufacturer and supporter of this thesis project) has been developing a buggy vehicle adopting a green composite concept by incorporating natural fibers reinforcements in a hood while minimizing manufacturing cost [9, 18]. Building upon that past research the palette of choices as regards the reinforcement options will be broadened while in parallel introducing further dimension of analysis and bringing added insights about the green composite adoption for the very same part application.

Having been triggered by the objectives and motivated by a number of research papers and industrial examples, the present thesis topic has been specially designed and constantly refined to validate the following: hypotheses and sub-hypothesis, which have been the thesis key-drivers

- **Hypothesis 1:**

**A prospective green composite embodied on automobile hood part of the buggy vehicle can provide mechanical performance close to a conventional synthetic composite solution. The exploration of modernized and readjusted manufacturing techniques may contribute additionally to its appropriateness of use.**

- **Hypothesis 1.1:**

**It is realistic that its fabrication can be rendered cost-appealing compared to the baseline manufacturing practice scenario.**

## 1.6 Summary

This thesis work is deliberately setting under consideration a forthcoming green composite component under a three stage analysis regarding its overall performance. It is expected that throughout that approach it will be succeeded an additional broad understanding of a green composite performance rather than getting a single dimensional mechanical study.

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# Chapter 2. STATE OF THE ART AND OF PRACTICE

## 2.1 Bio-plastic's Market Analysis

As expected, the novel bio-plastics will not just contribute to the prevention of global warming and the depletion of petroleum resources; their recyclable nature will also have a positive impact on waste management in urban areas and unlock the perspectives of revolutionizing the cycle of energy production and usage in all aspects, creating a self-re-enforcing cycle of producing, recycling and reusing [37]. Picking on that theme, bio-plastics' advantages of renewable resources derivation (biomass), as well as their gradual commercial availability are the primary reason that spur industry's dynamic development. Today, bio-plastics deriving from renewable resources only account for a very small share of the entire plastics market which is nominally less than 1% [5], eventhough the rapid advances in biotechnology and biochemistry will further move forward this fast growing market.

In an recent environmental report funded and published by the European commission on 2011, it is clearly pointed out that the production of bio-plastics will increase rapidly in the next years up to 2015 while retaining a relatively low proportion of the total plastic use inside EU [38]. Most important of all, with the annual depletion of the petroleum and the constant concern for the global environmental changes it has been opened a new era for early adoption of bio-resins also known as green resins by the plastic industries. Currently, driven by demands of the establishments in power and end consumers' calls; the aforementioned markets appear to be steadily growing according to a research conducted by the University of Applied Sciences and Arts Hanover (Germany) on behalf of European Bio-plastics. In rough calculations it is noted that there is an increment of 20% in production rates per year, in addition to that, the investigation demonstrate that production capacities worldwide are expected to be doubled reaching 6 million tons between the years 2010 and 2015 [39]. On another market analysis it is stressed out that biodegradable plastic markets will grow up to US$6 billion by 2015 and over US$12.5 billion by 2025. The market share of this segment for Automotive and Electronics will reach over 25% by 2025 with higher profit potential [40].

In fact the disposal and exportability of fossil carbon sources are known to be limited as being a finite resource that does not renew itself at a sufficient rate. As a result,

oil prices have constantly increased during the past few decades affecting the plastic industry on cost of the raw material. For instance, it was recently announced by Reichhold Inc— one of the leading supplying companies in the polymers market back on September 2012; a price increment for all unsaturated polyester resins, vinyl ester resins and flame retardant resins sold in North America for the composites industry [41]. This followed up after a persistent escalation of raw materials prices. It is even more evident, therefore, that the shortage and high cost of fossil resources will bring on alternative recourses and process to take over a leading role in the near future of plastics production.

### 2.1.1 The natural fiber composites market

According to Lucintel — a leading global management consulting and market research firm; the global natural fiber composites market reached US$2.1 billion in 2010 as quantified in their annual market report. Current indicators are showing that demand for natural fibers and resins will continue to grow rapidly in the global composites industry. Over the last five years the use of natural fiber composites has increased substantially in the construction and automotive industries. The natural fiber composites market is expected to grow with a Compound Annual Growth Rate (CAGR) of 10% over next a 5 year period from 2011-2016 [42]. Some of the positive factors which have the ability to drive natural fiber composites market growth above current projections are: low cost versus synthetic based products, light weight benefits, and the fact that they are eco-friendly reinforcement alternatives. According to the same report, the composite materials industry is expected to reach US$ 27.4 B by 2016 at a CAGR of 5.3% [43].

Recent dynamics which are driving market development are both internal and external. External factors make bio-plastics the attractive choice, as can be derived from the high consumer acceptance, the extensively publicized effects of climate change, drastic price increases of fossil materials, and the increasing dependence on fossil resources [5]. In addition, an increasing fraction of organic chemicals — comprising various low molecular weight compounds and biopolymer is being produced through the biotechnological or chemical conversion of renewable biomass [44].

From the internal perspective, bio-plastics have been rendered nowadays as efficient and technologically mature materials in terms of their use. They have the potential to improve the balance between the environmental benefits and the environmental impact of plastics. The increasing utilization of biomass in bio-plastic applications has a clear advantage: renewability and availability. The limited crude oil

reserves can be saved and additional crude oil imports from unstable regions can be reduced. From this standpoint, bio-plastics have the potential to reduce the petroleum consumption for plastic at 15-20% by the year 2025 [40]. What is more, a number of Life Cycle Analyses (LCA) show that bio-plastics can reduce $CO_2$ emissions by 30-80% compared to conventional plastics (depending on material and application and under certain conditions) [45, 46]. For instance, given that PLA resin production does not require petroleum feedstock, the carbon emissions result only from the equipment used to harvest the plant crop and from the energy required to run the manufacturing process [45].

Within the plastic industry, bio-plastics simply make sense because of increasingly advancing technical properties and functionality, the potential for cost reduction through economies of scale, and the new recycling option they represent. Automotive companies like Mazda having become conscious about the benefits of bioplastics are in a long research project in pursuit of bio-plastics to be incorporated in its car models as injection-molded interior parts. That project is a consortium consisting of two universities, six companies and two research institutes initiated on 2008 aiming to have bioplastics in Mazda models by the year 2013 [47].

### 2.1.2 Development in Europe and beyond

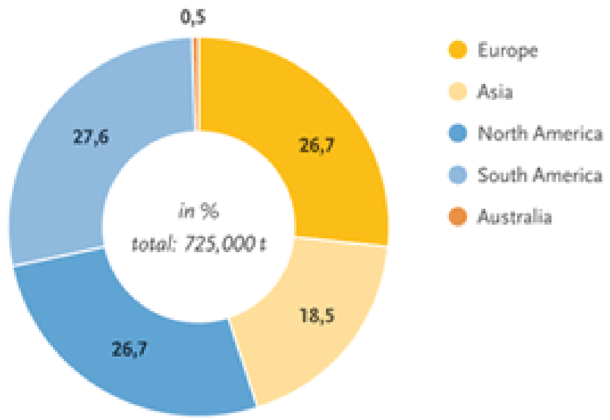
Numerous countries outside the European Union are actively pursuing the development of bio-plastics, yet Europe in particular offers excellent conditions to compete globally for future markets and technologies. Bio-plastics production in Brazil also remains very attractive due to its cost competitiveness and positive demand drivers, such as increased consumer interest in environmentally friendly packaging and a greater emphasis on sustainability on the part of product manufacturers worldwide [37].

They are both the constitutional materials and accessories for lots of sectors including automotive, maritime, aeronautics and construction industries which are sectors of competence with skilled workforce and a key driver of knowledge and innovation. Europe’s future economic success and prosperity depend on an efficient growth of more sustainable high-tech industries, among them bio-plastics and green chemicals (see Figure 2.1). Europe offers excellent conditions to compete globally for future markets and technologies including:

- A highly developed economy and educated society
- Leading global companies in the chemical and plastics industries
- Industrial users with the aim of promoting sustainable development

- Consumers with strong purchasing power and a high degree of environmental awareness
- Legislative and regulatory frameworks that actively promote sustainable development and aligned innovations

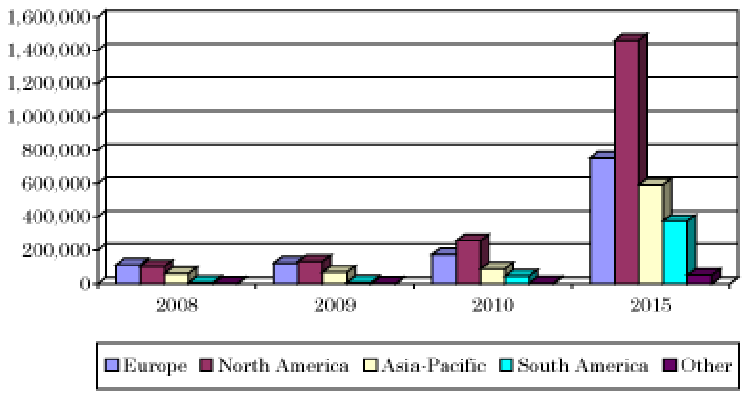
**Figure 2.1. Production capacity of biopolymers in 2010 (by region).**




*Source: European Bioplastics [5]*

The use of bio-plastics got off to a faster start in Europe than in the United States. European usage is now reported at 175,320 metric tons in 2010 and is expected to increase at a 33.9% CAGR to reach 753,760 metric tons in 2015 [48] (see Figure 2.2).

**Figure 2.2. Use of bio-plastics by global region 2008-2015 (metric ton).**




*Source: Douglas [48].*

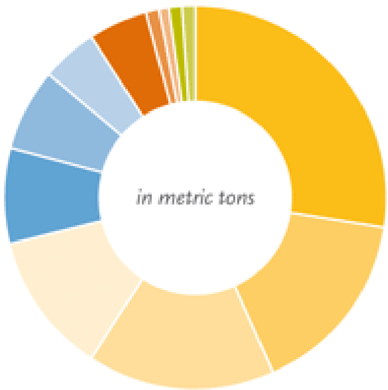
Continuous research and development efforts in bio-plastics are creating high quality products for a wide variety of industries. As far as the benefits of biologically sourced plastics are well-understood, their market share is likely to rise sharply. The drivers of growth as — the importance of brand image to consumer goods companies,

the value of joint composting and the reduction of litter – will spur continued growth in bio-plastics across the world [49].

### 2.1.3 Market development status

Bio-plastics materials and products have been on the European market for more than two decades. The European Union has traditionally been an important net exporter of "plastics" and plastic products. This trade balance grew by over 100% between 2000 and 2010, reaching a total trade surplus of 15.7 billion Euros in the year 2010. [50]. Taking in account global past statistics, it is projected that the demand for plastics will continue to rise following a trend that has increased since the 1950s. Below in Figure 2.3, are presented the most commonly used bio-plastics. These products are largely compostable like biowaste bags and loose fill.

**Figure 2.3. Biopolymers production capacity 2010 by type.**




| | | |
|---|---|---|
| Bio-PE | 200.000 | 28 % |
| Biodegradable Starch Blends | 117.800 | 16 % |
| PLA | 112.500 | 15 % |
| PHA | 88.100 | 12 % |
| Biodegradable Polyesters | 56.500 | 8 % |
| Bio-PET | 50.000 | 7 % |
| Regenerated Cellulose[2] | 36.000 | 5 % |
| Bio-PA | 35.000 | 5 % |
| Cellulose Derivatives[1] | 8.000 | 1 % |
| PLA-Blends | 8.000 | 1 % |
| Durable Starch-Blends | 5.100 | 1 % |
| Others | 7.500 | 1 % |
| **Total** | **724.500** | 100 % |

*[1] only cellulose ester | [2] only hydrated cellulose foils*

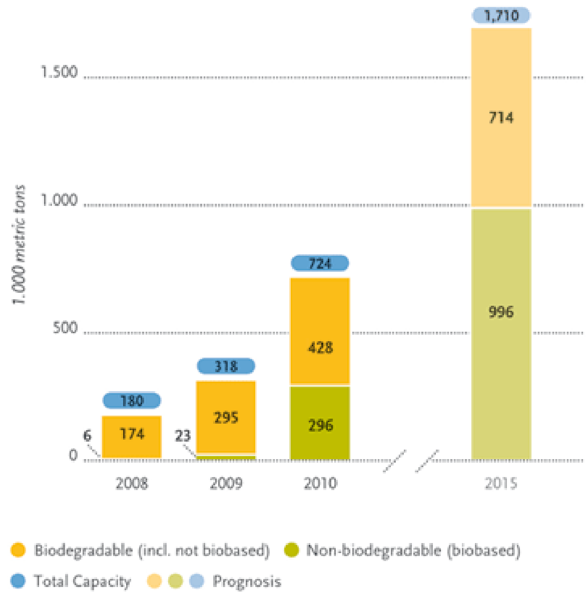
*Source : European Bioplastics [5]*

The global production capacity for bio-plastics summed up over 700,000 tons in 2010. Following the technical trial facilities at the beginning of the 1990s and the subsequent upscaling phase, industrial-scale capacity has now been achieved. As more facilities go on-stream, production of bio-plastics is projected to increase to more than 1.7 million tons by the year 2015 (see Figure 2.4).

The dynamic development of the bio-plastics industry has a huge impact on other sectors. The field of bio-chemicals is growing by a tenfold compared to the conventional chemical market. To put this into relative comparison: while the chemicals market is

expected to grow by 60% between 2007-2017, the bio-based chemicals market is projected to grow by more than 600 % [5].

**Figure 2.4. Global production capacity of bio-plastics**




*Source: European Bioplastics [5]*

### 2.1.4 Market drivers

As indicated above, the bio-plastics market is growing gradually in size capacity per year. For industry players, the advantages focus on advanced technical properties, which increase product attractiveness, impending cost reduction through economies of scale, and the development of additional disposal options.

#### 2.1.4.1 Potential

The European Union has initiated an important move towards efficiency and sustainability in the era of low carbon resource by taking the decision to formulate a "European Strategy and Action Plan on the bio-based economy by 2020" [51]. As the European Commission appropriately acknowledges, the bio-based economy has the perspective to contribute not only by tackling global problems such as climate change, $CO_2$ emissions reduction and sustainable economic growth, but also to advance research and innovation excellence in Europe. To that extend, more sustainable agricultural policies linked to regional and rural development can be achieved as well.

Plastic products are omnipresent in our society and will remain indispensable in the future. They are expected to make our life safer and more pleasant; while the substitution of petroleum-based plastics with bio-based plastics is seen as a promising

alternative that will prospectively reduce the dependency on fossil resources and the pressure on landfills from plastic solid waste. The chemical and plastics industries are changing their crude oil based products profile with up to date and greening strategies in order to be aligned with the current society demands. Many positive initiatives supporting sustainability are also evident, such as extending shelf-life and efficient material use. Development and commercialization of bio-based plastics for a variety of uses in products and packaging is also a domain of great interest where manufacturers are striving to substitute materials of concern with safer and healthier materials for their consumer products.

The development and expansion of the bio-plastics industry in Europe while enhancing the shift on renewable (non-food) feedstock as raw materials; it can contribute as well to the on-going shift of European agricultural policy towards more sustainable and environmentally friendly activities. The latter, may direct to excellent new business and innovation opportunities for European agriculture societies.

#### 2.1.4.2 Bio-plastics market growth

The total polymer consumption of Western Europe is about 50 million tons per year. According to an research group from the Netherland's University of Utrecht, bio-plastics could theoretically substitute about 42 million tons of this amount [52]. Technically, bio-based plastics could potentially substitute about 85% of polymers' use. Nevertheless, there is simply not enough volume produced yet to make this a short or midterm possibility. As aforesaid, the production of bio-plastics is projected to increase by 2015 therefore new polymers that are biodegradable (e.g. starch-based materials) provide ample opportunities for converters, brand owners, retailers and consumers.

Up to now though, these bio-materials are considered to be very expensive comparing to their cousin synthetic plastics. Given that production capacities grow, supply options for bio-plastic materials and products will increase considerably. In addition, based on forecasts for the development of crude oil prices, the use of renewable resources are expected also to become increasingly economical in the future. Moreover, as costs of raw materials play a crucial role for the economy of the Polyhydroxyalkanoates (PHA) production process, alternative substrates derived from waste streams could help reduce the costs [53]. An example to that is the PLA which in an industrial scale production, the manufacturing cost of lactic acid monomer will be targeted to less than 0.8 US$/kg because the selling price of PLA should decrease roughly by half from its price of 2,20 USD/kg [54] as referring to the year 2010. On the

other hand, the production cost of polyhydroxybutyrate (PHB) could be considerably reduced by replacing the pure substrates with activated sludge a well-known mixed culture [55], and likewise in industrial scale application lower cost can be achieved as expected.

### 2.1.5 The market of the natural fibers as reinforcements

Driven by increasing environmental consciousness, automakers in the 1990s made momentous advancements in the development of natural fiber composites, with end-use primarily in automotive interiors by Daimler AG [7, 56]. Since then, the market for industrial natural fibers has intensified its demand; with significant annual peaks per decade.

Germany-based Oerlikon Textile GmbH & Co. KG - a division of Switzerland-based OC Oerlikon Corp. AG - and The Fiber Year Consulting have published "The Fiber Year 2011" report providing a comprehensive survey of the global textile and non-woven industries. According to that document, the global textile industry in 2010 experienced the most potent growth in the latest twenty-five years. Annual fiber growth averaged 3.4% in the last decade, with manufacturing volumes of natural and man-made fibers rocked upwards by 8,6 %, or 6.4 million metric tons, to 80,8 million metric tons.

Getting into the market segment which is more related to this thesis research, namely the natural fibers, it is noted that their market has increased 2,2% while manufactured cellulosic and all major man-made fibers excluding acrylics increased at double-digit rates [57, 58] in the aforesaid 25 years period. This corresponds to an average per capita consumption of 11,8 kg. Thus, an average annual fiber growth of 3.4% in this decade compares to a yearly population rise of 1.2% in that time frame. While cellulosic and synthetic fiber segments both produced double-digit growth, natural fiber expansion was content with a lean 2.2% expansion [58].

Consequently, after carefully noticing this information and markets' statistics, it would be very attractive from the side of the stakeholders to invest in this upcoming market and take advantage of its potential growth. Regardless of whether or not the investment is highly profitable, natural fibers as reinforcement are proven to be worthy of remark for future composites. Specifically, considering that broader use in various composites constructions of larger scale is well anticipated.

## 2.2 Green Interior Composites in the Automotive Industry

In recent times conscientious effort has been made in order to reduce the amount of expensive glass, aramid or carbon fibers while in parallel lighten considerably cars' body by taking advantage of the lower density and cost that natural fibers provide. In such manner, renewable fibers as reinforcements were vastly exploited for producing composites of interior parts in a number of passenger and commercial vehicles.

Mercedes-Benz used an epoxy matrix with the addition of jute fibers in the door panels in its E-class vehicles back in 1996 [7]. Another paradigm of green composites' application appeared commercially in 2000, Audi launched the A2 midrange car where the door trim panels made of polyurethane reinforced with a mixed flax/sisal mat [56]. Toyota on its turn claims to be the leading brand in adoption of environmentally friendly materials as 100% bio-plastics. The natural fiber reinforced green composite was used in the RAUM 2003 model in the spare tire cover. The part made of a PLA matrix from sugar cane and sweet potato and it was reinforced with kenaf fibers [19]. In later examples Mitsubishi motors developed interior components which combine bamboo fibers and a plant-based resin polybutylene succinate (PBS), and floor mats made from PLA and nylon fibers for [30]. Toyota started incorporating renewables on its models during 2007 by introducing soy-based seat foams Corolla and Lexus RX models. At the summer of 2008, following its own initiative it added the Matrix and RAV4 to the list of vehicles utilizing renewable resourced materials. [59]. Recently, Ford selected wheat straw as reinforcement for the storage bin and inner lid in its 2010 Flex crossover vehicle while BMW, for the 7 Series sedan used prepreg natural fiber mats and a unique thermosetting acrylic copolymer for the lower door panel [60]. Lately, Toyota developed an eco-plastic made from sugar cane and will use it to line the interiors of the cars. In fact, its first use will be on the new CT 200 for its luggage compartment as announced at Automotive World Congress on January 2011 [61].

## 2.3 Green Exterior Composites in the Automotive Industry

The concept of natural fiber incorporation in exterior automotive parts is not new; dealing with an exterior part though is more complex compared with the interiors cousin parts which are protected from weather conditions. The exterior components must be able to withstand extreme conditions such as exposure to wetness and chipping (not splinter due to mechanical impacts) [7] caused by debris making contact with the external surface. For this reason these components pose interesting issues for the manufacturers,

bearing in mind that these applications must function as a protective cover for the vehicle and thus maintain their performance.

The first release of exteriors green composites for automotive parts appeared back in the year 2000, when the Mercedes-Benz Travego travel coach model, was equipped with a polyester/flax-reinforced engine and transmission enclosures for sound insulation [13]. These are the first examples of natural fibers' use for standard exterior components in a production vehicle and represent a milestone in the application of natural fibers [7]. However, these parts were under the hood and thus it is questionable whether they can be classified as exteriors. Some years well ahead, Daimler-Chrysler AG (Stuttgart, Germany) started using fibers of the abaca plant in place of fiberglass for the production of the spare tire well covers of the Mercedes-Benz A-Class, two-door coupe vehicle in 2004. They patented this novel mixture of polypropylene (PP)-thermoplastic and abaca fibers back in the year 2002 [14]. That was the first large-scale application (about 40 metric tons/88,000 lb. per year) of natural fiber composites in an exterior part [62].

In another research project, bio-based materials were used in high ratio content while presenting very notable structural performance. A homogenous part made of thermoset resin (PTP® prepreg) and hemp fibers successfully replaced a conventional polyester-fiberglass reinforced component. The novel bio-based resin consisted of 90% renewable content materials. The green composite was assembled on the middle section between the headlights above the fender of MAN passenger's bus and was successfully tested for its resistance to weather conditions [31]. In ECO Elise concept car which demonstrated on July 2008, Lotus swapped out its typical fiberglass reinforcements for hemp fibers in the composite body panels, the double-curvature fixed hardtop and the spoiler [20]. Sustainable hemp technical fabrics have been used as the primary constituent in the high quality 'A' class composite body of polyester base. Exposed hemp fibers in an unpainted stripe from the bumper to the spoiler made a striking eco-contrast to the metallic finish which signals immediately that this car is different.

**Figure 2.5. Eco Eclipse concept car by Lotus**

Some of the abovementioned concepts are indeed taking advantage of natural fibers into bio-resins and are striving to combine the optimum materials for a light weight composite production of high renewable content. Nevertheless, these composites either employ only partially renewable constituents (resin or reinforcements) or they are not applied in large surfaces of the vehicle's body. Therefore, on one hand they are not considered fully green solutions and on the other hand they cannot contribute to great material's saving and to noteworthy weight reduction.

## 2.4 Constituent Materials for a Green Hood Composite

An integrated procedure to identify the most adequate constituents (resin and reinforcement) for the production of a prospective green composite to be applied as a hood part is presented concisely in this paragraph. By comparing measured values adopted by studies regarding the mechanical performances of fibers, matrices and identical composites, it is depicted which combination holds the best potential for a composite of fair structural performance.

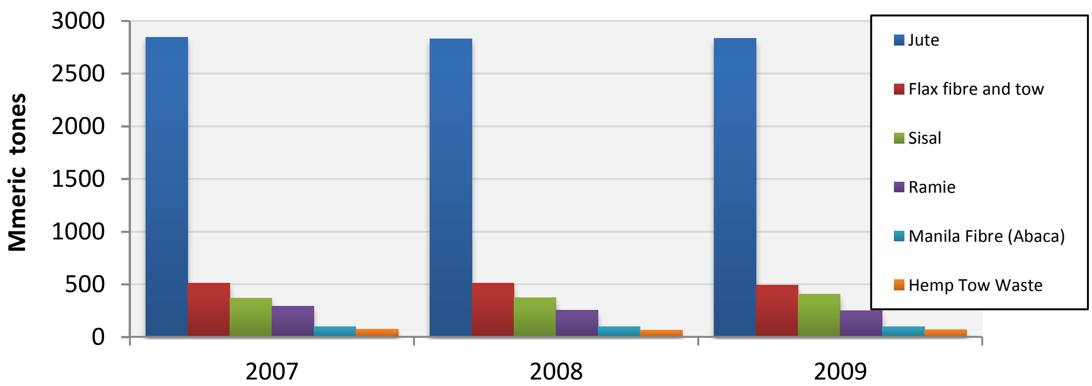
### 2.4.1 The reinforcement element

Natural fibers come from renewable plants that grow in crop fields and can be used as filaments or reinforcements in composites manufacturing in the same way as ceramic or glass fibers for instance. They exhibit numerous of distinct advantages over synthetic ones which have been extensively acknowledged by the scientific community in recent years [3, 6, 63, 64]. Among the advantages as regards the natural fiber adoption is that they are less abrasive to processing equipment, they are cheaper to buy and of lower density while additionally have high thermal conductivity and acoustic insulating properties. They have also competitive specific mechanical properties, carbon dioxide sequestration, and lower eco-toxicity while bringing attached higher sustainability,

recyclability, and biodegradability. Furthermore, they lack of residues upon incineration and the amount of energy required for the production of plant fiber textiles fabrics is estimated to be ~ 80% lower than for the production of glass fibers [3].

Throughout the bibliographic research it was set out that a lot of interest on composites construction in automotive applications has been given to fibers like abaca [14], kenaf [32], hemp [20, 31] and flax [25]. That is partially observable because of their present application in other automotive enclosures parts and consumer plastic products. Recently, significant attention has been given to the abundant jute [9] and to the stiff ramie fiber [35]. Figure 2.6, contains data on the annual volume production per plant for many kinds of fibers that were found on the aforesaid studies. The data was adopted from the FAOSTAT information bulletin of the food and agriculture organization from the United Nations.

**Figure 2.6. Annual volume grown per fiber plants in world production**




At the outset, it is clearly understood why lots of studies are focused on jute fiber composites aiming for automobile applications [9, 65, 66]. In fact, they are by far one of the most abundant fiber plants being cultivated worldwide and with fair mechanical performance. On the other hand, flax is one of the most important and widespread bast fibers in Europe. About 80% of the total world flax crop is grown in France, Belgium, Spain, UK and Holland. Flax is relatively stronger, crisper and stiffer to handle [67]. Ramie fibers are highlighted by numerous studies because of their valuable mechanical properties [68-70]. From the early years of natural reinforcement research, they have been proven to provide good performance when compared to the other fibers as seen in the study of Hermann et al., [8]. Abaca fiber (or manilla hemp) has been proven another good exemplar for reinforcing exterior automotive parts as previously indicated in paragraph 2.3 for the case of Mercedes-Benz cars. On the contrary, considering a recent study of Bledzki, et al [71] whereas abaca fibers were tested in a composite system and

were characterized by lower mechanical parameters in comparison to jute. The explanation for this untypical behavior of the composite could be the fiber processing method which differed from the one of jute. Similar results were shown in another past study of the same author [23] where jute and abaca were tested in PP matrices.

### 2.4.2 Mechanical performance of natural fibers

In order to have a broader view of the mechanical and physical properties of different natural fibers, available data from several authors has been compiled as seen on Table 2.1. Indicative prices (USD/kg) listed below are adopted from several nonconcurring sources and thus may not represent the present state.

**Table 2.1. Properties of several natural fibers in relation with E-glass.**

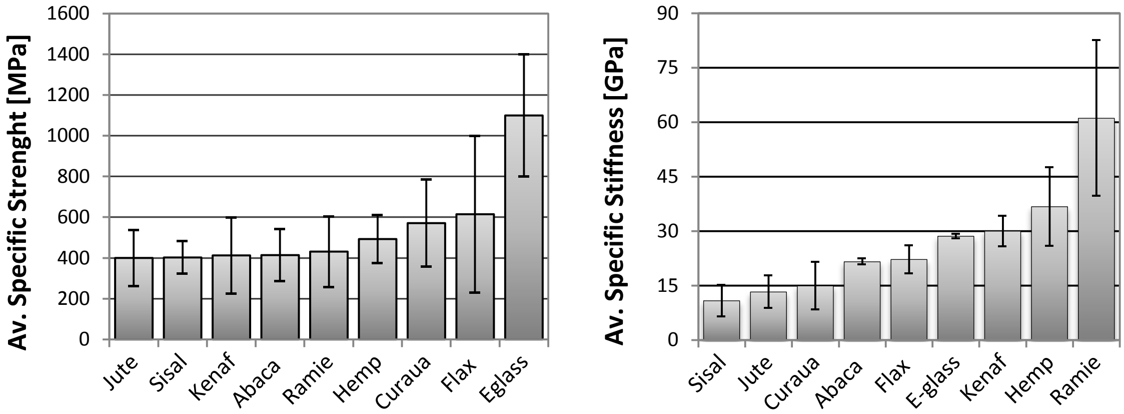
| Fibers | Density (g/cm3) | Diameter (mm) | Tensile Strength (MPa) | Young's Modulus (GPa) | Elongation at Brake (%) | Price (USD/kilo) | |
|---|---|---|---|---|---|---|---|
| Flax | 1,5 | 40 – 600 | 345– 1500 | 27 – 39 | 2,7 – 3,2 | 3,11 | [72] |
| Hemp | 1,47 | 25 – 250 | 550 – 900 | 38 – 70 | 1,6 – 4 | 1,55 | [72] |
| Jute | 1,3- 1,49 | 25 – 250 | 393 – 800 | 13– 26,5 | 1,16 – 1,5 | 0,92 | [72] |
| Kenaf | 1,5 – 1,6 | 2,6 – 4 | 350 – 930 | 40 – 53 | 1,6 | 0,37 | [72] |
| Ramie | 1,5 – 1,6 | 0,049 | 400 – 938 | 61,4– 128 | 1,2 – 3,8 | 2 | [72] |
| Sisal | 1,45 | 50 – 200 | 468 – 700 | 9,4 – 22 | 3 – 7 | 0,65 | [72] |
| Curaua | 1,4 | 7– 10 | 500 – 1100 | 11,8 – 30 | 3,7 – 4,3 | 0,45 | [73] |
| Abaca | 1,5 | 10 – 30 | 430 – 813 | 31,1–33,6 | 2,9 | 0,34 | [74] |
| E–glass | 2,55 | 15 – 25 | 2000– 3500 | 70 – 73 | 2,5 – 3,7 | 2 | [72] |

*note: The values are adopted from the studies and databases [22, 25, 56, 70, 75-79]*

[a] *References inside the table are indicating prices only.*

By the values obtained from Table 2.1, two graphs are created in Figure 2.7 illustrating the mechanical performance of the fibers reviewed. Average specific stiffness and specific strength were calculated as they are important indicators of structural performance for automobile panels. The former two values happen to be the most critical engineering characteristics of automobile design over the past years [80]. Specifically, materials with high specific stiffness and specific strength are more likely to have special merit in applications in which weight will be a critical factor. Because the values of Young's Modulus and Tensile Strength used for the charts calculations were found to be variable and of different range in the studies reviewed, the extreme values (of specific stiffness and strength) were marked as high/low deviation bars. In parallel to that occurrence, the variation of values in the physical properties of the fibers is attributable to different harvesting seasons and / or regions of the planet.

**Figure 2.7. Mechanical performance of several fibers**




It can be noticed from Figure 2.7, that there is no optimum fiber which overtakes the rest in terms of performance the rest fibers in both charts. E-glass is clearly carrying out more potential regarding specific strength, but is outperformed by kenaf, hemp and ramie in specific stiffness. In an effort to have an average performance similar to E-glass, a realistic choice would be to select hemp which is stronger than ramie and still stiffer than E-glass. Despite that, more factors need to be considered in order to choose the optimum material besides mechanical performance being akin. One factor that was not taken into account is the raw materials' cost as it varies widely with the region of harvest and season. The selection procedure elaborated by the author will be further discussed and presented in the next chapters.

### 2.4.3 Major concerns regarding the use of natural fibers as reinforcements

Parallel to the advantages natural fibers bring with their use in composites constructions they are also innate drawbacks regarding their performance, their behavior in polymeric matrix systems and their processing.

First of all, natural fibers display an inability to provide a consistent pattern of physical properties in a given year; those properties can vary from every harvesting season and/or from harvesting region based on interchangeable sun, rain and soil conditions. Additionally, these variations can be surprisingly observed even in the very same cultivation's population in between the crops. More precisely, their properties are essentially dependent on the locality, on the part of the plant they are extracted from (leaf or stem), the maturity of the plant and how the fibers are harvested and preconditioned in the form of mats or chopped fibers, woven or unwoven.

All the above factors may result in substantial variation in properties compared to their ceramic fiber counterparts (e-glass) [81]. Moreover essential parameters are the type

of ground on which the plant grows, the amount of water the plant receives during its growth, the year of the harvest, and most importantly the kind of processing and production route. An approach to address this problem is to mix batches of fibers from different harvests. Blending fibers provides a hedge against variability in any single fiber crop. By having multiple suppliers of fiber and harvests, the ratio of fibers ensures relatively consistent performance in the finished part [62]. Alternatively, it is introduced to the market that a genetic transformed fiber variety may guarantee reinforced composite of consistent performance [82].

One other major negative issue of natural fibers is their poor compatibility with several polymeric matrices. That may result in non-uniform dispersion of fibers within the matrix. Their high moisture sensitivity leads to severe reduction of mechanical properties and delaminating. Furthermore, low microbial resistance and susceptibility to rotting can act as restriction factors particularly during shipment and long-term storage, as well as during composite processing [3]. Similar to the case of wood composites, natural fibers and plastic are like oil and water, and do not mix well. As most polymers, especially thermoplastics, are non-polar ("hydrophobic", repelling water) substances and not compatible with polar ("hydrophilic", absorbing water) wood fibers and, therefore, poor adhesion between polymer and fiber may result [83]. In order to improve the affinity and adhesion between reinforcements and thermoplastic matrices in production, chemical "coupling" or "compatibilising" agents have to be employed [3, 35, 84]. Chemical coupling agents are substances, typically polymers that are used in small quantities to treat the reinforcement's surface in such a way that increased interface bonding occurs between the treated surface and matrix surfaces.

Another main drawback of the use of fibers is the low processing temperature required (limited thermal stability). An increase in temperature can create irreversible damage and leads to porosity which reduces the mechanical properties of the fibers[85]. The permitted temperature limit is up to 200ºC, above this limit the fibers start to degrade and shrink which subsequently results in lower performance of the composite and thus confine the variety of resins they can be blended with [8, 86]. In general, when fibers are subjected to heat, the physical and/or chemical structural changes that occur are depolymerization, hydrolysis, oxidation, dehydration, decarboxylation, and recrystallization [85]. In order to avoid this processing defect, the range of temperatures as well as the processing time have to be limited accordingly [87].

All earlier aspects as specified render the natural fibers incorporation in exterior surfaces of vehicles complicated, especially when legislations in force and requirements of safety demand certain levels of performance to be fulfilled. For that reason, car makers are skeptical for their use in the exterior body panels even if they are widely used for interiors or hidden parts of the vehicles' chassis. However, it must be acknowledged that when employing composites containing natural fibers, added benefits for instant enhanced environmental performance due to the mass per unit volume of natural fiber are achieved. Those results were presented in the study of Alves et al., [9] where environmental analysis was performed on a jute fiber/polyester hood part compared with a conventional fiberglass/ polyester component. Analogous performance have been reported by Mitsubishi [30] and Toyota [59] when incorporated natural fiber reinforces in their components.

### 2.4.4 The matrix material

Several matrix materials deriving from renewable resources may well represent a promising candidate for a green composite application either being biodegradable or non-biodegradable. The emerging issue henceforth is the level of recyclability and/or decomposition when they are disposed. In the case of a hypothetical 100% bio-based composite, even if the material could not be recycled directly there are ways to be opted out through incineration for energy recovery. In the case of incineration, there are no emissions of toxic gases [88] and by decomposition there are no gases at all.

On one hand, traditional thermosets render the overall product not easily recyclable. On the other hand, traditional thermoplastics have processing limitations as high melt viscosity, a serious problem in the case of injection molding processing. The novel bio-based thermosets (plant oil-based resins) resembling the synthetic thermosets (phenolics, polyesters, epoxies, etc) are indeed difficult to recycle and reuse but can be later decomposed in most cases. Also, some, but not all, soybean resins or other plant based oils resins can be manufactured by means of processes so to be biodegradable [63, 89]. Thermoset polymers coming from vegetable oils are usually formed by cationic polymerization with other monomers, such as styrene, divinyl benzene, and cyclopentadiene. In other cases epoxidized oils are converted directly, either in the presence of thermally latent catalysts to initiate the polymerization, or in the presence of acid anhydrides (organic compound) as curing agent. Some of these interpenetrating polymer networks are also potentially (bio) degradable in soil [90, 91]. All these additives

are synthetic derivatives and nonrenewable and thus they are not contributing to a total green composite manufacturing. It would be preferable then to opt for materials which are bio-thermoplastics that do not need the polymerization process and may combine both benefits of recyclability and prospect disposal. However, thermosetting resin provides better impregnation, and to some extent better reactivity with fillers during the curing processes, leading to finer morphological structures [92] and prevent plastic deformation in the matrix at low stresses [93].

### 2.4.5 Mechanical performance of plant based resins

Table 2.2 shows information from several studies on bio-resins for green composites production. Once again, because the values were differing in each study, the extreme values were marked in ranges. Contrary to natural fibers though, these bio-based resins provide reproducible properties since they are industrialized products designed specifically for a number of applications in the consumer market. The acronyms listed in the table are the following: PLA represents the poly(lactic acid) and PLLA connotes the poly-L-lactide, they are both thermoplastic aliphatic polyester. PHB stands for polyhydroxybutyrate another aliphatic polyester, and PHBV is the copolymer poly(3-hydroxybutyrate-co-3-hydroxyvalerate). Finally, PP acronym represents the conventional polypropylene polymer

**Table 2.2. Properties of natural polymers in relation with polypropylene**

| Polymer | Density (g /cm $^3$) | Melting Point (Tm $^o$C) | Tensile Strength (MPa) | Young Modulus (GPa) | Elongation at Brake (%) | Price [a] (USD/kilo) | |
|---|---|---|---|---|---|---|---|
| Thermoplastic starch | 1,00 – 1,39 | 110 – 115 | 5 – 6 | 0,125 – 0,85 | 31 – 44 | 5,5 | [72] |
| PLA | 1,21 – 1,25 | 150 – 162 | 21 – 60 | 0,35 – 3,5 | 2,5 – 6,0 | 2,42 | [72] |
| PLLA | 1,25 – 1,29 | 170 – 190 | 15,5 – 65,5 | 0,83 – 2,7 | 3,0 – 4,0 | 4,5 | [94] |
| PHB | 1,18 – 1,26 | 168 – 182 | 24 – 40 | 3,5 – 4,0 | 5,0 – 8,0 | 4, | [95] |
| PHBV | 1,23 – 1,25 | 144 – 172 | 20 – 25 | 0,5 – 1,5 | 17,5 – 25,0 | 3,5 | [96] |
| PP | 0,90 – 1,16 | 161 – 170 | 30 – 40 | 1,1 – 1,6 | 20 – 400 | 1,65 | [72] |

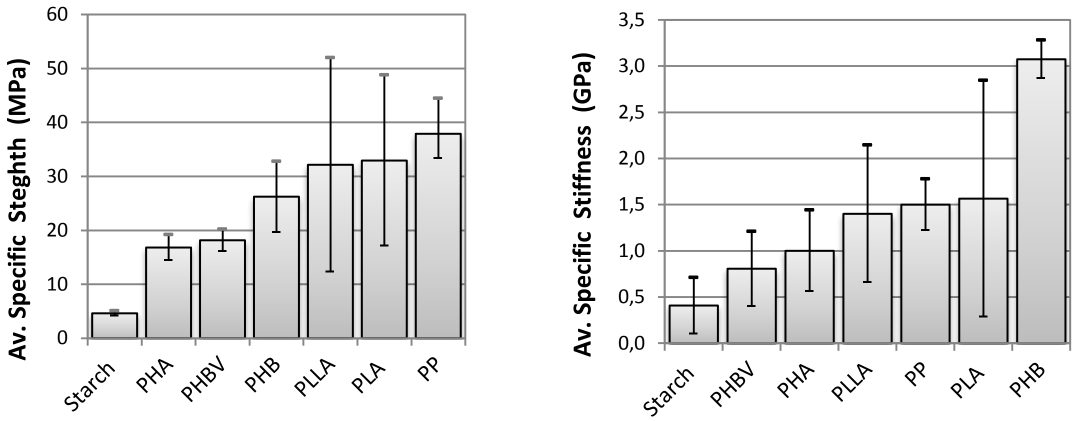
*note: The values marked down are adopted by the studies of [56, 94, 97-103].*

*[a] References inside the table are indicating the price source.*

Raw materials in each study are provided from several suppliers which may provide different invoice prices regarding the ordered quantity per year or per shipment. Furthermore, the price of each polymer does not represent a direct performance measure. While for instance PHB has almost the same strength of PP, its price is very high comparing to PLA, which makes it inefficient in cost for large scale applications. With the data provided by the Table 2.2 two different graphs were created as seen on

Figure 2.8 being in accordance to the same modeling that was followed in the charts of the previous paragraph 2.4.2.

**Figure 2.8. Mechanical performance of several polymer resins**




Focusing on both charts of Figure 2.8, it is once again observed that there is no optimum resin that would outperform all the rest in performance. PP overtakes the rest in strength but it falls behind PLA and PHB in the average stiffness chart to the right. Moreover, it is important mentioning that PP has a short range of variations and at the same time high performance values, for that reason its average performance is higher than the other resins presented here. Alternatively, if only maximum values were considered, PP would have held lower ranks in both properties associated within the bar charts.

### 2.4.6 Major concerns regarding the use of bio-based resins as matrices

Bio-resins are resin or resin formulations derived from a biological source and can be biodegradable or not, theoretically after their use they can be disposed and decomposed if no synthetics are added to the compound formulation. Insofar as regards their decomposition nature, bioresin integration on A-class finish surfaces is rather problematic considering long-life applications without delicate treatments and / or coating. That also may occur in natural fibers as they may degrade even when reinforcing synthetic resins due to the inevitable void contend generated by the incompatibility between the fiber and resin (hydrophilic reinforcement – hydrophobic matrix). Additional decomposing can be observed when the composite structure is exposed in high/low temperature and humidity.

Another major drawback for those resins is their high cost which makes them unaffordable even for large scale productions. An example of this is the PLA resin, a commonly used bio-resin that is at least 1,5 times more expensive than the extensively

used synthetic resin PP. On the same time, PLA is the less expensive of the biopolymers as seen on market prices of Table 2.2. For that reason bio-thermoset would have been a good alternative in terms of associated production cost which is one of the whys and wherefores to be used in the present study. Some other drawbacks of bio-based resins include brittleness, low heat distortion temperature, high gas permeability, low melt viscosity for further processing which restrict their use in a wide-range of applications [104].

Finally, there is a grand debate for whether or not these materials represent a real sustainable alternative to conventional plastics. Considering a future shift from the current synthetic-based to a bio-based dominant plastics economy, it is rather possible that the economic stability relations between societies will be torn down. Such a shift requires substitution of many common raw materials that are currently produced in vast volumes from fossil (petrochemical) or mineral resources, by products produced from renewable (plant-based) resource [105]. The sensitive point in this adequate selection of materials concerns the occurring composite which should not contain materials from edible sources for instance. Edible crops or any kind of edible raw material can subtract a part of food quantity from the human food chain and may result in social upheaval in the global balance of the food supply.

Additionally, it remains to be seen whether that upcoming shift will be likely to decrease the fertile lands, or increase the incentive to cut down forested areas to create more arable land. For that reason, scientist and researchers are on research for non-edible or by-product resourced materials instead of edible biomass in order to avoid the antagonism in-between bio-plastic and comestible goods.

One way to tackle one of the forthcoming problems is by producing the desirable quantity of materials in the lab through microbial production (e.g. biotechnological fermentation processes). Renewable polyesters based upon biotechnological fermentation processes have been successfully produced and are currently being introduced to the market as well as about 90% of the literature on lactic acid production is focused on the same process [105]. However, in such processes cheap raw materials should be improved further to make them competitive with the chemically derived ones [106]. The question then arises if these laboratory produced green materials can be considered natural and what their environmental impact is during production. This research will not address these issues.

## 2.5 Mechanical Performance of Green Composites

Green composites fabricated with the addition of plant fibers (cellulose) and resins such as modified starches have already introduced in interiors parts of automobiles while few examples have displayed for exteriors. Innovative green composites have been tested in numerous studies in an attempt to explore their performance in several applications. Table 2.3, illustrates a number of studies that investigated several types of reinforced bio-resins with different kinds of natural fibers. The traditional composite of PP - fiberglass reinforcement is referred below in order to have a comparison to the novel green candidates.

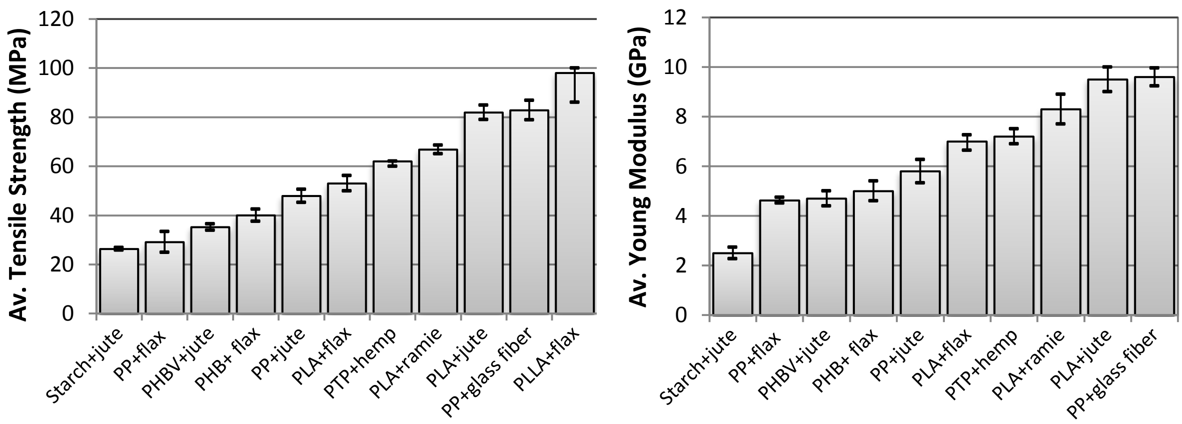
**Table 2.3. Mechanical properties of several green composites and PP composites**

| Resin - Reinforcement | Elongation to Break (%) | Tensile Strength (MPa) | Young Modulus (GPa) | Processing | Ref. |
|---|---|---|---|---|---|
| 1. Starch + 30 % jute | 2 ± 0,2 | 26,3 ± 0,55 | 2,5 ± 0,23 | Thermoplastic injection molding | [29] |
| 2. PLA + 30% ramie | 4,8 ± 0,2 | 66,8 ± 1,7 | n.s | Hot pressing sheet molding | [35] |
| 3. PLA + 30% jute | 1,8 ± 0 | 81,9±2,9 | 9,6±0,36 | Thermoplastic injection molding | [78] |
| 4. PTP® + 25% hemp | n.s | ≈62 ±2 | ≈7,2±0,3 | Compression molding | [31] |
| 5. PHBV+30% jute | 0,8± 0 | 35,2,± 1,3 | 7± 0,26 | Thermoplastic injection molding | [71] |
| 6. PLLA + 30% flax | ≈2,3 ±0,2 | ≈98 ± 12 | ≈9,5± 0,5 | Film stacking compression molding | [107] |
| 7. PHB + 30% flax | ≈7±1,5 | ≈40± 2,5 | ≈4,7± 0,3 | Film stacking compression molding | [107] |
| 8. PLA + 30% flax | 1±0,2 | 53±3,1 | 8,3±0,6 | Twin-screw extruder + compression | [33] |
| 9. PP + 30%flax | 2,7±1,5 | 29,1±4,2 | 5±0,4 | Twin-screw extruder + compression | [33] |
| 10. PP + 30% jute | 1,4 ± 0,1 | 47,9 ± 2,7 | 5,8 ± 0,47 | Thermoplastic injection molding | [78] |
| 11. PP + 30% fiberglass | 3,01 ± 0,22 | 82,8 ±4,0 | 4,62 ±0,11 | Compression molding | [72] |

[1] : long fibers composite
[n.s] : non studied

Using the data provided by the Table 2.3, two different graphs have been completed as illustrated in Figure 2.9, following the same graph modeling as on Figure 2.8 and Figure 2.7. It is discernible that in most cases green composites made of PLA, PLLA and natural fibers such as flax, ramie or jute resemble the performance of the traditional PP-fiberglass reinforced composites. As reported from the study of Oksman et al., [33] (instance 8, 9 on Table 2.3) the flax reinforced PLLA composite is demonstrating noteworthy performance comparing to PP-fiberglass, where flax shows better performance when blended with PLLA rather than with PP. Furthermore, jute fiber appears to have higher compatibility to PLA than the PP, PHB or starch matrices judging by their mechanical performance. On the study of Bledzki and Jaszkiewicz (2010) (instance 5 in Table 2.3), jute fibers have the highest tensile strength within the natural fiber group, although the jute fiber composites are characterized by lower mechanical values compared to abaca reinforced ones. This could be an outcome of the fiber processing method used [71].

**Figure 2.9. Mechanical performance of several composites**




Therefore, only the knowledge of mechanical properties of the tested composites is not sufficient to access the performance of the resulting composite by means of comprehensiveness. Those composites have been produced by different kinds of molds and with the aid of different fiber treatments on their reinforcements. Consequently, each manufacturing process shall result in produced composites of diverse performances and it is impractical to compare studies with dissimilar processing. But since there are no studies being akin in all levels identified so far in order to have a full comparative review for green composites with different fibers, this study will suggest an intermediate way to qualify the composites' constituent elements.

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# Chapter 3. The Materials Selection Methodology

Before analyzing further the factors that will trigger the selection mechanism, it is essential to designate the criteria to be used and then bring out their necessity virtues. Regularly cost per unit tensile strength ($$/MPa) is one of the most important criterion and hence materials with lower cost per unit strength are preferable. However, the main limitation of this explanation is that it considers only one property as the most critical and ignores the others [108]. In order to avoid that ambiguous practice; the decision making process utilized in this research has adopted practical steps from the Life Cycle Engineering approach (LCE) of Ribeiro et al., [15] and the system of weighting variables as introduced by the study of Saur et al., [109], although executed in a more cohesive way as will be explained in the next section. In this way, it is impartially performed a global comparison of the candidate materials and it is supported an informed decision regarding the selection of the "best material" as intended to different business scenarios or corporate strategies.

Materials selection is an analysis of physical characteristics under a predetermined set of requirements. Only after a particular material has been proven to meet these certain requirements it may afterwards be subjected to the economic criteria. For this research; the range of materials to be evaluated and the selection procedure has been rendered by means of an intermediate methodological tool - thoroughly presented inside this chapter. The material selection criteria will be described merely to explain the basic reasons why this project focuses on natural renewable materials or to synthetic materials with a considerable bio-content proportion.

With the aid of the abovementioned tools, the decision maker can be in a position to select the most appropriate candidate material regarding the percentage of importance given to each dimension of these "best material domains" which are presented in the ternary diagrams of Figure 3.1 and Figure 3.2.

## 3.1 The Selection Model

Basically the LCE approach encompasses three dimensions of analysis where the materials are evaluated in three distinguished manners: economically, technically and

environmentally. In the spectrum of this research in favor of simplicity three parameters are deliberated in place of the former dimension: two mechanical properties (specific strength and stiffness) and one economical aspect (cost per weight). Based in literature information the two former engineering properties were highlighted as the most critical of the automobile's design over the past years [80]. It was included thereafter the cost per unit weight as it is considered a fundamental factor and a good engineering practice used in most materials selection processes of new product development. These three parameters are considered to be orthogonal as they are uncorrelated and thus fulfill their purpose and pertinence of use. The author did not consider environmental data among the selection criteria. However, given that weight is implicitly included as one of the most important factors when the environmental impact of an automobile is computed, it is presumed that, until more accurate data is obtained on these natural composites, the more general approach followed in the present study is still valid.

In the analytical part of this methodological tool, distinctive evaluation among the dimensions of analysis —as indicated by the LCE of Ribeiro et al., [15] — did not occur. Instead of that a technical performance evaluation was used; intact and expanded in all of the dimensions in order to have a quantitative comparison. Eventually, the final outcome is a global evaluation presented in a ternary diagram (Figure 3.1), clearly showing the possible choices according to the importance given to the three parameters/dimensions of analysis.

### 3.1.1 The technical evaluation process

The integrated process adopted, was performed using decision matrices as introduced by Saur et al., [109], with the materials analyzed based on their quantified properties. Hereupon, each of the compared candidates' parameters has a relative importance weight $\mathbf{wP_i}$ assigned to it. It is essential formerly to have an approach where a number of materials can be compared against each other and this should come out through normalization and ranking of the parameter values. The structural outline used is shown on Table 3.1.

Each of the parameters values **j** for every material **k** is $\mathbf{P}_{jk}$, though, as long as the parameter values have their own numeric units immediately sets the comparison among them improper. Therefore, these three parameters values must be normalized —this is to say— adjust the values measured on different scales into a scale of notional common. This is carried out by creating a new array of converted dimensionless values $\mathbf{DP}_{i,j}$ and thus rendering the comparison between values of different scales possible. By taking each

$P_{i,j}$ entry and dividing it by the maximum entry of that sequence, a new $\mathbf{DP}_k$ array of dimensionless values is created. The same procedure is followed across all the candidate materials when the maximum value is the best value. Assuming that the most desirable value is the minimum one across the array (as often occurs for cost), then the anticipated dimensionless parameter must be calculated by dividing the minimum value of the parameter across all the materials by the value of each material —yielding $DP_{jk}$. Now these dimensionless values have to be weighted according the parameters weights and get the dimensionless importance weight WDP, so as the comparison to occur. In that manner, each of the weighted dimensionless value $WDP_{ij}$ should be calculated according to the formula:

$$WDP_{ij} = DP_{ij} \times wP_i \quad \textbf{(Eq. 1)}$$

Finally, adding all the weighted dimensionless values, a weighted material index $WMI_k$ is created including all candidates values (Table 3.1 last row instance). The potentially best material for each scenario will be the one that holds the highest WMI score.

**Table 3.1: Ranking of the candidate materials**

| **Parameters** | **Parameter Weight** | **Candidate Material 1** | **Candidate Material 2** | **—** | **Candidate Material k** | **—** |
|---|---|---|---|---|---|---|
| Specific Strength | $wP_1$ | $P_{11}$ | $P_{12}$ | — | $P_{1k}$ | — |
| | | $DP_{11}$ | $DP_{12}$ | — | $DP_{ik}$ | — |
| | | $WDP_{11}$ | $WDP_{12}$ | — | $WDP_{ik}$ | — |
| Specific Stiffness | — | — | — | — | — | — |
| Cost per Weight | $wP_3$ | $P_{31}$ | $P_{32}$ | — | $P_{jk}$ | — |
| | | $DP_{j1}$ | $DP_{32}$ | — | $DP_{jk}$ | — |
| | | $WDP_{31}$ | $WDP_{32}$ | — | $WDP_{jk}$ | — |
| Weighted Material Index = | | $WMI_1$ | $WMI_2$ | — | $WMI_k$ | — |

### 3.1.2 The ternary diagrams construction and global evaluation

Finally, with the results obtained for the candidate material involving the dimension of analysis; a global evaluation can be performed. In each competitive scenario and according to each corporate strategy the importance associated to each dimension may be ranging differently. As it is considered so far, each dimension has a

weight, ranging from 0 to 100%, and the sum of the weights for the three dimensions is 100%. Different combinations of weights might result in a different "best material for the application" and a slight modification of such weights might deeply modify this "best material". To have a clear view of the possible choices according to the importance given to the dimensions, the results are then presented in a ternary diagram. The diagram contains the best choices for all the different combinations of importance attributed to the technical performance in three parameters.

In a first stage, all the weighted values $wP_n$ (strength, stiffness, and cost) are randomly swapped in an iterative sequence in order to eliminate a portion of the candidate materials population and come out shortly with a representative diagram of the most dominant ones. The non-promising candidates are expected to be eliminated as they will not be holding any space inside the diagrams as regards their parameter values.

Ideally, these $wP_n$ importance's values would have been set after conducting a meeting in between the stakeholders and the decision maker or investigator responsible for using this tool. However, despite that practice and given that no company was affiliated to this research project during the material selection stage, the author undertook the setback by the use of iteration checks as explained above. The result was to come up with a set of possible choices.

**Table 3.2 Materials screening matrix among natural fibers**

| **Parameters (Pj)** | **Parameters Weight (PW)** | | **Flax** | **Ramie** | **Curaua** | **Jute** | **Others** |
|---|---|---|---|---|---|---|---|
| | | Value (MPa) | 615 | 413 | 517 | 400 | — |
| Sp.Strength | 30 | Dimensionless (DP) | 100 | 70,18 | 20,77 | 14,55 | — |
| | | Score (WDP) | 30 | 21,05 | 27,87 | 19,53 | — |
| | | Value (GPa) | 2,22 | 6,1 | 1,49 | 1,32 | — |
| Sp.Stiffness | 50 | Dimensionless (DP) | 36,34 | 100 | 20,87 | 18,53 | — |
| | | Score (WDP) | 18,79 | 50 | 12,21 | 10,85 | — |
| | | Value (USD) | 4,65 | 3,1 | 0,63 | 1,37 | — |
| Cost | 20 | Dimensionless (DP) | 10,93 | 16,49 | 80,89 | 37,20 | — |
| | | Score (WDP) | 2,19 | 3,29 | 16,19 | 7,4 | — |
| Weight Material Index = | | | 50 | 74 | 56 | 38 | — |

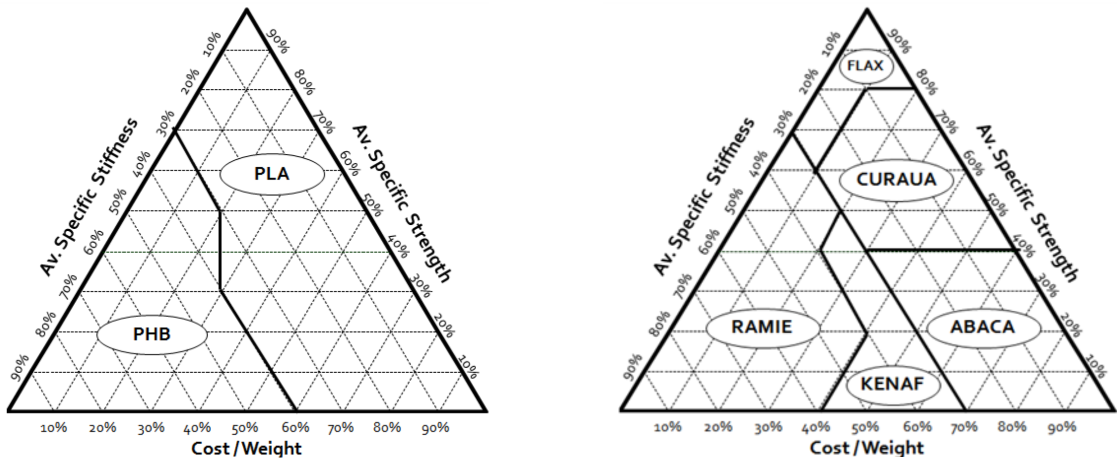
**Table 3.3 Materials screening matrix among bio-resins**

| Parameters (Pj) | Parameters Weight (PW) | | PLA | PHB | PLLA | T.Starch | Others |
|---|---|---|---|---|---|---|---|
| Sp.Strength | 30 | Value (MPa/(g/cm³)) | 32,93 | 26,23 | 32,14 | 4,60 | — |
| | | Dimensionless (DP) | 100 | 79,66 | 97,62 | 13,98 | — |
| | | Score (WDP) | 30 | 23,90 | 29,29 | 4,19 | — |
| Sp.Stiffness | 50 | Value (GPa/( g/cm³)) | 1,35 | 3,07 | 1,40 | 0,47 | — |
| | | Dimensionless (DP) | 50,92 | 100 | 45,57 | 13,27 | — |
| | | Score (WDP) | 25,46 | 50 | 22,79 | 6,64 | — |
| Cost | 20 | Value (USD) | 1,97 | 3,28 | 3,57 | 4,6 | — |
| | | Dimensionless (DP) | 100 | 60,01 | 55,09 | 35,13 | — |
| | | Score (WDP) | 20 | 12 | 11,02 | 7,03 | — |
| Weight Material Index = | | | 75 | 86 | 63 | 18 | — |

*Note: the Weight Material Index, WMI, for each material k is the sum of the scores ($WDP_{jk}$) for all parameters.*

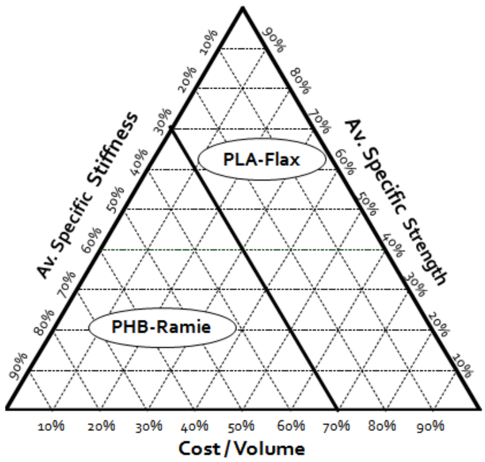
Figure 3.1 below, illustrates the best materials out of the initial candidates as presented in the Table 2.1 and Table 2.2. With all the aforementioned dimensionless data and having run trial and error calculations regarding the candidates' area in the triangle, the borders between candidate materials are tracked down. As a result, materials which did not show up in the diagrams are not representing the best combination of cost, specific strength and stiffness in any partitioning of these properties. Concisely after having a clear idea about how the weights are contributing to our selection a decision can be taken. Giving an example on that, a weighted decision on fiber selection (Table 3.2 and Figure 3.1), considering a decision of 30-50-20% for stiffness-strength, cost—then the best selection is ramie.

**Figure 3.1. Ternary diagrams for matrix resin and fibers reinforcement.**



Following the choices presented for the two basic elements regarding the green composites composition, another familiar diagram was created but this time containing a prospective green composite which is presented in Figure 3.2. Taking the two dominant resins (out of Figure 3.1 on the left) and combining them with the fibers that occupy similar areas in the fibers triangle (Figure 3.1 on the right), five potential composites were made in order to be compared. Consequently, the combinations were: PLA-flax, PLA-abaca, PLA-curaua, PHB kenaf and PHB-ramie. The values of the mechanical performances of each composite were calculated by the rule of mixtures adopting the values from Table 2.2 and Table 2.1. Likewise the cost of each composite was calculated by the percentages of the materials that it incorporates (30% reinforcement and 70% resin volume fraction).

**Figure 3.2. Ternary diagram for green composites.**




Once more, the possible composites with low overall ranks did not appear on the diagram. Specifically in that comparison, PLA-flax ranked first both in average specific strength and cost/volume while PHB-Ramie was the stiffest of all composites and therefore these two dominated all the rest candidates. When the relative importance of specific stiffness in the selection process is higher than 30% PHB-ramie is the best selection, regardless of the other factors. The other possible green composites had displayed performance and cost values much lower than those two while not showing appraisable values. The final diagram could have been different if other sets of constituent materials were chosen, however it was preferred to combine those that were emerging as promising choices in the identical regions of both diagrams of Figure 3.1.

The results are not expected to be accurate in absolute terms but are considered accurate enough to have a first-hand comparison of relative performance in between the choices of promising materials. It must be noted once again that both stiffness and

strength are highly affected by the interface bonding between fiber and matrix. And this is especially evident when associating natural fibers subjected to different treatments. The author considered that, all things being equal, the ternary diagrams are a good decision making tool when three parameters stand out as important in the selection process. When fiber treatments and composite processing parameters are established in a relatively standard practice for these types of composites, it will be possible then to build more sophisticated ternary selection diagrams.

### 3.1.3 The selection of constituents practical and scholarly significance

**The matrix system**

Throughout the literature review it was concluded that thermoplastic materials should be used in the matrix system as they are considered more promising in bringing out a green composite of high renewable content (or totally green). Yet, it was not possible to produce thermoplastics sheets both in IST and in Ancel Ltda due to unavailability of a mold machine appropriate for injecting thermoplastic polymers like PLA and PHB which were both suggested by the ternary diagrams.

Therefore, it was envisaged the possibility of using the available materials and equipment that was already available at IST. Eventually, the RTM process deployed as it was already accessible for composites thermosetting production. Bio-thermosets are also appropriate in terms of durability properties but thereafter the resin itself is not of high renewable content since nominally vegetable oil resins tend to be mixed with other synthetic additives (as styrene) in order to promote cross linking by the use of catalysts. Added to that there are not a lot of commercial products on the market rather than studies suggesting mixing methods [28, 63, 81, 110].

To get an initial grasp of the behavior of natural fabric in conjunction with green composites conventional polyester was used in the matrix as found at the IST workshop. At the Ancel production site it was used a novel polyester resin which is manufactured by polymers and the addition of renewable plant oils and thus cited as bioresin, more details about all the materials employed will be given in the following chapters.

**The reinforcing element**

In the present thesis, the Chinese ramie fiber had been selected as the reinforcing element for the composite which is under investigation in this work. Eventually, the methodological procedure suggested two kinds of fibers as promising, one is flax and the

other was ramie. Considering the commercial prices provided by the Table 2.1, it is evidenced that flax is more than 50% expensive which will subsequently increase the cost of the upcoming composite.

The significance of exploring the ramie fiber in this research and not some other well studied fiber such as jute (which numbers already two theses in IST [18, 111]) or flax (as concluded also on page ii of the motivation chapter) is comprised from two solid facts. First of all, the ramie fiber has added advantages regarding their mechanical performance comparing to other fibers as acknowledged by relevant studies on the composites research field. As indicated, ramie is clearly the longest and one of the stiffest fine textile fibers and therefore demonstrates high potential as reinforcement in polymer composites [35, 56]. Currently, Yu et al. [35] concluded that ramie has higher values than flax and jute and its tensile strength is approximately that of fiberglass, analogous evidence regarding ramie properties have been displayed on Table 2.1. Ramie fiber is preferred also because it has low water absorption (low hydroscopic behavior) among a number of fibers and thus increasing adhesion bonding between the latter and the matrix [69, 112]. Moreover, ramie fibers have good resistance to bacteria, mildew, and insect attack. The fibers are stable in alkaline media and not harmed by mild acids [3].

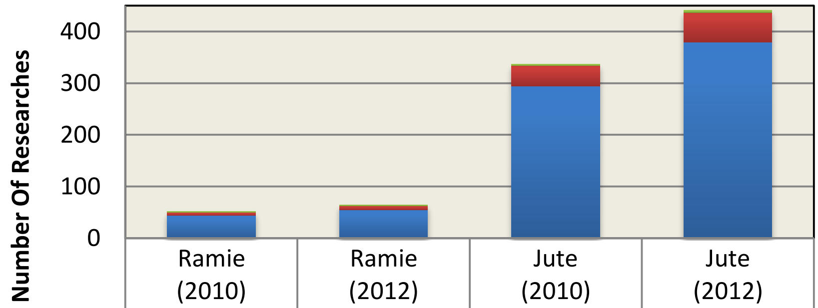
What tips the scales in favor of ramie fiber is that in a direct comparison to the widespread jute fiber where ramie was proven to be superior as reported by Yu et al., [36]. More specifically, the mechanical properties of ramie reinforced composite were higher than those of jute's because the strength of former is higher than that of latter. Jute fiber has been proven a very good exemplar by successfully swapping e-glass in a hood part made of unsaturated polyester matrix [9] or indoor sound insulation parts [113], thus ramie fibers (since considered stronger and stiffer) might bring enhanced mechanical performance by replacing jute as a long fiber reinforcement.

Secondly, no more than a few studies are published regarding ramie which shows a shortage of behavioral data exist regarding real industry's applications. Therefore, there is additional scientific interest in subjecting ramie under investigation as an appropriate reinforcement of prospective green composites. A plain keyword search on Thomson Reuters' Web of Knowledge database (http://apps.webofknowledge.com) showed that until the year 2010, up to 295 researches embedded jute reinforcement in composites comparing to 44 intended for ramie. When introducing more specific keywords; particularly "jute" or "ramie fabrics" along with word "composites", then the search engine returned over 39 investigations which have been conducted by the use of jute

while only 6 by ramie. Getting forward on the year 2012 the increment percentage in researches for jute composites appeared to be 28%, when for ramies was almost 25% (data as accessed on Nov. 2012). Especially when typing in the keywords “composites” along with “fabrics” for the year 2012; a number of 57 investigations were published for jute while only 8 for ramie, the increment is 46% for jute and 22% for ramie accordingly. Finally the composite systems that are purposefully bound for automotive applications are much less; basically returning 2 ensuing researches for ramie and 4 for jute. All this enquiry procedure clearly indicated a lack of research outcomes on that field and thus comprises an opportunity on conducting an original research that shall cover these aspects.

**Figure 3.3. Number of research projects on ramie and jute.**

*(keywords as typed in the search engine of Web of Knowledge webpage)*




| | Ramie (2010) | Ramie (2012) | Jute (2010) | Jute (2012) |
|---|---|---|---|---|
| vehicles | 2 | 2 | 3 | 4 |
| composites + fabric | 6 | 8 | 39 | 57 |
| composites | 44 | 55 | 295 | 380 |

### 3.1.4 The ramie fiber

Ramie fiber (Boehmeria nivea (L.) Gaud., Boehmeria nivea var tenacissima), also referred as Chinese grass, white ramie, member of the Urticaceae family or Nettle, is produced mainly in China, Japan, several other southern Asian countries and Brazil [70, 114]. However, its cultivation in Brazil has been significantly decreased by production volume after the year 2002 [115]. A second type, Boehmeria nivea var tenacissima, is known as “green ramie” or “rhea” and is believed to have originated in the Malay Peninsula; the area contains territories of Burma, Malaysia, Singapore, and Thailand. This type has smaller leaves which are green on the underside and in general is better suited to tropical conditions. All the countries that ramie plant grows are illustrated in the Figure 3.4.

In the European side of the world, owing to the plant’s wide capacity for adaptation, it can also be successfully grown in a Mediterranean climate (in Italy

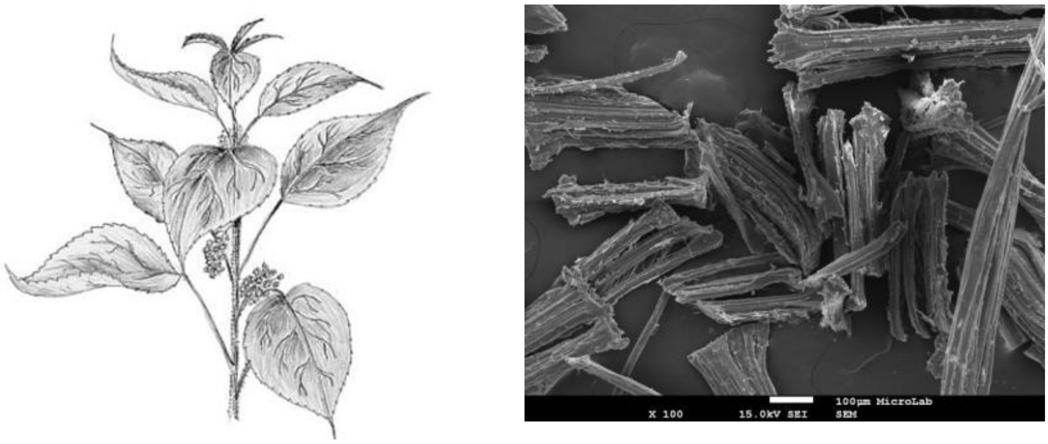
specifically) and under temperate environment it is possible to be harvested three times a year [69]. Ten years after the former venture of the plant introduction to the Mediterranean region, the same group of researchers conducted another study in which they are still contented about the ramie's high yield and wide adaptability to temperate and semi-arid environments. Thanks to that, ramie could represent a viable alternative crop for rained cropping system [116].

**Figure 3.4. Production quantities by country (average 1992-2010).**

*Source: Food and agriculture organization of the United Nations FAOSTAT[115]*

Ramie produces a large number of unbranched stems from underground rhizomes. Morphologically, it has large heart-shaped, crenate leaves covered on the underside with white hair that give it a silvery appearance as seen in Figure 3.5a below. The fibers obtained from the outer part of the stalk are the longest and considered one of the strongest fine textile fibers. Ramie's fiber is very durable, is pure white in color and has a silky luster. The diameter of the elementary fibers varies from 10 – 25 μm, seen in Figure 3.5b obtained by a scanning electron microscope (SEM). The ultimate fiber is flat and irregular in shape, with a thick cell wall, and taper to rounded ends. The primary cell wall is often lignified, and this aspect is responsible for the low hygroscopic character of the fibers [69].

**Figure 3.5. The ramie plant schematic and SEM image for cut ramie fiber.**




(a) (b)

The ramie fiber has been employed in many fields including clothing fabrics, twines and industrial packaging due to its excellent features and in particular, its higher cellulose content (65-75 wt%) compared with bast fibers such as hemp, flax and jute [70, 117]. And as it has been accredited by the literature, the tensile strength and Young's modulus of plant fibers increases with increasing cellulose content of the fibers [3].

Lately because of their sufficient strength and toughness they have been tested for level II bullet testing, on bulletproof panel composites [68]. Ramie is also available in continuous form with the length between 60 – 250 mm and this physical property is one of the benefits to be utilized for reinforcement fiber polymer composite in continuous form applied for panel [68]. However, its high degree of crystallinity which makes it strong but brittle along with its high degree of molecular chain orientation restricts the sufficient utilization and exploitation of ramie fibers. Consequently, it is very important to find a way to more efficiently utilize the abundant natural ramie resource in China [118]. One way to do that is by using them in future composite systems as will be proposed by the present thesis.

## 3.2 Project Requirements and Restrictions

At this point it shall be discussed the conditions imposed regarding the desired parts characteristics. As far as this research aims to optimize and measure the performance of Buggy parts (the hood), in accordance to a three dimensional analysis thereafter each one the dimensions under consideration will provide one requirement each.

### 3.2.1 Required characteristics

**Mechanical Aspects**

As mentioned above in the previous sections of this document, the two principal mechanical prerequisites are stiffness and strength [80] which both must be in accordance to the performance of the successful natural composites as suggested by the thesis work of Alves et al.,[18]. Therefore, maximum tensile stress (TS) of at least **30,38 MPa** and elastic modulus (YM) of **5,29 GPa** or higher; will be intended as referential. The selected jute reinforced composites of the former study have been produced in IST laboratories via the Resin Transfer Molding (RTM) process incorporating unsaturated polyester and dried fibers at the 28 Vf (%) by means of the same tooling and Instron testing machines as to be exploited on the present thesis work.

Additionally, mostly on composites of exterior applications the surface properties are related to aspects of reactivity as corrosion, UV degradation, and galvanic or gel coating. Having an exterior part the morphology of a Class-A finish is generally required. This factor and to a less significant extent polarity (not attractive for coatings), crucially determine surface appearance and durability by controlling smoothness and adhesion between the paint and the components surface. However, this research will not tackle all the aforesaid aspects as the main focus is on topic of durability. What will be additionally examined is the amount of the void inside the composite as well as the surface finish in terms of degradation in after UV radiation, elevated ambient heating and humidity. In that sense it is expected that this work's green composites will have a comparable durability performance after being subjected to environmental degradation.

**Economic Issues**

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 [119]. The composite production is expected to be competitive as regards the current practice intended to be used by Ancel for the production of the hood. The methodological tool to check the proposed composite is the process cost modeling as introduced by Field et al., [16]. An acceptable solution should have cost savings attached or at least equivalent expenses unless its cost is promoted by other factors being incentive to seriously consider biobased alternatives to petroleum based materials. If customers may be willing to pay more as for green products [12] and prefer to purchase from "green"

organizations [120] that on its turn will balance the investment gap from the corporate side.

**Environmental Goals**

In recent years, there has been an increasing emphasis on the concept of 'win-win' environmental strategies, whereby environmental product benefits go hand-in-hand with technical and economic cost-effectiveness [121]. This is intuitively appealing, since products whose production and use entail less energy, less material input and less waste and pollution should be cost-effective for both consumer and producer. In practice, however, developing a product which excels in environmental terms while remaining economically and technically competitive, is a significant challenge[121]. Untimely, environmental performance superior to the baseline scenario and analogous to the study of Alves [18] will be targeted. The novel hood construction is estimated to be less energy and gas emissions intensive in order to bridge the "win-win strategies".

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# Chapter 4. Materials and Experimental Procedure

In this chapter it will be presented in length all materials, equipment and methods deployed for the preparation and mechanical characterization of the green composites produced in Lisbon – Portugal; where is the base institution in which this research was conducted and at Rio Claro – Brazil; where the internship for this investigation took place. The experimental phase results and discussion regarding the composite's performance will follow up in a later part near the end of this chapter.

## 4.1 Composite Reinforcements: Natural Fibers and Fillers.

### 4.1.1 Type of reinforcement

Long fibers reinforced plastics (LFRP) were and still are the 'shining star' of the compounding industry covering a big market share. Specifically automotive applications are being dominated by LFRP use in front-end modules, underbody structures, facial panels, battery trays, housings, hardware etc. LFRP are proven to combine high stiffness and flexural strength, comparable processing costs and densities, making them more effective as automotive composites over short fiber reinforced plastics (SFRPs) [24, 122, 123], which rely upon the matrix to carry the majority of applied load. In particular LFR with continuous fiber reinforcement in the form of multilayer woven fabrics display enhanced performance compared to SFRPs [124, 125]. Additionally, they allow for better control of the reinforcement material distribution, and can be easily tailored to obtain customized material properties because the fibers can be placed along the load direction.

The use of long fibers has proven to increase the elastic modulus and the tensile strength of the material as close as to 90% of that obtained when using continuous fibers [126]. In LFRPs, the full strength of the reinforcements is utilized because the fiber length is above the critical fiber length easing the effective load transfer. As a result, they are much stiffer and stronger than the same material in a bulk form.

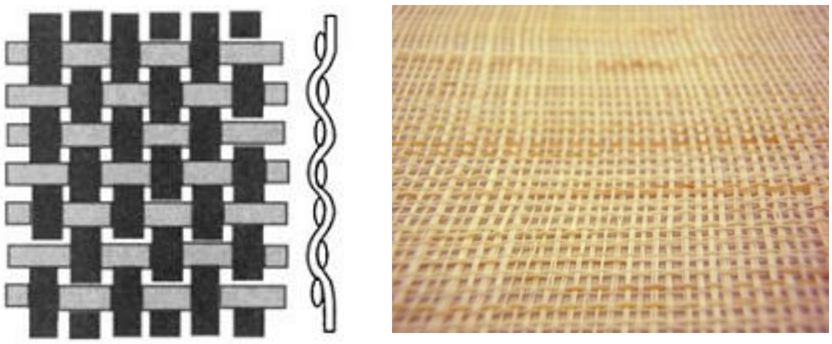
It is well known that in all of the composite structures, the reinforcement plays an important and substantial role in its mechanical performance. It can increase significantly the systems' performance in terms of tensile and flexural properties

[18, 22, 107, 127, 128] when compared to neat, unfilled resins. The type of natural reinforcement used in this research's composites is ramie woven fabric bought from Zifine Industrial Co., Ltd (Shangai, China). It was shipped in roll form initially to Portugal at IST University of Lisbon and thereafter to Ancel Ltda (Rio Claro, Brazil) where production of composites took place, although with different matrix systems. The produced green composites had two different stacking sequences while different fiber loadings were attempted so as to achieve maximum tensile and flexural properties but also appropriate surface finish. The fabric characteristics are summarized in the table figure below. The jute fabric information is adopted from the study of Alves [18].

**Table 4.1. Fabric characteristics**

| Fiber mat | Grammage (g/m2) | Weave type | Material |
|---|---|---|---|
| **Ramie** | 36 | Plain | 100% Linen |
| **Jute** | 310 | Plain | 100% Linen |

**Figure 4.1. Plain weave fabric schematic and ramie fabric**



Their properties are identical in both axes and form a sacking sequence of 0/90 when weaved in that way. The above ramie biaxial fabric were been cut out and placed carefully as single laminated sheets inside the mold during the production of test specimens.

Plain weave fabrics as illustrated on Figure 4.1 (right incidence) are very firm in their composition and quite stable and therefore well suited for flat or low curvature surfaces. As indicated by the Chinese fabric producer they have been produced by slub yarns which are yarns of irregular in diameter which has lump or thick points on caused by small length yarns adhering to it. Generally, in filament yarn, a slub or thick spot in a yarn is created by varying the tightness of the twist of the yarn at various intervals

### 4.1.2 Additives in the matrix mix

At Ancel Ltda, according to their manufacturing process specifications, specific additives are used on the resin while preparing it along with the addition of other

promoters/accelerators so as to speed up and enhance the composite curing in closable molds with no temperature adjustment or pressure.

**Mineral filler**

The polymorph calcium carbonate ($CaCO_3$) or simply calcite is a natural mineral and major component of rocks like limestone, marbles (metamorphosed limestone), chalks, calcareous sandstones, etc. Calcite filler powder as seen in Figure 4.2 was blended together with the other matrix materials in a stainless steel fluid agitator so as to turn the resin mix denser and easier to polymerize with the addition of a catalyst after injection. As also detected in the literature, calcite is reducing resin shrinkage after polymerization and is used in various fiber reinforced polymeric materials. It is has been pointed out that the effect of calcium carbonate on the mechanical performance of the composites is not significant [129]. However, it is a cost effective approach in order to balance cost of the outcoming composite as calcite price per kilo is much less than the cost of polyester (almost 30 times less according to the Brazilian market prices provided by Ancel's sales department).

**Figure 4.2. Calcite in powdery form.**

**Promoter and catalyst**

The amine N, N-dimethylaniline (DMA) was thoroughly mixed with the polyester resin and filler in the same vessel and in a similar manner as mixing the traditional unsaturated polyester systems. DMA is a promoter used in the curing of polyester and vinyl ester resins and can be used on its own or in combination with cobalt 6% promoters with methyl-ethyl-ketone (MEKP) type catalysts. These liquid systems give rapid cure at room temperature in contact with the catalyst.

## 4.2 The Polymeric Matrix System

In IST workshop at Lisbon a standard thermosetting liquid resin was used in the matrix in the form of orthophthalic unsaturated polyester (UP), with the commercial brand name Quires 406 PA. It was acquired from the company MR-Dinis dos Santos

(Lisbon, Portugal) and its characteristics are presented in the Table 4.2. Peroxide Methyl-Ethyl-Ketone (PMEK) used as the curing agent of matrix, was also bought from MR-Dinis dos Santos (Lisbon, Portugal).

In Rio Claro at Ancel Ltda workshop, a novel bio-resin was used as one of the resin suppliers; Elekeiroz S.A (Sao Paolo, Brazil) was distributing a green resin solution made of 20% renewable content, with the commercial name BioPoli 507 [130]. The latter solution had been proposed to Research & Development department as an alternative to the traditional polyester resin, however, it had never been used in any of its projects eventhough the price was the same as the traditional solution. From then on it was kindly provided enough quantity for sampling it for this research and for prospective projects. Additionally, Peroxide Methyl Ethyl Ketone (PMEK) was used as a curing agent which was bought from a regular catalysts distributor company Polinox Ltd (Sao Paolo, Brazil).

**Table 4.2. Characteristics of the polyester matrixes**

| Characteristic (value) | Quires 406 PA | BioPoli 507 |
|---|---|---|
| Density (g/cm$^3$) | 1.2 | 1.10 – 1.15 |
| Viscosity at 25 °C (cPs) | 600 – 800 | 150 – 250 |
| Gel time at 25 °C (min) | 14.5 –15.5 | 9 – 13 |
| Styrene content (%) | 38 – 42 | 45 |
| Acidity (mgKOH/g) | 15 – 21 | 30 |

## 4.3 Preparation of Green Composite Plates in IST Workshop

The ramie roll were cut in square shaped sheets of 330×330 mm and then placed in the mold appropriately. These stacks were created by using several bi-directional fabrics of [0°/90°] fiber-oriented layers while few made-up by the addition of [0°/±45°] fabrics. Polyester resin was mixed with PMEK catalyst at the percentage of 1% before it was put in to the injection piston for resin transfer procedure. The RTM mold system (as seen on Figure 4.3a below) for the composite plates production was supplied by Ancel Ltda (Rio Claro, Brazil). It was made of composite material (polyester matrix reinforced with glass fibers) and the metallic square ring part of the mold plates —which adjust the thickness of the sheets— had been produced by aluminum.

Bi-directional symmetric quasi-isotropic composite specimens were fabricated at room temperature and under constant pressure in the shape of rectangular plate by the RTM technique. Ample precautions were taken to minimize voids and maintain

homogeneity such as resin air bubble removal via void distillation. The specimens were prepared for varied volume fractions.

**Figure 4.3. Composite mold machine and mold used at IST workshop.**

(a)

(b)

The RTM system consists of two separate components, which optionally may or may not be used together for composites production:

- A heated press unit (model PRESSE 3508 SERIES – 15 kW): acquired from ISOJET Equipments (France). It consists of two heated plates of 500 x 500 mm with the maximum temperature of 200°C and the maximum pressure of 14 bars assisted by a pneumatic system (Figure 4.3b);
- RTM unit (model RTM PISTON 2006 – 3kW): acquired from ISOJET Equipments (France). It is composed of a heated injection piston (maximum volume at 3 litters) and a heated injection tube, a pressure control cell, a computer assisted control unit /data acquisition and a vacuum pump (Figure 4.3 b).

### 4.3.1 Preparation of composite plates in Ancel’s workshop

In the Ancel’s production site, an versatile RTM machine as seen on Figure 4.4 is used for injecting resin at a constant pressure based on a piston type apparatus driven by compressed air. The hand pistol is operated by one worker and dispenses resin from storage unit as small as 30 litters.

**Figure 4.4. Ancel RTM injector machine**

The given mold (as seen on Figure 4.5) consists of one base part (including the bottom cavity, floor support and lock clips) and one bottom part (top cavity and cylindrical rod handles). The top and the bottom parts were made of composite material (polyester matrix reinforced with glass fibers) and of surface finish made of aluminum material with rubber inserts to avoid resin leakage. The mold has been overused by the previous projects and it was impossible to produce composites with efficient surface finish and narrow part tolerance as the one of IST University. The injection port and resin exit point were drilled on the top part and the pressure is being applied by four clamping clips on the perimeter of the two molds cavities. Around the perimeter of the cavity there is a rubber sealing gasket (white path on Figure 4.5 instance b). The support of the base part was produced by metallic rods and put together by electric welding by Ancels' personnel.

**Figure 4.5. The mold used in Ancel's workshop.**
**bottom part (a), top part (b) and closed mold (c).**

(a) (b) (c)

Once more bi-directional symmetric quasi-isotropic bio-composite specimens were fabricated at room temperature in the shape of rectangular plate by the RTM technique. This time by the use of different resin referred as green resin [130] was combined with bidirectional ramie fabric to produce specimens with a nominal thickness of 4 mm accordingly.

## 4.4 Void Detection and Defects Tracing

It is well known among composite's industry experts that voids inside the composite's volume material may significantly affect its mechanical properties. High void volumes usually bring on lower fatigue resistance, greater susceptibility to moisture penetration and weathering, and cause increased variation or scatter in strength properties. Knowledge of the void content of a composite material is desirable as an indication of the quality of a composite [131]. The void content may be reduced by carefully chosen process parameters, such as pressure and temperature, but often at the higher cost.

In order to become able of having a rough calculation of void/trapped air — a two-step approach was applied to assess the quality of the produced composites and their setup for production. Firstly, it was scanned a representative sample composite by means of ultrasonic inspection with non-constructive device so as to trace voids and matrix material defects; then, a numerical calculation will follows in accordance to the ASTM standard Test Methods for Void Content of Reinforced Plastics, D 2734 [132].

Initially, the composite sheets were scanned using on ultrasound machine ULTRAPAC II Immersion Systems from Physical Acoustics Corporation (USA) via Ultrawin software which is a data acquisition, imaging and analysis software system. Holes with different depths and diameter were drilled in the plates (see green region – Figure 4.6), they were used as calibration control to detect if any other similar void or trapped air were to be found in the rest of the composite. By the use of the ultrasound transmission it is possible to detect the presence of voids/gaps inside the composites based on acoustic differences in-between the sheet's layers. However, as it is not possible to quantify its "percentage" as the image provided is not a three dimensional image but a two dimensional representation (see Figure 4.6). A convenient way to evaluate the void content with numerical calculation is possible when plugging in all the information in the equation provided by the ASTM standard D 2734 – 94 [132] as follows:

$$\%V_p = 100 - \rho_{lam} \left( \frac{\%W_m}{\rho_m} + \frac{\%W_f}{\rho_f} \right) \qquad \textbf{(Eq. 2)}$$

Where $V_p$ is the void content of composite in percentage of the volume, $\rho_{lam}$ is the measured density, $\%W_m$ is the resin's weight in percentage of the plate, $\rho_m$ is the resin's density, $\%W_f$ is the fiber weight in percentage and $\rho_f$ is the fiber's density. Typically, void contents of about1 % are required for aerospace applications, but void contents of up to 5 % are acceptable for other less demanding applications (e.g. automotive and marine) [133-136] With the use of the (Eq. 2) subsequently it was possible to build Table 4.3, which reports the void percentage of different sheet batches scanned.

**Figure 4.6. Ultrasonic of the plates**

**(Left) Time on fly image. (Right) Amplitude image.**

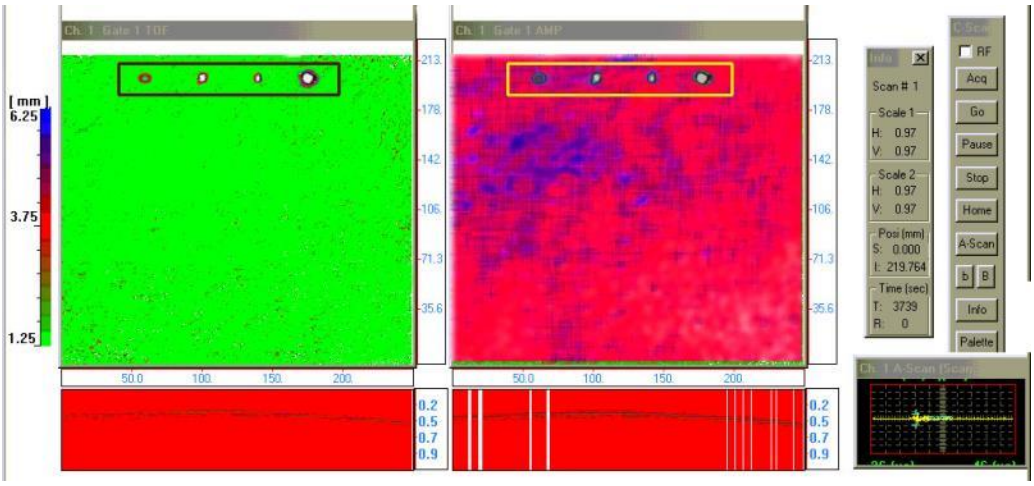



**Table 4.3. Void percentage in the composites.**

| Composites | Vp% | Average |
|---|---|---|
| **RUB1** | 4.82 | |
| **RUB3** | 4.46 | |
| **RUB4** | 4.46 | 4.5 |
| **RUB5** | 4.51 | |
| **RUB12** | 4.56 | |

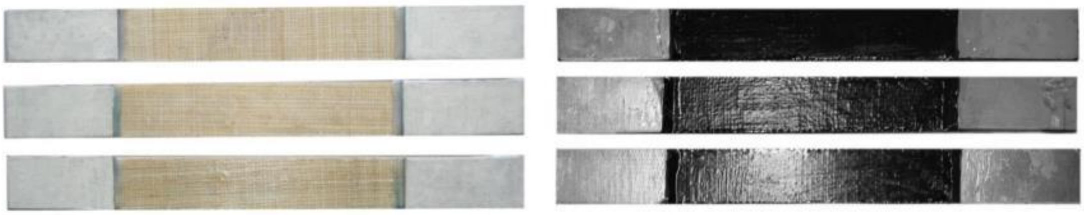
A number of batches of [(0,90)/(0,90)/(0,90)]s stacking sequence were selected for measuring the amount of possible void in between the sheet plate. As seen in Table 4.3 a percentage of 4.5 % is averaged for the five randomly selected samples of this table. With the proviso that the average calculated content is below the 5% consequently the composites are considered suitable.

## 4.5 Preliminary Test Phase

The green composites production was carried out in the form of plates. Coupons intended for tensile and flexural tests were cut from the resulting plates using a table circular saw in order to obtain the appropriate dimensions for the destructive mechanical tests.

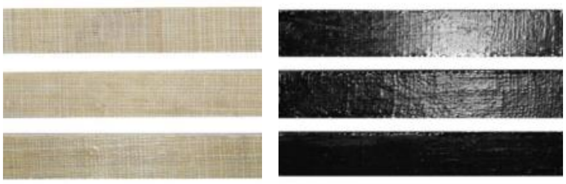
For the tensile tests the coupons had constant rectangular cross-section with 250 mm in length, 25 mm width and 4 mm thickness. Four tabs were bonded in the top/bottom faces of the test coupons as indicated by the ASTM Standard D 3039/D 3039M [137] and seen in Figure 4.7 to successfully load the specimen and prevent premature failure as a result of significant discontinuity in the gripping. The tab material used is galvanized steel of 2,5 mm thickness and glued by an adhesive mean (Araldite two part epoxy glue) to ensure the adequate bonding and stabilized griping during the application of load.

**Figure 4.7. Tensile ramie composites coupons unpainted and painted.**



For the flexural tests, the dimensions of the specimens derived from the ASTM Standard D-790 [138] were 80 mm length, 16 mm width and 4 mm thickness. No tab material attached on the specimens faces in order to perform these tests as seen on Figure 4.8.

**Figure 4.8. Flexural ramie composites coupons unpainted and painted.**



A number of of these specimens were sprayed with paint so as to simulate the painting process in Ancel's workshop. It was intentionally selected black paint so as to have a worst-case-scenario simulation as far as the black color absorbs more sun radiation and heat than the rest of the indexed colors. Two different types of coating systems were applied and tested in different coupon batches for their appropriateness to protect the composites from exposure to harsh weather conditions. The systems to be

compared are an all-purpose acrylic paint and afterwards an aliphatic enamel protective solution.

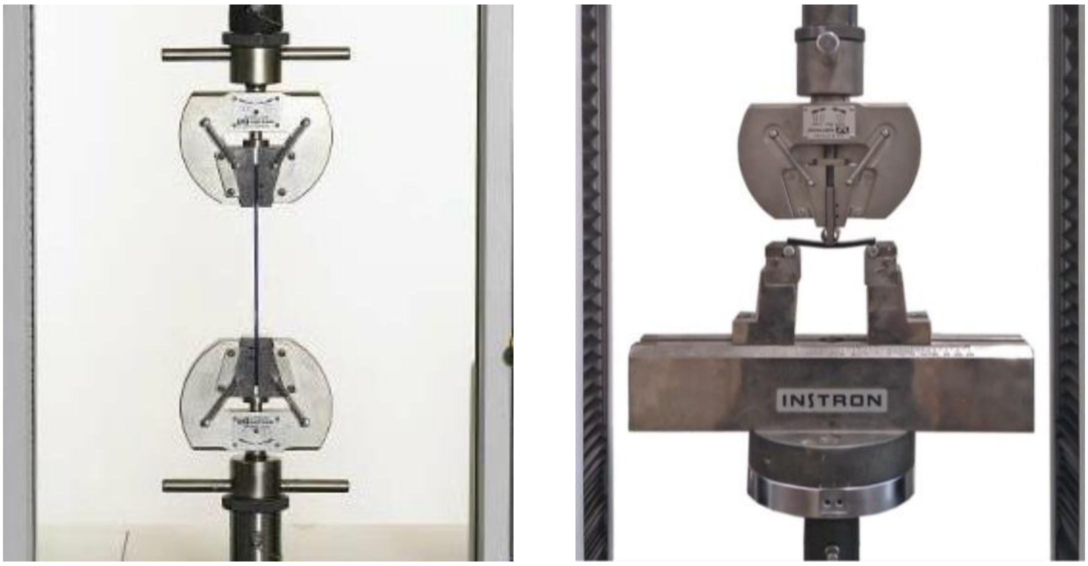
In the case of the acrylic paint, one layer of acrylic zinc phosphate-based primer had to be applied prior to painting to improve the adhesion between the surface and the finishing coat which is in this case the paint. Afterwards, all-purpose acrylic sprayed paint was used to seal the specimens and prepare them for the aging chamber.

The second type of coating is an aliphatic coating system from CIN-Corporação Industrial [22] applied to the specimens with the same procedure used at Ancel to coat plastics for exterior applications (wind turbines, fuel tanks, etc). The C-Thane S610 Sat product is an aliphatic polyurethane enamel and its main properties are excellent resistance to weathering and UV, good water resistance, hard and resistant to impact and abrasion. In order to promote adhesion of the enamel to the surface of the polyester surface C-THANE PRIMER PL was applied previously to the specimens.

## 4.6 Experimental Characterization of the Green Composite Materials

A series of mechanical tests were performed in order to measure stiffness along with flexural properties and further understand the practical behavioral aspects of these novel composite materials. For that case, ramie reinforced composites which were produced in both Mechanical Testing Laboratories and in Ancel's workshop were tested in a Universal Instron® Tension Testing Machine (3360 Series - Dual Column Tabletop System) equipped with pneumatic grips of 50KN max load. All testing was conducted at ambient temperature around 25ºC and relative humidity of about 60%. The test results were summarized with the use of the computer aided software for static systems Bluehill®2 Universal Testing Software.

**Figure 4.9. Intron machine testing settings for tension and flexure**




For the tensile tests, the crosshead speed rate of the tests was set to 1 mm/min. Tensile strain was measured directly with a static axial clip-on extensometer (Instron® 2630-100 Series) of 25mm gauge length. On the extensometer grip, wire clips were attached particularly for the evaluation of rectangle specimens.

For the bending tests, the applied load was set at 1 mm/min crosshead motion rate. The support span-to-thickness ratio was set at 16:1. During the determination of flexural properties calculations and due to the absence of extensometer, the strains of the coupons were calculated in accordance with ASTM 790 standard by the following equation.

$$\epsilon_f = 6Dd/L^2 \qquad \textbf{(Eq. 3)}$$

Where $\epsilon_f$, is the flexural strain in the outer coupon's surface, D equals the maximum deflection of the neutral axis of the coupon, L is the support span and d is the coupon's thickness.

## 4.7 Experimental Test Results

Regarding the tensile properties, the respective average values for tensile stress ($F_{tu}$) and strain ($\epsilon$) as well as the tensile modulus of elasticity ($E^{chord}$) were listed in tables and plotted in column charts. As for the flexural properties it was considered the flexural strength ($\sigma_f$) and strain ($\epsilon_f$) and the modulus of elasticity in bending ($E_B$). For all of the above properties the standard deviation (SD) and the samples' coefficient of variation static in percentage (CV) as specified in the ASTM designations of D-790 and D 3039 standards[137, 138] are presented.

As imposed by the standards used; a minimum number of five specimens are necessary to validate a given property for each of the testing methods. During the tests more than that number was tested from each batch but unfortunately after some failed runs not all of the batches numbered more than five valid records. As for the ones they had more, five specimens out of the total sample population have been chosen to provide a representative value range as follows. The stress/strain curves that presented a schematically similar trail pattern and were branching in an analogous area were chosen so as to get the minimum variation possible. It was observed subsequently, that the bigger the number sample population was; the higher was the possibility to identify curves with lower coefficient of variation.

It is essential to realize that in order to acquire reliable results in terms of the composite mechanical performance all the values to be presented were measured in an intentionally limited deformation. Regularly, the ultimate tensile and flexural values can be calculated on the highest point on the stress/strain chart after the manifestation of a sharp audible crack which is accompanied by a catastrophic specimen shear failure. Nevertheless, in this study the failure point was considered much earlier, precisely when the first crack propagated after a slight drop which changed the slope of the load/displacement curve. As a result, the true ultimate values were marked lower even if complete failure did not occur at the first crack but generally much later following a series of interlaminar cracks up to the point of the coupon shear failure.

### 4.7.1 Tensile and flexural properties acquisition for non-aged specimens

Table 4.4 and Table 4.5 report the results of mechanical performance. There is listed the data in average value for a satisfactory specimens population. For all tensile and flexural coupons, it was displayed a range of linear elastic behavior following by an non-linear, inelastic behavior up to rupture excluding the BP specimens (neat thermosetting bio-polyester) which were proven to be very brittle (refer to charts on Figure 4.10 and Figure 4.11).

Moreover, explaining the acronyms: the RBP is ramie reinforced bio-polyester with 6, 9, and 12 layers; RPD (ramie polyester dried); RPUN (non-dried ramie polyester); RDX (appeared only in the flexural testes because the tensile tests did not have satisfactory coupons to be presented) is a ramie reinforced polyester in different stacking with the balanced symmetric sequence **[(0, 90), (0, 45), (0, 90)]2s** labeling a 12 layered ramie composite. The tables are also list data values of tested specimens adopted from the doctorate thesis of Alves et al., [18] for composites produced in the same mold

machine (at IST University) through a similar manufacturing process and using the same resin matrix . However, the fiber and its contents are different and their presence to this table is present only for comparison purposes. The acronyms for these specimens are JFBD (jute fiber bleached and dried), JFC (jute fiber control — no treatment applied), JFD (jute fiber dried), GFC (glass fiber control).

It is noticeable in the tables that the column indicating the renewable content of the composite (**$V_{ren\%}$**); is different from its fiber volume (**$V_{f\%}$**) only for the RBP series coupons. The **$V_{ren\%}$** value is a sum of all renewables added to the composites indicating the total renewable volume of the composite (fiber and resin). The incidents that have the same values for both **$V_{ren\%}$** and **$V_{f\%}$** means that no renewable content is included in the resin mix and thus the value **$V_{ren\%}$** comes out only from the natural fiber addition.

**Table 4.4: Tensile properties**

| Sample | Resin | $V_{ren}$(%) | Vf(%) | $F_{tu}$(MPa) | $E^{chord}$(GPa) | E CV(%) | $\epsilon$ (%) |
|---|---|---|---|---|---|---|---|
| BP | BioPoli | 13,5 | 0 | 19,3± 9,3 | 4,1± 0,1 | 3,3 | 0,4± 0,08 |
| RBP6L | BioPoli | 30 | 20 | 27,1± 1,6 | 4,4± 0,4 | 9,3 | 0,5± 0,05 |
| RBP9L | BioPoli | 37,5 | 22 | 39,0± 9,0 | 3,8± 0,2 | 3,7 | 1,3± 0,29 |
| RBP12L | BioPoli | 45 | 32 | 45,9± 5,9 | 3,8± 0,6 | 17,9 | 1,8± 0,24 |
| [a]JFC | Quires | 31 | 31 | 27,7±7,7 | 1,8± 0,2 | 5,0 | 1,4± 0,0 |
| [a]UP | Quires | — | — | 35,24 | 2,78 | 8,6 | 1,27 |
| RPD | Quires | 10 | 10 | 37,2± 7,2 | 3,3± 0,5 | 16,6 | 1,1± 0,00 |
| RPUN | Quires | 15 | 15 | 29,6± 9,6 | 3,0± 0,1 | 3,3 | 1,0± 0,01 |
| [a]JFD | Quires | 28 | 28 | 30,3±0,3 | 5,2± 0,2 | 4,0 | 0,6± 0,0 |
| JFBD | Quires | 18 | 18 | 35,3±5,3 | 4,9± 0,1 | 4,0 | 0,7± 0,0 |
| [a]GFC | Quires | — | 21 | 60,5±0,5 | 8,8± 0,5 | 4,0 | 0,5± 0,0 |

[a] *Values from Alves [18].*

**Figure 4.10. Evolution of tensile stress for a representative number of specimen on each configuration**

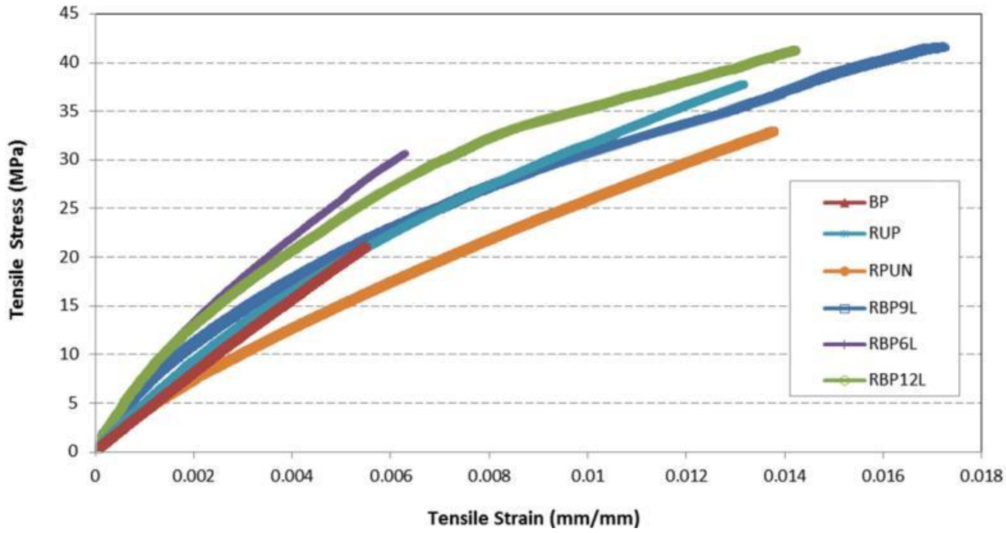
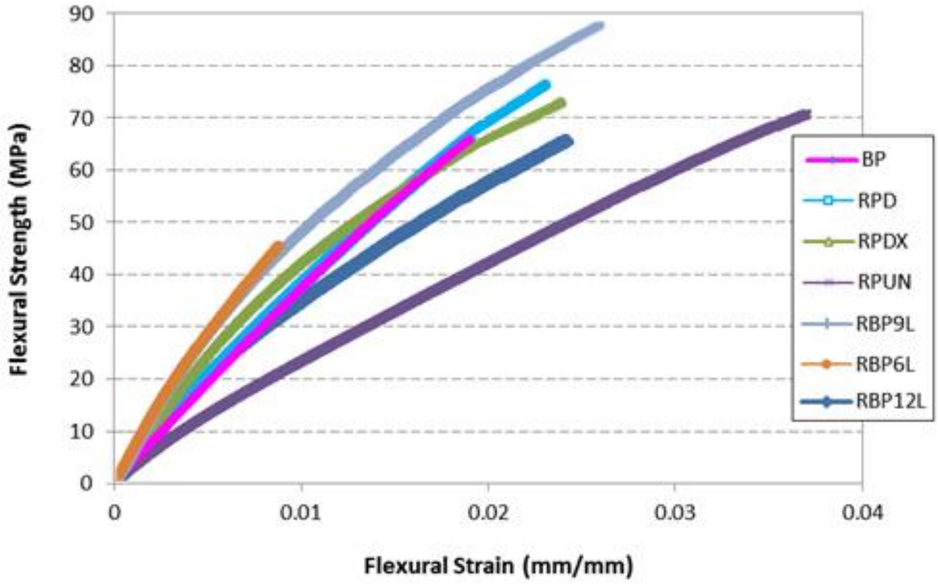



**Table 4.5: Flexural properties**

| Sample | $V_{ren}$(%) | Vf (%) | $\sigma_f$ (MPa) | $E_B$ (GPa) | $E_B$ CV (%) | $\epsilon_f$ (%) |
|---|---|---|---|---|---|---|
| BP | 13,5 | 0 | 60,6± 7,4 | 3,6± 0,3 | 9,74 | 1,7±0,0 |
| RBP6L | 30 | 20 | 49,6± 9,5 | 5,8± 0,4 | 7,10 | 0,9±0,00 |
| RBP9L | 37,5 | 22 | 79,3± 5,9 | 6,4± 0,3 | 5,76 | 2,1±0,00 |
| RBP12L | 45 | 32 | 69,3± 7,2 | 4,6± 0,7 | 17,15 | 2,5±0,00 |
| [a]JFC | 31 | 31 | 49,5 | 1,5± 0,1 | 7,26 | 2,92 |
| [a]UP | — | — | 79,16 | 1,89± 0,1 | 7,35 | 4,36 |
| RPD | 10 | 10 | 68,7± 5,6 | 3,8± 0,3 | 8,26 | 2,3±0,00 |
| RPUN | 15 | 15 | 67,2± 7,1 | 2,6± 0,1 | 4,93 | 3,5±0,1 |
| RPDX | 35 | 35 | 71,9± 3,4 | 4,7± 0,4 | 8,37 | 2,5±0,2 |
| [a]JFD | 28 | 28 | 59,1 | 3,0± 0,1 | 6,30 | 1,94 |
| [a]GFC | — | 21 | 70,0 | 4,6± 0,1 | 2,49 | 1,53 |

[a] *Values from Alves [18].*

**Figure 4.11. Evolution of flexural tension in produced composites**




### 4.7.2 Discussion on the mechanical properties

There are a number of observations and conclusions that can be drawn out after going through Table 4.4 and Table 4.5 concerning the relation of the mechanical properties with the fiber volume and/or the drying treatment applied.

**Tensile Properties**

First of all, it is noticed that by increasing the fiber volume (Vf %) as in the batches RBP 6-9-12; the tensile strength is increased linearly. The difference when compared with the neat polyester is clear as the tensile strength was increased gradually from 40 — 138% by the addition of the ramie fabrics. Also, the strain shows a remarkable increase with the fiber volume from 12% — 276% accordingly. In contrast, it is evident that change in the fiber volume does not contribute significantly to the Young's modulus but rather decreases excluding the instance of the RBP6L where it was slightly improved by the fiber presence. It is necessary to consider pointing out at this point that the RPD composites batches produced in IST, ranked higher than the RPUN although having lower fiber content. That is an outcome of the effect of the drying treatment. In general, when reducing the absorbed water in the fibers before the composite fabrication then that on its turn strongly affects the adhesion of the fiber in the polymeric matrix, and therefore enhancing the fiber to matrix interaction. Several authors have shown that when the temperature of the fiber increases, the absorbed water is vaporized and thus the fiber develops internal mechanical stress [85, 107].

Secondly, another remark can be pointed out regarding a comparison of the JFC samples to the RBP6L from a mechanical property standpoint as both have the same number of fabrics layers. The latter demonstrates a relatively better performance in both testing methods even with lower fiber content. After a more careful reading of the results it is apparent that all RBP specimens have mutually better performance in terms of strength while several of them also in strain and modulus. This is indeed interesting if bearing in mind that they are produced with less fiber volume without neglecting the fact that at the same time they have higher renewable content. The earlier comparison is considering coupons with fabrics as reinforcements that had not been dried. Undoubtedly, the untreated RBP6L —12L can actually compete with the JFD and JFBD on which fabrics had been applied after drying and bleaching treatments. Regarding the RP series they both have a very close performance or actually improved in terms of tensile strength comparing to the JFD, however outperformed in young modulus values. That is a result of the low fiber volume (10-15%) comparing to the ones produced by jute (18-28%), the author wanted to keep the same amount of layers (namely six) so as to have a more direct comparison in terms of layer number and not being fiber volume dependent.

Finally, when comparing all ramie composites to the GFCs it can be concluded that from the RBP series, the one that can be directly compared is the RBP9L if analogous Vf(%) is considered. In that case the RBP9L specimens are 35% less strong and 56% less stiff from the GFC specimens. If fiber loading is disregarded; the RBP12L ranks a bit higher in stress among the RBPs as it contains more fabric layers however the overall performance is still as much 25%-50% less than the one of GFC. As for the RP series (6 layered ramie fabric) it can be seen that they cannot reach the fiberglass reinforced polyester having that low fiber content while their performance can be presumed to reach the half of the referenced synthetic samples.

**Flexural properties**

Again, with the addition of the ramie fabrics in the composite construction — as compared to the neat bio-polyester, both flexural strength and flexural strain were increased accordingly. Conversely to the tensile tests; the flexural modulus conjointly followed an incremental behavior up to the fiber volume of 22% (incident RBP9L on Table 4.5). On the RBP12L coupons, the gradual high marking of flexural modulus was interrupted, although still standing higher from the neat BioPoli 507. For this batch a

high CV in bending modulus $E_B$ (of 17%) may partially explain that behavior. The presence of fiber has improved the composites modulus because the molecular chain mobility of the polymer matrix was hindered by the incorporation of the fibers [22]. The strength partially increased up to 31% (incidence 9L) with the addition of fabrics, as well as the modulus from 60-79%, although both did not follow the same increment as the instance RBL12L of which only strain ranked gradually higher by increasing the volume of fibers.

In the case of the RPs series specimens, it can be marked out that all outclassed the JFDs in flexural stress values while being really close to GFCs. More specifically, the high fiber volume RPDX specimens indeed outranked the GFC in terms of flexural strength. Furthermore, the RPD scores higher comparing to JFD for both and $\sigma_f$ and $E_B$ and with lower strain; even if the RDP contains 180% less fiber volume. It is a general trend and has been also pointed out in the study of Alves al. [18] that the flexural strength is not increased by the presence of fiber but rather decreased in all the specimens produced by Quires UP resin (RP composite series). On the other hand, the BioPoli resin presented different and more complicated results. What was noticed for both is that the flexural modulus was always increased in all cases by the addition of fibers in the thermoset matrixes.

## 4.8 Results for the specimens subjected to accelerated Aging

In this section are presented the results of mechanical testing before and after the accelerating weathering exposure on painted and unpainted specimens. The coupons' batches with the index name RB6L were produced by six layers of ramie fabrics at the stacking sequence of **[(0/90),(0/90),(0/90)]s**. Then several samples of them were placed in the aging chamber for two different periods of time. Two proportionally-based settings of accelerated aging have been applied in two separate specimens' batches which were placed in the aging chamber for different periods. A third batch on which different coating was applied was aged in the chamber differently having exposed to fewer cycles. In total 49 cycles were imposed for the 1st batch (approximately 7.25 days) and for the 2nd batch 99 cycles (around 14.5 days). The 3rd batch remained in the environmental chamber for 69 cycles (around 10 days). The conditions simulated per cycle in the oven were UVB radiation, humidity and air circulation; analytically the conditions and alteration are presented below.

**Table 4.6. Aging chamber conditions**

| Time (min) | Temperature (ºC) | FAN speed (%) | Humidity (%) | UVB |
|---|---|---|---|---|
| **0** | room | 0 | room | off |
| **30** | 30 | 100 | 0 | off |
| **150** | 60 | 100 | 60 | on |
| **30** | 30 | 100 | 0 | off |

Table 4.7 and Table 4.8 are reporting the tensile and flexural properties of the coupons tested after the weathering exposure. The RP6LNA acronym stands for the control specimen, not having undergone exposure inside the chamber. The indicator "1W" that follows the acronyms of two batches is to specify the one week of aging while the "2W" indicates two weeks of aging. The "ENM" characterizes the specimen covered by enamel paint (mentioned as 3rd batch in the previous paragraph) and aged for 10 days. The indicator PN denotes that they were painted before being placed to the chamber. It is worthy of remark that after two weeks of exposure the specimens became very brittle, adopting the behavior of the neat polyester specimens. For that reason the coupons typically failed (in the occurrence of the first crack) before the strain reached 0.006 — mainly around 0.004 and thus a different range for the calculation of the Young's modulus was necessary as the standards designate for the acquisition of the tensile properties. In order to make a true comparison, the range on the stress/strain curve was set in the same span for all the specimens that were included in this comparison, namely at 0,0105% – 0,0021% strain which represented the 25% – 50% of the stress/strain curve in all of the coupons tested

Untimely Figure 4.7 and Figure 4.8 show the results for the non-aged specimens with this inclusive method of calculating the Young's modulus (see RBP6L NA), and the aged specimens, for tension and bending.

**Table 4.7. Tensile properties of aged tested composites**

| **Sample #** | $F_{tu}$ (MPa) | E (GPa) | E CV (%) | $\epsilon$ (%) |
|---|---|---|---|---|
| **RB6L NA** | 27,15± 1,6 | 5,2± 0,4 | 10,0 | 0,56± 0,05 |
| **RB6L-1W** | 23,9± 1,8 | 4,8± 0,1 | 4,0 | 0,54± 0,06 |
| **RB6L-1WPN** | 24,6± 1,6 | 4,4± 0,3 | 7,7 | 0,68± 0,11 |
| **RB6L-2W** | 21,5± 3,7 | 6,8± 0.8 | 12,3 | 0,32± 0,03 |
| **RB6L-2WPN** | 20,4± 3,0 | 5,6± 0,4 | 7,7 | 0,40± 0,06 |
| **RP6L-ENM** | 28,7± 2.9 | 5,2± 0.9 | 8,9 | 0,79±0.17 |

**Table 4.8. Flexural properties of aged tested specimens**

| Sample # | $\sigma_f$ (MPa) | $E_B$ (GPa) | $E_B$ CV (%) | $\epsilon_f$ (%) |
|---|---|---|---|---|
| **RPBL** | 49,6± 9,5 | 5,7± 0.41 | 8,7 | 1,01± 0,23 |
| **RPBL-1W** | 41,6± 3,9 | 3,6± 0,41 | 11,3 | 1,29± 0,03 |
| **RPBL-1WPN** | 40,7± 8,2 | 3,7± 0,93 | 2,5 | 1,20± 0,23 |
| **RPBL-2W** | 37.2±5.6 | 5.1± 0.92 | 33,3 | 0.98±0.05 |
| **RPBL-2WPN** | 36,4± 5,6 | 5,0± 1,25 | 24,9 | 0,85± 0,09 |
| **RP6L-ENM** | 44,56± 3,6 | 4.7± 0.45 | 9,46 | 0.96± 0.08 |

**Tensile properties after aging**

As seen from the results on Table 4.7 the tensile strength gradually dropped with increasing exposure time while the acrylic paint did not have a significant effect in sustaining their bulk properties. There is a peculiar behavior of the composite regarding the painted and unpainted coupons as determined by the tensile modulus measurement. After the first week of exposure, both 1W painted and unpainted specimens were found to have an insignificant drop on the tensile modulus which may be attributed as an occurrence of the variation in between the population of the tested coupons. Additionally there is a 4-10% CV on the Young's modulus in all aged (2 batches) and the non-aged specimens (1 batch). Later on, it can be observed that the tensile modulus increases after the exposure for two weeks in the harsh conditions of the chamber; precisely 32% higher modulus is marked for the non-painted coupons RB6L-2W. However, this is not unheard of since additional researchers also have come across the same results after the accelerated aging process on natural fiber reinforced polyester composites [139, 140]. A plausible explanation may be due to the increased stiffness of both the polymer and the fibers after thermal exposure. The remaining water in the fibers is evaporated and the fiber-matrix interface is strengthened. In the case of the painted coupons (incident RB6L-2WPN), the modulus also increased but much less (about 8%). It can be deduced therefore that the paint controlled the loss of moisture and hence the specimen did not have such a significant change in tensile modulus.

The acrylic paint seems to affect in different ways both 1W and 2W specimens batches in terms of the elongation behavior. After the first week of exposure; the painted specimens' series RB6L-1WPN did not present any drop but instead an increment of 22% on the strain contrary to the non-painted specimens which roughly retained their performance in elongation. The increased elongation behavior is an effect of the heating as the black painted specimens where found to be more flexible and were slightly bent

after the accelerated weathering. In the second stage of exposure, both painted and non-painted samples were found to have a drop in strain with the painted coupons showing improved performance compared to the non-painted as their strain decreased in the order of 26,5% on the contrary to the unpainted that dropped in the order of 41%..

Regarding the coated coupons (RP6L-ENM) the observations suggests that the enamel paint acted as a good protecting agent against the conditions simulated at the oven. According to the tests, no substantial changes are witnessed in the performance after 10 days aging rather than an increment of the strain by the order of 45%.

**Flexural properties after aging**

As for the flexural strength one may notice that it was gradually decreased after every aging period and in this case, more evidently, the acrylic paint did not contribute to any kind of additional protection against the conditions simulated in the aging chamber. The flexural strength decreased gradually by 16 – 26%. The same trend was followed for the modulus of the 1W flexure specimens where similarly the modulus obtained reduced by 35% for both painted and non-painted specimens. Although, in the 2W group the modulus increased in the same fashion as for the tensile specimens where once again the paint may have acted as a controlling mean for the moisture escape and hence the specimen did not show a significant change on the flexural modulus. Finally the strain seems to have increased after the first week of aging and then decreased after the second week of exposure with the lower values acquired for the coupons RB6L-2WPN. It may be concluded that after the first stage of aging the coupons become more elongated but after the second period of aging they lost that ability and converted into stiffer coupons.

According to the outcomes as concerns the coated coupons (RP6L-ENM), it is quite evident that the enamel paint represented once more a reliable protecting agent for the flexural properties. That is perceived by sustaining the properties with a slight drop by the order 10% which might have been an effect of the varying properties of the composite's fibers or alternatively due to variability of production in between the specimens population tested.

## 4.9 Conclusions for the Mechanical Testing Phase

- Two different sets of green composites combining bio-polyester or traditional unsaturated polyester along with the addition of ramie fabrics were successfully fabricated. In this research the maximum renewable content per plate volume was

attempted for the composite construction and was increased gradually up to the point that there were no significant defects in the finishing surface in terms of porosity. In the case of specimens reinforced by 12 layers, it was observed some lack of impregnation in between the resin and the fiber and thus composites of higher fiber volume were not manufactured. That occurred for a %Vf of 32% for both RP and RBP composites. Even though with higher fiber fraction, the composite loses part of its mechanical performance. As it has been also reported by other researchers, the decreased mechanical strength with higher fiber loading 40Wt% which corresponds to approximately 30Vf% was explained in terms of stress concentration and dispersion problems [28, 36, 141].

- Regarding the renewable content of the composite itself, it is necessary at this point to consider that Alves [18], on his doctorate thesis did not use polyester containing renewables in its substance and thus it is the fiber volume only that expresses the renewable content of the whole composite. Contrarily, on the present research a part of the produced plates were fabricated with the use of BioPoli 507 resin and therefore the total renewable content was increased when summed up with the fiber volume. As far as calcite was added to the mix for the matrix along with Biopoli; the renewable content did not reach the maximum percentage. Otherwise, it would have been even higher if the matrix mix contained only bio-polyester resin following the example of the RP series.
- Moreover, it is assumed that all of the mechanical properties analyzed in the present study would have been higher by the absence of the calcite in the composites which comprised roughly 30% of the resin. However, even with the addition of calcite powder filaments in ramie composites demonstrated relevant or better performance in comparison to the ones of jute. It is presumed subsequently that higher values in all range of properties could have been achieved through the absence of calcite which effect unfortunately was not studied in this research. Furthermore and unfortunately, without drying treatment applied on the composites' fibers of the RBP series (the ones produced in Ancel); it was not possible to evaluate and take advantage of their potential to their full extent.
- It can be summed up that the RPB9L series was found to give the higher values in terms of flexural properties while outperforming all the jute fiber composites even the ones of the GFC which hold the same fiber volume. As for the tensile test, the 9L BioPoli specimens get the second rank while still outmatching the JFC and with

a treatment they could even compete with the JFD, GFC. In both comparison though lower Vf(%) has been used as the grammage of the ramie fabric is lower than the one of jute and glass. Confidently then, it can be assumed that a drying treatment could have a complementary effect in improving the flexural and tensile properties of the composites.

- Regarding the enamel painting as applied to the specimens it can be deduced that such paint will additionally protect the composite against weather condition better than a common paint for metallic parts with no UV protection. The acrylic paint on the contrary did not show any possibility of retaining the coupons bulk properties after exposure to environmental chamber harsh conditions and has therefore proven inappropriate.

# Chapter 5. ECONOMIC ANALYSIS

## 5.1 General Discussion

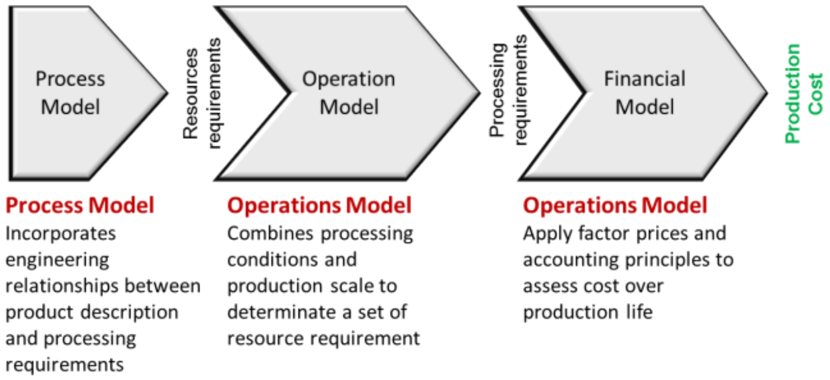
The goal of the present economic analysis is to assess to what level the choice of materials and processing technology affects production costs. As such, it is generated a common framework of generalized operational and financial conditions within which it is analyzed each alternative solution, thereby highlighting the technical factors that influence manufacturing cost which minimizing the influence of plant-specific characteristics. The conditions at Ancel's production facility are used as an outline for the generalized operational conditions of the baseline scenario; thereafter a number of proposed improvements on this approach are applied and then ranked against each other and discussed in the following sections.

### 5.1.1 Process-based technical cost modeling approach

In order to evaluate the baseline design and alternative solution; a process-based technical cost modeling approach was used. This method combines three models: one of process, of operations and finance, in order to project the prospective manufacturing costs and provide a production cost estimation of high accuracy.

The first step in this approach utilizes a process model that incorporates engineering relationships between the part description and the materials processing technology to determine the necessary processing requirements. Next, an operations model combines the processing conditions with the desired production scale to determine plant resource requirements. Finally, a financial model applies factor prices and accounting principles to the set of resource requirements coming from the operations model in order to determine the production cost. A graphical representation of the entire cost modeling approach is illustrated in the Figure 5.1 below.

**Figure 5.1: Process-based cost model approach**




### 5.1.2 Manufacturing specific issues in process-based modeling

When adapted to manufacturing processes, a process-based cost modeling approach considers all the elements of a production scenario that contribute to operations cost. Thus the product description is the set of part characteristics such as size and weight that could influence processing requirements like forming tonnage, cycle time, and tool complexity. Furthermore, the process model is parametrically linked to the product description, so that processing requirements are automatically updated when the product description is modified.

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. For any process step a, the effective production volume is given by:

$$Production\ Volume_a = \frac{Production\ Volume_b}{(1 - Reject\ Rate_a)} \quad \textbf{(Eq. 4)}$$

Where, Production $\text{Volume}_b$ is the production volume of the process step immediately following process step a. 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.

Tool costs are generally fully allocated to the part (unless the tool can be used to make another part) and amortized over the product life only. Figure 5.2 summarizes the manufacturing-specific issues in process-based cost modeling.

**Figure 5.2: Main process-based cost model elements**

| | |
|---|---|
| **Consumables**<br>• Raw Materials<br>• Process materials<br>• Recycling<br>**Equipment utilization**<br>• % of the line required<br>**Building space**<br>• Energy | **Effective production volume**<br>(Rejects are considered)<br>• Labor<br>• Indirect<br>• Direct<br>**Equipment requirements**<br>• Press, tool<br>**Capital** |

It is very important to identify and consider the most important elements of manufacturing costs. Capital refers to the machines to be used for the production of the parts and their support equipment. Labor translates to factory's laborers who operate these 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.

The Buggy's hood is planned to be manufactured by the RTM process given that Ancel Ltda already owns all the necessary tooling and the manufacturing know-how. Therefore, its workforce is already familiarized and dexterous with all equipment and procedural steps as regards the RTM manufacturing.

### 5.1.3 Economics of the current practice of the buggy's hood

An interactive process based cost model was developed to describe and quantify the performance of thermoset RTM and Sheet Metal Forming (SMF) processes in the production line of Ancel industrial unit. The manufacturing costs and analysis are compared regarding the option of changing the polymer resin and the fiber reinforcement in the production of the composite. Operating conditions such as cycle time, material cost, labor cost, production volume and financial parameters were introduced into the model in order to estimate the total production cost per part and at several production runs. The objective of this step is to project cost and compare the green composite production and baseline practice of a complete synthetic composite. Thereafter, different charts will present cost behaviors and their relationship with production volume, batch size, effectiveness in materials' use and part's geometry.

### 5.1.4 Market Description

In fact BRM (British Racing Motors), a basic niche manufacturer of 45 years presence in the market is producing about 600 buggies per year. That represents about 30% of the total Brazilian buggy production and the final cost of its vehicles ranges from R$ 25,000.00 to R$ 40,000.00 (Brazilian currency). The anticipated selling price is of Ancels' Buggy to deal with the competitor is targeted to be R$ 15,000.00 – R$ 25,000.00 according to Ancel Sales Department;

- Total Brazilian market estimated: 2000 buggies per year.
- Intended annual production – 300 buggies per year (about 15% of the market), in the first 5 years.

The production after the first testing period that will be depended on its previous introduction to this market segment being expected to be increased. Although for the cost model it will be considered only the first five years of stable production volumes.

### 5.1.5 Description of approach to manufacturing

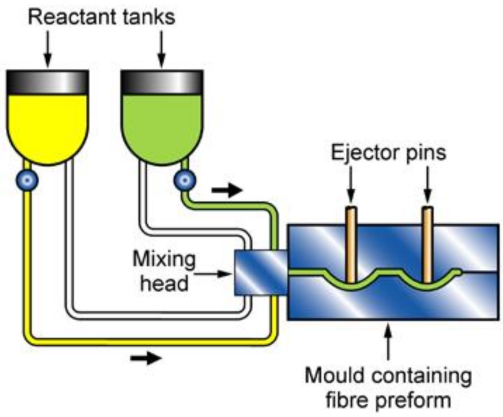
RTM process is a very popular technique in automotive and aerospace industries for producing large and complex parts [142, 143]. It has gained popularity in composite materials due to its high efficiency and good reproducibility, and recently it represents about 9,2% of the global composite production [144]. Following that popularity from the industry, a number of studies have been conducted by incorporating natural fibers as reinforcements with biopolymers or synthetic polymers as matrix using the RTM process [9, 28, 145, 146]. Among one of the reasons being its relatively low cost in terms of mold investment and tooling.

In thermoset RTM processes, the fiber preform or fabric layers are placed onto a mold surface; the mold is clamped and sealed and the resin is then injected into the mold under pressure. The motive force in RTM is pressure, thus, the pressure in the mold cavity will be higher than atmospheric pressure. This manufacturing process allows for great tailorability in the final part's strength and stiffness, and can produce complex and intricate part geometries.

In RTM several thermosetting types for polymeric matrices can be used as long as their viscosity is low enough to ensure a proper impregnation with the reinforcing element. Therefore, high permeability of the reinforcements is also required and for that the layers are carefully arranged in the mold cavity preventing the race tracking effect. Race racking is a phenomenon in which the resin flows faster along the minuscule

channels induced by imperfect fits between the preform edges and the mold walls. Injection pressure, constituent materials and gel times play an important role on that balance. A good practice to avoid that shortcoming flaw is by cutting the preforms/fabric layers in equally and homeomorphous shapes and stacking them rectilinearly. Another way to assist the resin wetting into the fiber mat is by creating vacuum inside the mold and thus removes the trapped air which might result in gaps in the form of bubbles.

**Figure 5.3. Resin Transfer Molding (RTM)**




*Adopted by CES Software [72]*

When the reinforcement is placed in the mold, the resin is pumped through one or additional injection points into the closed mold containing the preplaced fabric, forcing the matrix flow through dry fibers (see Figure 5.3). This process allows a maximum fiber volume fraction of about 65% in glass fiber applications, however by increasing the fiber volume fraction more injection pressure is required. After the injection phase, the resin and fibers have to remain inside the mold for prior curing for about several minutes (curing time will depend on the total part mass) and then the composite can be removed. The curing time can be optimized by the use of an accelerator, higher amount of catalyst and/or addition of mold heating so as to assist the chemical reactions which solidify the molded part. Finally, in order to extract the part from the mold cavity, tools are required to prevent cracking or other distortions of the cured part. In some cases, the part is moved for post-curing in a controlled heating environment, to further reinforce a part for enhanced performance.

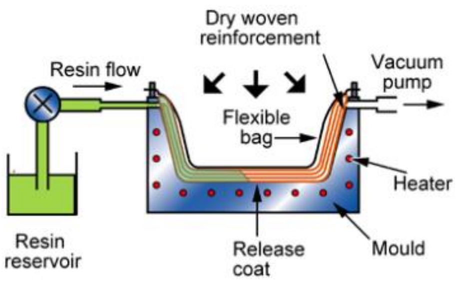
### 5.1.6 The future of RTM

Novel RTM adjustments and in-machine modifications define that procedure even more attractive for future product development in automotive industry. As it has been

suggested by Verrey et al., [147] it is feasible to use Thermoplastic RTM (TP-RTM), for automotive floor pans quadrant demonstrators by making the use of a mix of a novel reactive polyamide 12 (PA12) along with continuous carbon fibers. In order to initiate the procedure; polymerization temperatures need to be maintained 180 $^{0}$C during processing. Lastly as they indicate, there is an high potential for the expansion of this RTM technology into higher manufacturing volumes also for the production of complex 3D geometries [147].

In the Composites Europe 2010 exhibition, a team of scientists from the Fraunhofer Institute for Chemical Technology (ICT), presented a trunk liner for the Porsche Carrera 4 using a TP-RTM technique [148]. ICT engineers are claiming that the process is suitable for mass production of up to 100000 parts per year and with processing cost that are up to 50% lower than the equivalent costs for thermoset structures. That occurrence is perceived because the cycle time needed to produce thermoplastic components is only around 5 minutes whereas comparable thermoset components frequently require more than 20 minutes. Additionally as lately reported, A–Class finish surface can be obtained with the addition of thermoplastics through RTM process. An outer layer of a thermoplastic skin bonded to the composite material and shaped by the Light RTM process or LRTM (see Figure 5.4) which eliminates the need to use paint [149].

**Figure 5.4. Light RTM**

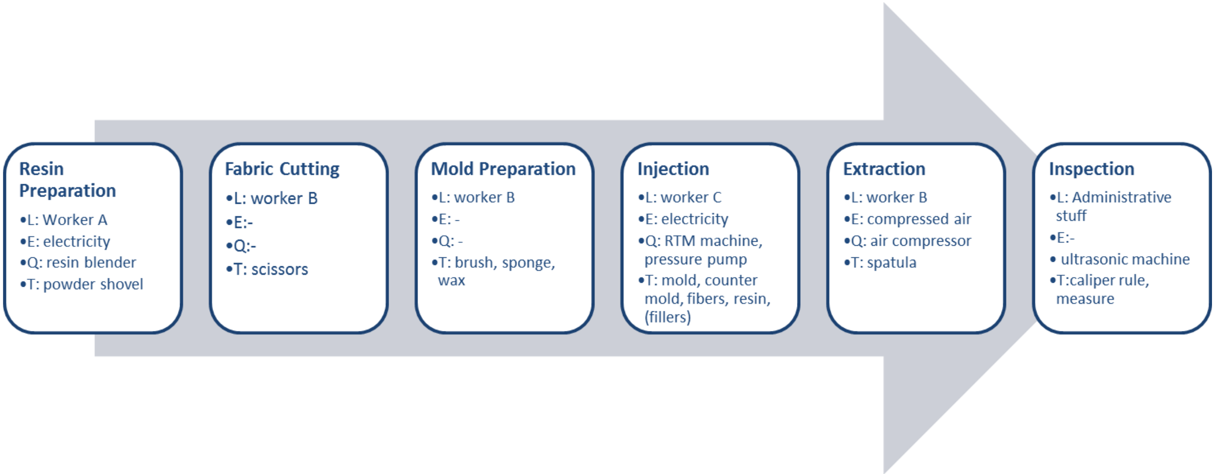



*Adopted by CES Software [72]*

## 5.2 Current Manufacturing Practice for the Buggy Vehicle

According to Ancel's past projects on relative parts production, the prospective manufacturing process (baseline scenario) of the hood is expected to be produced in a six-step sequence (as seen in the Figure 5.5) as will also described in the cost modeling spreadsheets of the next chapter. Inside that catalog for each process step, $L$ stands for labor, $E$ represents the what kind of energy is used, $Q$ indicates the equipment employed and $T$ translates to tools.

**Figure 5.5. Current buggy manufacturing practice steps outline**




At first, away from the RTM production section as illustrated on Figure 5.7, small amounts of matrix resin are being prepared (mixed with additives and promoters) and stored before injection is initiated. Later on the fabrics in unimpregnated form are cut and stacked accordingly ready to be place inside the mold.

In another section of the workshop; where the mold is set up, a worker cleans up the cavities with an alcoholic thinner and afterwards adds in a sequential way a demolding agent and wax on both molds' sets surfaces. At the end of this step, the mats are placed inside the mold and the two halves are closed and clamped down together.

In the fourth step the mold set is forwarded to the injection where the polymer resin is inserted in the mold through the injection's gun nozzle controlled by a laborer (Figure 5.6, left incident a). Only when the laborer releases the flow valve the resin is injected into the tightly closed molds. A second laborer as partially seen in Figure 5.6 (left incidence a) was needed only for a few seconds so as to block the injection and release point with two special iron pins during the time the other laborer puts the pistol away and place it in back to the injectors' base. After 10 minutes the composite could be extracted from the mold as the curing is finished. It is a common practice in Ancel to switch various molds of other projects as waiting for an injected part to cure. For that reason several filled molds are arranged nearby the injector and the two laborers are switching posts while waiting for each part to cure.

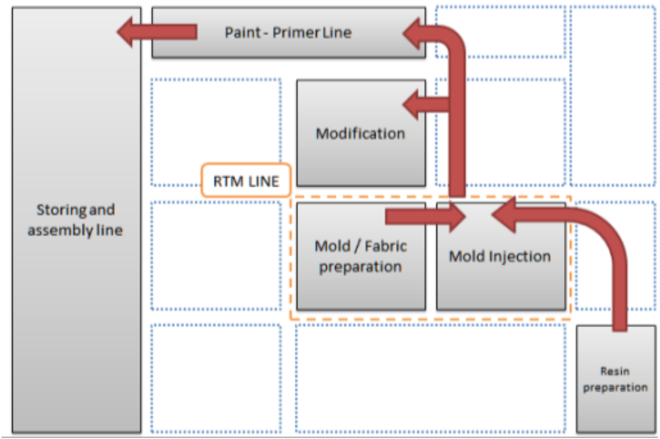
Soon after and when the part is cured (around 10 minutes after injection) the finished part can be extracted. With the use of hand tools if necessary or with an air pistol; the laborer will carefully remove the finished part from the mold. In the last step, the part should be inspected and tested for 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 being complementarily forwarded to the painting/trimming shop to be additionally processed.

**Figure 5.6. Laborer injecting in an RTM mold and the blocked exit point.**

(a) (b)

**Figure 5.7. Ancel workshop top view schematic in relative analogies**




### 5.2.1 RTM technical cost model

The RTM technical cost modeling was previously developed by Materials Systems Laboratory (MSL) at MIT and accordingly adjusted by the thesis author to the Ancels' workshop conditions. The manufacturing process followed in Ancel is exhibited at the Figure 5.8. As it can be seen, the model considers two parallel paths: fiber fabric making and resin preparation. Fiber fabrics making 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 making consists of preparing the resin by mixing it

with additives in the resin agitator machine. Afterwards, the resin and catalyst are transferred at the RTM step and finally after cured for inspection.

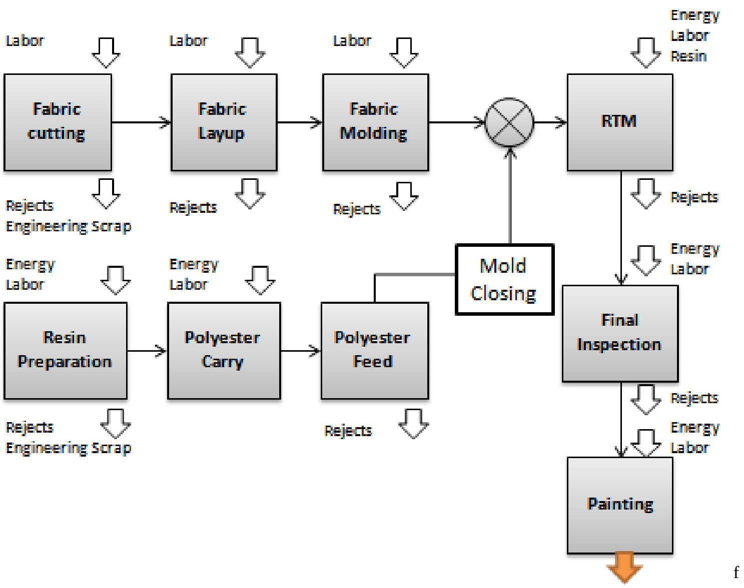



**Figure 5.8: RTM technical cost model**

It is essential to annotate here that the painting process is not considered in the cost modeling process as its assumptions may come up with a number of inaccuracies as regards the volume used for each part surface; especially for metallic parts. Partially for that, Ancel's personnel are not familiar with painting metallic parts and therefore could not provide substantiated information on this aspect. Henceforth, no prediction of the cost associated to painting will be taken in consideration for all processes listed in this research.

## 5.3 Baseline Scenario

Table 5.1 presents the general cost model assumptions used across all baseline economic analyses, including the economic analysis of the current Ancel manufacturing scenario. The values that are appearing here are either recorded at the Ancel production facility or reported by them on site.

The annual production volume (APV) is set in 300 hood parts per year and the plant operates on 302 days per year. It may be well to note that in Ancel facilities as it generally happens to most Brazilian companies the workshop was functioning for 8 hours of one shift during the weekdays and 4 hours on Saturdays. Labor wage (including benefits) is R$4.20 per hour. Energy costs R$0.39 per kilowatt hour. Idle space is the area surrounding machines that must be kept free in order to allow access and 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 R$ 3400/$m^2$ and is amortized over 40 years. Maintenance costs for all equipment is 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 which require much more space than the RTM.

Downtime, comprising all the time when equipment is not productive, totals 19.9 hours per day. This includes 16 hours when there are no shifts, 0.5 hours for unpaid breaks, 0.3 hours for paid breaks, 1 hour for on shift maintenance, 1.3 hours of idle time, and 0.8 hours of unplanned downtime.

**Table 5.1. Assumed plant conditions**

| | | | |
|---|---|---|---|
| **APV** | 300 parts | **Idle Space** | 50% |
| **Days per Year** | 302 | **Capacity Utilization** | 25% |
| **Wage** | $R 4.2 / hr | **Auxiliary Equipment** | Included in machine |
| **Unit Energy Cost** | $R 0.39 per kWhr | **Installation Cost** | 20% of capital cost |
| **Interest** | 15% | **Maintenance Cost** | 10% of capital cost |
| **Equipment Life** | 10 yrs | **Production Lots Size** | 20 parts |
| **Production Life** | 5 yrs | **Building Unit Cost** | $R 3400 per $m^2$ |
| | | **Building Life** | 40 yrs |
| **Downtime** | | | |
| **No Shifts** | 16 hrs | | |
| **Unpaid Brakes** | 0.5 hrs | | |
| **Paid Brakes** | 0.3 | | |
| **On Shift Maintenance** | 1 hrs | | |
| **Idle** | 1.3 hrs | | |
| **Unplanned** | 0.8 hrs | | |

### 5.3.1 Specific parameters related to Ancel production

**Injection machine**

Ancel owns an amortized RTM machine injector that has been functioning for almost 7 years, its cost has been calculated as follows. For a new RTM injector machine the retail price in Brazilian currency is at $R20.500 [150]. The one operating in Ancel's workshop it has been functioning for 7 years already (counting retroactively from 2004), while in its operation-life expectancy was designated for 10 years. In that manner, its price if it was sold would have been $R 6150.

**Labor**

The labor content that was documented at Ancel Tecnologia em Compositos 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 was on the rework line and one indirect worker; supervising the entire production workshop.

**Materials**

Fiber reinforcement: 0.80 kg (23%volume fraction). Resin: 0.82 kg (55,59 % volume fraction). Filler: 0.69 kg (19% volume fraction) for each hood part.

**Part Weight**

The polyester glass fiber reinforced hood produced in IST labs weighs 2.44 kg as adopted by the thesis of Alves et., al [18].

**Table 5.2: Materials characteristics and specifications**

**MATERIAL DATA**

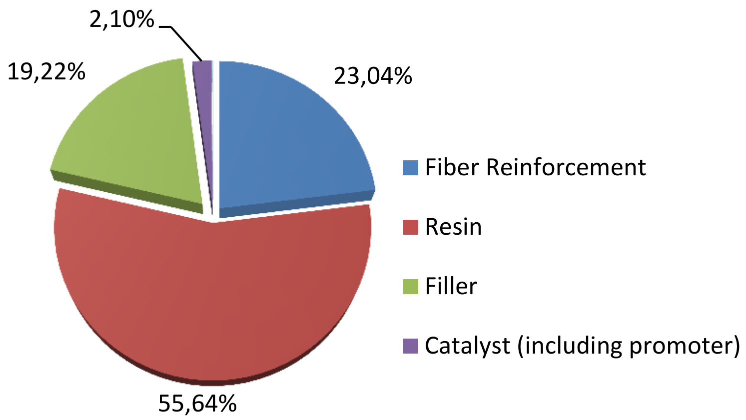
| RESIN | | |
|---|---|---|
| Component Name | Reichhold | |
| Density | 1100 | kg/m³ |
| Viscosity | 0.12 | (Pa*sec) |
| Price | $R 8.4 | /kg |
| Polymer System | POLYESTER | |
| Rate Coefficient | 1.61E+08 | /sec |
| Activation Energy | 7.51E+04 | J/mol |

| REINFORCEMENT | | |
|---|---|---|
| Component Name | Multiaxial Glass | |
| Fiber Density | 2600 | kg/m³ |
| Fiber Diameter | 1.05E -04 | m |
| Price | R$ 9,41 | /kg |

| CATALYST | | |
|---|---|---|
| Component Name | BRASNOX | |
| Density | 1100 | kg/m³ |
| Price | R$ 9.3 | /lt |

The materials identified in the Resin Transfer Molding Solution represent the following percentages in terms of total weight of the hood illustrated in the pie chart of the below figure.

**Figure 5.9: Mass fraction of material composition**




### 5.3.2 Other technical and economic parameters

The maintenance will cost 10% of the machinery initial price (ancillary over lifetime). The auxiliary equipment, installation, and overhead costs are all estimates 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 is actually used for part production. Tool changeover 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.

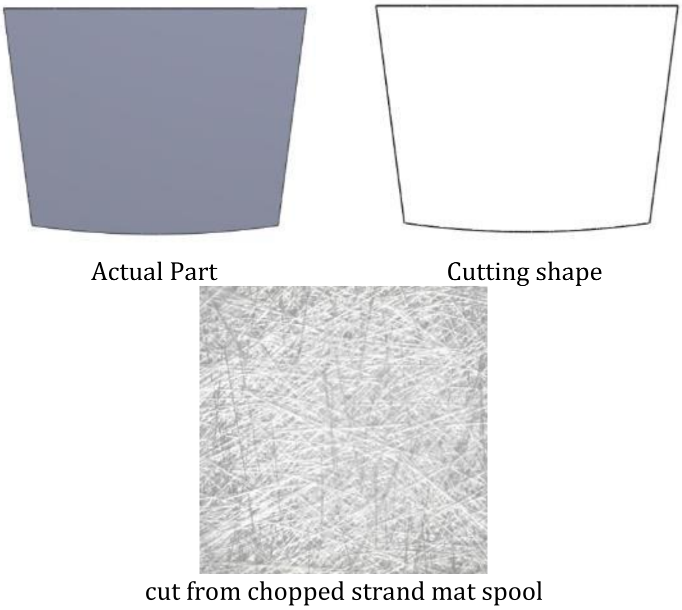
### 5.3.3 Additional RTM painting costs

There is no reliable prediction of the cost associated to this process and thus it will not be considered as previously debated on section 5.2.

### 5.3.4 Approach to ply cutting and layup

Figure 5.10 illustrates the cuts of fabric that are necessary to cut and lay up the fibers for each part. The cuts are from a randomly oriented chopped strand mat produced with long fibers (4" & 6"). In total two cuts, with the aid of one cutting tool (scissors) are required for this operation. It deserves of special consideration that the procedure is very delicate, as long as the biaxial glass fabrics are not woven it is possible that the bundles of fibers escape the fabric's orientation and may enable the race tracking phenomenon. Therefore they are carefully cut and meticulously placed into the mold before the injection.

**Figure 5.10. Approach to ply cutting and layup**




### 5.3.5 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 it is applied a sealing liquid to provide a base coat and increase the mold release effectiveness, that is applied three times in total. Finally four layers of liquid demolding agent are passed on the mold surfaces so as to facilitate the composite release from the mold's cavity. A breakdown of these steps and the times required is shown in Figure 5.11.

**Figure 5.11: RTM process steps**

| **Tasks Done Inside Mold Area** | | **Time (seconds)** |
|---|---|---|
| 680 secs | 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 | | Time (seconds) |
|---|---|---|
| 2866 secs | Preparation of Resin | 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 |

As witnessed on site, Ancel's plant is equipped only with one RTM injector machine and since production runs for the hood are small enough; there is no need for purchasing additional injectors to increase performance by the total cycle time to the lowest possible duration. Hereafter, one mold station is considered to be efficient according to cost modeling calculations and no alternative scenarios will be studied regarding parallel stream RTM production.

### 5.3.6 Production volumes by process step

Table 5.3 presents the effective production for each process step while considering rejected parts in each step.

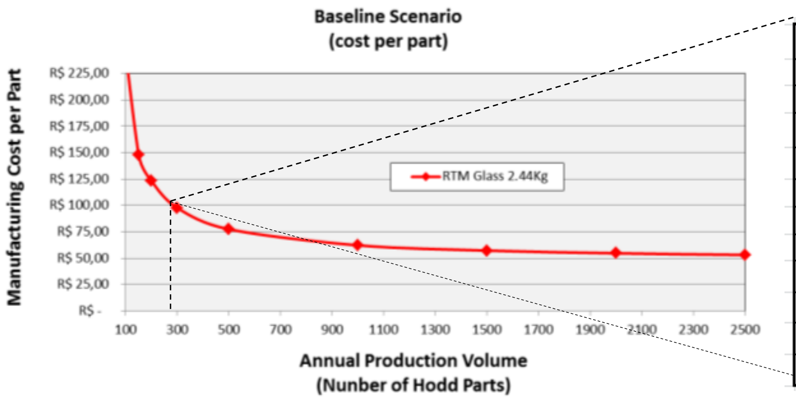
**Table 5.3: RTM production volumes by process step**

| | Effective Volume (per year) |
|---|---|
| **Fabric Cuts** | 660<br>cut fabric layers |
| **Fabric Layups** | 330<br>layered sets |
| **Fabrics molding** | 326<br>single parts |
| **RTM** | 318<br>single parts |
| **Final trim** | 302<br>single parts |
| **Final** | 300<br>single parts |

### 5.3.7 Cost results for baseline

Under Ancel's baseline manufacturing conditions and considering an annual production volume of 300 parts per year, hood was estimated to have R$99,15 of production cost. This includes R$2,02 (2.0%) for tooling, R$35,91 (36.2%) for material, and R$12.36 (12,5%) for the main injector. Manufacturing costs for production volumes from 50 to 2500 parts in Brazilian reais ($R) and a complete cost breakdown at 300 pairs is shown in Figure 5.12.

**Figure 5.12. Baseline cost**




| Variable Cost | | |
|---|---|---|
| Material | R$ 35,91 | 36,2% |
| Labor | R$ 19,08 | 19,2% |
| Energy | R$ 7,71 | 7,8% |
| Fixed Cost | | |
| Main Machine | R$ 12,36 | 12,5% |
| Tooling | R$ 2,02 | 2,0% |
| Building | R$ 8,37 | 8,4% |
| Auxiliary equipment | R$ 1,85 | 1,9% |
| Maintenance | R$ 2,46 | 2,5% |
| **Total** | **R$ 99,15** | **100%** |
| **Tool Investement** | **R$ 40.103,78** | |

### 5.3.8 Natural fibers incorporation

Along with the Glass reinforced composite it was considered the ramie and jute introduction to the hood matrix. The former is the fiber used in this research and the latter natural reinforcement was proposed by a past study of Alves,[18] for the very same

part application and corporation (referring Ancel). However no economic analysis was completed for the cost projection on that work.

Accordingly the constituent materials were set for each case scenario, the glass reinforced composite was containing 23% of fiber the jute 31% and the ramie 20%. The reason for that variation is the different grammage of each fabric added in; however, all composites were manufactured by the addition of six layered fabrics.

As seen in Figure 5.13 for all Baseline scenarios, the cost of having a low volume production is very high in terms of manufacturing cost. Ancel should consider increasing the production volume of the buggies if they are expecting to drop down costs considerably and have additional cost benefits over their competitors.

**Figure 5.13. Hood baseline Scenarios**

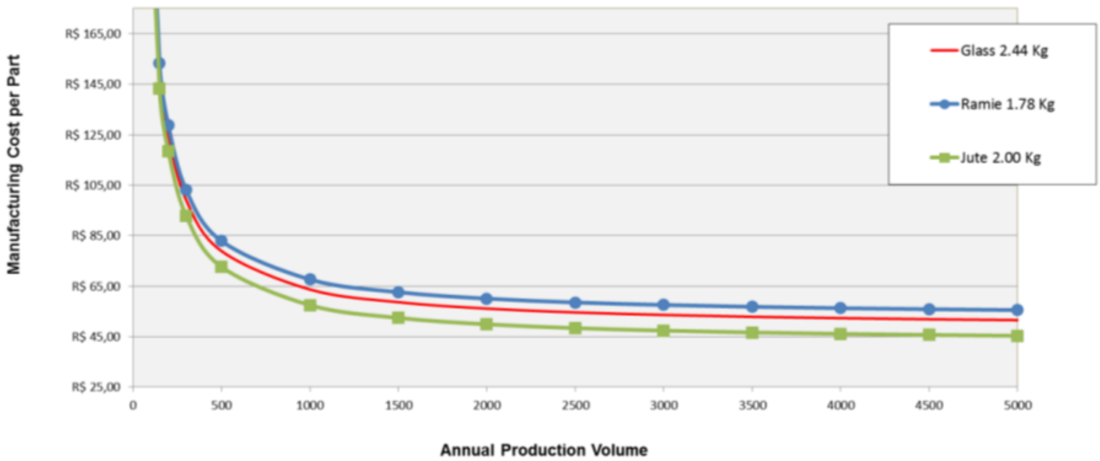



**Table 5.4: Plot baseline RTM composites cost in production volumes**

| PLOT | Glass R$ | Ramie R$ | Jute R$ |
|---|---|---|---|
| **50** | 352,24 | 356,37 | 345,77 |
| **150** | 149,49 | 153,47 | 143,22 |
| **200** | 124,66 | 128,68 | 118,35 |
| **300** | 99,15 | 103,13 | 92,88 |
| **500** | 78,92 | 82,88 | 72,67 |
| **1000** | 63,70 | 67,65 | 57,47 |
| **1500** | 58,67 | 62,63 | 52,44 |
| **2000** | 56,12 | 60,08 | 49,90 |
| **2500** | 54,61 | 58,55 | 48,38 |
| **3000** | 53,60 | 57,55 | 47,38 |
| **3500** | 52,88 | 56,82 | 46,65 |
| **4000** | 52,33 | 56,28 | 46,11 |
| **4500** | 51,91 | 55,86 | 45,69 |
| **5000** | 51,57 | 55,52 | 45,35 |

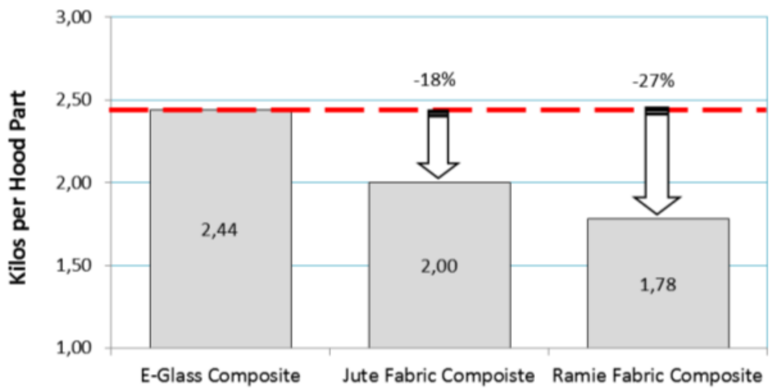
As determined by the comparison chart and the Table 5.4 above; ramie fiber integration in the green composite by the baseline practice does not represent a

convenient candidate in terms of economic performance. It cannot take advantage over the glass-reinforced baseline scenario in the same manner that jute fabrics would have and therefore process optimization will be considered in the next sections of this chapter.

The point is that the price of the ramie is very high including increased shipment cost (from China) comparing to the glass-fiber fabrics which are produced by a supplier based on the same industrial zone where Ancel runs its facilities. These factors are adversely affecting the production cost for each ramie-reinforced hood which for this case in 4% higher than the conventional glass-reinforced solution at 300 parts. Jute fiber has lower price from ramie as well because it is a native crop of Brazil and in a high worldwide annual harvesting yield (as previously discussed on 2.4.1 and illustrated on Figure 2.6). Even if jute was more expensive than per unit weight glass since the jute composite is lighter (in an 18%) it takes cost benefit over the glass. Ramie indeed appeared as an equivalent candidate in terms of fiber price (not fabric) on Table 2.1, however the mats used for the production of the composite coupons did not follow the same price setting.

Typically, with the incorporation of the natural fiber fabrics in a composite as opposed to glass fabrics; there are weight savings attached. Another fact is that both ramie and jute are less dense than the glass fiber and the forthcoming green composite is also lighter (see Figure 5.14 below). On their turn, ramie composites are the less weighty among the three candidates. This attribute is explained because they are requiring less fiber volume to reach equivalent performance of the ones of reinforced by jute (which has already considered acceptable/equivalent to glass) as analyzed at 4.7.2. As a result, the polyester resin which fills up the remaining percentage is less dense than all fibers mentioned and therefore makes the hood composite lighter.

**Figure 5.14. Summary of weight reduction potential.**




## 5.4 Alternative Approaches and Sensitivity Analysis

Since only by just changing fibers in the baseline production process no cost savings for ramie were envisioned for the reasons mentioned above; two strategies for confidently cutting down the manufacturing cost will be proposed. Initially, by using a novel bio-resin BioPoli 507— as was tested for its appropriateness on Chapter 4 and does not require the addition of accelerators. As a second step it shall be used a modernized injection machine. The new machine with the addition of a vacuum pump will upgrade the process from RTM to LRTM. With this addition, labor use will be supplementary optimized. The reason is that the upgraded technique is requiring less labor resources as only one worker is needed to run one part production. The process becomes slower because of its moderate pressure (assisted by void), however, more precession is succeeded in terms of surface finish. This is possible because of the vacuum which eliminates the void on the molded part surface. That subsequently means that less reject will be generated and eventually less scrap material [151]. What is more, is that with LRTM, the workspace will be considerably cleaner over traditional RTM [152].

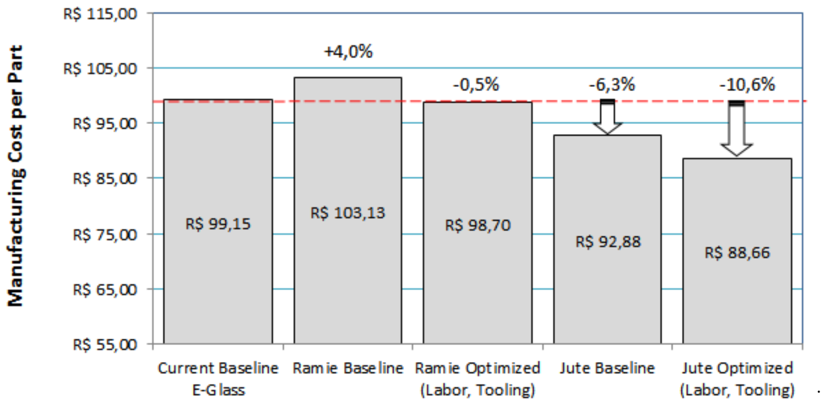
### 5.4.1 Optimization by means of constituent materials and tool upgrade

The cost savings (if any noticed) by the application of alternative strategies to manufacturing are plotted in Figure 5.15. The first set of alternative approaches is addressed to ramie scenario and the second one is for jute fabrics optimized scenarios.

In the baseline ramie incidence by just swapping to the natural fiber there was no improvement observed in the total cost per part but contrarily an additional increment of 4% as far as ramie fabrics were more expensive than glass (4 times higher price per kilo). As can be seen from the graph, the optimized ramie alternative strategy does not reduce the manufacturing cost per hood part significantly, only by 0.5%. Although by using the

cheaper jute fabrics, the cost can be reduced in the order of 6.3%, followed by an additional 10.6% when labor and tooling optimization (LRTM upgrade) are applied.

**Figure 5.15: Cumulative cost reduction potential from optimized approaches at 300 parts / year**



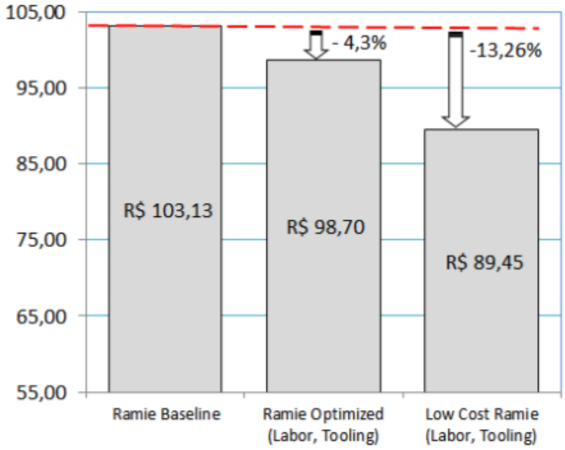

### 5.4.2 Low cost ramie scenario

In a hypothetical scenario where ramie fabrics would have been cultivated and manufactured in the Brazilian landscape; subsequently they could be sold at a lower price than the imported Chinese ones. In that case the cost model results would have been a lot different for ramie composite in terms of associated retail price costs. Considering such a scenario (referred here  as low cost ramie scenario), the ramie fabric price was given a 50% increased value as ramie weaving involves more processing before being used as reinforcement because of the fact that the pectinuous substances in it are very difficult to remove.

All three ramie scenarios baseline, optimized and the abovementioned cheap are summarized in the bar chart of Figure 5.16. The price benefits could the cheap ramie scenario could achieve a 13,26% drop on top of the baseline ramie scenario of the hood price, having an additional 9% drop over the optimized ramie scenario price.

As also depicted earlier, the glass-baseline scenario continues to be cheaper at the target volume of 300 parts (1,3% cheaper price). The ones for the jute and cheap ramie scenarios are getting immediately price benefits over the other scenarios at the 300 parts while followed by an additional drop in cost as the production increases. The low priced ramie scenario is becoming subsequently almost as cheap as the jute which is definitely the least expensive among all.

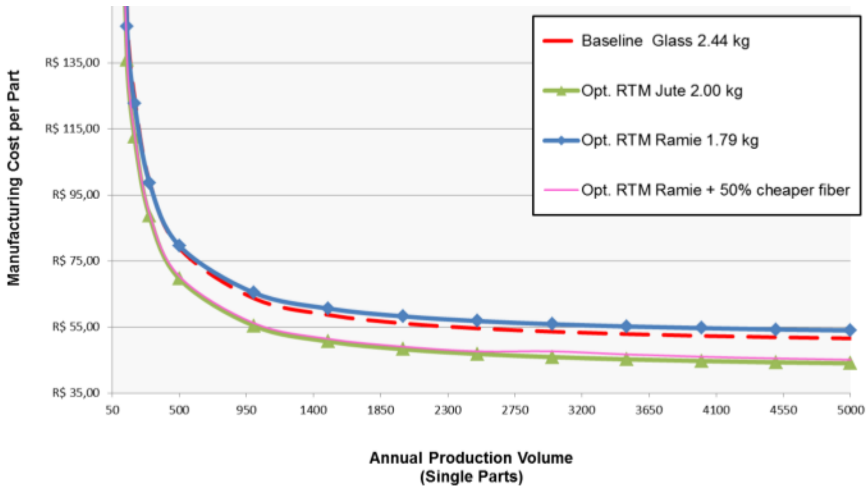
**Figure 5.16. Cost drop potential by optimization or cheaper ramie fiber at 300 parts / year**




If higher production volume will be considered, for instance say 1000 parts, the glass baseline would have become more economical and would surpass the optimized ramie and the lower priced ramie scenarios as illustrated in Figure 5.17. That would never happen for jute as it will be continuing having price gaining over the glass baseline. Finally, in these production runs there will be a decrement on the price of the product 33%-44% for all scenarios considered.

**Figure 5.17. Optimized RTM scenarios**

**Manufacturing cost per hood parts**




### 5.4.3 Sensitivity analysis

The Sensitivity analysis determines the impact of changing one or several variables in a model and how that change will affect the outcome of the analysis itself. A sensitivity analysis allows a range of plausible inputs to be considered when there is uncertainty about the true value of an input. The scenario to be studied here is the optimized ramie scenario as it appeared to be the more cost appealing in between the ramie scenarios that can be actually applied.

**Cost vs. Production Volume**

In this case the sensitivity analysis is defining the impact of changing the Annual Production Volume in the Cost of the Hood, according to the RTM Cost Model. The following chart shows that the total cost of the buggy's hood is reduced by increasing the production volume, until annual productions volume of 3000 parts. It is obvious that the cost of the 300–500 parts is very high and therefore additional production volumes are requested for efficient cost and higher profit margins. As seen in Figure 5.18 and Table 5.5 the Total Cost of hood, for annual production volumes higher than 3500 parts, tends to become approximately constant. Between 3500 - 5000 parts the RTM technique has manufacturing costs of about R$55,08 - $53,86 per hood part considering the optimized process

**Figure 5.18 Sensitivity analysis, cost vs. production volume for optimized RTM ramie**

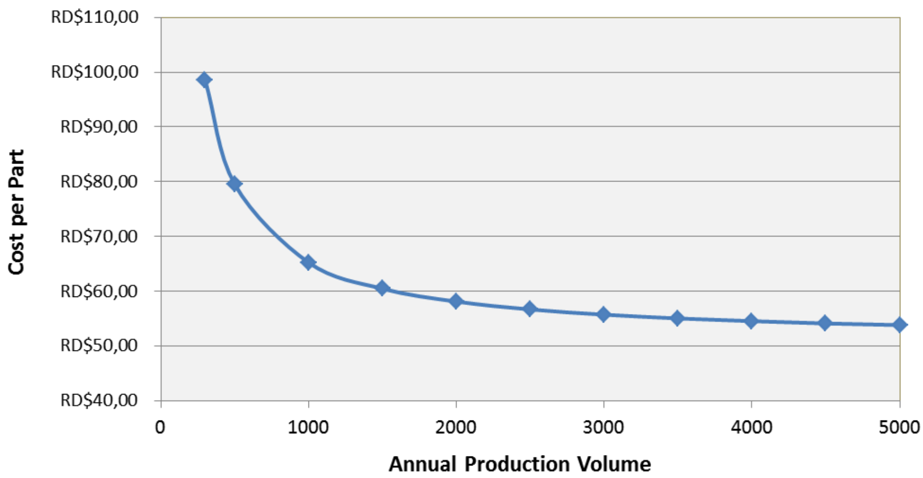



**Table 5.5. Sensitivity analysis, cost vs. production volume.**

| Production Volume (Per Part) | Cost |
|---|---|
| 300 | R$ 98,60 |
| 500 | R$ 79,53 |
| 1000 | R$ 65,28 |
| 1500 | R$ 60,49 |
| 2000 | R$ 58,15 |
| 2500 | R$ 56,72 |
| 3000 | R$ 55,77 |
| 3500 | R$ 55,08 |
| 4000 | R$ 54,58 |
| 4500 | R$ 54,17 |
| 5000 | R$ 53,86 |

**Cost vs. Fiber Price**

The chart on Figure 5.19 analyzes the Manufacturing Cost Sensitivity vs. Fiber Price. As it can be seen the manufacturing cost varies in a linear way with the increase of the fiber price. The fiber cost represents a significant part, practically 25% of total hood cost.

**Figure 5.19. Manufacturing cost sensitivity to fiber price (APV=300 Parts).**

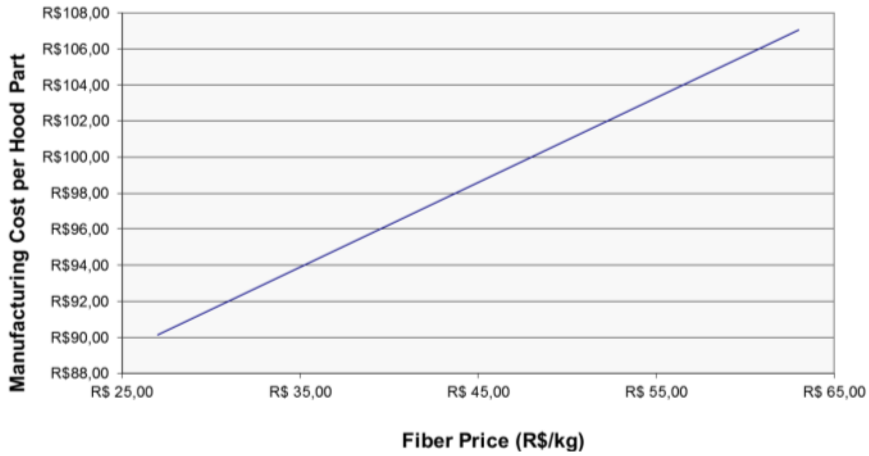
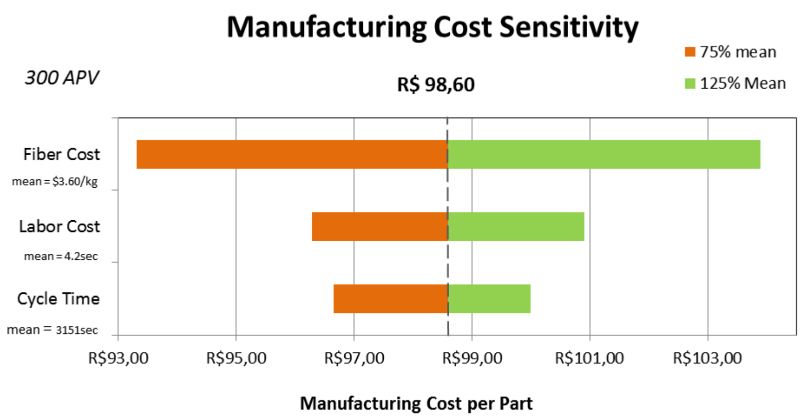



Figure 5.20 illustrates the RTM manufacturing cost sensitivity of variation in three cost drivers as they appeared to hold the highest cost percentages in the cost breakdown analysis: the fiber cost, the labor cost, and the cycle time. Out of these factors, fiber cost and in a less extend labor cost have the most influential role, increasing or decreasing the manufacturing cost by approximately $2 for every 25% change in fiber cost (from a mean of R$ 44,00/kg). Reducing the final cure time by 25% has no significant impact on manufacturing cost because the mold station will be always one as explained on paragraph 5.3.5 and therefore no parallel production lines can be considered.

**Figure 5.20. RTM manufacturing cost sensitivity**

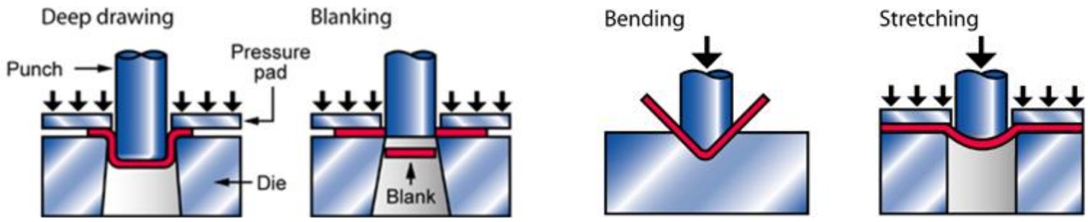


## 5.5 Stamping Scenarios

### 5.5.1 Stamping technical cost model

Sheet Metal Forming (SMF) or simply stamping covers a range of sheet forming processes performed by means of a die and a press. Processes used include blanking, shearing, drawing, bending, forming, coining and swaging. All shapes produced by stamping have a uniform cross-sectional thickness. Only materials available in sheet form can be stamped and the thickness is limited to available sheet size.

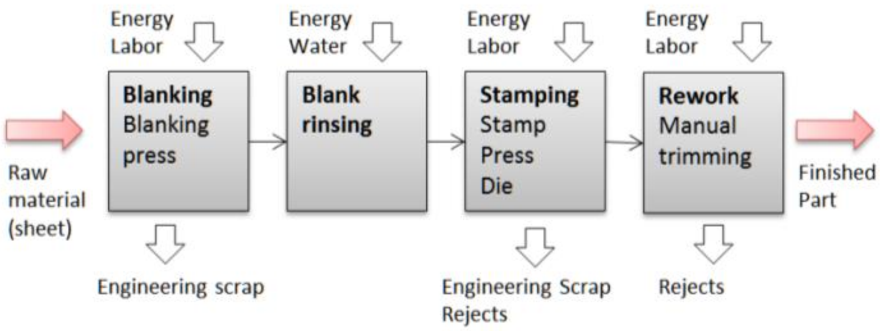
**Figure 5.21. Stamping processes schematic**




*[adopted by CES Software]*

The stamping technical cost model as depicted on Figure 5.22, was formerly developed by the Materials Systems Laboratory at MIT for earlier analogous projects and accordingly adapted for alike scenarios in this research project. As it is illustrated above, the stamping model considers four steps: blanking, blank rinsing, stamping, and rework. Process-level inputs and outputs appear above and below each process step, respectively.

**Figure 5.22. Stamping technical cost model**




The selected sheet metal materials were adopted from the Pilot Project for Engineering Design and advanced manufacturing (EDAM) namely three steels and one aluminum and accordingly fitted for the present application as to be explained in paragraph 5.5.3.

### 5.5.2 Cost results for baseline assumptions

Table 5.6 reports all exogenous variables that characterize the Stamping manufacturing process. The assigned values are identical to the equivalent elements of the baseline RTM scenario. The machines for blank rinsing, stamping and finishing were considered non-dedicated as it is expected that in such a substantial investment Ancel would have been using them in other production projects. For that reason, low cost and low dedicated investment for part production are then considered for further refinement of the analysis and evaluation process.

**Table 5.6: Exogenous variables**

| | |
|---|---|
| Direct Wages | R$ 4,20/hr |
| Interest Rate | 15% |
| Equipment Life (years) | 10 |
| Electricity Prices | R$ 0,39/KWh |
| Auxiliary Equipment Cost | 15% |
| Installation Cost | 20% |
| Overhead Burden | 37,75% |
| Maintenance Cost | 10% |
| Price Of Building Space | R$ 3,400/$m^2$ |
| Building Recovery Life (years) | 40 |

Table 5.7 presents manufacturing specifications for the RTM process. An average down-time percent is used instead of the hour-by-hour downtime accounting that the stamping cost model uses. This 18.75% average downtime is equivalent to the amount of downtime represented in the assumed baseline plant conditions of Table 5.1

**Table 5.7. Manufacturing specifications**

| | |
|---|---|
| Annual Production Volume | 300/yr |
| Average downtime | 18,75% |
| Product lifetime (years) | 5 |
| Working hours per day | 7,3 hrs/day |
| Working days per year | 302 days/year |

As both high strength steel and aluminum are more difficult to form than mild steel, production entails different reject rates, line rates, and tool investments. Table 5.8 summarizes the changes incorporated in the stamping technical cost model to account for these difficulties. In general, it is assumed that costs, reject rates, and cycle times for aluminum would be slightly more affected than for high strength steel.

**Table 5.8. Technical cost model variation of high strength steel and aluminum**

| 700 MPA Steel | 6010 Aluminum |
|---|---|
| 15% Higher reject rate | 20% Higher reject Rate |
| 15% Slower line rate | 20 % Slower line rate |
| 15% Higher Tool investment | 20% Higher tool investment |

### 5.5.3 Equivalent designs

In order to replace metal parts with plastic, the equivalent stiffness of a plastic part can be determined as a criterion to be fulfilled. When the two parts are of equivalent stiffness, deflection is the same. Deflection is inversely proportional to the bending stiffness (R) described by the formula:

$$R = E \times I \qquad \textbf{(Eq. 5)}$$

Where E is the modulus of elasticity and *I* is the moment of inertia (The moment of inertia is set for rectangular cross section as the one of the specimens tested on this research). Therefore, by equating the bending stiffness of the metal and plastic parts with subscripts Mt and Pl, the condition of equivalent stiffness will be satisfied as follows.

$$E_{Mt} \times I_{Mt} = E_{Pl} \times I_{Pl} \qquad \textbf{(Eq. 6)}$$

For solid shape of equal width it is considered the (Eq. 7). As for bending – strength limited designs (same bending strength at minimum mass), where tensile or compressive stress occurs with no risk of buckling, it must be verified that the permitted stresses are identical and therefore. According to Luo [153] all that can be expressed in the (Eq. 8) where *YS* stands for yield strength of the materials and *h* is their thickness.

$$E_{Mt} \times h^3_{Mt} = E_{Pl} \times h^3_{Pl} \equiv h_{Mt} = h_{Pl}\sqrt[3]{\frac{E_{Pl}}{E_{Mt}}} \qquad \textbf{(Eq. 7)}$$

$$YS_{Mt} \times h^2_{Mt} = YS_{Pl} \times h^2_{Pl} \equiv h_{Mt} = h_{Pl}\sqrt{\frac{YS_{Pl}}{YS_{Mt}}} \qquad \textbf{(Eq. 8)}$$

In an attempt to satisfy both objectives (stiffness and strength) in terms of proximity values; the selected thickness column of the Table 5.9 summarizes the appropriate thicknesses for equivalent performance based in the above nomenclature. The RUP acronym denotes the ramie reinforced polyester as fabricated and tested in the IST University. The GFC is the glass reinforced hood from another study of Alves [18]. The weights of the metallic scenarios were calculated with the aid of the mass tool

calculator of the Solidworks 3D design software [154]. When assigning the appropriate material's density on the hood's 3D-model; it is displayed subsequently its weight in a decimal value.

**Table 5.9. Equivalent performance designs**

| Material | Equal Bending Stiffness Thickness | | Equal Bending Strength Thickness | | Selected Thickness | Part Weight |
|---|---|---|---|---|---|---|
| — | (mm) | Ratio | (mm) | Ratio | (mm) | (kg) |
| GFC | 4,00 | 1,0 | 4,00 | 1,00 | — | 2,44 |
| RUP | 4,00 | 1,0 | 4,00 | 1,00 | — | 1,79 |
| 220 MPa Steel | 1,20 | 3,5 | 1,90 | 2,6 | 1,90 | 4,85 |
| 350 MPa Steel | 1,20 | 3,5 | 1,40 | 3,5 | 1,40 | 3,60 |
| 700 MPa Steel | 1,20 | 3,5 | 1,07 | 4,6 | 1,20 | 3,14 |
| AL 6010 | 1,75 | 2,5 | 1,65 | 3,1 | 1,75 | 1,64 |

### 5.5.4 Tool cost

Table 5.10 presents the main machine tool cost as calculated for the Stamping Mild steel scenario with the strength of 220MPa. The model is computing the appropriate press tonnage based on the parts dimension as introduced inside the model's spreadsheets. Machine costs are calculated by multiplying the machine utilization rate with the amortized annual machine investment, using the machine life as the amortization period. Tool costs are considered to be fully allocated to the part (unless the tool can be used to make another part) and amortized over the product life only.

**Table 5.10. Main machine and tooling costs**

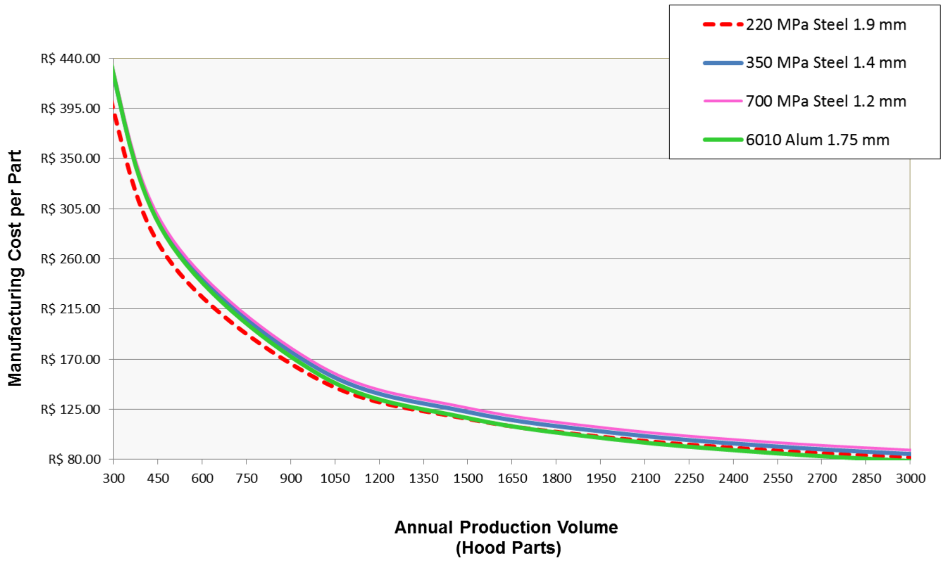
| | BLANKING | STAMPING |
|---|---|---|
| Press Line Name | 400t Blanking Press | 600t S/A Tandem Press |
| Minimum Required Tonnage | 0 | 401 |
| Actual Press Tonnage | 400 | 600 |
| Allocated Base Cost ($/press) | R$ 5.682,10 | R$13.671,62 |
| Allocated Auxiliary & Installation Costs | — | R$192.634,99 |
| Power Consumption (kW/press) | 200 | 250 |
| Space Requirement (sqm/press) | 100 | 30 |
| Total Tool Cost | R$ 223.289,20 | |

### 5.5.5 Cost results for all stamping scenarios

Cost results for the alternative metal solutions under a baseline manufacturing assumption are presented in Figure 5.23. As it can be observed, each of the alternative solutions is more expensive than the mild steel for the range of production volumes of all ferrous materials analyzed. Although it is not in all ranges for the aluminum scenario

as it is was found to be cheaper comparing to the mild steel over the 1500 parts. Among the lightweight ferrous options alternatives, the 1,2 mm high strength steel is least expensive, followed by the 1,4 mm mild steel.

**Figure 5.23. Cost results for stamping manufacturing scenarios**




At the 300 target batch size, the least expensive scenarios are ones of the mild steel beginning with the 220 MPa Steel and followed by the 350 MPa steel. The aluminum is the third best choice and the most expensive is the high strength lightweight steel of 700 MPa. However as the batch size increases gradually, the order of the projected cost is interchanging. This is to say that over 2500 hood parts the aluminum scenario will surpass both mild steel scenarios and will be rendered the most cost efficient choice among all options. The high strength steel will still remain the most costly manufacturing scenario without any chance of getting cheaper as it follows a non-progressive curve always above the others.

**Table 5.11. Production volumes for stamping scenarios**

| PLOT | 220 MPa | 350 MPa | 700 MPa | 6010 AL |
|---|---|---|---|---|
| **150** | $R 738,88 | $R 802,35 | $R 806,16 | $R 810,17 |
| **300** | $R 393,02 | $R 424,70 | $R 428,37 | $R 425,13 |
| **500** | $R 254,70 | $R 273,63 | $R 277,24 | $R 271,11 |
| **1000** | $R 150,94 | $R 160,36 | $R 163,94 | $R 155,62 |
| **1500** | $R 116,34 | $R 122,60 | $R 126,16 | $R 117,12 |
| **2000** | $R 99,06 | $R 103,73 | $R 107,28 | $R 97,87 |
| **2500** | $R 88,68 | $R 92,40 | $R 95,95 | $R 86,32 |
| **3000** | $R 81,76 | $R 84,84 | $R 88,39 | $R 78,62 |
| **3500** | $R 76,82 | $R 79,45 | $R 83,00 | $R 73,12 |
| **4000** | $R 73,12 | $R 75,41 | $R 78,95 | $R 69,00 |
| **4500** | $R 70,24 | $R 72,26 | $R 75,81 | $R 65,79 |
| **5000** | $R 67,93 | $R 69,75 | $R 73,29 | $R 63,23 |

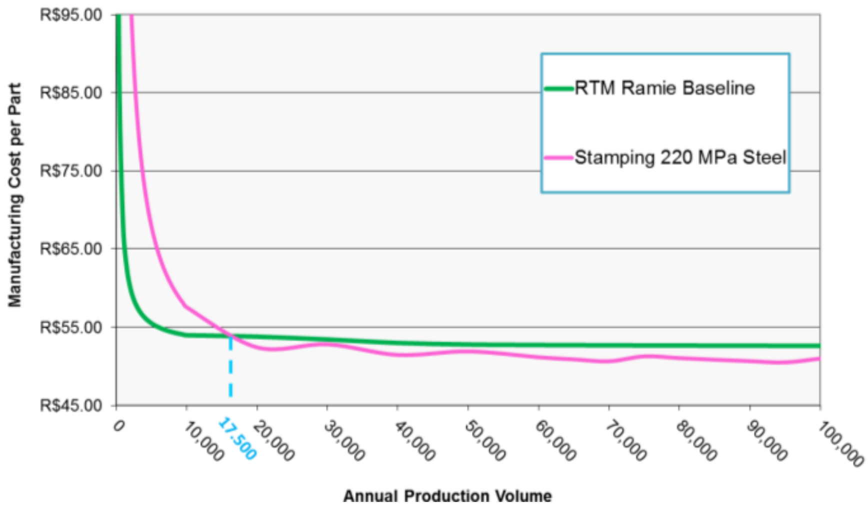
### 5.5.6 Cost vs. production volume – RTM and mild steel SMF processes

SFM (stamping) is a process suitable for high production runs providing short cycle times, however high investment costs are required for equipment, maintenance and tooling. On the other hand, Resin Transfer Molding (RTM) allows the molding of components with complex shapes and large surface areas with a good surface finish on both sides. But it is a process suited for short and medium production runs.

Comparing the Manufacturing Cost vs. Annual Production Volume (hood parts) for RTM Ramie and the Mild Steel Solution it can be concluded that:

- RTM Process has lower manufacturing costs than a prospective mild steel solution to Annual Productions Volumes when low production volume is considered.
- Due to high investment cost on stamping, the latter meets the production costs of the RTM–ramie process (with no designed improvements added) only in - production runs generated over 17500 parts.
- In a large scale production batch of 50.000 stamped hood parts, the mild steel can be as much as 18.5% cheaper than the a ramie composite scenario of Ancel's baseline associated production.
- In mass production of 100.000 parts and for both processes; the cost will not drop additionally in a significant rate (that will be 0.5% for both cases). Although, the stamping will gain an extra 2% improvement in cost over the ramie RTM.

**Figure 5.24. Production volume - Mild steel stamping and RTM baseline APV**

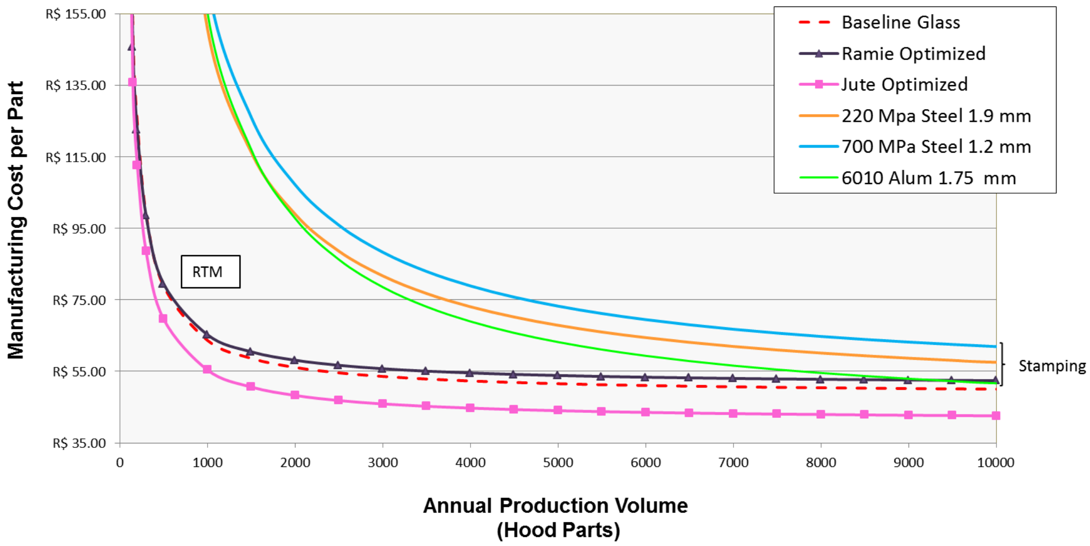


## 5.6 Economic Analysis of All Designs

### 5.6.1 Comparison of all solutions

Figure 5.25 displays the economic performance of all manufacturing solutions against the estimated baseline fiberglass polyester hood under the baseline RTM scenario —as was presented previously in the Figure 5.12 and the fully optimized RTM approach (integrating raw material, injection machine and labor improvements) —as also described in the Figure 5.15: Cumulative cost reduction potential from optimized approaches.

**Figure 5.25. Economic comparison of optimized solutions & baseline scenarios**




It can be concluded that the optimized RTM-Jute scenario is the least expensive approach being followed by the RTM-Ramie up to the batch size of the 500 parts. After that occurrence, Opt. Ramie is surpassed by RTM Glass scenario and all RTM scenarios appears to be stabilized in terms of manufacturing cost. Added to that it is observable a slight cost decrement as the batch is exponentially increased above 3000 production runs. Over 9000 parts the aluminum stamping scenario become less expensive as opposed to the optimized RTM-Ramie and Glass-Baseline. Beyond the production of 10000 parts, the Al 6010 will outmatch both the Glass baseline and the optimized RTM-Ramie. No stamping scenario will be cheaper that the RTM Jute which is the least expensive manufacturing scenario among all. Analytical data can be found on the Table 5.12.

**Table 5.12. Production volume for all scenarios**

*(all prices are in Brazilian currency R$)*

| PLOT | Baseline RTM | | | Optimized RTM | | | Sheet Stamping | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Glass | Ramie | Jute | Opt.Ramie | Opt.Jute | Cheap Ramie | 220Mpa | 350MPa | 700MPa | AL 6010 |
| | 2.44 kg | 1,78 kg | 2.00 kg | 1.79 kg | 2.00 kg | 1.79 kg | 3,9 kg | 3,60 kg | 3,15 kg | 1,65 kg |
| 0 | 500.00 | 500.00 | 500.00 | 500.00 | 500.00 | 500.00 | 1000.00 | 1000.00 | 1000.00 | 1000.00 |
| 50 | 352.24 | 356.37 | 345.77 | 336.67 | 326.30 | 327.11 | 2122.55 | 2312.84 | 2317.21 | 2350.23 |
| 150 | 149.49 | 153.47 | 143.22 | 145.84 | 135.90 | 136.69 | 738.88 | 802.35 | 806.16 | 810.17 |
| 200 | 124.66 | 128.68 | 118.35 | 122.69 | 112.64 | 113.44 | 566.01 | 613.50 | 617.24 | 617.63 |
| 300 | 99.15 | 103.13 | 92.88 | 98.60 | 88.66 | 89.45 | 393.02 | 424.70 | 428.37 | 425.13 |
| 500 | 78.92 | 82.88 | 72.67 | 79.53 | 69.63 | 70.43 | 254.70 | 273.63 | 277.24 | 271.11 |
| 1000 | 63.70 | 67.65 | 57.47 | 65.28 | 55.40 | 56.20 | 150.94 | 160.36 | 163.94 | 155.62 |
| 1500 | 58.67 | 62.63 | 52.44 | 60.49 | 50.63 | 51.43 | 116.34 | 122.60 | 126.16 | 117.12 |
| 2000 | 56.12 | 60.08 | 49.90 | 58.15 | 48.29 | 49.08 | 99.06 | 103.73 | 107.28 | 97.87 |
| 2500 | 54.61 | 58.55 | 48.38 | 56.72 | 46.86 | 47.65 | 88.68 | 92.40 | 95.95 | 86.32 |
| 3000 | 53.60 | 57.55 | 47.38 | 55.77 | 45.91 | 47.65 | 81.76 | 84.84 | 88.39 | 78.62 |
| 3500 | 52.88 | 56.82 | 46.65 | 55.08 | 45.23 | 46.70 | 76.82 | 79.45 | 83.00 | 73.12 |
| 4000 | 52.33 | 56.28 | 46.11 | 54.58 | 44.73 | 46.02 | 73.12 | 75.41 | 78.95 | 69.00 |
| 4500 | 51.91 | 55.86 | 45.69 | 54.17 | 44.31 | 45.52 | 70.24 | 72.26 | 75.81 | 65.79 |
| 5000 | 51.57 | 55.52 | 45.35 | 53.86 | 44.01 | 45.11 | 67.93 | 69.75 | 73.29 | 63.23 |
| 5500 | 51.29 | 55.23 | 45.07 | 53.60 | 43.74 | 44.80 | 66.05 | 67.68 | 71.23 | 61.13 |
| 6000 | 51.07 | 55.02 | 44.85 | 53.39 | 43.53 | 44.54 | 64.48 | 65.97 | 69.51 | 59.38 |
| 6500 | 50.87 | 54.81 | 44.65 | 53.20 | 43.35 | 44.33 | 63.15 | 64.52 | 68.06 | 57.90 |
| 7000 | 50.70 | 54.65 | 44.48 | 53.04 | 43.19 | 44.14 | 62.01 | 63.28 | 66.82 | 56.63 |
| 7500 | 50.55 | 54.50 | 44.33 | 52.91 | 43.05 | 43.99 | 61.02 | 62.20 | 65.74 | 55.53 |
| 8000 | 50.44 | 54.38 | 44.21 | 52.80 | 42.94 | 43.85 | 60.16 | 61.26 | 64.80 | 54.57 |
| 8500 | 50.31 | 54.26 | 44.10 | 52.69 | 42.83 | 43.74 | 59.40 | 60.42 | 63.97 | 53.73 |
| 9000 | 50.23 | 54.17 | 44.01 | 52.59 | 42.74 | 43.63 | 58.72 | 59.68 | 63.23 | 52.97 |
| 9500 | 50.13 | 54.08 | 43.91 | 52.50 | 42.65 | 43.53 | 58.11 | 59.02 | 62.57 | 52.30 |
| 10000 | 50.05 | 54.00 | 43.83 | 52.44 | 42.58 | 43.44 | 57.57 | 58.43 | 61.97 | 51.69 |
| 50000 | 49.29 | 0.00 | 43.00 | 52.07 | 41.96 | 43.38 | 51.92 | 52.40 | 55.97 | 45.60 |
| 60000 | 49.04 | 0.00 | 42.57 | 51.81 | 41.69 | 42.19 | 51.17 | 51.57 | 55.14 | 44.74 |
| 65000 | 48.91 | 0.00 | 42.55 | 51.67 | 41.56 | 42.17 | 50.89 | 51.25 | 54.82 | 44.42 |
| 70000 | 48.84 | 0.00 | 42.53 | 51.59 | 41.48 | 42.15 | 50.65 | 50.98 | 54.55 | 44.14 |
| 75000 | 49.29 | 52.73 | 42.52 | 51.24 | 41.42 | 42.14 | 51.29 | 51.71 | 55.29 | 44.90 |
| 80000 | 49.04 | 52.71 | 42.51 | 51.23 | 41.39 | 42.13 | 51.06 | 51.45 | 55.03 | 44.64 |
| 85000 | 48.91 | 52.70 | 42.48 | 51.21 | 41.36 | 42.12 | 50.85 | 51.22 | 54.80 | 44.40 |
| 90000 | 48.84 | 52.68 | 42.48 | 51.20 | 41.34 | 42.11 | 50.67 | 51.01 | 54.59 | 44.19 |
| 95000 | 48.79 | 52.67 | 42.47 | 51.19 | 41.32 | 42.10 | 50.51 | 50.83 | 54.42 | 44.01 |
| 100000 | 48.75 | 52.66 | 42.46 | 51.18 | 41.33 | 42.09 | 51.00 | 51.39 | 54.98 | 44.59 |

## 5.7 Conclusions and Discussion

- Three methods for improving the RTM baseline manufacturing approach were considered for performance enhancement and lowering cost: optimizing the injector machine runs (actually converting it to RTM Lite), optimizing the labor content, and optimizing the raw materials use. When considering the optimized RTM conditions compared to the baseline, a more economical production may be found and the process may become even more competitive when compared to both glass baseline and the metal stamping scenarios. Unambiguously, the optimization of the RTM-Jute baseline scenario can reduce its baseline costs by 8.6% and make it the cheapest scenario among all. An optimized RTM-Ramie production line as determined may limit cost by 8.3% additionally to the Ramie-Baseline and get advanced by 0.5% over the Glass-Baseline scenario. Finally, considering a prospective Low-Cost-Ramie

scenario; that could have provided a 9% cut on the former optimized RTM-Ramie and would have become 7.9% less expensive than the glass baseline. However, even in that case ramie will not have outmatched the performance of the RTM-Jute.

- If structural requirements are not relaxed it is outlined that the current use of Ancel's RTM manufacturing process — Glass-fiber polyester composite manufactured through RTM — is economically competitive comparing to the cheapest stamping solution for as much as 17500 parts per year and before painting costs. In fact, the relatively flat cost-production volume curve that characterizes the RTM process means that RTM becomes more attractive relative to metal solutions (including the baseline) at low annual production volumes. The optimized scenarios for RTM-Ramie can provide cost reductions over the ramie-baseline and render the procedure competitive up to 9500 production runs against the aluminum solution. This can be attributed in general terms as an effect of lower startup cost associated with RTM, at least initially as less expensive mold materials are used as opposed to stamping. When the production volume is high enough to make the capital cost per part very low, the material cost dominates the component price and stamping is competitive in terms of production costs.
- Alternative metal lightweight strategies that meet the stamping baseline hood performance are the high strength steel and the aluminum alloy. However, the high strength steel will always be more expensive than mild steels and aluminum in high production volumes. For instance, at 5000 hood parts produced per year, high strength steel with of 1,2 mm thickness is 8% more expensive than the mild strength steel with 1,4 mm thickness which in turn is 2% more expensive than the 220MPa steel, and aluminum with 1.75 mm thickness is 4.7% less expensive than the 220MPa steel. These cost penalties are roughly the same for the range of annual production volumes analyzed in this research. More specifically by an 128% increment of the production size (from 3500 to 8000 parts/year), the cost remains competitive contrary to the metallic baseline scenario that can be competitive up to a much less size of 3500 parts/year.
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# Chapter 6. Environmental Analysis

Global concern regarding the damaging effect of human activity on the environment prompts efforts to analyze the environmental burden and damp it down or even better correct it via eco-design on the early stage of product development. The focus of this chapter is to evaluate the role of selected materials and related processes of the buggy vehicle project. In a second stage it is attempted to run a comparison among them while aiming on reducing the environmental damage that each choice has.

Granta's Eco Audit Tool [72] within CES Edupack software, provides a set of quick and interactive means to determine the factors that make the greatest contribution regarding product's environmental impact. In a second level it assists on making materials and process choices that would minimize the energy spent in an effort to sequester the $CO_2$ as much as possible. Granta's software incorporates an extensive materials database where thousands of materials records are listed along with their mechanical/environmental performance and production characteristics. Selecting materials from that list it is possible to have a quick comparison between alternative choices, while getting a relative idea of the energy associated with their manufacturing.

The software user can experiment with 'what-if' scenarios during the early stages of design, before time has been spent and funds have been committed. It draws on the environmental data available in CES Selector to quantify key life-cycle phases of a material, helping identify the most significant environmental costs, and thus focus attention on the areas which can lead to the biggest improvements. It points out in general, and identifies where the greatest gains might be made on a draft appraisal of the concept design.

Otherwise, a full LCA is time-consuming, expensive and it cannot cope with the problem that 80% of the environmental burden of a product is determined in the early stages of design when many decisions are still fluid [17]. Unlike LCA assessment, which is intended for producing detailed environmental reports after the product design is completed, the Eco Audit Tool aims to inform design decisions during the early stages of design, where changes cost least but matter most.

The Eco Audit Tool can be considered as a short version of an LCA analysis. In that sense will not reach the depth of a long multi-parametric LCA analysis performed in the SimaPro software for example. Indeed a number of factors are considered here as

will be explained below: material use, transportation, manufacturing and end of life; but with efficient data to run a quick and accurate comparison in a shorter analysis' scope.

## 6.1 Case Study Baseline: The Glass Reinforced Hood

The reference baseline hood part is being produced by glass fiber mat reinforcements and thermosetting polyester as already described in Chapter 4 and paragraph 5.3.4 above. 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 including curing solutions as additives, promoter and catalyst.

Table 6.1 shows the data as introduced in the Eco Audit Tool spreadsheets for the three different phases. Two well understood environmental stressors — Energy Usage and $CO_2$ Emissions — come out of this analysis.

**Table 6.1. Eco-Audit tool inputs**

**Step 1: Material and manufacturing, joining and finishing**

| Component Name | Material | Process | Recycled |
|---|---|---|---|
| Car hood, 318 units | Polyester | Molded | Virgin (0%) |
| Mat Fabric, 318 units | Glass, E-Grade | Fabric Production | Virgin (0%) |

| Treatment Name | Material | Process | Amount ($m^2$) |
|---|---|---|---|
| Surface Finishing, 300 units | Polyurethane Aliphatic | Painting | 102 |

**Step 2 : Transport**

| Stage Name | Transport Type | Distance (km) |
|---|---|---|
| Finished part to point of sale | 32 tons track | 560 |

**Step 3 : Use phase : mobile mode**[i]

| Fuel & Mobility Type | Usage (days/year) | Distance (km/day) |
|---|---|---|
| Diesel-Family Car | 80 | 40 |

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

## 6.2 Materials, Manufacture, End of Life

At the first stage, the Eco Audit Tool assesses the components inputs that are involved with the part's manufacturing. In that step it is introduced to the project database the energy's and $CO_2$ profiles for the materials and processes.

As it was described in the cost model chapter, RTM-Light provides more precision in terms product quality from RTM-Baseline; as a result less rejected parts will be generated by RTM-Light. The same outline is also considered for the cost model of section 5.1.3, however, only the batch planned number will be requested to be painted (namely 300 units). In the Table 6.2 are presented the inputs for the components profile characteristics.

**Table 6.2. Components elements profile in Eco-Audit**

| Component name | Primary Process | Secondary Process | Fabric Removed (% scrap) | Mass (kg) |
|---|---|---|---|---|
| Polyester Cast (rigid) | Polymer Molding | Cutting & Trimming | 6,20 | 1.51 |
| E-grade glass Mat | Fabric production | Cutting & Trimming | 3,50 | 0.80 |

In the research of Alves et al., 2011 [9], mechanical recycling of the composite materials was performed successfully although at low percentages (11%-12%). Afterwards, the remaining material from recycling (GFC-89%, JFD-88%) 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 will be also adopted so as to define the disposal phase of this evaluation. Therefore, energy recovery was assumed in the percentages as shown in the Table 6.3, where are also presented the disposal phase inputs for ramie the reference reinforced composite scenario.

**Table 6.3. Disposal phase (energy inputs, outputs) for reference composite**

| Component | End of life option | % recovered | Energy (MJ) | % |
|---|---|---|---|---|
| Matrix | Re-manufacture | 10,0 | 96,04 | 65,4 |
| Reinforcement | Landfill | 20,0 | 50,88 | 34,6 |
| Total | | | **146,92** | **100** |

## 6.3 Transportation

This section relates to the transport of the finished product from the source of manufacture to the customer. Basically it is introduced 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 greatest burden.

The hood which is part of a buggy vehicle was assumed to be transported at Rio de Janeiro Brazil for a distance or 560 km where ideally would have been the buggy's

distribution center. These energy usage and $CO_2$ footprint values are combined with the product mass and distance to determine the environmental impact of each stage.

The Eco-Audit Tool calculates the energy usage and $CO_2$ footprint following the below equations.

*Transport Energy = Transport energy per unit mass & distance — Distance — Product mass* **(Eq. 9)**

*Transport $CO_2$ = Transport energy per unit mass & distance — Distance — Product mass — $CO_2$ footprint (source)* **(Eq. 10)**

It has to be noted at this point the software extrapolation does not take in concern the raw material background in terms of area shipped. Therefore that phase of the product will not be part of the transportation energy. On one hand, a part of valuable data will not be included but on the other hand would not contribute to great changes in the resulting data.

## 6.4 Use Phase

This is the final stage of the analysis where the software retrieves an efficiency factor for the chosen energy conversion mode, finding in its look-up table. The eco-audit identifies the design objective that is a key input for the established materials selection methodology that is built into the CES EduPack software.

The final grouping in the country electricity mix menu specifies the electricity mix based on the proportion derived from fossil fuels (0% to 100% at 5% intervals). The environmental impact of these has been calculated using the following assumptions. The $CO_2$ footprint of electricity is dominated by the contribution from fossil fuels, with the proportion derived from other sources having no, or negligible, contribution. The tool makes the use of this method and the user-entered values for power and usage to calculate the energy and $CO_2$ profile of the use phase.

More specifically on the baseline scenario, the product life of the car is assigned for a 20 years period, as it commonly occurs for most Brazilian automobiles [155]. This expected use-phase life is based on Brazilian Association of Automotive Components Manufacturers Reports (Sindipeças), which contain important data about the auto-parts sector in Brazil. Since the hood is a part of a mobile mean of transport; therefore 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 of 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.[1]

**Table 6.4. User phase inputs for glass reference composite**

| Country electricity mix | Mobility Type | Usage (days/year) | Distance (km/day) | Product life (years) |
|---|---|---|---|---|
| Brazil | Diesel - Car | 80 | 40 | 20 |

## 6.5 Audit Report Summary Charts [1]

It is promptly obvious from both charts displayed on Figure 6.1 that the most energy intensive phases and overwhelmingly dominant environmental stressors (Energy, $CO_2$ Footprint), are the Use Phase (44.8%, 51.9%) being followed by the Material (42.6%, 31.7%) and Manufacture (12.3%, 16.1%). Subsequently it makes sense to focus first on this dominant phase, since it is here that the potential innovative material choice to reduce energy and carbon is greater.

The use phase appears to be the most dominant because of the diesel engine selected by the drop down menu. It is estimated that if an electric engine is used instead to power the buggy, the use phase would not have been so energy and $CO_2$ aggravated comparing to the other stages. This is an interesting outcome that Ancel should consider in the future given the current transition to more energy efficient forms of transportation as the electric cars. Even without the impetus of rising fuel costs, there are important reasons to find ways so as to reduce the environmental impact. That is even more essential specially when considering buggy cars which are not indented for long trips and/or heavy duty use.

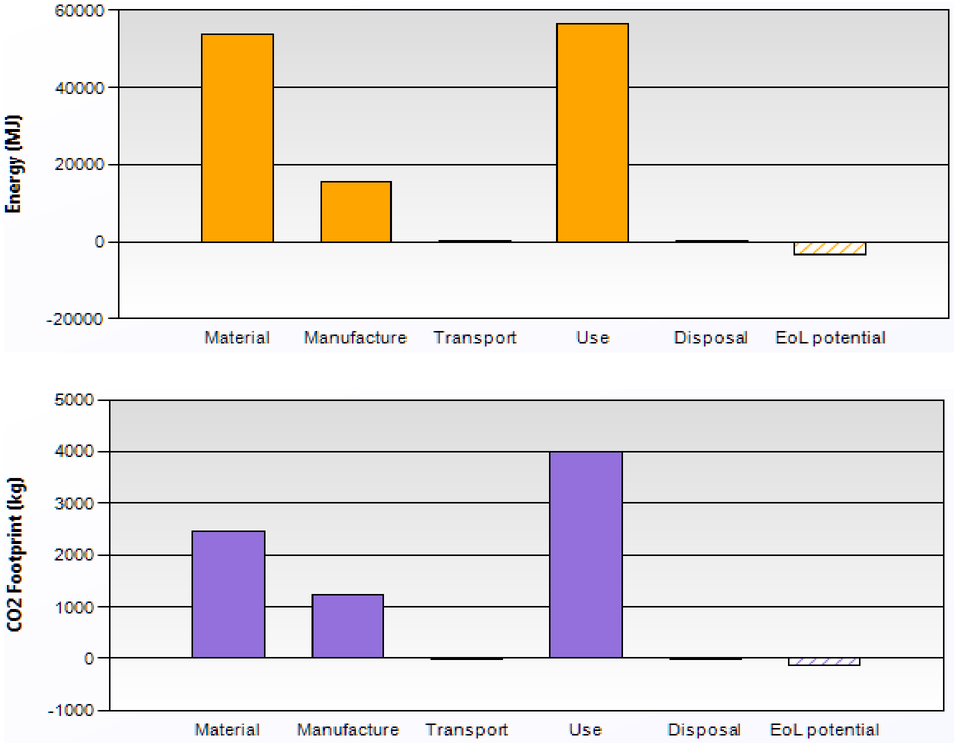
The material use stands out high because E-glass fibers; as well as polyester (the constituents of the reinforcement), are synthesized from polymeric materials and therefore their production requires high embodied energy. This on its own results has an enormous impact on the environment as opposed to natural fibers which acquired by harvesting the ground.

[1] For more analytical data regarding the inputs as inserted in the software menus and also for complete report, refer on the ANNEX 2.

Finally the low recyclability of both constituents is not contributing into high impact on the disposal phase and the potential for end of life recovery (0.1% of the total for first life), which implies that material of higher recyclability should have been used to avoid damaging effect and save nonrenewable resources.

**Figure 6.1. Eco Audit summary charts breakdown**

**energy associated with each life-phase for E-glass reinforced polymer hood**




## 6.6 Case Study: A Bio-Based Composite Hood

In the scenario for bio-composite (ramie hood), the fibers were given use along with a mix of polyester and natural renewable resources. The bio-resin considered in that scenario is based on the composition of BioPoli 507 resin [130] with the incorporation of reused materials as the one used for the coupons production for the mechanical testing phase. Accordingly, a 20% of the matrix material is renewable which translates to one degree a burden decrement factor on the material phase and disposal. Polymer molding for the matrix and cutting along with trimming for fabric were set to the process. Therefore, energy recovery was assumed in the percentages as shown in the Table 6.5, where are also presented the disposal phase inputs for ramie.

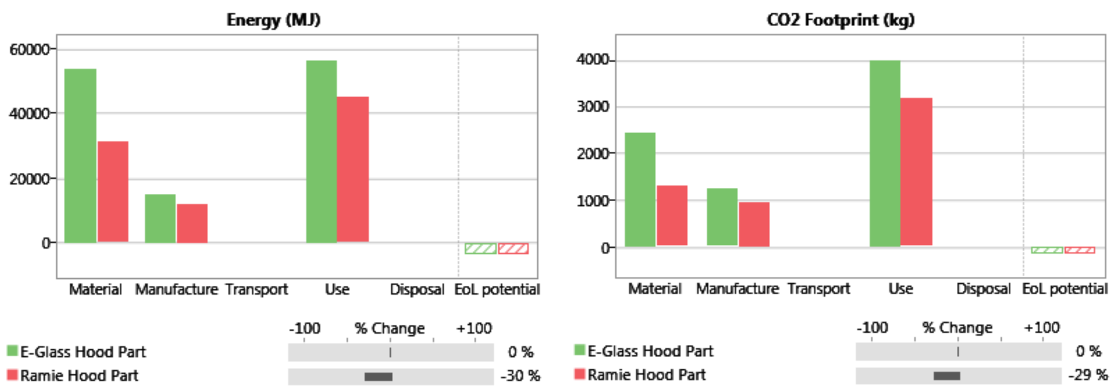
**Table 6.5. Disposal phase (energy inputs, outputs), ramie composite**

| Component | End of life option | % recovered | Energy (MJ) | % |
|---|---|---|---|---|
| Matrix | Re-manufacture | 12,0 | 73,78 | 56,3 |
| Resin Additive 20% | Downcycle | 50,0 | 32,55 | 24,8 |
| Biaxial Woven Fabric | Landfill | 20,0 | 24,80 | 18,9 |
| Total | | | 131,13 | 100 |

The baseline glass reinforced polyester scenario was compared with a prospective ramie reinforced bio-composite which was evaluated by this research. Several observations can be drawn out of this assessment as regards the MJ/kg of Energy spent and the $CO_2$ emissions generated per mass at Figure 6.2. At first sight and as determined by the column charts, ramie composites demonstrated to be less energy and carbon intensive in all categories under comparison (material, manufacturing, use etc). That is explicable to some extend because ramie reinforced composites will predominantly be less heavy and thus will have less total product mass than the ones of glass while a smaller amount of embodied energy is associated with the primary material production, $CO_2$ and also as water usage associated to the natural ramie fibers.

As determined by the report, 30% less energy and 29% $CO_2$ per kilo will be needed when swapping from glass to ramie fabrics reinforced composites. Furthermore, the sulfur oxides (NOx) and nitrogen oxides (SOx) creation are 10 times lower for the natural fabrics. The value for the End of Life potential (EoL) is not appearing to be very high as composite materials and especially thermoset materials are very unlikely to be recycled after the use but partially downcycled for their use in byproducts and/or fillings in additional composites. Eco Audit tool does not consider thermosetting recycling at all and as a result its EoL potential drops down a large scale compared to recyclables.

**Figure 6.2. Ramie and glass fiber hoods comparison**



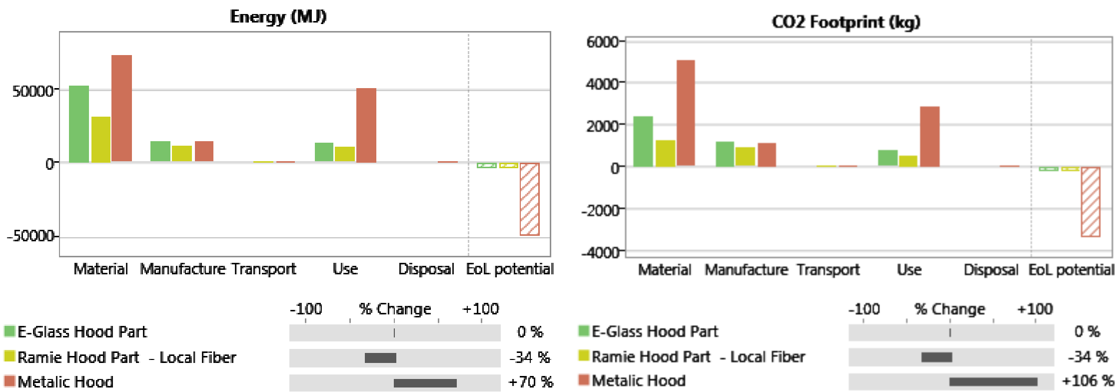
## 6.7 Case Study: The Alloy Steel Solution

In this evaluation it is considered a steel hood stamped solution. The alloy steel scenario is adopted in the same manner as was introduced by the process cost model of section 5.5.1. A number of 315 hoods will be stamped (including rejects) although as aforementioned, 300 parts will be painted in accordance to the project's planned batch.

As it can be seen through the comparison charts of Figure 6.3; ramie would outmatch the rest two in the use phase. The steel hood is so much heavier (almost twice as much) as opposed to the composite solutions and subsequently considered as more energy and $CO_2$ intensive. As a result is outperformed by the two other candidates and considered the least appropriate in environmental terms

On the other hand, the metallic hood part takes a huge advantage in the disposal and end of life potential as it can be recycled in a high percentage without losing its mechanical properties. Recycling is the best way to extract value from waste and return materials to the supply-stream, preserving material stock. Additionally less energy is demanded for its primary production and less $CO_2$ footprint although being as heavy as steel is contributing as an adverse effect.

**Figure 6.3. Summary of all hood parts**

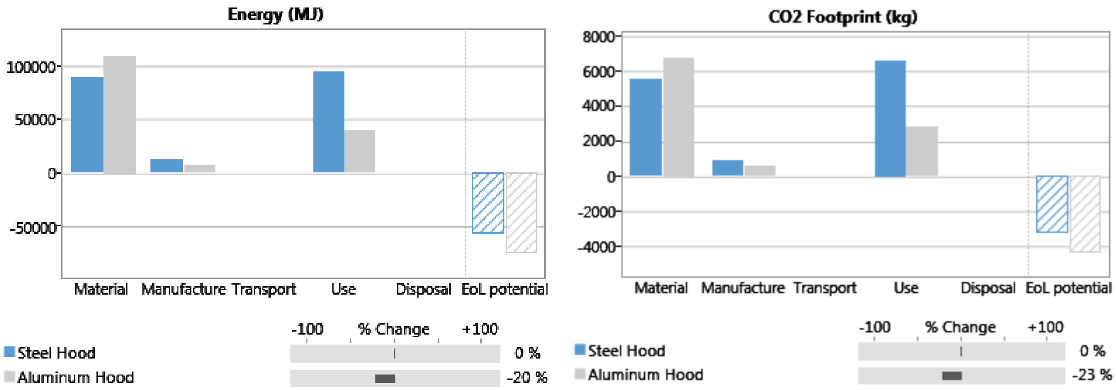



## 6.8 Case Study: The Aluminum Hood

The aluminum solution shows indeed improved environmental performance as opposed to the alloy steel according to the charts of Figure 6.4. Generally the Al 6010, wrought is described as a high energy demanding material comparing to steels as regards its composition overview on Eco Audit tool. The primary material production energy (almost five times more) but also and $CO_2$, water and material processing energy are also high. However, there are no SOx and NOx creation within the aluminum production as commonly generated during the steel processing. Since the aluminum hood weights less (almost half the weight of the steel hood), results in a not so intensive use phase. In

addition to that, the aluminum has enhanced recycling performance and disposal as it shall require less disposal energy and $CO_2$ and higher end of life potential. In the summary comparison aluminum will be around 20% more efficient in both comparisons versus the 220 MPa alloy steel hood.

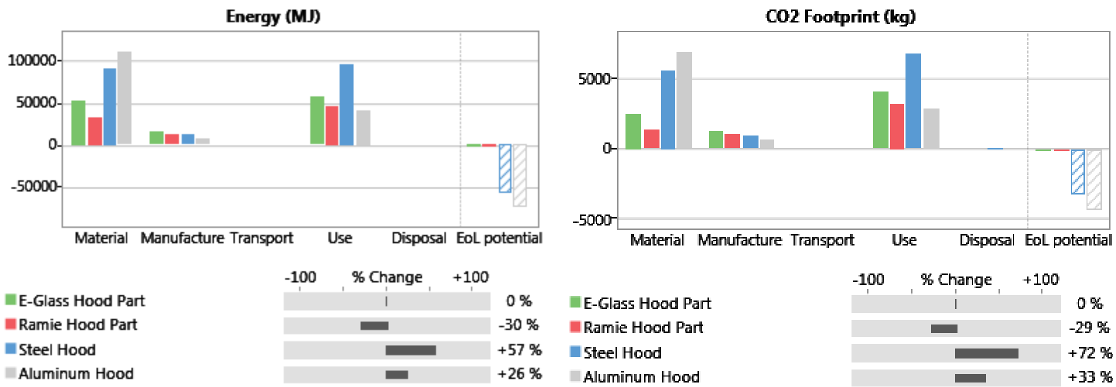
**Figure 6.4. Aluminum against steel hood summary charts**




## 6.9 Environmental Comparison in Between All Case Scenarios

It is illustrated in the Figure 6.5 all the scenarios that were described within the Eco-Audit tool versus the reference hood of glass fiber. Ramie hood has the least intensive performance in the total impact as it is scoring lower in all categories considered. On the other hand the most demanding project would be considered the steel hood as for energy and $CO_2$ values has the highest total impact. Another point is that even if the aluminum has high primary production thereafter balances the difference in the next stages and finally outmatches the heavy steel hood.

**Figure 6.5. All solution summary charts comparison**




## 6.10 Environmental Analysis Conclusions

1) The advantages of swapping from synthetic fiber to natural ones are clear within the scope of the Eco-Audit Tool analysis. Energy saving and $CO_2$ decrease are

among the benefits for all of the phases that are under comparison. The greater savings are observed for the stage of material usage and product use where the type of materials used and the weight of the final part are showing great contribution to have less environmental impact. In that achievement it is contributing the lower primary material production energy of natural fibers as opposed to ceramics.

2) When considering a metallic solution even with the recycling advantages that are attached to steel, thereafter it is noted that little is gained for its own sake as regards its total performance. As a result it does not hold the best potential in terms of material selection.
3) A lighter metallic hood made of aluminum would have high potential to minimize the environmental impact when compared to a steel hood (20% less energy/$CO_2$ footprint) but thereafter it will not succeed in performing close to a composite hood of e-glass and ramie.
4) Among all four solutions presented previously, the ramie reinforced hood would be the optimum candidate when enhanced environmental performance is under consideration. The most dominant reason for that is its non-damaging primary production of the raw material which is a non-fossil energy demanding fiber. The addition of bio content and natural fibers acts absolutely as a complementary effect and increases its environmental performance given that both are deriving from annually renewable resources.

# Chapter 7. SUMMARY AND CONCLUSIONS

The need for substituting synthetic automobile compounds by composites of renewable substance is becoming imperative. Not only as a recent trend but also as a necessity towards a more sustainable society in terms of materials use. It is expected that producers, end-users and the environment can benefit equally through that shift. Under this lens it was attempted the production of composites that contain in high percentage of renewable biomass resources. This is an effort to cut down the environmental effect of the burdensome synthetic materials that derive from the dwindling petroleum resources. Unfortunately, to the present the bio-plastics manufacturing cost is a major barrier for their generalized use in the automotive industry but it is expected that soon manufacturers of these materials will turn up affordable solutions as their demand in industrial scale applications will no doubt tend to decrease their prices to more affordable levels. The trend can also be reversed in the sense that the necessity for environmentally conscious solutions can overturn the value chain and put a premium price on environmental impact of current solutions.

**Methodology applied**

Primarily a lengthy literature review on the field of green composites applications was conducted for documenting the theoretical and technical background of the present thesis. Collecting all the available information and data, unbiased from local and personal interests, a more leveled playing field was build. Following the review, an assessment was performed so as to test the suitability of these materials in terms of durability properties. Green renewable composite's candidates for matrix and reinforcement were screened accordingly in order to identify which hold adequate performance and affordable cost in order to be applied in the aforesaid automotive industry applications.

In a second stage, it was envisaged a three dimensional evaluation with the intention of assessing and comparing selected composite's constituents as for their suitable performance at a mechanical, economic and environmental level. Furthermore, the selection method employed for indicating the composite material constituents considered orthogonal factors that have led the composites production and use by automakers in recent years.

## Summary of the performance analysis

Development of composite sheet panels through thermosetting RTM has been performed by the use of polyester and novel bio-polyester resin with the addition of ramie woven fabrics. Accelerated degradation conditions were applied on specimens in the form of rectangle coupons including simultaneous exposure to high temperature, high humidity and UV radiation in painted and unpainted batches. Tensile and bending tests were performed in order to determine the influence of the different VF% loading, coating, and their compatibility with reference sheets from other researchers.

The polyurethane paint was proven to be a good coating practice to retain the bulk mechanical performance in terms of tensile and bending performance.

Reflecting the overall performance to the hypotheses and objectives it can established at the very outset that the composites under investigation in this thesis had a close and better performance to the study of Alves [18] inside the range of common properties under comparison. This is an outcome of the better performance of the ramie fabrics comparing when compared to jute. It may be asserted, however, that their overall performance is not close to the performance of GFC composites. For this to happen, additional fiber volume fraction should have been considered.

## Summary of the economic analysis

The use of cost models allowed an additional comparison of competing material technologies between the RTM baseline and metal sheet forming procedures. It was concluded that when considering a niche market production of 300 parts it would be advisable to use RTM techniques as being more competitive than metallic scenarios in general. When improvements are considered then the bio-composite scenario would be more appealing to be produced if only cost is the leading factor. By further increasing the production volume size, the manufacturing cost could drop further and thus accomplishing higher profits.

Normally, most of the car makers would have been resistant to deploy low volume productions as the market is insufficiently large to pay for tooling and startup technology around which their manufacturing system is based. Accordingly, in the case of a Brazilian vehicle, until the buggy's market expands its margins enough to justify the startup expenses for steel manufacturing, the RTM will be the most cost efficient manufacturing process for a small scale production.

**Summary of environmental analysis**

The final stage of analysis contributes in having a quick snapshot of the impact that a prospective product has on the environment. Via all scenarios analyzed and under the range of values investigated in the previous chapter it had been perceived that products of bio-materials are less energy and $CO_2$ intensive as opposed to a completely synthetic material (UP and glass fibers). Under this lens, it has provided that the optimal scenario is indeed the one of ramie.

## 7.1 Future Work

Green composites reinforced by natural fibers as ramie and jute seem to be rather problematic due to their decomposable nature, in the mechanical performance after exposure to natural conditions. That biodegradability issue is one problem that needs to be addressed when aiming for 100% bio-based composites applications, especially when dealing with structural parts of exterior panels for future vehicles. More aspects have to be considered such as reproducibility of these composites' properties and their long life cycle as parts of the exterior body. An essential point is whether these synthetic materials can be combined in the best way to reach the level of performance of their predecessors while having the lowest possible cost. Aspects that have to do with supply chain were not taken into account while still very critical and would be interesting to be investigated in future studies.

Added to that comes the need of seriously exploring the concept of sustainable supply chains in order to improve companies' revenue growth and costumer's recognition. This is clearly the case of supply chains dealing with renewable materials. The design and planning of such logistic structures is a challenge where both forward and reverse chains need to be considered on future studies so as to allow for a sustainable production and usage of renewable materials. In such an initiative the effective integration of suppliers into the product value/supply chain will be a key factor for some manufacturers in achieving the improvements necessary to remain competitive [156].

Another prospect research field for exterior body panels is that the material and processing parameters must be optimized in order to achieve a Class-A surface finish. In practice, Class-A surface finish refers to a perfectly polished, high luster surface which is free of porosity and scratches of any kind. A standard method for Class A surface finish measurement has never been developed for composites. An related study has been

conducted by Palardy et al..,[157], but more are definitely needed on the field of bio composites specially when reinforced with natural fibers.

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# ANNEX 1. Cost model inputs

**Table 1: Materials Characteristics and Specifications for Ramie Fabric Composite**

MATERIAL DATA

| RESIN | | |
|---|---|---|
| Component Name | Biopoli | |
| Density | 1100 | kg/m$^3$ |
| Viscosity | 0,25 | (Pa*sec) |
| Price | $R8,4 | /kg |
| Polymer System | POLYE | |
| Rate Coefficient | 1,61E+ | /sec |
| Activation Energy | 7,51E+ | J/mol |

| REINFORCEMENT | | |
|---|---|---|
| Component Name | Ramie Slub | |
| Fiber Density | 1500 | kg/m$^3$ |
| Fiber Diameter | 1.05E -04 | m |
| Price | R$ 44,00 | /kg |

| CATALYST | | |
|---|---|---|
| Component Name | BRASNOX | |
| Density | 1100 | kg/m$^3$ |
| Price | R$ 9,3 | /kg |

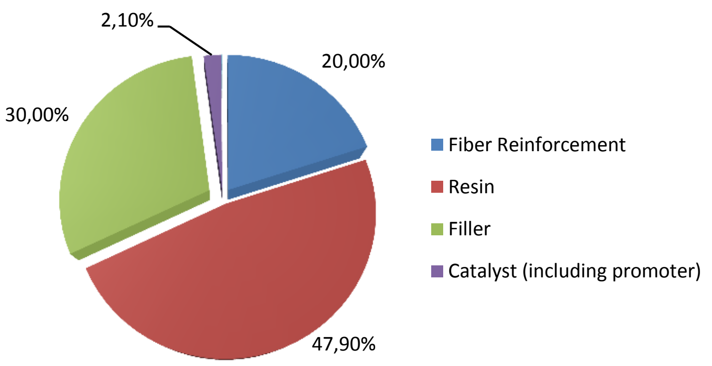


**Figure 7.1. Mass fraction of material composition**

According to Resin Transfer Molding Solution assumptions the weight of each hood shall be 1,74 kg.

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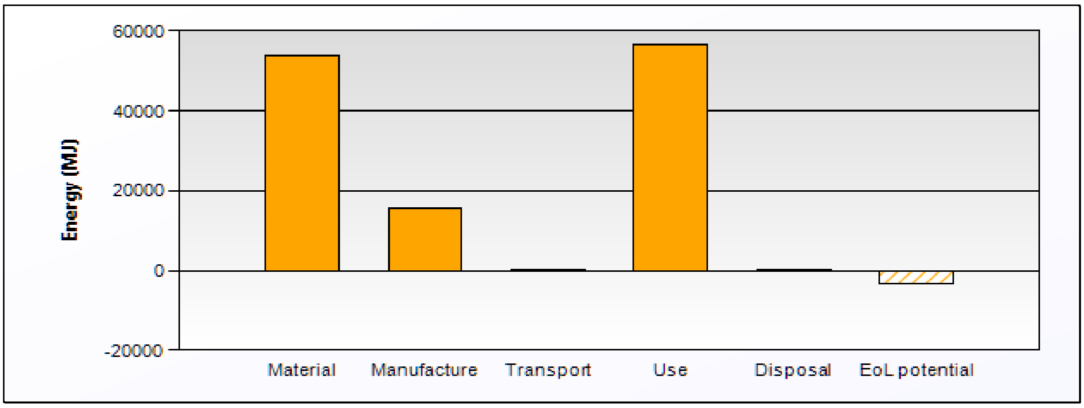
# ANNEX 2. Eco audit reports

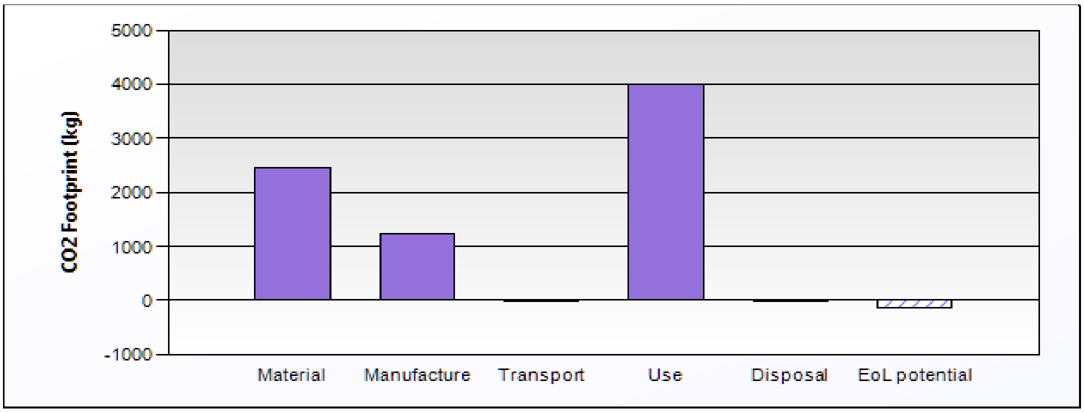
## Reference Scenario

Product Name E-Glass Hood Part

Product Life (years) 20

**Energy and CO2 Footprint Summary:**




| Phase | Energy (MJ) | Energy (%) | CO2 (kg) | CO2 (%) |
|---|---|---|---|---|
| **Material** | 53703.001 | 42.6 | 2446.935 | 31.7 |
| **Manufacture** | 15520.769 | 12.3 | 1243.661 | 16.1 |
| **Transport** | 189.228 | 0.2 | 13.435 | 0.2 |
| **Use** | 56415.744 | 44.8 | 4005.518 | 51.9 |
| **Disposal** | 146.916 | 0.1 | 10.284 | 0.1 |
| Total (for first life) | **125975.657** | **100** | **7719.833** | **100** |
| **End of life potential** | -3501.590 | | -142.053 | |

## Energy Analysis

| | Energy (MJ)/year |
|---|---|
| Equivalent annual environmental burden (averaged over 20 year product life): | 6291.951 |

## Detailed breakdown of individual life phases

### Material:

| Component | Material | Recycled content* (%) | Part mass (kg) | Qty. | Total mass processed** (kg) | Energy (MJ) | % |
|---|---|---|---|---|---|---|---|
| Hood Matrix | Polyester cast (rigid) | Virgin (0%) | 1.51 | 318 | 511.92 | 36456.44 | 67.9 |
| Random Mat Fabric | Glass, E grade (0.4-12 micron monofilament, f) | Virgin (0%) | 0.80 | 318 | 263.63 | 17246.56 | 32.1 |
| Total | | | | 636 | 775.55 | 53703.00 | 100 |

*Typical: Includes 'recycle fraction in current supply'

**Where applicable, includes material mass removed by secondary processes

### Manufacture:

| Component | Process | % Removed | Amount processed | Energy (MJ) | % |
|---|---|---|---|---|---|
| Hood Matrix | Polymer molding | - | 511.92 kg | 13598.52 | 87.6 |
| Hood Matrix | Cutting and trimming | 6.2 | 31.74 kg | 9.52 | 0.1 |
| Random Mat Fabric | Fabric production | - | 263.63 kg | 685.96 | 4.4 |
| Random Mat Fabric | Cutting and trimming | 3.5 | 9.23 kg | 2.77 | 0.0 |
| Surface Finishing | Painting | - | 102.00 m^2 | 1224.00 | 7.9 |
| Total | | | | 15520.77 | 100 |

### Transport:

**Breakdown by transport stage** Total product mass = 7.3e+02 kg

| Stage name | Transport type | Distance (km) | Energy (MJ) | % |
|---|---|---|---|---|
| Finished Car to Point of Sale Santos | 32 tonne truck | 560.00 | 189.23 | 100.0 |
| Total | | 560.00 | 189.23 | 100 |

**Breakdown by components**

| Component | Component mass (kg) | Energy (MJ) | % |
|---|---|---|---|
| Hood Matrix | 480.18 | 123.69 | 65.4 |
| Random Mat Fabric | 254.40 | 65.53 | 34.6 |
| Total | 734.58 | 189.23 | 100 |

### Use:

**Mobile mode**

| | |
|---|---|
| Fuel and mobility type | Diesel - family car |
| Use location | Brazil |
| Product mass (kg) | 734.58 |
| Distance (km per day) | 30.00 |
| Usage (days per year) | 80.00 |
| Product life (years) | 20.00 |

**Relative contribution of static and mobile modes**

| Mode | Energy (MJ) | % |
|---|---|---|
| Static | 0.00 | |
| Mobile | 56415.74 | 100.0 |
| Total | 56415.74 | 100 |

**Breakdown of mobile mode by components**

| Component | Energy (MJ) | % |
|---|---|---|
| Hood Matrix | 36877.82 | 65.4 |
| Random Mat Fabric | 19537.92 | 34.6 |
| Total | 56415.74 | 100 |

## Disposal:

| Component | End of life option | % recovered | Energy (MJ) | % |
|---|---|---|---|---|
| Hood Matrix | Re-manufacture | 10.0 | 96.04 | 65.4 |
| Random Mat Fabric | Landfill | 20.0 | 50.88 | 34.6 |
| Total | | | 146.92 | 100 |

## EoL potential:

| Component | End of life option | % recovered | Energy (MJ) | % |
|---|---|---|---|---|
| Hood Matrix | Re-manufacture | 10.0 | -3501.59 | 100.0 |
| Random Mat Fabric | Landfill | 20.0 | 0.00 | 0.0 |
| Total | | | -3501.59 | 100 |

# CO2 Footprint Analysis

| | CO2 (kg)/year |
|---|---|
| Equivalent annual environmental burden (averaged over 20 year product life): | 385.992 |

## Detailed breakdown of individual life phases

## Material:

| Component | Material | Recycled content* (%) | Part mass (kg) | Qty. | Total mass processed** (kg) | CO2 footprint (kg) | % |
|---|---|---|---|---|---|---|---|
| Hood Matrix | Polyester cast (rigid) | Virgin (0%) | 1.51 | 318 | 511.92 | 1521.37 | 62.2 |
| Random Mat Fabric | Glass, E grade (0.4-12 micron monofilament, f) | Virgin (0%) | 0.80 | 318 | 263.63 | 925.56 | 37.8 |
| Total | | | | 636 | 775.55 | 2446.94 | 100 |

*Typical: Includes 'recycle fraction in current supply'

**Where applicable, includes material mass removed by secondary processes

## Manufacture:

| Component | Process | % Removed | Amount processed | CO2 footprint | % |
|---|---|---|---|---|---|
| Hood Matrix | Polymer molding | - | 511.92 kg | 1087.88 | 87.5 |
| Hood Matrix | Cutting and trimming | 6.2 | 31.74 kg | 0.73 | 0.1 |
| Random Mat Fabric | Fabric production | - | 263.63 kg | 54.88 | 4.4 |
| Random Mat Fabric | Cutting and trimming | 3.5 | 9.23 kg | 0.21 | 0.0 |
| Surface Finishing | Painting | - | 102.00 m^2 | 99.96 | 8.0 |
| Total | | | | 1243.66 | 100 |

## Transport:

**Breakdown by transport stage** Total product mass = 7.3e+02 kg

| Stage name | Transport type | Distance (km) | CO2 footprint (kg) | % |
|---|---|---|---|---|
| Finished Car to Point of Sale Santos | 32 tonne truck | 560.00 | 13.44 | 100.0 |
| Total | | 560.00 | 13.44 | 100 |

**Breakdown by components**

| Component | Component mass (kg) | CO2 footprint (kg) | % |
|---|---|---|---|
| Hood Matrix | 480.18 | 8.78 | 65.4 |
| Random Mat Fabric | 254.40 | 4.65 | 34.6 |
| Total | 734.58 | 13.44 | 100 |

## Use:

### Mobile mode

| | |
|---|---|
| **Fuel and mobility type** | Diesel - family car |
| **Use location** | Brazil |
| **Product mass (kg)** | 734.58 |
| **Distance (km per day)** | 30.00 |
| **Usage (days per year)** | 80.00 |
| **Product life (years)** | 20.00 |

### Relative contribution of static and mobile modes

| Mode | CO2 footprint (kg) | % |
|---|---|---|
| **Static** | 0.00 | |
| **Mobile** | 4005.52 | 100.0 |
| Total | **4005.52** | **100** |

### Breakdown of mobile mode by components

| Component | CO2 (kg) | % |
|---|---|---|
| **Hood Matrix** | 2618.33 | 65.4 |
| **Random Mat Fabric** | 1387.19 | 34.6 |
| Total | **4005.52** | **100** |

## Disposal:

| Component | End of life option | % recovered | CO2 footprint (kg) | % |
|---|---|---|---|---|
| **Hood Matrix** | Re-manufacture | 10.0 | 6.72 | 65.4 |
| **Random Mat Fabric** | Landfill | 20.0 | 3.56 | 34.6 |
| Total | | | **10.28** | **100** |

## EoL potential:

| Component | End of life option | % recovered | CO2 footprint (kg) | % |
|---|---|---|---|---|
| **Hood Matrix** | Re-manufacture | 10.0 | -142.05 | 100.0 |
| **Random Mat Fabric** | Landfill | 20.0 | 0.00 | 0.0 |
| Total | | | **-142.05** | **100** |

## Notes:

Random mat of glass fiber scenario described according to the Baseline RTM procedure as currently manufactured in Ancel w orkshop.

# ANNEX 3. RTM technical cost model for ramie bio-polyester hood

## General Inputs

| EXOGENOUS VARIABLES | | | |
|---|---|---|---|
| Direct Wages | R$ 4.20 | /hr | wage |
| Interest Rate | 15% | | crr |
| Equipment Life | 10 | yrs | crp |
| Electricity Price | R$ 0.39 | /KWh | elec |
| Auxiliary Equipment Cost | 15% | | aux |
| Installation Cost | 20% | | install |
| Overhead Burden | 37.5% | | ovhd |
| Maintenance Cost | 10% | | maint |
| Price of Building Space | R$ 3,400.00 | /m^2 | bldg |
| Building Recovery Life | 40 | yrs | blife |

| CONSTANTS, CONVERSION FACTORS | | | |
|---|---|---|---|
| Universal Gas Constant | 8.314 | J/mol*K | gas_const |
| N to tons | 1.12E-04 | ton/N | newt_ton |

| MANUFACTURING SPECIFICATIONS | | | |
|---|---|---|---|
| Annual Production Volume | 300 | /yr | num |
| Average Downtime | 18.75 | % | down |
| Product Lifetime | 5 | yrs. | plife |
| Working Hours per Day | 7.3 | hrs./day | hours |
| Working Days per Year | 302 | days/yr. | days |

| PROCESS STEP SELECTIONS | | | |
|---|---|---|---|
| PREFORM CUTTING | 1 | 0=NO, 1=YES | pfcut? |
| PREFORM LAYUP | 1 | 0=NO, 1=PLY, 2=SPRAY | fibmethod? |
| RESIN TRANSFER MOLDING | 1 | '0=NO, 1=YES | **rtm?** |
| SRIM | 0 | '0=NO, 1=YES | **srim?** |
| FINAL TRIM/INSPECTION | 1 | 0=NO, 1=YES | ti? |

| AUXILIARY OPERATION CYCLE TIMES | | | |
|---|---|---|---|
| Foam Core Trimming Cycle Time: | | sec | ofctcyc |
| Preform/Foam Core Assembly Cycle Time: | 10 | sec | osubcyc |
| Final Trim/Inspection Cycle Times: | 80 | sec | oticyc |

## *Part-specific inputs*

### MOLDED PART

| | | | |
|---|---|---|---|
| Are you making one part or a pair of parts? | **1** | 1=One Part, 2=Pair | numpart |
| Maximum Part Length | **0.69915** | m | plen |
| Maximum Part Width | **0.5013** | m | pwidth |
| Average Part Thickness | **0.0415** | m | pthk |
| Surface Area | **0.34** | m^2 | psurf |
| Perimeter | **2.31** | m | pper |
| Total Weight | **2** | kg | pwgt |
| Total Volume | **0.00135** | m^3 | pvol |

### MATERIAL SPECIFICATIONS

| **Laminate** | Menu Selection | Material Name | Volume % of Laminate |
|---|---|---|---|
| Fiber Reinforcement | **4** | Bi-axial Jute Fabric | **31.00%** |
| Resin | **2** | Biopoli BP 507 | **49.90%** |
| Filler | **1** | Calcium Carbonate (fine) | **17.00%** |
| Catalyst (including promoter) | **1** | Brasnox | **2.00%** |
| Promoter | **2** | Dimethylacetamide | **0.10%** |
| | | Entire Laminate | 100.00% |

| **Entire Part Excluding Coating** | Volume (m^3) | Volume % |
|---|---|---|
| Laminate | 0.001350 | 100.00% |
| Foam Cores | 0.000000 | 0.00% |
| Inserts | 0.000000 | 0.00% |
| Total | 0.001350 | 100.00% |

| | Volume (m^3) | Weight (kg) | Weight % |
|---|---|---|---|
| Fiber Reinforcement (including binder) | 4.19E-04 | 0.6487 | 31.81% |
| Resin | 6.74E-04 | 0.7410 | 36.34% |
| Filler | 2.30E-04 | 0.6197 | 30.39% |
| Catalyst | 2.70E-05 | 0.0297 | 1.46% |
| Foam Cores | 0.00E+00 | 0.0000 | 0.00% |
| Promoter | 1.35E-06 | 0.0013 | 0.06% |
| Inserts | 0.00E+00 | 0.0000 | 0.00% |
| Total | 0.001350 | 2.0390 | 100.00% |

## SELECTED PART & MATERIALS CHARACTERISTICS

### *Part-specific inputs*

#### MOLDED PART

| | | | |
|---|---|---|---|
| Are you making one part or a pair of parts? | 1 | 1=One Part, 2=Pair | numpart |
| Maximum Part Length | 0.69915 | m | plen |
| Maximum Part Width | 0.5013 | m | pwidth |
| Average Part Thickness | 0.0415 | m | pthk |
| Surface Area | 0.34 | m^2 | psurf |
| Perimeter | 2.31 | m | pper |
| Total Weight | 1.78 | kg | pwgt |
| Total Volume | 0.00135 | m^3 | pvol |

#### MATERIAL SPECIFICATIONS

| **Laminate** | Menu Selection | Material Name | Volume % of Laminate |
|---|---|---|---|
| Fiber Reinforcement | 3 | Bi-axial Ramie Fabric | 20.00% |
| Resin | 2 | Biopoli BP 507 | 61.90% |
| Filler | 1 | Calcium Carbonate (fi | 16.00% |
| Catalyst (including promoter) | 1 | Brasnox | 2.00% |
| Promoter | 2 | Dimethylacetamide | 0.10% |
| | | Entire Laminate | 100.00% |

| **Entire Part Excluding Coating** | Volume (m^3) | Volume % |
|---|---|---|
| Laminate | 0.001350 | 100.00% |
| Foam Cores | 0.000000 | 0.00% |
| Inserts | 0.000000 | 0.00% |
| Total | 0.001350 | 100.00% |

| | Volume (m^3) | Weight (kg) | Weight % |
|---|---|---|---|
| Fiber Reinforcement (including binder) | 4.19E-04 | 0.6487 | 31.81% |
| Resin | 6.74E-04 | 0.7410 | 36.34% |
| Filler | 2.30E-04 | 0.6197 | 30.39% |
| Catalyst | 2.70E-05 | 0.0297 | 1.46% |
| Foam Cores | 0.00E+00 | 0.0000 | 0.00% |
| Promoter | 1.35E-06 | 0.0013 | 0.06% |
| Inserts | 0.00E+00 | 0.0000 | 0.00% |
| Total | 0.001350 | 2.0390 | 100.00% |

#### PREFORM

| | | | |
|---|---|---|---|
| How many preforms needed? (Assumes all are unique) | 1 | (1 or 2 preforms) | pfnum |
| How many preforms per part are you molding? | 1 | | preformperpart |
| PREFORM #1: | | | |
| Maximum Length | 0.699 | m | pflen1 |
| Maximum Width | 0.501 | m | pfwidth1 |
| Average Ply Thickness | 4.50E-04 | m | pfthk1 |
| Surface Area (w/o cutout) | 0.338 | m^2 | pfsurf1 |
| Cutout Area | 0.03945177 | m^2 | carea1 |
| Perimeter | 2.314 | m | pfper1 |
| Cutout Perimeter | 0 | m | cper1 |
| Number of Plies per Preform | 6 | | plyperpreform1 |
| Number of Plies per Fabric Layer | 1 | | plyperfab1 |
| Permeability (Optional) | 0.000 | x 10^-9 m^2 | opfperm1 |

## MATERIAL DATA

### RESIN

| | | | |
|---|---|---|---|
| Component Name | Biopoli BP 507 | | resname |
| Density | 1100 | kg/m^3 | rden |
| Viscosity | 0.25 | Pa*sec | dvis |
| Price | R$ 8.40 | /kg | rescost |
| Polymer System | POLYESTER | | polymer1 |
| Rate Coefficient | 1.61E+08 | /sec | rate1 |
| Activation Energy | 7.51E+04 | J/mol | activ1 |

### FILLER

| | | | |
|---|---|---|---|
| Component Name | alcium Carbonate (fine) | | fillname |
| Density | 2700 | kg/m^3 | fillden |
| Price | R$ 0.25 | /kg | fillcost |

### REINFORCEMENT

| | | | |
|---|---|---|---|
| Component Name | Bi-axial Ramie Fabric | | rfname |
| Fiber Density | 1500 | kg/m^3 | rfdens |
| Fiber Diameter | 0.000034 | m | rfdia |
| Price | R$ 45.00 | /kg | rfcost |
| Scrap price | R$ 0.00 | | |

### CATALYST

| | | | |
|---|---|---|---|
| Component Name | Brasnox | | catname |
| Density | 1100 | kg/m^3 | cden |
| Price | R$ 9.30 | /kg | catcost |

### PROMOTER

| | | | |
|---|---|---|---|
| Component Name | Dimethylacetamide | | catname |
| Density | 940 | kg/m^3 | cden |
| Price | R$ 12.80 | /kg | catcost |

## PART GEOMETRY DATA

### ENTIRE MOLDED PART (Geometric characteristics)

| | | | |
|---|---|---|---|
| Total Volume of the Molded Part | 1.35E-03 | m^3 | |
| Vol. Fraction of Reinforcement | 31.0% | | volfrac |
| Porosity | 69.0% | | rfpor |
| Shear coefficincy k | 5.1 | | k |
| Kozeny Coefficient | 13.3 | | kozeny |
| Permeability Used | 2.97E-10 | m^2 | pfperm |
| Calculated Permeability | 2.97E-10 | m^2 | pfpermcalc |
| Characteristic Injection Thickness | 3.99E-03 | m | effpthk |
| Mass of Part w/o Inserts | 1.78 | kg | pwgt_wo_inserts |

### FOAM CORES

| | | | |
|---|---|---|---|
| Volume of Foam Core #1 | 0.000 | m^3 | fvol1 |
| Weight of Foam Core #1 | 0.000 | kg | fwgt1 |
| Volume of Foam Core #2 | 0.000 | m^3 | fvol2 |
| Weight of Foam Core #2 | 0.000 | kg | fwgt2 |
| Volume of Foam Core #3 | 0.000 | m^3 | fvol3 |
| Weight of Foam Core #3 | 0.000 | kg | fwgt3 |

### PREFORMS

| | | | |
|---|---|---|---|
| Weight of Preform #1 (inlcuding binder) | 0.37 | kg | pfwgt1 |

**PROCESS INPUTS**

**Resin Preparation**

| | | | |
|---|---|---|---|
| Dedicated Capital Equipment? | 0 | 0=NO, 1=YES | prepded |
| Number of Laborers | 0.5 | /station | preplab |
| Electricity Usage | 25 | KW | prepelec |
| Resin Preparation Cycle Time | 282.00 | sec | preprate |
| Scrap Rate | 5.00% | | prepscr |
| Rejection Rate | 1.00% | | preprej |
| Mixing Maching Cost | $1,500 | | prepmcost |
| Tooling Life | 1,000 | 000 cycles | preptlife |
| Floorspace requirement for resin preparation | 25 | m^2 | prepflr |

**PREFORM CUTTING**

| | | | |
|---|---|---|---|
| Dedicated Capital Equipment? | 0 | 0=NO, 1=YES | cutded |
| How many different fabric shapes are you cutting? | 1 | | shapes |
| Is fabric cutting done on the same tool? | yes | | samecuttool |
| If separate cutting tools, how many are run simultaneously? | 1 | | cuttoolsim |
| Number of Fabric Layers Cut Simultaneously | 1 | | fabsim |
| Number of Laborers | 0.25 | /station | fiblab |
| Cutting Cycle Time | 223.00 | sec | cutrate |
| Scrap Rate | 15.00% | | fibscr |
| Rejection Rate | 1.00% | | fibrej |
| Tool Resharpening Period | 1,000 | cycles | resharpenperiod |
| Tool Resharpening Cost | $1 | per resharpening | resharpencost |
| Tooling Life | 1,000 | 000 cycles | fibtlife |
| Floorspace requirement for preform cutting | 25 | m^2 | fibflr |

**PREFORM LAYUP**

| | | | |
|---|---|---|---|
| Dedicated Capital Equipment? | 0 | 0=NO, 1=YES | layded |
| | | **PLY LAY-UP METHOD** | |
| Number of Laborers (same laborer loads preform in mold) | 0.25 | /station | plylab |
| Time to Layup One Fabric Layer and Spray Binder | 5 | sec | bindtime |
| Binder Usage | 0 | L/m^2 | bindusage |
| Floorspace Requirement for Ply Lay-up | 20 | m^2 | plyflr |
| Binder Density | | kg/m^3 | |
| Reject Rate | 1.00% | | plyrej |

| RESIN TRANSFER MOLDING | | | | |
|---|---|---|---|---|
| Dedicated Capital Equipment? | 0 | 0=NO, 1=YES | | rtmded |
| If making a pair of parts, are you molding in the same die? | 0 | 0=NO, 1=YES | | rtmsim |
| If pair and separate tools, can you use the same tool design for both? | 0 | 0=NO, 1=YES | | rtmsametool |
| Number of Laborers | 0.35 | /station | | rtmlab |
| Electricity Usage | 21 | KW | | rtmelec |
| Insert Replacement and Treatment Time | 0 | minutes | | rtmsetup |
| | Usage (unit/m^2) | | Price ($/unit) | |
| Mold Release Agent Material Usage, Price (L) | 0.10 | | R$ 70.00 | rtmrau/rtmrap |
| Mold Sealer Usage, Price (L) | 0.08 | | R$ 142.39 | rtmsu/rtmras |
| Mold Cleaning Thinner Usage, Price (L) | 0.03 | | R$ 5.38 | rtmctu/rtmrat |
| Preform/Foam Core Placement Time | 10 | sec | | rtmplacetime |
| Open/Close Mold Time | 175 | sec | | rtmopentime |
| Demold Time | 65 | sec | | rtmdemtime |
| Dispenser Movement Time | 0 | sec | | rtmdmvtime |
| Gel time (of resin) | 600 | sec | | rtmgeltime |
| | Rate (sec/m^2) | | Frequency (parts/opperation) | |
| Mold Cleaning Rate, Frequency | 10.00 | | 1 | rtmcr/rtmcf |
| Mold Release Agent Coating Rate, Frequency | 40.00 | | 1 | rtmrar/rtmraf |
| Mold Sealant Liquid Coating Rate, Frequency | 30.00 | | 1 | rtmslr/rtmrsf |
| Mold Inspection Rate, Frequency | 10.00 | | 1 | rtminsr/rtminsf |
| Rectilinear or Radial Flow? | 1 | 0=Rect, 1=Rad | | rtmrec_rad? |
| Radial Source or Sink? | 0 | 0=Source, 1=Sink | | rtmsource_sink? |
| Constant Flow Rate or Constant Pressure Filling? | 1 | 0=Flow, 1=Pressure | | rtmflow_pres? |
| Mold Temperature | 20 | oC | | rtmtemp |
| Minimum Conversion for Demold | 98% | | | rtmconv |
| Flow Rate | 0.003 | N/A | | rtmflowrate |
| Injection Pressure (Initial) | 6.00E+05 | Pa | | rtminjpres1 |
| Injection Port Radius | 0.002 | m | | rtmro |
| Number of Injectors per Cavity | 1 | | | rtmnuminj |
| Scrap Rate | 1.25% | | | rtmscr |
| Reject Rate | 2.50% | | | rtmrej |
| Injection Machine Unit Cost | R$ 20,500 | $/unit | | rtmdispencost |
| Waste Material Handling Cost (scrap and rejects) | R$ 2 | $/kg | | rtmwaste_cost |
| **RESIN TRANSFER MOLDING OVERRIDES** | | | | |
| Resin Transfer Molding Equipment & Cycle Times: | | | | |
| Mold Force | 0 | N | | ortmmforce |
| Press Cost | $0 | $/press | | ortmpresscost |
| Fill time | 120 | sec | | ortmltime |
| Other Time Outside Press (=0 if no shuttle) | 0 | sec | | ortmototime |
| Cure Time | 1600 | | | ortmctime |
| Overall Cycle Time | 5080 | sec | | ortmtime |
| Mold Radius Override | 0 | m | | rtmriov |
| Resin Transfer Molding Tools: | | | | |
| Tooling Life | 0 | | | ortmtlife |
| Cost of Additional Tools (percent of 1st tool) | 0% | cost of tool model/total cost of tool | | ortmadditionaltool |
| Tool Cost | $0 | $/tool set | | ortmtcost |

| FINAL TRIM/INSPECTION | | | |
|---|---|---|---|
| Dedicated Capital Equipment? | 0 | 0=NO, 1=YES | tided |
| Number of Laborers | 0.5 | /station | tilab |
| Equipment power rating | 10 | kw | tielec |
| Scrap Rate | 5.00% | | tiscr |
| Rejection Rate | 0.50% | | tirej |
| Tooling Cost | $30 | /toolset | titcost |
| Tooling Life | 100 | 000 cycles | titlife |
| Machine Cost | $550 | /machine | timcost |
| Floorspace Requirement | 65 | m^2 | tiflr |

**COST SUMMARY**

| VARIABLE COST ELEMENTS | per part | per year | percent |
|---|---|---|---|
| *Material Cost* | $ 34.79 | $ 10,436 | 35% |
| *Labor Cost* | $ 9.24 | $ 2,773 | 9% |
| *Energy Cost* | $ 7.60 | $ 2,279 | 8% |
| ***Total Variable Cost*** | **$ 51.63** | **$ 15,488** | **52.4%** |

| FIXED COST ELEMENTS | per part | per year | percent | investment |
|---|---|---|---|---|
| *Main Machine Cost* | $ 16.34 | $4,902.17 | 17% | $ 24,603 |
| *Tooling Cost* | $ 2.02 | $605.58 | 2% | $ 2,030 |
| *Fixed Overhead Cost* | $ 12.26 | $ 3,678 | 12% | $ - |
| *Building Cost* | $ 10.86 | $3,258.66 | 11% | $ 21,643 |
| *Auxiliary Equipment Cost* | $ 2.45 | $735.33 | 2% | $ 3,690 |
| *Maintenance Cost* | $ 3.04 | $912.06 | 3% | $ - |
| ***Total Fixed Cost*** | **$ 46.97** | **$ 14,091.97** | **$ 0.48** | **$51,966.59** |

| TOTAL COSTS | $ 98.60 | $ 29,580.36 | $ 1.00 |
|---|---|---|---|

**Table 7.1. Annual production volume of all scenarios**

| PLOT | Baseline RTM | | | Optimized RTM | | |
|---|---|---|---|---|---|---|
| | Glass | Ramie | Jute | Opt.Ramie | Opt.Jute | Cheap Ramie |
| | 2.44 kg | 1,78 kg | 2.00 kg | 1.79 kg | 2.00 kg | 1.79 kg |
| **0** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **50** | 352.24 | 356.37 | 345.77 | 336.67 | 326.30 | 327.11 |
| **150** | 149.49 | 153.47 | 143.22 | 145.84 | 135.90 | 136.69 |
| **200** | 124.66 | 128.68 | 118.35 | 122.69 | 112.64 | 113.44 |
| **300** | 99.15 | 103.13 | 92.88 | 98.60 | 88.66 | 89.45 |
| **500** | 78.92 | 82.88 | 72.67 | 79.53 | 69.63 | 70.43 |
| **1000** | 63.70 | 67.65 | 57.47 | 65.28 | 55.40 | 56.20 |
| **1500** | 58.67 | 62.63 | 52.44 | 60.49 | 50.63 | 51.43 |
| **2000** | 56.12 | 60.08 | 49.90 | 58.15 | 48.29 | 49.08 |
| **2500** | 54.61 | 58.55 | 48.38 | 56.72 | 46.86 | 47.65 |
| **3000** | 53.60 | 57.55 | 47.38 | 55.77 | 45.91 | 47.65 |
| **3500** | 52.88 | 56.82 | 46.65 | 55.08 | 45.23 | 46.70 |
| **4000** | 52.33 | 56.28 | 46.11 | 54.58 | 44.73 | 46.02 |
| **4500** | 51.91 | 55.86 | 45.69 | 54.17 | 44.31 | 45.52 |
| **5000** | 51.57 | 55.52 | 45.35 | 53.86 | 44.01 | 45.11 |
| **5500** | 51.29 | 55.23 | 45.07 | 53.60 | 43.74 | 44.80 |
| **6000** | 51.07 | 55.02 | 44.85 | 53.39 | 43.53 | 44.54 |
| **6500** | 50.87 | 54.81 | 44.65 | 53.20 | 43.35 | 44.33 |
| **7000** | 50.70 | 54.65 | 44.48 | 53.04 | 43.19 | 44.14 |
| **7500** | 50.55 | 54.50 | 44.33 | 52.91 | 43.05 | 43.99 |
| **8000** | 50.44 | 54.38 | 44.21 | 52.80 | 42.94 | 43.85 |
| **8500** | 50.31 | 54.26 | 44.10 | 52.69 | 42.83 | 43.74 |
| **9000** | 50.23 | 54.17 | 44.01 | 52.59 | 42.74 | 43.63 |
| **9500** | 50.13 | 54.08 | 43.91 | 52.50 | 42.65 | 43.53 |
| **10000** | 50.05 | 54.00 | 43.83 | 52.44 | 42.58 | 43.44 |
| **50000** | 49.29 | 0.00 | 43.00 | 52.07 | 41.96 | 43.38 |
| **60000** | 49.04 | 0.00 | 42.57 | 51.81 | 41.69 | 42.19 |
| **65000** | 48.91 | 0.00 | 42.55 | 51.67 | 41.56 | 42.17 |
| **70000** | 48.84 | 0.00 | 42.53 | 51.59 | 41.48 | 42.15 |
| **75000** | 49.29 | 52.73 | 42.52 | 51.24 | 41.42 | 42.14 |
| **80000** | 49.04 | 52.71 | 42.51 | 51.23 | 41.39 | 42.13 |
| **85000** | 48.91 | 52.70 | 42.48 | 51.21 | 41.36 | 42.12 |
| **90000** | 48.84 | 52.68 | 42.48 | 51.20 | 41.34 | 42.11 |
| **95000** | 48.79 | 52.67 | 42.47 | 51.19 | 41.32 | 42.10 |
| **100000** | 48.75 | 52.66 | 42.46 | 51.18 | 41.33 | 42.09 |

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# ANNEX 4. Stamping technical cost model for steel part

**STAMPING TECHNICAL COST MODEL**
**MIT - Materials Systems Laboratory**

| | | | |
|---|---|---|---|
| **Annual Production Volume** | 300 | parts/yr | PRODVOL |
| **Low Volume Production** | 1 | [0=N 1=Y] | LOWVOLTOG |

**Exogenous Variables**

| | | | |
|---|---|---|---|
| Days per Year | 302 | days/yr | DAYS |
| Wage (including benefits) | R$ 4.20 | $/hr | WAGE |
| Unit Energy Cost | R$ 0.39 | $/kWhr | ENERGY |
| Interest | 15% | % | INTEREST |
| Equipment Life | 10 | yr | EQUIP_LIFE |
| Indirect workers/Direct Worker | 0.33 | | INDIRECT_DIRECT |
| Building Unit Cost | R$ 3,400 | R$/sqm | BUILDING |
| Building Life | 40 | yrs | BUILD_LIFE |
| Production Life | 5 | yrs | PRODUCT_LIFE |
| Idle Space | 50% | % | IDLE |
| Capacity Utilization | 100% | % | CAPACITY |
| Loss From Coil Ends | 1.00% | % | COIL_END_LOSS |

**Blanking Inputs**

| | | | |
|---|---|---|---|
| Is the line dedicated? | 0 | [0=N 1=Y] | BLANK_DED_TOG |
| Workers / Blank Line | 1 | #/line | BLANK_WORKERS |
| Average Blanking Die Change Time | 0.13 | hr | BL_DIE_CHANGE |
| Average Blanking Lot Size | 100 | parts(sets)/lo | BLANK_LOT |
| Blanking Maintenance Percent | 5% | % | BLANK_MAINT_PER |
| Indirect workers/Direct Worker | 1.25 | | BL_INDIRECT_DIRECT |
| **Overrides** | | | |
| Line Rate | 4500 | hits/hr | |
| Space Requirement | 300 | sqm | |

**Blank Rinsing Inputs**

| | | | |
|---|---|---|---|
| Is rinsing done? | 1 | [0=N 1=Y] | RINSETOG |
| Is Washing Dedicated? | 0 | [0=N 1=Y] | RINSE_DED_TOG |
| Maintenance Percent | 10% | % | RINSE_MAINT |
| Rinse Time in Addition to Line Rate | 0.69 | seconds | RINSE_TIME |
| Washer Space Requirement | 200 | sqm | WASHER_SPACE |
| Blank Washer Unit Cost | R$ 600,000 | $ | WASHER_COST |
| Roll Cost | R$ 40,000 | $/year | WASH_ROLL_COSTS |
| Washer Flow Rate | 0.07 | liters/min | WASH_FLOW_RATE |
| Wash Solution Cost | R$ 10 | $/liter | WASH_SOLN_COST |
| Washer Unit Energy Usage | 20 | kW | WASH_ENERGY |
| Indirect workers/Direct workers | 0.214 | | ST_INDIRECT_DIRECT |

**Stamping Inputs**

| | | | |
|---|---|---|---|
| Is the line dedicated? | 0 | [0=N 1=Y] | STAMP_DED_TOG |
| Press Line Average Lot Size | 100 | parts/lot | STAMP_LOT_SIZE |
| Press Line Average Die Change Time | 23 | minutes | STAMP_DIE_CHANGE_TIME |
| Low Volume Tool Life | 250,000 | hits | STAMP_PRESS_DIELIFE_LOW |
| Regular Volume Tool Life | 25,000,000 | hits | STAMP_PRESS_DIELIFE |
| Press Line Maintenance Percent | 10% | % | PRESS_MAINT |
| Press Tonnage Additional Margin | 25% | % | STAMP_PRESS_MARGIN |
| **Overrides** | | | |
| Number of hits | 1 | # | |
| Number of workers | 1 | # | |
| Press Line Space Requirement | 300 | sqm | |

**Finishing**

| | | | |
|---|---|---|---|
| Does Finishing Occur? | 0 | [0=N 1=Y] | FINISHTOG |
| Is the line dedicated? | 0 | [0=N 1=Y] | FINISH_DED_TOG |
| % of Good Parts Finished | 5.00% | % | FINISH_PER |
| % of Finished Parts that are Rejected | 1.00% | % | FINISH_REJECT |
| Fixture Cost | R$ 40,000 | R$ | FINISH_FIX_COST |
| Average Time Per Part | 60 | sec | FINISH_TIME |
| Fixture Space Requirement | 100 | sqm | FINISH_SPACE |
| Finishing Maintenance Percent | 5% | % | FINISH_MAINT |
| Indirect workers/Direct workers | 1 | | FI_INDIRECT_DIRECT |
| **Overrides** | | | |
| Workers Override | 1 | # | |
| Labor Cost Override | | R$ | |

**GENERAL INTERMEDIATE OUTPUTS**

**Part Information**

| | | | | |
|---|---|---|---|---|
| Name | 220MPa Alloy Steel Front Hood - 1,91 mm | | | |
| Material # | 5 | This is 220 Mpa Steel | | MAT |
| Complexity | 1 | 1,2,3 | | COMPLEX |
| Finishing? | 1 | | | FINISHTOG |
| Press Type # | 2 | This is a Tandem press | | PRESS_TYPE |
| Part Weight (combined weight) | 4.85 | kg | | PA_WEIGHT |
| Part Width (combined width) | 521.87 | mm | | PA_WIDTH |
| Part Length | 699.15 | mm | | PA_LENGTH |
| Part Surface Area (combined if simult stamp) | 0.34 | sqm | | PA_SURF_AREA |
| Projected Part Surface Area (combined) | 0.33 | sqm | | PA_PROJ_SURF_AREA |
| Preblank Cost | $0.00 | $ | | PREBLANK |
| Blank/Coil Gage | 1.91 | mm | | BL_GAGE |
| Blank/Coil Width | 630 | mm | | BL_WIDTH |
| Coil Progression | 800 | mm | | COIL_PROGRESSION |
| Blank/Cutting Perimeter | 700 | mm | | BL_CUT_PER |
| Parts Stamped Simultaneously | 1 | | | |
| Blanks Used per Stamping Cycle | 1 | | | |

**Material Information**

| | | | |
|---|---|---|---|
| Material | 220 Mpa Steel | | |
| Density | 7.87 | g/cm^3 | MAT_DENS |
| Unit Cost | $2.00 | $/kg | MAT_COST |
| Scrap Price | $0.45 | $/kg | SCRAP_COST |
| Yield Strength | 220 | MPa | MAT_YS |
| UTS | 410 | MPa | MAT_UTS |
| Thickness Factor | 1 | | MAT_THICK_FAC |
| Line Rate Factor | 0.95 | | MAT_LR_FAC |
| Reject Rate Factor | 1 | | MAT_RR_FAC |
| Tool Invest. Factor | 1 | | MAT_TI_FAC |

**BLANKING**

**Press Information**

| | | | |
|---|---|---|---|
| Is a progressive press used? | N | | PROG_CHECK |
| Blank Weight | 7.58 | kg | BL_WEIGHT |
| Blanking Press Tonnage Req'd | 48.73 | | BL_TON |
| Blanking Press Name | 400t Blanking Press | | |
| Blanking Press Cost | $4,000,000 | $ | BL_PRESS_COST |
| Blanking Aux. and Instal. Cost | $1,334,000 | $ | BL_AI_COST |
| Blanking Line Rate | 4500 | hits/hr | BL_LINERATE |
| Blanking Power Consumption | 200 | kW | BL_POWER |
| Blanking Space Requirement | 300 | sqm | BL_SPACE |
| Blanking Reject Rate | 0.05% | % | BL_REJECT |

**Downtime Information**

| | | | |
|---|---|---|---|
| No Shifts | 16.0 | hr/day | BL_DT_NS |
| Worker Unpaid Breaks | 0.5 | hr/day | BL_DT_UN_BR |
| Worker Paid Breaks | 0.3 | hr/day | BL_DT_PA_BR |
| On Shift Maintenance | 1.0 | hr/day | BL_DT_MAINT |
| Idle | 1.3 | hr/day | BL_DT_ID |
| Unplanned Downtime | 0.8 | hr/day | BL_DT_UNPLAN |
| Total Downtime | 19.8 | hr/day | BL_DT_TOT |

**Volumes, Times, and Workers**

| | | | |
|---|---|---|---|
| Effective Annual Blanking Volume | 603 | blanks/yr | BL_VOL |
| Number of Lots Per Year | 7 | lots/yr | BL_AN_LOTS |
| Annual Production Time | 0 | hr/yr | BL_PROD_TIME |
| Die Change Time | 1 | hr/yr | BL_AN_DIE_TIME |
| Line Time Required | 1 | hr/yr | BL_TIME_REQ |
| Line Uptime | 1268 | hr/yr | BL_UPTIME |
| Percent of the Line Req'd | 0.08% | % | BL_PER_LINE |
| Percent of the Line Allocated | 0.08% | % | BL_PER_ALLO |
| Blanking Direct Workers | 0.00 | # | BL_DIRECT |
| Blanking Indirect Workers | 0.00 | # | BL_INDIRECT |
| Blanking Annual Paid Time | 2265 | hr/yr | BL_AN_PAID_TIME |

Actual Indirect Workers at any time 1.25

**BLANK RINSING**

**Downtime Information**

| | | | |
|---|---|---|---|
| No Shifts | 16.0 | hr/day | RI_DT_NS |
| Worker Unpaid Breaks | 0.5 | hr/day | RI_DT_UN_BR |
| Worker Paid Breaks | 0.3 | hr/day | RI_DT_PA_BR |
| On Shift Maintenance | 1.0 | hr/day | RI_DT_MAINT |
| Idle | 1.3 | hr/day | RI_DT_ID |
| Unplanned Downtime | 0.8 | hr/day | RI_DT_UNPLAN |
| Total Downtime | 19.8 | hr/day | RI_DT_TOT |

**Volumes, Times, and Workers** 4560.738034

| | | | |
|---|---|---|---|
| Effective Production Volume | 602 | blanks/yr | RI_VOL |
| Line Uptime | 1268.4 | hr/yr | RI_UPTIME |
| Line Rate | 250 | parts/hr | RI_LINERATE |
| Additional Line Time | 0 | hr/yr | RI_ADD_TIME |
| Total Line Time Required | 3 | hr/yr | RI_TOT_TIME |
| Percent of Line Required | 0% | % | RI_PER_LINE |
| Percent of the Line Allocated | 0% | % | RI_PER_ALLO |
| Rinsing Direct Workers | 0.00 | # | RI_DIRECT |
| Rinsing Indirect Workers | 0.00 | # | RI_INDIRECT |
| Rinsing Annual Paid Time | 2265 | hr/yr | RI_AN_PAID_TIME |

**Water Requirement**

| | | | |
|---|---|---|---|
| Annual water consumption | 11 | liters/year | RI_WATER |

## STAMPING

### Press Information

| | | | |
|---|---|---|---|
| Number of parts per hit | 1 | # | PART_HIT |
| Projected Part Area (combined part) | 0.330 | sqm | EST_PART_AREA |
| Estimated Part Forming Area | 0.0099 | sqm | EST_PART_FORM_ARE |
| Stamping Press Tonnage Req'd per hit | 346.5 | tons | |
| Stamping Press Tonnage Req'd plus marg | 433.1 | tons | ST_TON |
| Number of Hits | 1 | # | ST_HITS |
| Stamping Equipment | **1 x 600t S/A Tandem** | | |
| Press Line Cost | $2,500,000 | R$ | ST_PRESS_COST |
| Press Line Auxiliary and Installation Cost | $120,000 | R$ | ST_AI_COST |
| Press Line Power Consumption | 250 | kW | ST_POWER |
| Press Line Space Requirement | 300 | sqm | ST_SPACE |
| Tooling Costs | $192,635 | R$ | ST_TOOL_COST |
| Lifetime # Tools Needed | 1 | # | ST_NUM_TOOLS |
| Line Rate | 250 | hits/hr | ST_LINERATE |
| Reject Rate | 0.33% | % | ST_REJECT |

### Downtime Information

| | | | |
|---|---|---|---|
| No Shifts | 16.0 | hr/day | ST_DT_NS |
| Worker Unpaid Breaks | 0.5 | hr/day | ST_DT_UN_BR |
| Worker Paid Breaks | 0.3 | hr/day | ST_DT_PA_BR |
| On Shift Maintenance | 1.0 | hr/day | ST_DT_MAINT |
| Idle | 1.3 | hr/day | ST_DT_ID |
| Unplanned Downtime | 0.8 | hr/day | ST_DT_UNPLAN |
| Total Downtime | 19.8 | hr/day | ST_DT_TOT |

### Volumes, Times, and Workers

| | | | |
|---|---|---|---|
| Workers Per Line | 1 | # | ST_WORKERS |
| Effective Annual Stamping Volume | 602 | cycles/yr | ST_VOL |
| Number of lots per year | 7 | lots/year | ST_AN_LOTS |
| Annual Production Time | 2 | hr/yr | ST_PROD_TIME |
| Line Time Required | 7 | hr/yr | ST_TIME_REQ |
| Line Uptime | 1268.4 | hr/yr | ST_UPTIME |
| Percent of the Line Required | 1% | % | ST_PER_LINE |
| Percent of the Line Allocated | 1% | % | ST_PER_ALLO |
| Stamping Direct Workers | 0.01 | # | ST_DIRECT |
| Stamping Indirect Workers | 0.00 | # | ST_INDIRECT |
| Stamping Annual Paid Time | 2265 | hr/yr | ST_AN_PAID_TIME |

Actual Indirect Workers 0.214285714

**Tandem Presses, 360 hit baseline**

| | 220 MPa | | 350 MPa Steel | | 700 MPa Steel | | Al 6010 | |
|---|---|---|---|---|---|---|---|---|
| *Material Cost* | R$ | 26.02 | R$ | 24.35 | R$ | 24.96 | R$ | 21.14 |
| *Process Material Cost* | R$ | 0.00 | R$ | 0.00 | R$ | 0.00 | R$ | 0.00 |
| *Labor Cost* | R$ | 0.19 | R$ | 0.19 | R$ | 0.20 | R$ | 0.20 |
| *Energy Cost* | R$ | 2.49 | R$ | 2.93 | R$ | 3.98 | R$ | 1.26 |
| *Main Machine Cost* | R$ | 12.85 | R$ | 14.04 | R$ | 15.54 | R$ | 11.45 |
| *Tooling Cost* | R$ | 191.55 | R$ | 220.29 | R$ | 220.29 | R$ | 227.37 |
| *Fixed Overhead Cost* | R$ | 0.07 | R$ | 0.07 | R$ | 0.07 | R$ | 0.07 |
| *Building Cost* | R$ | 5.67 | R$ | 5.68 | R$ | 6.00 | R$ | 6.00 |
| *Maintenance Cost* | R$ | 154.16 | R$ | 157.15 | R$ | 157.33 | R$ | 157.63 |
| **TOTAL FABRICATION COST** | **R$** | **393.02** | **R$** | **424.70** | **R$** | **428.37** | **R$** | **425.13** |
| *Press type* | 1 x 600t S/A Tandem | | 1 x 800t S/A Tandem | | 1 x 1000t S/A Tandem | | 1 x 350t S/A Tandem | |
| *Line rate* | | 250 | | 250 | | 225 | | 225 |
| *Allocated Press Investment* | R$ | 19,354 | R$ | 21,143 | R$ | 23,402 | R$ | 17,245 |
| *Tool Investment* | R$ | 192,635 | R$ | 221,530 | R$ | 221,530 | R$ | 228,658 |
| *Part Weight (kg)* | | 4.85 | | 3.60 | | 3.14 | | 1.64 |

## FINISHING

### Downtime Information

| | | | |
|---|---|---|---|
| No Shifts | 16.0 | hr/day | FI_DT_NS |
| Worker Unpaid Breaks | 0.5 | hr/day | FI_DT_UN_BR |
| Worker Paid Breaks | 0.3 | hr/day | FI_DT_PA_BR |
| On Shift Maintenance | 1.0 | hr/day | FI_DT_MAINT |
| Idle | 1.3 | hr/day | FI_DT_ID |
| Unplanned Downtime | 0.8 | hr/day | FI_DT_UNPLAN |
| Total Downtime | 19.8 | hr/day | FI_DT_TOT |

### Volumes, Times, and Workers

| | | | |
|---|---|---|---|
| Reworked good parts | 15 | | |
| Reworked rejected parts | 285 | | |
| Reworked good parts + rejects | 300 | parts/yr | FI_VOL |
| Effective Production Volume | 585 | parts/yr | FI_VOL |
| Number of Parts Finished (Reworked) | 300 | parts/yr | FI_VOL1 |
| Line Uptime | 1268.4 | hr/yr | FI_UPTIME |
| Annual Production Time | 0 | hr/yr | FI_PROD_TIME |
| Percent of Time | 0.0% | % | FI_PERCENT |
| Percent of Line Allocated | 0.0% | % | FI_PER_ALLO |
| Workers | 0 | # | FI_WORKERS |
| Finishing Direct Workers | 0.000 | # | FI_DIRECT |
| Finishing Indirect Workers | 0.00 | # | FI_INDIRECT |
| Finishing Annual Paid Time | 2265 | hr/yr | FI_AN_PAID_TIME |

### Equipment

| | | | |
|---|---|---|---|
| Number of Fixtures Required | 0 | # | FI_NUM_FIX |
| Cost of All Fixtures | $0 | $ | FI_TOT_FIX_COST |
| Building Space Required | 0 | sqm | FI_TOT_SPACE |

### COST SUMMARY

| VARIABLE COSTS | per piece | per year | percent | |
|---|---|---|---|---|
| *Material Cost* | $26.02 | $7,807.16 | 6.62% | |
| *Process Material Cost* | $0.00 | $0.21 | 0.00% | |
| *Labor Cost* | $0.19 | $57.65 | 0.05% | |
| *Energy Cost* | $2.49 | $748.26 | 0.63% | |
| **Total Variable Cost** | **$28.71** | **$8,613.28** | **7%** | |
| **FIXED COSTS** | **per piece** | **per year** | **percent** | **investment** |
| *Main Machine Cost* | $12.85 | $3,856.27 | 3.27% | $ 19,354 |
| *Tooling Cost* | $191.55 | $57,466.01 | 48.74% | $ 192,635 |
| *Fixed Overhead Cost* | $0.07 | $20.64 | 0.02% | $ - |
| *Building Cost* | $5.67 | $1,701.42 | 1.44% | $ 11,300 |
| *Maintenance Cost* | $154.16 | $46,247.96 | 39.22% | $ - |
| **Total Fixed Cost** | **$364.31** | **$109,292.31** | **93%** | **$223,289.20** |
| **TOTAL FABRICATION COST** | **$393.02** | **$117,905.59** | **100%** | |

| PLOT | Sheet Stamping | | | |
|---|---|---|---|---|
| | 220Mpa 3,9 kg | 350MPa 3,60 kg | 700MPa 3,15 kg | AL 6010 1,65 kg |
| **0** | 1000.00 | 1000.00 | 1000.00 | 1000.00 |
| **50** | 2122.55 | 2312.84 | 2317.21 | 2350.23 |
| **150** | 738.88 | 802.35 | 806.16 | 810.17 |
| **200** | 566.01 | 613.50 | 617.24 | 617.63 |
| **300** | 393.02 | 424.70 | 428.37 | 425.13 |
| **500** | 254.70 | 273.63 | 277.24 | 271.11 |
| **1000** | 150.94 | 160.36 | 163.94 | 155.62 |
| **1500** | 116.34 | 122.60 | 126.16 | 117.12 |
| **2000** | 99.06 | 103.73 | 107.28 | 97.87 |
| **2500** | 88.68 | 92.40 | 95.95 | 86.32 |
| **3000** | 81.76 | 84.84 | 88.39 | 78.62 |
| **3500** | 76.82 | 79.45 | 83.00 | 73.12 |
| **4000** | 73.12 | 75.41 | 78.95 | 69.00 |
| **4500** | 70.24 | 72.26 | 75.81 | 65.79 |
| **5000** | 67.93 | 69.75 | 73.29 | 63.23 |
| **5500** | 66.05 | 67.68 | 71.23 | 61.13 |
| **6000** | 64.48 | 65.97 | 69.51 | 59.38 |
| **6500** | 63.15 | 64.52 | 68.06 | 57.90 |
| **7000** | 62.01 | 63.28 | 66.82 | 56.63 |
| **7500** | 61.02 | 62.20 | 65.74 | 55.53 |
| **8000** | 60.16 | 61.26 | 64.80 | 54.57 |
| **8500** | 59.40 | 60.42 | 63.97 | 53.73 |
| **9000** | 58.72 | 59.68 | 63.23 | 52.97 |
| **9500** | 58.11 | 59.02 | 62.57 | 52.30 |
| **10000** | 57.57 | 58.43 | 61.97 | 51.69 |
| **50000** | 51.92 | 52.40 | 55.97 | 45.60 |
| **60000** | 51.17 | 51.57 | 55.14 | 44.74 |
| **65000** | 50.89 | 51.25 | 54.82 | 44.42 |
| **70000** | 50.65 | 50.98 | 54.55 | 44.14 |
| **75000** | 51.29 | 51.71 | 55.29 | 44.90 |
| **80000** | 51.06 | 51.45 | 55.03 | 44.64 |
| **85000** | 50.85 | 51.22 | 54.80 | 44.40 |
| **90000** | 50.67 | 51.01 | 54.59 | 44.19 |
| **95000** | 50.51 | 50.83 | 54.42 | 44.01 |
| **100000** | 51.00 | 51.39 | 54.98 | 44.59 |