UNIVERSIDADE DE LISBOA

INSTITUTO SUPERIOR TÉCNICO

An integrated approach to composite engineering design considering economic, environmental and mechanical inputs

Bruno Alexandre Rodrigues Simões Soares

Supervisor: Doctor Luís Filipe Galrão dos Reis

Co-supervisor: Doctor Luís Alberto Gonçalves de Sousa

Thesis approved in public session to obtain the PhD Degree in
Leaders for Technical Industries

Jury Final Classification: Pass

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Chairperson: Chairman of the IST Scientific Board

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The power of population is so superior to the power of the earth to produce subsistence for man, that premature death must in some shape or other visit the human race.

Malthus T.R. 1798. *An essay on the principle of population*.

Abstract

With the current rate of development of new materials, it has become harder and harder for a designer/engineer to properly evaluate and select the best material for any given application, and at the same time for the engineers developing these new materials to give them visibility. With the increased interest in sustainable development and environmental concerns, the material selection problem cannot still be constrained to the nominal performance/cost metrics of yesterday. Environmental concerns increase the complexity of material selection, since the selection should also consider such problems. This thesis investigates the material selection problem when applied to composite materials, when environmental concerns are introduced as a key concept in material selection.

For that purpose, this thesis first investigates the themes of Ecological impacts and Sustainability, and then proceeds to investigate a "normative" material selection case study based only on performance (mechanical)/cost metrics. The thesis then discusses the problems inherent to materials selection especially when considering new composite materials, and how they can be introduced to the market.

Finally a framework was developed to tackle both the material selection problem when faced with multiple options for composite materials, and the environmental concerns that now permeates all layers of society.

This tool is of interest to multiple stakeholders, from fiber and resin manufacturers to R&D companies and to the Design stages of a new product by simultaneously analyzing performance metrics, Economic cost, Environmental Cost from a database in order to select the "Best" materials for a given part under specified geometry, supports and loadings.

Resumo

Com a atual taxa de desenvolvimento de novos materiais, tornou-se cada vez mais difícil para um designer/engenheiro avaliar adequadamente e selecionar o melhor material para uma determinada aplicação, e ao mesmo tempo, dar exposição a esses novos materiais. Com o aumento do interesse em desenvolvimento sustentável e preocupações ambientais, o problema de seleção de materiais não pode ser apenas constrangido pelas métricas performance/custo de outrora. Por outro lado as preocupações ambientais aumentam a complexidade da selecção de materiais, uma vez que a selecção deverá também considerar tais problemas.

Esta dissertação investiga o problema de seleção de materiais, quando aplicado a materiais compósitos, quando as preocupações ambientais são introduzidas como um conceito-chave na seleção de materiais.

Para o efeito, esta dissertação investiga primeiro os temas de impactos ambientais e sustentabilidade, e em seguida investiga um caso de estudo de seleção de materiais "normativa" com base apenas no desempenho mecânico/ métricas de custo. A dissertação discute também os problemas inerentes à seleção de materiais, especialmente quando se consideram novos materiais compósitos, e como eles podem ser introduzidos no mercado .

Finalmente, foi desenvolvida uma ferramenta para auxiliar no problema de seleção de materiais, quando confrontado com vários materiais compósitos, e as preocupações ambientais que hoje em dia permeiam todas as camadas da sociedade.

Esta ferramenta é do interesse de várias partes interessadas, desde fabricantes de fibra e resina, passando pelas empresas de Pesquisa e Desenvolvimento e para os engenheiros responsáveis pelo desenvolvimento de novos produtos, analisando simultaneamente as métricas de desempenho, custo económico e custo ambiental de todos os materiais que possam estar presentes numa base de dados, a fim de selecionar os "melhores" materiais para uma peça com uma determinada geometria, suportes e carregamento.

Dedicated to

Graça Maria Rodrigues Simões

I wish you could have seen this Mom.

I did it!

Acknowledgments

It has been a long road to this point, with enough ups, downs, twists and turns to help me grow in every aspect. Now, at the final stretch, as I look back to the road travelled, I would like to acknowledge the people that helped me and supported me along the way.

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To everyone at Mar-Kayaks, for the patience to hear me, teach me, and listen to me, and for accepting me as one of their own during the duration of the internship.

To everyone that shared a laugh or a tear with me all of these years, you are the foundation of my life. I would name you all, but I fear I might be myself and forget some of you. I hope you know who you are and what you mean to me, since every one of you is now a very important part of who I am.

To a very dear friend Marco Leite, who has been there for everything, including hearing me talk with no rhyme or reason, and truly being a good friend as well as an exceptional individual. And a very good advisor to boot.

My father. There were really some bad times along the way but we emerged stronger, better and as close as father and son could ever be.

Last but not least, my girlfriend, Carla Real. For someone who knows me as well as you do, I’m still amazed that you put up with me. Thank you for everything.

On with the show.

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A estrada tem sido longa e cheia de percalços, mas felizmente permitiu-me crescer em todos os aspectos. Agora, na recta final gostaria de agradecer a todos os que me ajudaram ao longo do caminho.

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A todos na empresa Mar-Kayaks, pela paciência pare me ouvirem e ensinarem e pela rapidez com que me fizeram sentir um de vós.

A todos os que riram, pensaram e choraram comigo todos estes anos, vocês são a rocha na qual me elevo. É apenas pelo medo de me esquecer de alguém que não vos nomeio a todos. Espero que saibam quem são e o que sinto por vós, dado que cada um é uma parte grande de quem eu sou.

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Ao meu Pai. Passámos pelas trevas e voltámos mais fortes e mais perto um do outro. Continência.

E obviamente, à Carla Real. Conhecendo-me como me conheces há tanto tempo acho extraordinário ainda me aturares. Obrigado por tudo.

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List of abbreviations

Abbreviation	Meaning
AHP	Analytical Hierarchical Process
ASTM	American Society for Testing and Materials
BMC	Bulk Molding Compounds
BVID	Barely Visible Impact Damage
CNC	Computer Numerical Control
DfE	Design for Environment
DfX	Design for X
ELECTRE	ELimination and Choice Expressing REality
EOL	End of Life
FEA	Finite Element Analysis
GDP	Gross Domestic Product
GFRP	Glass Fiber Reinforced Plastic
HLU	Wet/Hand Lay-up
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCE	Design for Life Cycle/Life Cycle Engineering
MCDM	Multi Criteria Decision Making
MDF	Medium Density Fiberboard
MEW	Multiplicative Exponential Weighting
MIT	Massachusetts Institute of Technology
MODM	Multiple Objective Decision Making
PROMETHEE	Preference Ranking Organization METHod for Enrichment of Evaluations
PVC	Polyvinyl chloride
R&D	Research and Development
RTM	Resin Transfer Molding
SAW	Simple Additive Weighting
SMC	Sheet molding compound

SWOT	Strength, Weaknesses, Opportunities and Threats
TIFF	Tagged Image File Format
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
UP	Unsaturated Polyester
VARTM	Vacuum Assisted Resin Transfer Molding
VIKOR	Multicriteria Optimization and Compromise Solution
WCED	World Commission on Environment and Development
WPM	Weighted Product Method

1. Introduction

As the concerns for our common future continue to increase, sustainability and sustainable development is fast becoming the main driving force, with a few exceptions, of our innovation, in order to maintain a balance between our resource consumption and the ability of nature to replenish said resources, or as defined in "Our common Future" sustainable development is "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" [1].

1.1. From Malthus to Sustainable Development

This issue was first brought to attention by Thomas Malthus in his book "An Essay on the Principle of Population" [2] where he posited that the potential for growth of the human population is vastly superior to nature's ability to sustain it, with the inevitable outcome of strife to all involved. In it, laid the foundations of Malthusianism where the geometric growth of a population would at some point overtake the linear growth of the resources. This idea has been expanded beyond Malthus original scope but retains the same impact. The growth of population, coupled with the basic tenets of the economic model used since the industrial revolution (one of continuous economic growth, by a continuous increase in consumption of goods and services), leads to a geometric growth on the need of resources, which at some point will (or have depending on the point of view) overtake earths ability to supply them (Figure 1). This model can also be applied to other effects of the population growth.

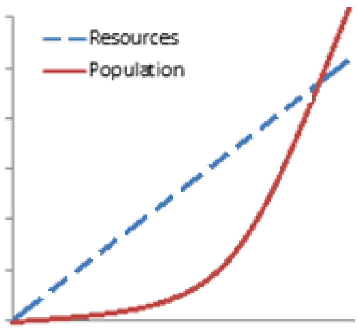


Figure 1 – Malthus Problem. The geometric progression of the population eventually overcomes the linear progressions of Resources [2]

Although the concept of Malthusian catastrophe would be highly and continuously debated, specifically the fact that Malthus developed the concept to rally against, what were at the time, novel ways to improve the life condition of the high percentage of poor people that suffered the brunt of what would become the industrial revolution.

Other topics of discussion of Malthusianism were mainly on the problems that Humanity would face and how to avoid them, with little time spent in the environmental implications of the concept. Environmental issues remained largely under the radar for the next 150 years resurfacing with the Club of Rome, and its publishing of the book "*The limits of growth*" (LtG) [3].

This book, commissioned by the Club of Rome to the Massachusetts Institute of Technology (MIT), analyzed the evolution of the world through a computer model (World 3) which analyzed the interplay of five systems comprising a total of 8 variables. Several scenarios were run to determine the evolution of the simulation (Figure 2).

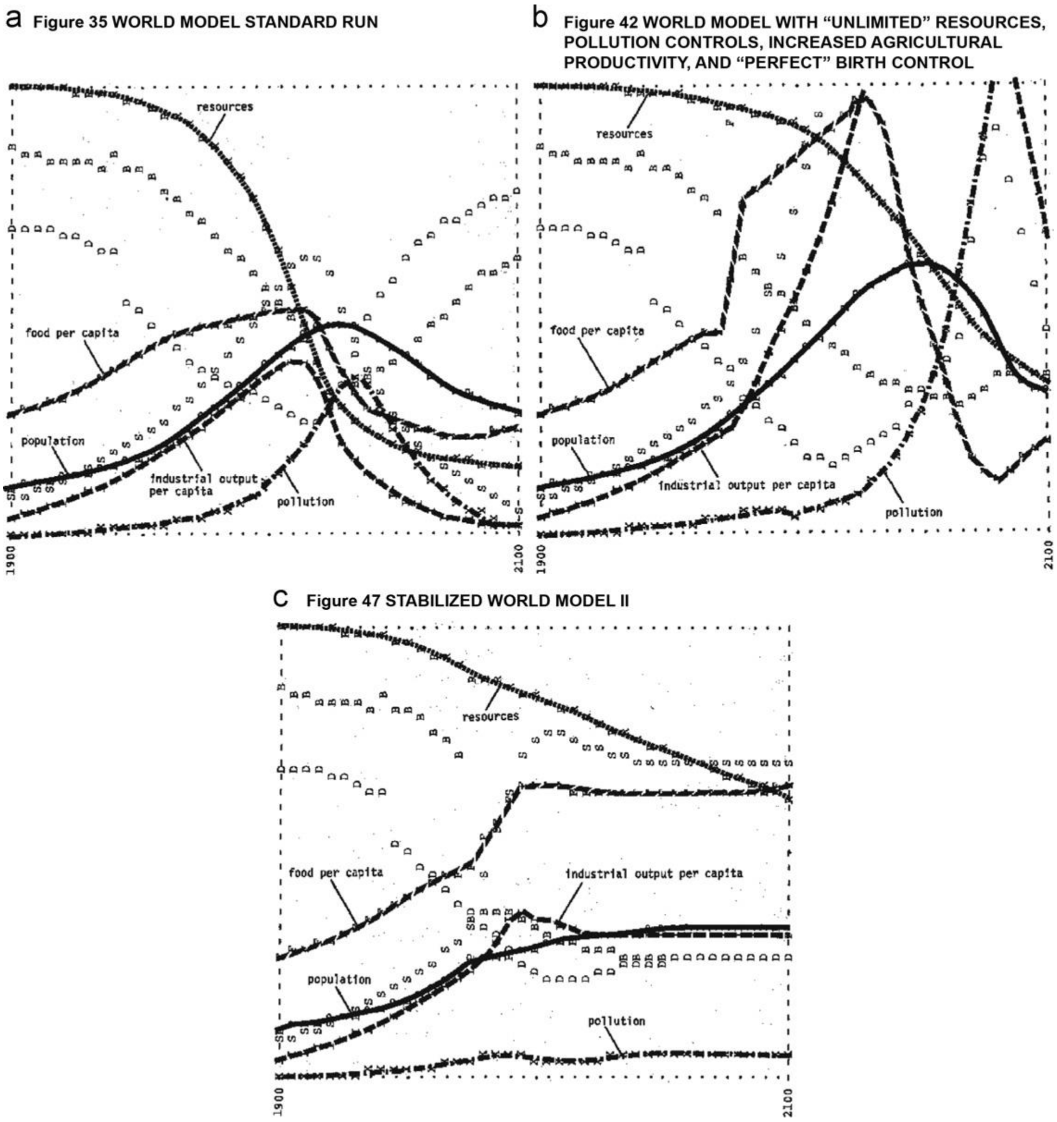


Figure 2 - Output from the modeling for three scenarios ((a) standard run, (b) comprehensive technology, and (c) stabilized world) that are considered the extreme limits and midpoints of the model explored in the LtG. [4]

The results were dramatic, in the standard run, with the World3 model running with what was considered the continuation of the relationships between economic and social relationships consistent with the period between 1900 and 1970, the model predicted a full collapse of the economy in the middle of the 21st century, due to resource depletion, pollution, and population growth. The two other scenarios also present interesting hypothesis. The comprehensive technology scenario posits that there is little to no limit to the yield of resources, and that technology continues to advance at a rapid pace. Unfortunately the skyrocketing of product manufacture and consumption increases the levels of pollution to a unsustainable level with a concurrent crash similar to the "normal" scenario, but of higher impact. The final scenario of a stabilized model posits that by controlling birth rates, rationing the resources and develop a better use of the resources available would produce a stable environment towards the future. Once again this approach was hotly contested, since it seemed that the book was making a case for population control.

It was in the wake of this book that the United Nations established the World Commission on Environment and Development (WCED), that headed by the former Norwegian Prime Minister Gro Harlem Brundtland, commissioned a study to examine what could be the critical issues of environment and development, what could be done to raise awareness of these issues from the individual to the nations, and to determine how to best engage nations in a common understanding and cooperation regarding environmental issues.

The results of the study were published in the landmark book "*Our Common Future*" [1], often termed the Brundtland Report where the term sustainable development was first coined. The report recognized, among other things, that there are environmental limits to economic growth, lest humanity overshoot the capabilities of the resources to recover.

Although all of the discussed documents above introduced the notion that human progress is inextricably linked to the planet Earth, through an interconnecting system where one change in one node multiplies across the whole systems, they are not without its detractors.

Whether we are moving into a Malthusian catastrophe or not there is sufficient evidence that human activity has an impact on the environment. So how can the human impact,

on the environment be reduced, in particular regarding design issues? And if it can be reduced what would be the economic impact of such reduction?

1.2. Eco Impacts

With the concerns born from the publication of the limits to growth, several methodologies have been developed, or adapted, to address the impact of products from the design stage to the end of life, in the economic and environmental spaces, foremost among them Life Cycle Assessment (LCA) and Life cycle Cost (LCC), Eco Design, Design for Environment (DfE) and Design for Life Cycle/Life Cycle Engineering (LCE). Most of these have in common the "no free lunch" mindset, *i.e.*, that there is no way to: a) reduce the impacts to zero, and b) that such reductions do not impact other product considerations.

They can be separated into "big scope" Methodologies, such as LCE and Eco Design, and "Application" Methodologies like LCA and LCC.

Design For Environment is a Design for X (DfX) strategy, being a general term for any Design Methodology that focuses in a small number of vital elements in a product in order to best use the available resources towards the elements selected [5]. In this case Design for Environment seeks to minimize the environmental impact of new products. The main drawback is that DfE, as with all DfX strategies, focuses too much on the on what the Design is for, somewhat disregarding the impact of other elements, which may prove a limiting factor for a new product.

Eco Design is a refinement on DfE, with less focus on the "perfect" environmental product, and more focus on how can the process, materials and end of life, be made more environmental friendly, with some concerns on how to also make it a market product [6-8].

Design for Life Cycle/Life Cycle Engineering (LCE) is a broader approach than most DfX methodologies by focusing on a "cradle-to-grave" approach which takes into account the technical performance and the economic and environmental performance through the lifetime of a product [9] with the main keywords shown in Figure 3. Jeswiet [10] defined LCE as:

"*Engineering activities which include: the application of technological and scientific principles to the design and manufacture of products, with the goal of protecting the environment and conserving resources, while encouraging economic progress, keeping in mind the need for sustainability, and at the same time optimizing the product life cycle and minimizing pollution and waste.*"

Figure 3 – Keywords of Life Cycle Engineering [9]

Of importance to LCE is Life Cycle Assessment (LCA). LCA is often considered a "cradle to grave" approach to the evaluation of environmental impacts, by analyzing a product environmental performance from the raw material extraction and refinement, to its end of Life (EOL) disposal and recycling.

Although some scholars tend to speak of Eco Design, LCE and DfE as the same methodologies with different names, there are in fact, differences among them. In some ways LCE is Eco Design plus several components such as LCA, Product manufacturing and whether or not it includes the service industry [6]. The boundary between Design for Environment and Eco Design is less understood and even the same authors have referred to them as different methodologies [6] and as the same methodology with different names [11].

All of the approaches mentioned above also understand the principle that most impacts are defined in the early stages of a new product design [12], which means that the most effective means of improving a product (be it in regards to technical, cost and environment performance, among others), has to involve the design stage, before it is set in stone, and that any attempts to correct/improve a product after the design stage will have a less significant impact. As important, methodologies like LCE also recognize that a product not only has to be environmentally friendly, but also has to comply with the technical requirements and economic cost, for the product to have any significant impact, *i.e.*, no matter how "green" a product is, it will never be successful unless it sells.

Coupled with the possible resource scarcity as described by *The Limits To Growth* something must be done to attempt to solve both these issues, *i.e.*, if something must be done to reduce the environmental impact of human activity on the planet why not couple it with an attempt to minimize the resource scarcity that might hinder human production?

1.3. The material issue

To answer the question, several solutions are available. Always keeping in mind the environmental impact of these solutions, materials could be improved, so that less material could perform the same task, new materials could be created, that would perform equal or better than current materials, or materials could be imported from other fields, thereby reducing pressure on the resources, by simultaneously reducing the need for a certain material, and increasing the need for another material not currently at full capacity, from the resources point of view. In other words, one solution would be the substitution of established materials by "high performance" versions of such materials, such as the new high strength steels in the automotive industry that would allow for a much lighter chassis while at the same time improving structural rigidity, with the lighter weight corresponding to a smaller environmental impact during the use phase.

A second Solution would be to utilize new materials that perform the same function as the incumbent material, albeit with lighter weight and/or smaller cost and/or smaller environmental impact during production, with aluminum and composite materials being a good example of this case. Finally a third solution would be to adopt materials already

in use in other industries or clusters for the same function, an example of this being the use of corn based Ethanol in substitution of gasoline. This material adoption sometimes have unintended side effects that must be carefully monitored and accounted for. Again the Corn based Ethanol is a great example of this since it had the unintended consequence of diminishing the Corn stockpiles reserved for food production, ultimately rising the price of flour and causing a noticeable social impact contrary to the sustainable development ethos.

One thing that these solutions have in common is the fact that, in one form or another, the material space increases, which increases the number of options available. The problem then becomes how to choose the best material for an application, when taking into account multiple attributes, and, if it is a new material in the market, how to surface this material, *i.e.*, what steps must a new material take to be noticed amongst other materials.

With the current rate of development of new materials, it has become harder and harder for a designer/engineer to properly evaluate and select the best material for any given application, and at the same time for the engineers developing these new materials to give them exposition. By 2007 there were estimated to be over 100000 materials to choose from [13], which is an enormous number of materials to search which in turn make choosing a material for a new product an expensive and time consuming task [14]. In order to alleviate the load engineers and designers face, new tools have been developed [14-16], that allow an engineer to select the best materials in a relative short amount of time. Most of these tools fall within the Multi Criteria Decision Making methods (MCDM), which can be defined as a method that evaluates multiple conflicting criteria in order to reach a decision [17].

Given the number of existing materials, it then becomes a struggle for a new material to be introduced to markets, since, even if completely characterized, the materials are somewhat of an unknown quantity, a trait most undesirable for the anecdotally risk averse Engineers. The problem is compounded if the material is not completely characterized, which would require mechanical testing to fully evaluate the mechanical performance of the material, something that most companies do not have the resources to perform.

Additionally there is still the composite material problem. As suitable, possibly ideal, substitute to metals and alloys such as steels and aluminum, which besides being some of the most used resources on the planet, its extraction and transformation have a high environmental impact, composites are in the forefront of Research and Development, especially in the aeronautical, aerospace and automobile industries. Unfortunately, the high number of fibers and matrixes available in the market, not to mention the almost limitless number of stacking sequences, make choosing a composite material that best suits the products' needs a burdensome decision during the design stage with many interactions necessary to determine the best stacking sequence/fiber/matrix combination, compounded by the fact that in most examples there is no best unique solution, since the problem is multicriteria. If we combine this issue with the apocryphal risk-averse engineer that generally desires "familiar" materials or small iterations on known materials, new composite materials (especially with fibers not part of the trinity of Glass fibers, Carbon Fibers or Aramid/Kevlar Fibers) have difficulties in entering the market.

1.4. Hypothesis

The environmental risk to humanity continued well-being has at last been identified and understood and has become a powerful motive force behind innovation and the development of new techniques and materials. The problem is that there are more constraints to a product other than "is it green?" The product with the best environmental performance is not immediately the best product, since it also has to satisfy requirements of cost (for it to sell and be adopted by the largest population possible, in the industry and market both), and technical performance (in order to perform its function). Thus a tool that determines the *trade-offs* between metrics is necessary to explore the design space in order to determine the "best solutions" to a particular product. The problem with this approach is that for highly combinatorial materials such as composites, the amount of possible composites obtainable from a relatively small number of variables, such as fiber percentage, number of layers, ply stacking sequence, production method and obviously fiber and matrix materials, make an analysis of such possibilities cumbersome at best. Finally we have the new material problem.

With so many materials entering an already very crowded market, it is difficult for a new material to gain a foothold on the product engineer handbook as a suitable material,

unless it is an exceptional material. In short, the working hypothesis of this document is as follows:

"It is possible to determine in the design phase the best solutions for a composite material application, taking into account economic, environmental and technical performance, from a large selection of materials, in a timely manner".

1.5. Research questions

With this hypothesis in mind, and with all that has been said so far these are the main questions that drive this document:

- **How can we couple the possible resource scarcity with environmental concerns?**

Although there is still some dissent on the issue, resource scarcity is fast becoming one of the main issues of this day. The concept of overconsumption of Earth's Natural Resources has given rise to the term Ecological Overshoot Day, which basically means the day in a given year that Humanity exhausts the Earths resource capacity for that year. As Table 1 shows, Earth has been running over budget at least since 1987, and it has been drawn deeper to the red line every year, so steps must be taken to address this issue.

Table 1 – Earth Overshoot Day [18]

Year	Overshoot Date
1987	December 19
1990	December 7
1995	November 21
2000	November 1
2005	October 20
2007	October 26
2008	September 23
2009	September 25
2010	August 21
2011	September 27
2012	August 22
2013	August 20

Earth Overshoot Day is also about the day where, theoretically, Earth has reached full capacity to absorb the damage being done to it by human activity. In this case the outcast can be considered slightly more positive since environmental concerns are of paramount importance these days, with all stakeholders (companies, the countries and the general public) realizing that Human activity is taking its toll on the environment. As such the drive to improve the Ecological footprint of businesses and services has been growing.

Whether or not the resource scarcity will happen should not be the question, but instead the question should be how can the resource needs of Humanity be lessened, *i.e.*, whether or not Earth is being run to the ground, the fact is that resource consumption need to be curbed, if not for the fact that the growing rate of consumption is damaging the environment. This is the basis for the first research question. Some solutions have been presented above in the introduction but even those solutions have their set of problems which leads us to the next Research Question.

- **How can a new material be introduced in the market, specifically composite materials?**
    - How to surface the material?

In each of the solutions presented in the introduction, the main issue they all share is that when new material surfaces, either by iteration, discovery or transplant, the fact is that, in one form or another, the material space increases, which increases the number of options available. The problem then becomes how to choose the "best" material for an application, when taking into account multiple attributes, and, if it is a new material in the market, how to surface this material, *i.e.*, what steps must a new material take to be noticed amongst other materials, since with so many materials entering an already very crowded market, it is difficult for a new material to gain a foothold on the product engineer handbook as a suitable material, unless it is an exceptional material.

- **What is a good method to choose from an enormous material database?**

With an ever increasing material space, choosing the "best" material for an application is a daunting task. Apocryphal data states that Engineers, being quite risk-averse, tend

to prefer known solutions or small iterations on known solutions. This creates a problem since, better materials for an application may exist outside an Engineers "Safe Zone", but with so many materials to choose from, what methods can/should be used to select better materials?

1.6. Document and Structure

The ultimate goal of the thesis was to answer the research questions posed and develop a tool that could perform the analysis presented in the study. Included is a simple case of one to one material substitution in order to understand what material properties are required, and what tests to perform based on a real life study of the substitution of Divinycell for Corecork in a Kayak produced by Mar Kayaks. With the understanding gathered from this first test case a bibliographical review on the subjects of Sustainability, Environmental impacts, and Multi Criteria Decision Making methods, was performed to ascertain where the avenues of investigation were. To determine how a new material could be introduced, Basalt fibers for composite applications were studied, and are presented as a counterpart to the theoretical study.

Finally, the tool itself was developed. Based on the MATLAB programming language, with an interface with the ABAQUS Finite Element Analysis (FEA) program, the tool considers multiple pairs of fiber/matrix composites, and by determining what problem is to be studied (what part, what dimensions and what loads the part carries), the tool calculates the best possible ply-stacking sequence (number of plies and orientation) for the given part and composite, ensuring that the mechanical performance of all composite candidates is fulfilled. Afterwards the tool collects the stacking sequence for each pair, and considering two production methods that use the same base material (Resin Transfer Molding (RTM) and Wet/Hand Lay-up (HLU)), determines the Economic performance, the Environmental performance and the Technical Performance (weight in the general case, since the mechanical performance is guaranteed in the FEA analysis), and determines the "best" candidates after a pareto optimal analysis.

The structure is as follows:

Chapter 1 is the introduction, where the main issues regarding this work are presented, the Hypothesis given form, and the Research Questions are posed.

Chapter 2 is the Bibliographical Review where the themes of Sustainability, Environmental Assessment, and Multi Criteria Decision Making methods are reviewed to understand what work has been done and what are the main drivers of each field.

Chapter 3 presents a test case of material substitution, developed during the Mar-Kayaks internship as a demonstrator of what is needed and the amount of testing required for a direct material to material substitution based on technical performance.

Chapter 4 deals with the results of Chapter 3, expanding on the remarks and conclusions presented in order to demonstrate the need for a more encompassing study of materials and presents and develops the general makeup of a framework intended to study composite material selection for any given part, taking into account more than just the mechanical properties.

Chapter 5 describes the tool and its development, from background explanation of the tool structure and the analysis that determined the tool structure.

Chapter 6 presents the test cases used to validate the tool, including relevant results.

Chapter 7 is the Conclusions of this work and Future Work recommendations.

2. Bibliographical Review

2.1. Introduction

In this chapter the Bibliographical Review on subjects such as Sustainable Development, Environmental Assessment, and Multi Criteria Decision Methods (MCDM) is performed, with further bibliographical studies being addressed in other chapters.

2.2. Sustainable Development

To understand how to best go on with Sustainable Development the story must start at the beginning, with Malthusianism, and then with "*The Limits to Growth*" [3] and "*Our Common Future*" [1].

Malthusianism has drawn criticism from several areas since its inception, since some extreme interpretations of "*An essay on the principles of population*" [2] are, for instance that the exponential growth of humanity is due to a "overabundance of charity" towards the working class, *i.e.*, that by helping those of less means not dying because of poverty would lead to a population explosion, a not completely incorrect statement given the contents of the first edition [19].

Seidl et al. [20], consider Malthus position to be Political and Normative, since it is difficult to establish and/or project a carrying capacity for Malthus Essay and as such the scientific background is somewhat lacking. Markert [21] states that the Malthusian Trap predicted has not happened yet *and will never happen*, since he argues that Malthusianism is fundamentally flawed, since Malthus only considers changes to one parameter without considering the entire system, *i.e.*, that although the population does indeed increase, so do the methods of production increase the output.

This logic taken to the edge that "technology/innovation/ingenuity solves everything" became the basis of what is called Cornucopianism, which essentially posits that "technology saves".

Malthus revised the essay multiple times, but the idea of the Malthusian trap even if not directed to the working class never left the essay. Proponents such as Elwell [22] defends that the Malthusian trap is merely an observation of a natural phenomenon, *i.e.*, if left unchecked the possibilities of reproduction will always outstrip the possibilities of

gathering sufficient resources to maintain the offspring. Birth control, loss of quality of life associated with multiple children, purely from an economic mindset, or other far reaching checks such as wars, or severe famine, act as negative checks on growth, while positive checks are generally considered as increased crop yields, among others.

There are no greater contributes to sustainability practices that the two publications that started the trend. The impact of "*The limits to Growth*" [3] and "*Our Common Future*" [1] on the way the population sees and understands the impacts of human activity on the planet and its possible consequences on it was tremendous and led to a rethinking of the way human activity must develop.

These publications arguably spurred fields of study such as Life Cycle Engineering (LCE) and Life Cycle Assessment (LCA), with The Limits to Growth introducing system dynamics and quantitative scenario analysis in the environmental disciplines and the concept of overshoot and collapse [23]. The basis for the publishing was the design of a computer model dubbed World3. that examined the interactions of five major subsystems, for a total of eight variables [4]. As mentioned in the introduction the results were staggering, predicting a world collapse in the near to mid future.

Almost at once the results were subjected to intense scrutiny and poor reception [24], and according to Constanza even misinformation [25], stating that the prophecies of doom have not come to pass, although the most recent data compares favorably to the initial model assumptions [4]. Some critics have pointed out that some assumptions, such as diminished arable land and population growth have not been proven to cause problems [19].

The methodology has been thoroughly dissected, with some authors decrying it [26], since the model assumes that resources are ultimately limited, that the model simplifies connections between its subsystems and that the authors do not present estimates of the statistical uncertainty of the variables, although the 30 year comparison [4] and the 40 year comparison [27], using new data and compared to the original model shows that the world is still on track for an eventual collapse.

The idea that technology solves everything, the founding principle of "Cornucopians", as the alternative to "Neo-Malthusians", is not supported by the fact that some, if not most, of the dwindling resources are not technologically replaceable [28].

Finally and on a personal note, even if technology does solve everything, or if the resources are indeed limitless, why not still work to diminish the impact of human activity on the planet? To put it in admittedly simplistic terms, if “Neo-Malthusians” are wrong, all that humanity will have wasted is money and gained new technology. But if the Cornucopians are wrong, all will be lost.

For all of the discussion surrounding “*The Limits to Growth*” perhaps its long lasting victory is the fact that it spurred the United Nations to investigate the matter, and ultimately publishing “*Our Common Future*”, where the concept of Sustainable Development was first mentioned.

The WCED defines Sustainable Development in “*Our Common Future*” as:

“…development that meets the needs of the present without compromising the ability of future generations to meet their own needs.”

In other words, Sustainable Development is development that focuses not only in the short term benefits but must also take into account the long term benefits/costs of such development. It has now become one of the most important fields of study since it has been acknowledged that one must take care of the future if one is to live in it, with companies, academia and states, actively engaging in conversation and developing multiple areas with a sustainable development focus, with the express purpose of diminishing the effect of today’s decisions tomorrow, with a high focus on Environmental concerns [29].

Sustainable Development is widely used in a variety of fields such as urban planning and development, with Liu [30] analyzing the various concepts being used in China regarding the urban planning of its enormous cities and Deakin [31] studying urban development using environmental assessment methods, energy policy with Gaygalis [32] studying the development of a new energy policy in Lithuania in the wake of the country’s entrance in the EU, supply chain management (SCM) with Searing [33] devising a conceptual framework for a sustainable SCM and Shen *et al* [34] discuss the adoption of a green SCM to diminish the environmental impact of the mining industry and as demonstration of the wide range of uses of sustainable development it has also been used in helping determining management plans for savannah ecosystems [35].

Other authors such as Milutinović [36] research education from a sustainability perspective, in order to bring Higher Education to the masses. In the 4th UNESCO Chair Conference on Higher Education for Sustainable Development (HESD) [37], three round tables discussed the role of Universities, and its users in espousing Sustainable Development views in the Universities, with Adomßent *et al* [38], considering that Higher Education for Sustainable Development must be considered a new field of study.

Sustainable Development impact on day to day operations is now so large that some faculties are interested in introducing curricula targeting Sustainable Development [39], with some authors such as Dimitrova [40] discussing the need for more Sustainable Development curricula based on her experiences in a program in urbanism in Sofia, Hungary. Even concepts such as the Human Sustainable Development Index (HSDI) [41], which aims to amend the Human Development Index (HDI) used by the United Nations as a gauge for the development of Countries. The goal of HSDI is to add an environmental data to the data already present in the HDI, namely life expectancy at birth, education, and income. The pervasiveness of Sustainable Development thinking can be also measured by the fact that nowadays Sustainable Development indicators are used to gauge a country [42] on a global scale. One such gauge, the Environmental Performance Index developed by Yale University measures 25 indicators into a Composite Index (more information at epi.yale.edu). Figure 4 shows the Performance index versus the per capita Gross Domestic Product (GDP) of countries.

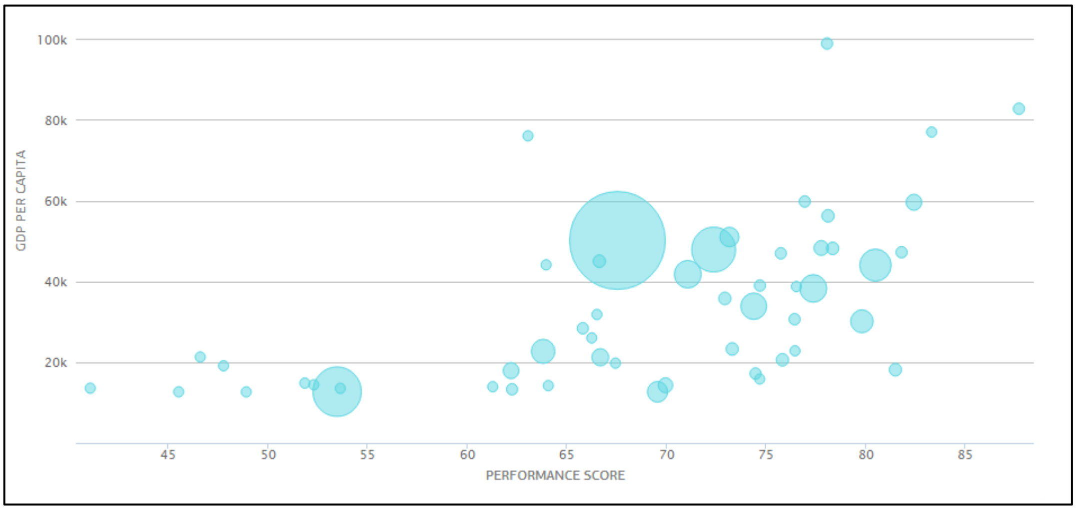


Figure 4 – Environmental Performance Index vs GDP per capita [43]

Several frameworks have been proposed to quantify sustainability, for instance Mansoor *et al* [44] developed a guidance framework for energy engineers to help guide them towards sustainable solutions. A good summation of various Sustainability frameworks can be found in Kharrazi *et al* [45].

All in all it can finally be said that "*Sustainability is increasingly used to describe a paradigm for shaping the social and economic future of mankind*." [45].

2.3. Eco Design, Life Cycle Engineering/Assessment

With the Sustainable Development model going forward, methodologies have been created and studied that allow environmental concerns to enter not only day to day talks among citizens, but to also become an important word in companies, able to be discussed, measured and used as indicators that shape new products and services.

As a new approach Life Cycle Methodologies (LCM) appeared in the mid 60's with Life Cycle Cost (LCC) [46] and Life Cycle Assessment (LCA) [47], but although LCC was accepted and introduced almost after its conception, LCA lingered in obscurity for the better part of 30 years.

Only in the 1990's, with the first overt signs of man-made environmental issues and with the rediscovery of concepts such as sustainable development, was LCA merits begun to be studied in earnest. Coupled with companies facing public pressure regarding environmental concerns, LCA finally began to enter the design phase of new products [48].

It is considered as a Methodology designed for the analysis of a product or process environmental performance from the raw material extraction and refinement, from the transportation to a manufacturing plant and the processing of the material into a product and the product use phase and its end of Life (EOL) disposal and recycling [6]. Hence, LCA is often considered a "cradle to grave" approach to the evaluation of environmental impacts [49].

Codified by ISO 14000 series of standards LCA has 4 steps (Figure 5):

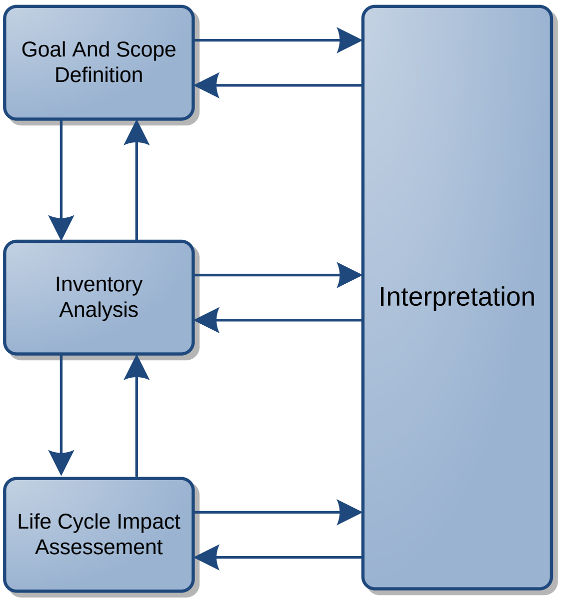


Figure 5 – LCA Framework according to ISO 14040 [49]

- Goal and Scope definition – In this stage, the system boundaries are defined, the functional units are declared, and the procedure is determined. Given that this step guides the subsequent steps, it is considered the most important step in LCA [47].
- Life Cycle Inventory (LCI) – This stage regards the collection and analysis of relevant input and outputs of the system, *i.e.*, information on the material and energy flows to and from the system boundaries in all the stages of the product life cycle. This stage can be separated into specifications of the process and data and the construction of inventory tables. The construction on the inventory processes is the most time consuming operation of a LCA, since it implies a huge effort in data collection and cross referencing, although the number and quality of databases has increased in the last decades in order to streamline the process of data collecting.
- Life Cycle Impact Assessment (LCIA) – This stage deals with the environmental impacts of the flow of material and energy defined in LCI. These flows are assigned to different impact categories, such as climate change, human toxicity, ecotoxicity, resource depletion etc., and then converted into indicators using an impact assessment model. LCIA can be separated into two main components, Classification, where the inputs and outputs defined in LCA are divided into the categories mentioned, and Characterization where each of the flows are multiplied by a factor assigned to the impact category on where the

inputs/outputs are placed, *i.e.*, each input/output is weighted according to the category assigned to them so that all of the results can be aggregated into a score reflecting the potential impact of each input/output. There are a good number of indicators for the impact assessment divided into two broad categories, with some methods demonstrating the environmental effect in one index, and others in multiple indexes [50].

- Interpretation – In this final stage the results from LCI and LCIA are interpreted and compared with the goal and scope in order to reach conclusions and recommendations regarding a product/process, etc.

With this codification LCA is now a commonly used tool to quantify inputs, outputs and associated environmental impacts of a system, although it cannot be considered a method of environmental accounting since it lacks information on costs.

Although the first applications of LCA were in large potential causes of environmental damage (mills, heavy and chemical industry power plants, etc.), with the dissemination of LCA in the 90's and beyond LCA is nowadays also used in the service industry, transport and housing, and it is a fundamental tool of Eco Design and Life Cycle Engineering, although LCA has a big drawback due to the fact that, by being used in the concept stage of a new product all of the work of a LCA must be done for each alternative and revision, a considerable, and somewhat expensive workload [51].

Another consequence of the increasing environmental concerns from the past two decades is the shift in companies from simple technical and/or economical performances to a more holistic view of the whole process/product. This shift must not focus entirely on making only good environmental products (since as mentioned in the introduction DfX strategies often give unduly importance to only one characteristic, neglecting the product as a whole, which can imperil the products viability), but on making environmental concerns part (even if a big part) of the design stage. Such is the principle of Life Cycle Engineering (LCE), which evaluates and considers not only the environmental dimension , but also cost and performance issues [52], comprising Life Cycle Cost, Life Cycle Assessment and Life Cycle Management, and is defined as "*Engineering activities which include: the application of technological and scientific principles to the design and manufacture of products, with the goal of protecting the*

environment and conserving resources, while encouraging economic progress, keeping in mind the need for sustainability, and at the same time optimizing the product life cycle and minimizing pollution and waste" [10]. It is nowadays a quite active field of study [53-60].

2.4. Multi Criteria Decision Methods (MCDM)

With the advancement in technology and manufacturing processes, coupled with improvements in materials, means that process design and development is no longer a search for the cheapest solution for the required features. Nowadays a new project is faced with a multitude of alternatives for a given problem, and there is no single criterion of selection. A new project has to take into account a large number of criteria, technological, social, environmental, ethical, political and economic, most of them with conflicting goals. In order to analyze the multiple conflicting criteria, new tools and methodologies have been developed, in order to help the designer select the best candidate, among a multitude of possible solutions and multiple conflicting criteria. This sub-discipline of operations research is called Multiple Criteria Decision Methods (MCDM), which can be defined as methods that evaluates multiple conflicting criteria in order to reach a decision, and can be divided into two types of decision making continuous or discrete: Multiple Objective Decision Making (MODM), where a number of functions are optimized regarding its constraints, and the solution that best fit all of the disparate objectives is sought ,*i.e.*, the solution to the method is one that cannot be replaced by another without loss of performance in another objective across a large number of objectives, and Multiple Attribute Decision Making (MADM), where a small number of alternatives are compared given a number of attributes. The best solution is then, the alternative that compares best in every attribute against all other alternatives.

Figure 6 shows the usual Multi Criteria Decision process flowchart;

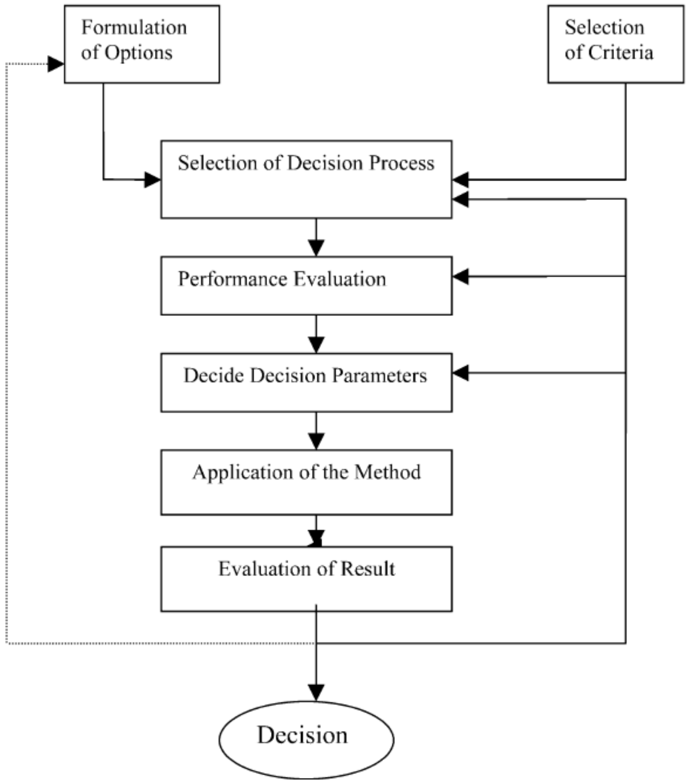


Figure 6 – Multi criteria decision process [61]

MCDM has been extensively studied, from its mathematical foundation [62, 63], to the methods themselves with the most studied Method being the Analytical Hierarchical Process (AHP) [34, 64-69] There are quite a few other decision methods, such as Simple Additive Weighting (SAW), Weighted Product Method (WPM), TOPSIS, VIKOR, ELECTRE among others. Pohekar [61], Venkata Rao [70] , Ananda [71] and Stewart [72] have a good description of some of these methods, including some use examples.

Some authors are also combining various MCDM methods, such as Anojkumar *et al.* [15], which used a variation of AHP to determine the weights of evaluation criteria, and used them as inputs for four decision making methods, TOPSIS, VIKOR, ELECTRE and PROMETHEE, for ranking material alternatives to determine the best pipe material in the sugar industry. Kurttila [68], uses AHP with a Strength, Weaknesses, Opportunities and Threats (SWOT) Analysis, to minimize the weaknesses of SWOT, especially the long term uncertainty related to outcomes of different factors which may complicate comparisons, which helps prioritizing the SWOT factors.

MCDM and MODM have a number of problems with the higher ranked being Rank Reversal. Rank reversal, in the simplest terms is when after applying a MCDM and

obtaining the ranking of the alternatives, the same MCDM is used, but with another, non-ideal alternative, *i.e.*, one that is not the best alternative. In some cases the addition of that non ideal alternative will change the rankings when the MCDM is re-run, with some authors considering that if by adding a non-optimal alternative changes the relative ranking the method used is unacceptable [73]. The problem then is why is adding a middling alternative to the bodies of alternatives causes the MCDM to change the top ranking alternative. Finally the fact that different MCDM return different results, even when using the same or comparable weighting of the objectives is also a problem.

One of the papers that studied both these problems was authored by Zanakis *et al* [69], in which he studied the amount of rank reversal present in eight MCDM methods (ELECTRE, TOPSIS, Multiplicative Exponential Weighting (MEW), Simple Additive Weighting (SAW) and four types of AHP, and labored to discover the reason for different rankings among the eight different MCDM.

Regarding Rank Reversal, only two methods did not produce any rank reversal and on those methods that produced rank reversal, the causes in order of effect were, number of alternatives, number of criteria and distribution of criteria weights. The reason that the number of alternatives caused more rank reversals may be due to the fact that with more and more non-optimal alternatives to choose from the difference in ranking between successive alternatives becomes smaller and smaller facilitating rank reversal. The fact that much of the MCDM suffer from Rank reversal was also corroborated by Wang *at al.* [74].

Regarding the fact that different methodologies produce different results can be attributed to a number of causes, mainly that the dissimilarity in the way the Methods use weighting can cause problems, especially when the number of alternatives is big, the way that the criteria weighting is distributed have an influence on the solution, and the fact that many algorithms attempt to scale and/or introduce parameters which affect the solution, with the differences between most solutions being of one or two ranks [15, 75].

Finally there exists what Triantaphyllou [76] called the decision making paradox. Simply put in order to determine the best solution given a number of options with a number of criteria we need to use MCDM to reach a decision. The problem is that the adoption of a MCDM is a decision that must be made, and so technically, a MCDM

must be selected to select the best MCDM to select the best material, and thus the paradox is revealed, since this problem can be demonstrated ad infinitum. A couple of methods have been developed to overcome the paradox, some authors [77] have used more than one method to determine the best decision. Other authors, for instance in the Anojkumar *et al.* [15], ranked each solution according to each Decision Method, while using a hybrid methodology, and choose the best solution as the one with the best performance in each method (Table 2), which served to approximate almost all of the decision methods to just one solution, thus avoiding the problem of each Decision Method producing a different result.

Table 2 - Material Ranking according to each methodology [15]. The numbers denote the ranking of the pipe materials according to the corresponding methodology

Result of proposed methodologies				
Materials	TOPSIS	VIKOR	ELECTRE	PROMETHEE
J4	3	3	3	2
JSLAUS	4	4	4	4
202Cu	2	2	2	1
409M	5	5	5	5
304	1	1	1	3

As we can see on Table 2, although three methodologies (TOPSIS, VIKOR and ELECTRE) produce the same ranking order, with material 304 being ranked nº 1 and material 409M ranked in 5th place, the PROMETHEE methodology gives a somewhat different ranking order from the first three.

Given that when using different MCDM may result in different alternatives being selected, care must be taken when using Multi Criteria Decision Methods, although, if a Decision Maker keeps in mind that no MCDM delivers the "perfect solution", MCDM continue to be the best methods to be used when facing multiple conflicting criteria.

3. M.A.R. Kayaks - Internship, production methods and mechanical testing

3.1. Introduction

In order to study how to adopt new materials and how to create environmental friendly products, an internship was accepted by M.A.R. Kayaks® (NELO). Situated in Vila do Conde, Portugal, it is one of the most established companies in the production of competition kayaks worldwide winning 20 of the 36 medals available for competition in the Beijing Olympic Games in 2008, and 26 of the 36 medals available for competition in the London Olympic Games in 2012 [78]. The goal of the internship was initially twofold: to understand the production of composites and sandwich structures, specifically the wet/hand lay-up process, from an industrial point of view, and to test and compare new, less environmentally "damaging materials". The former was used as the basis reference for the cost model regarding the wet/hand lay-up process presented in Chapter 4, and the latter to perform a material substitution problem with composites, regarding mechanical properties in this Chapter.

3.2. The Internship

In order to better understand the process at NELO the first part of the internship was focused on understanding the process of production of a Kayak. Ingrained in the production team, data was collected on all aspects of production from the mold to the finished product. The production process is described in the following section.

3.2.1. Production flow

In their production process NELO uses the wet/hand lay-up (HLU) process with vacuum bagging [79] and oven cure. The number of layers is dependent on the model of kayak being made, the fiber cloths used and on the external painting used (for some models without carbon fiber cloths in the composite (that can be a sandwich structure), there is an option for a clear carbon finish that implies the use of Carbon fiber as the outer layer). The kayaks are produced in two halves, which after the first curing process are then joined and cured a second time.

The general production flow of the company, where the test specimens used in this Chapter were produced, is as follows (Figure 7):

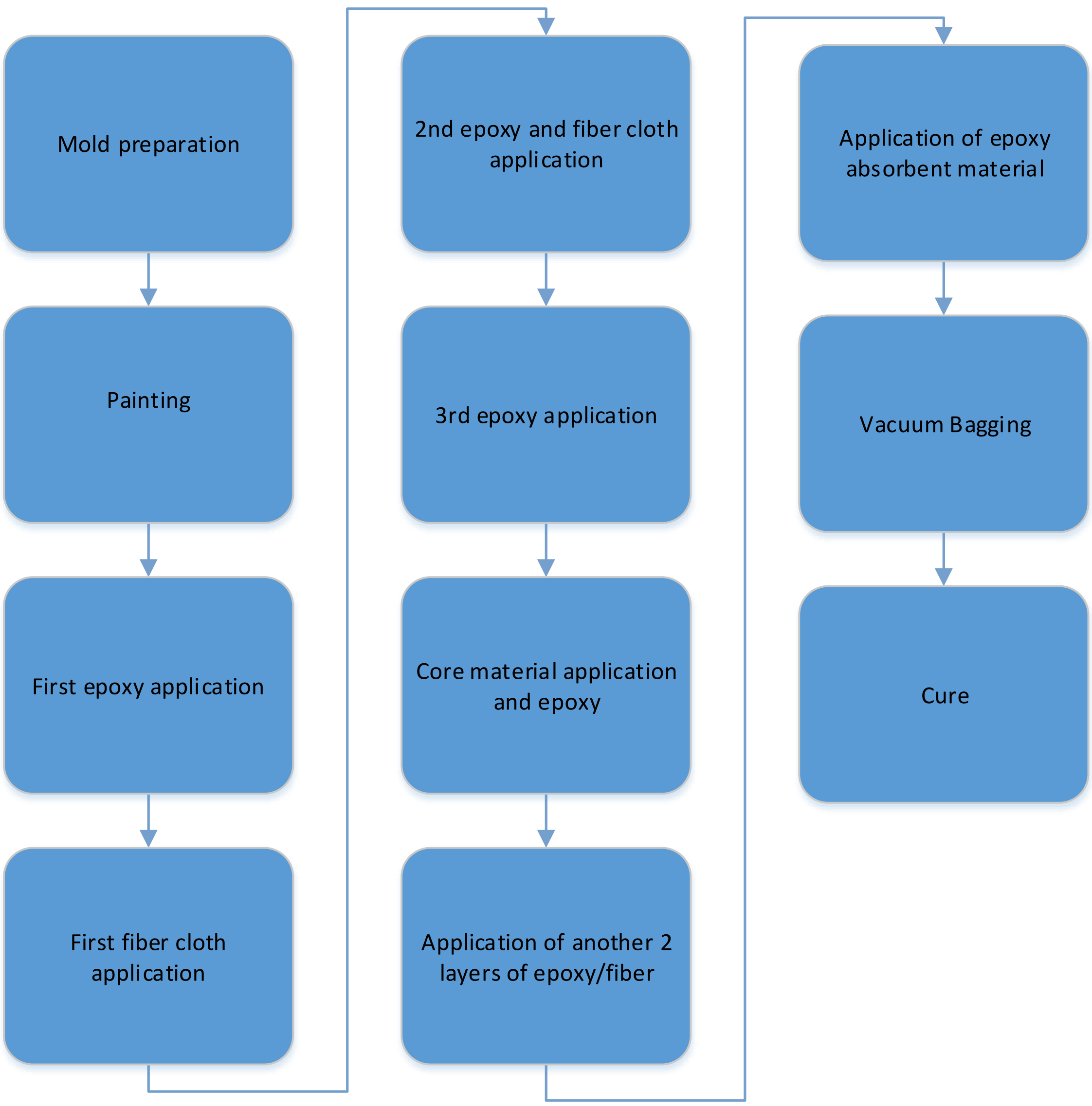


Figure 7 – Kayak Production Flowchart

- **Mold preparation**
  - General cleaning processes and spraying of the mold cavity with a release agent.
- **Painting**

- Given that the mold is actually the outside of the kayak, the production is done outside in, *i.e.*, the first operation is the painting of the kayak mold cavity, using specific gel coating paint.

- **1st epoxy application**
  - In order to insure correct bonding between the gel coat and the first layer, the mold is dabbed with a first application of epoxy in gel state (Figure 8).
- **1st fiber cloth application**
  - The first fiber cloth is applied. In this case the cloth used is an E-Glass fiber cloth plain weave 0º/90º with 240g/m^3 density. The cloth is then pressed against the epoxy already in place using rollers in order to ensure that the fibers are completely "wet" and to remove excess epoxy from underneath the cloth.
- **2nd epoxy and fiber cloth application**
  - The process is repeated with another layer of epoxy and fiber cloth for the second layer.
- **3rd epoxy application**
  - Another epoxy layer is applied in order to ensure bonding between the lower layers and the core material to be used. This layer is generally thicker than previous layers since the core material is generally not permeable to the epoxy and a correct bonding must be ensured.
- **Core material application and epoxy**
  - A core material is then applied, generally DivinyCell H80. Generally this material is not permeable to epoxy, so great care must be taken to ensure correct bonding to the lower layers, since there is no possibility of a visual inspection to determine if there is bonding, *i.e.*, the core material does not get "wet".
- **Application of another 2 layers of epoxy/fiber**
  - Two other layers of epoxy/fiber are applied in order to complete the sandwich. This inner skin is not painted and as so the sandwich is not completely symmetrical since the gel coating mechanical properties have to be taken into account.

- **Application of epoxy absorbent material**
    - Before vacuum bagging the mold, a layer of epoxy absorbent material is applied inside the mold cavity, in order to absorb any excess epoxy resin that could cause layer imperfections and to insure that no epoxy enters the vacuum system.
- **Vacuum Bagging**
    - The mold cavity is then covered and sealed with a plastic sheet designed for wet/hand lay-up, and then the air is removed from the cavity in order to improve its consolidation, since up to one atmosphere of pressure can be applied to the laminate to consolidate it.
- **Cure**
    - After a number of kayaks have been produced and vacuum bagged the mold is then placed in a curing oven for 12 hours at 45ºC.

A similar process is used for the top part of the kayak.

Figure 8 – Fiber cloth being applied (Carbon Fiber in this case)

After the curing process several fitting are installed in the kayak (seat holder, rudder mechanism, foot controls, and skirt holder among others) and the two halves are joined with epoxy. Then the kayak is cured again for another 12 hours at 30º C, and goes to the finishing station where it is polished, small imperfections are corrected and it is conditioned for transport. Further data collected at NELO, such as cycle times, wages, mold production, the materials used during production, the machines used, among many others, are present in Chapter 4.

3.2.2. Competing materials

During the initial discussions at NELO it was determined that the ecological footprint of their products could be diminished by changing materials used in the Kayaks sandwich structure.

Figure 9 – NELO Kayak Model Viper 51 (www.mar-kayaks.com)

Three main components were evaluated for possible substitution, the resins used, the fibers used and the core material used. Some assumptions, set as constraints, were materials that could be readily applied in the process used by NELO and the wall thickness of the kayak structure should remain constant, *i.e.*, the inside dimensions should not change in order for the kayaker to fit inside the kayak and the outer dimensions had to remain constant as to use the same molds. Furthermore, any resin considered had to have approximately the same Gel time as the Epoxy, the mechanical properties of this new sandwich structure should be comparable to the mechanical properties of the sandwich structure used, and the cost should also be comparable.

It was decided to first find a suitable substitute to the core material, since at the time, no natural fiber was found with constant comparable performance, especially given the aquatic environment where the kayaks operate in [80]. The main issue with Bio-resins, apart from the general lower performance when compared to epoxy is the unsuitability of such resins to the wet/hand lay-up process [81].

Regarding core materials, after analyzing several potential candidates, and drawing on prior knowledge of Cork and its composites it was determined that Cork Composites could be a suitable replacement for the foam core used (Divinycell® H80 see Table 3), given the principles proposed by sustainability. Cork composites are produced in Portugal, and an increase in demand could lead to several positive social impacts. They are considered a much "greener" material than Divinycell, specifically for the huge difference in oil based products required for its production compared to Divinycell, and it is much less expensive than the foam core used. The main drawbacks of the Cork

Composites are a higher density and worse mechanical properties, compared with Divinycell. After analyzing the production method at NELO and the different specifications of several cork composites the choice of material fell on CoreCork NL10 (see Table 4) produced by Amorim CorkComposites as the core material, given its similar characteristics, yet higher density, and its suitability to the wet/hand lay-up process used at NELO.

Table 3 – Mechanical Properties of DivinyCell H80

Mechanical Properties of DivinyCell H80			
Property	Method	Unit	Value
Density	ISO 845	kg/m3	80
Compressive Strength	ASTM D 1621	MPa	1.4
Compressive Modulus	ASTM D1621-B-73	MPa	90
Tensile Strength	ASTM D 1623	MPa	2.5
Tensile Modulus	ASTM D 1623	MPa	95
Shear Strength	ASTM C273	MPa	1.15
Shear Modulus	ASTM C273	MPa	27

Table 4 - Mechanical Properties of CoreCork NL10

Mechanical Properties of CoreCork NL10			
Property	Method	Unit	Value
Density	ASTM C271	kg/m3	120
Compressive Strength	ASTM C365	MPa	0.3
Compressive Modulus	ASTM C365	MPa	5.1
Tensile Strength	ASTM C297	MPa	0.6
Shear Strength	ASTM C273	MPa	0.9
Shear Modulus	ASTM C273	MPa	5.9

Figure 10 – Core being applied at the NELO facility

Finally, the main service loading conditions of the sandwich structures would be in bending, with possible impacts and compression loads and as such tests were performed that evaluated the mechanical performance of both composites in impact, pre and post impact bending, and compression.

3.3. Mechanical testing

Mechanical testing is the most important step that a new material must undergo in order to be accepted into the materials databases. The way it behaves under a given load, what type of loads the material supports best, how consistent the material is during the tests, marks the uses that a given material can have. Thus the tests performed are also crucial, and somewhat a challenge since the way the materials are tested is of extreme importance. Badly prepared specimens, uncalibrated machines and test conditions are a few of the problems faced when testing. Finally, design of mechanical test coupons remains to a large extent an art rather than a science, with no industry consensus on how to approach the engineering of the specimens' gripping method during tests. Each major composite testing laboratory has developed gripping methods for the specific material systems and environments commonly found on those laboratories.

The test specimens for the following tests were obtained from the production line at Mar Kayaks in boards of 1.0 m x0.25 m produced by wet/hand lay-up, with the same stacking sequence and thickness as the one present in the Viper 51 model, and prepared at IST in the Mechanical department laboratories. All the specimens were sandwich structures with Glass fiber/epoxy multiaxial 0º/90º laminate with 240g/m^3 density, and the core materials were either Cork composites CoreCork® NL10 (reference C) or PVC Foam cores Divinycell H80 (Reference P), both with 2 mm thickness. One of the skins was painted with Gelcoat Crystic 253PA, for protection and aesthetic purposes. The bonding agent between the materials used was Resoltech 1040 Epoxy resin. The goal was to compare the behavior of the sandwich structures when the Divinycell cores were replaced with CoreCork cores with the same thickness, to understand if the material substitution had major impact in the mechanical performance.

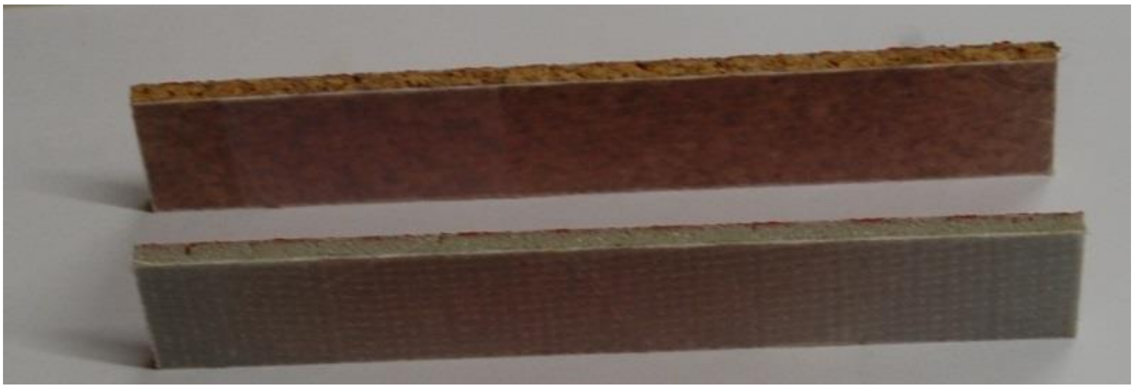


Figure 11 – Test specimens with Divinycell (bottom specimen) and CoreCork (top specimen) cores

3.4. Compression Test

The first tests carried out were edgewise compression tests of both specimen types (sandwich structures with either Divinycell or Cork core), to determine the properties of the specimens in compression and to determine the differences between them, by the way of the ASTM C-364 Test method.

3.4.1. Specimen production and dimensions

The test specimens were obtained from the production line at Mar Kayaks in boards of 1x0.25 m produced by wet/hand lay-up, and prepared at IST. The boards were selected randomly and care was taken to insure that the specimen groups had samples from all the boards taken from production. The specimen dimensions were 50x50mm with an average thickness of 4.2mm, with a 2mm core. Ten specimens were cut in a Bosch GTS10 Professional Cutting table with a Bosch multimaterial cutting saw with a for each core type for a total of twenty specimens tested.

Figure 12 – Bosch GTS10 cutting table

Figure 13 – Bosch multimaterial cutting saw

3.4.2. Test methodology

The specimens were placed edgewise in the testing machine and loaded at a constant crosshead speed of 0.5mm/min, until a 50% loading drop is recorded.

To carry out the tests a special apparatus was designed and built according to the specifications of the test method in order to insure that the specimens were laterally supported to prevent buckling failure at the point of contact. The specimens had to be fit within the raised part of the apparatus, tightened in order to prevent failure, but not enough to provoke excessive flatwise compression in the specimens, as shown in Figure 14 and Figure 15.

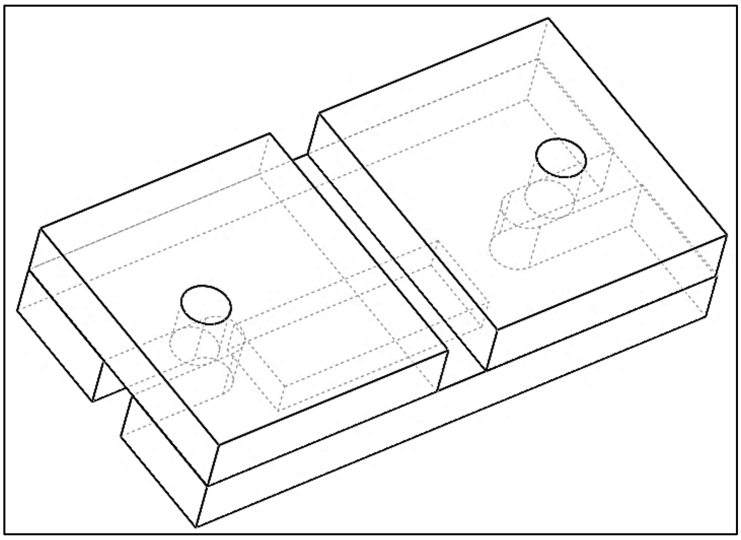


Figure 14 – 3D View of the first model of the apparatus

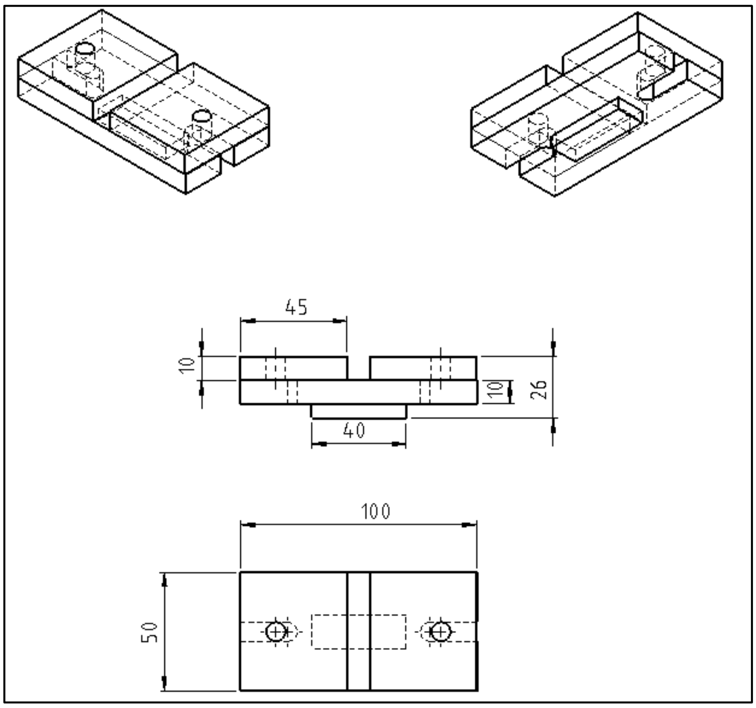


Figure 15 – Assembly view with main dimensions (mm)

An Instron 3369 electromechanical testing machine, with a 10kN loading cell (Figure 16), was used to perform the tests.

Figure 16 - Instron 3369 testing machine

3.4.3. Test results

Figure 17 and Table 5 represent the test results in compression, regarding Compressive Loads and Compressive Stress. Table 5 also shows the values for the standard Deviation and Coefficient of variation.

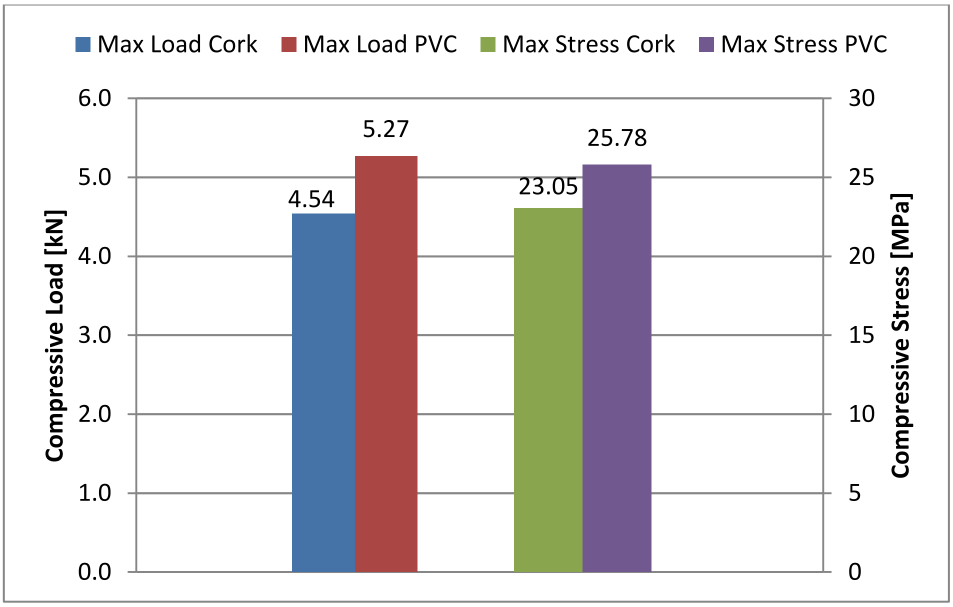


Figure 17 – Test Results of the Compression tests

Table 5 – Test Results of the Compression tests

	Max Load [kN]		**σ max [MPa]**	
	Cork	PVC	Cork	PVC
Average	4.536	5.267	23.049	25.78
StDev	0.532	0.951	2.620	4.88
Var	11.73%	18.06%	11.37%	18.92%

Although in figure 15 there seems to be a clear difference between the cork core sandwich and the Divinycell ones, with the DivinyCell cores sustaining a higher load and a higher maximum stress, looking at the values of the standard deviation of table 3 there is no statistical significance in the higher values. Both the Maximum load and Maximum Stress for both cores are well inside the calculated deviation, which means that for all intents and purposes there is no difference between the cores. This possibly means that for compressive loads, which are primarily carried by the composite skins of the sandwich structure, and given the sandwich geometry, there is little impact of the core type, although the high degree of variability would be attributed to the cores

themselves rather than the skins. If that is the case, that the cores are more responsible for the variability than the skins, then the cork cores function slightly better given its lower variability, although at 11.37% coefficient of variation, slightly better is still not very good.

Finally the geometry of the specimens themselves, with around 4.2 mm thickness is possibly the main culprit of the variability, since such thin columns are not the best geometry for a compressive load state.

3.4.4. Failure modes

One of the reasons for the variability found in the tests is due to the fact that there was no dominant failure mode in compression. All core types suffered debonding, shear buckling, and general buckling, which means that either the sandwich structures were designed in such a way that at failure all these failure modes are possible, *i.e.*, that the mechanisms responsible for debonding reacts at about the same loads as the mechanism responsible for core shear buckling and general buckling, or, more likely, small differences in production, such as small differences in resin quantity, curing time, voids caused by trapped air bubbles during the vacuum bagging process, can cause different failure modes. Finally, if as stated by Mamallis *et al.* [82], that the failure mode is highly dependent on the core properties, then it can be assumed that the core materials properties do not have much influence in the failure mode.

3.4.5. Conclusions

The Divinycell cores support higher values of load and stress, although the difference to the Cork Cores is statistically insignificant given the Deviation calculated.

There is a high degree of variability in the test results, which can be attributed to the cores and/or the manufacturing process, but mainly to the geometry of the specimens, namely the *slenderness ratio*.

The variability of the cork core specimens is two thirds smaller than the Divinycell cores, but at almost 12% there is still a high degree of variability.

There was no dominant failure mode, but 3 different failure modes occurred, with two possible causes, specimen geometry and/or small manufacturing variations. From a compression load performance standpoint, both sandwich structures can be considered similar in terms of performance.

3.5. Bending Test

The goal was to determine the composites behavior in bending and what would be the differences between the cork cored composites and the Divinycell cored composites.

3.5.1. Specimens production and dimensions

The test specimens were obtained from the production line at Mar Kayaks in boards of 1.0x0.25m produced by wet/hand lay-up, and prepared at IST. The boards were selected randomly and care was taken to insure that the specimen groups had samples from all the boards taken from production. Sample specimens are shown in Figure 18, Figure 19 and Figure 20.

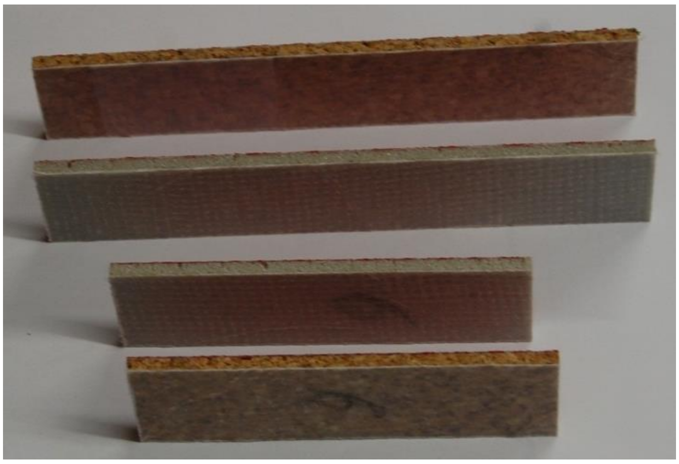


Figure 18 – Sandwich specimens 150 mm and 100 mm length

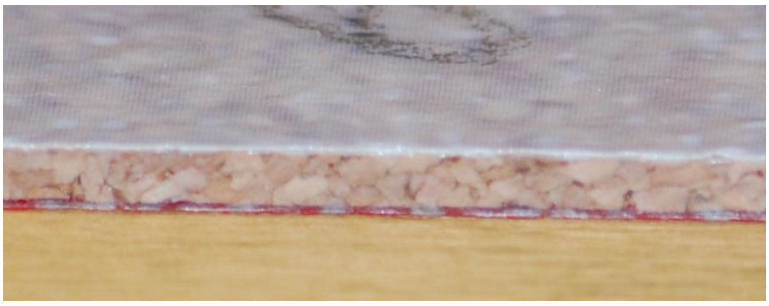


Figure 19 - Cork composite sandwich showing non gelcoated face

Figure 20 – Cork composite sandwich with gelcoating (Red) in one facing

Sixty three tests were performed using different spans, lengths, widths and gel coat facing positioning as shown in Table 6. The registry of each specimen was devised as a way to keep tabs on all specimens tested and its general form is Txxy.aa, with the first letter denoting core type (Cork or Divinycell), the first two numbers are the specimen length in cm, the next number the specimen width (cm) and finally the two letters after the period the specimen number, if multiple specimens of the same length, width and core type are present. For example, specimen P103.09 is the ninth specimen with a Divinycell core, 100 mm length and 30 mm width.

Table 6 – Specimen registry by type

			Gelcoat			
			Compression		Tension	
			PVC	Cork	PVC	Cork
30 mm width	150 mm Total length	100 mm support span	P153.01	C153.05	P153.04	C153.01
			P153.02		P153.05	C153.02
			P153.06			C153.03
						C153.04
		70 mm support span	P153.07	C153.06	P153.10	
			P153.08	C153.07	P153.11	C153.08
			P153.09	C153.10	P153.12	C153.09
					P153.13	
	100 mm Total length	50 mm support span	P103.02	C103.02	P103.01	C103.01
			P103.07	C103.03	P103.03	C103.05
			P103.08	C103.04	P103.04	C103.08
			P103.09	C103.06	P103.05	C103.09
			P103.10	C103.07	P103.06	C103.10
50 mm width	150 mm Total length	100 mm support span	P155.02	C155.02	P155.03	C155.03
		70 mm support span	P155.04	C155.04		
			P155.05	C155.05		
			P155.06	C155.06		
			P155.07	C155.07		
		50 mm support span	P155.08	C155.08		
			P155.09	C155.09		
			P155.10	C155.10		
			P155.01	C155.01		

The thickness of the specimens was preset from factory standards, so three different support spans were used in order to ascertain the value of the core shear stress, given that the core thickness was relatively low (2 mm on average) when compared the skin

thickness (about 1mm each). Two widths were also tested, to ascertain the influence of a larger area of contact between the specimens and the loading apparatus. Finally, to measure the influence of the gel coating, the specimens were tested with the coating working in tension (bottom face) and in compression (top face). Unfortunately, since the sandwich dimensions are preset from factory it was not possible to study the influence of skin and core thickness on the behavior and construct an envelope of failure.

3.5.2. Test methodology

The tests were all conducted considering the test methods ASTM C-393 3-point bending methodologies, as the properties sought after were the core properties of the sandwich structures, and ensuring that the crosshead rate of motion and deflection at failure fulfilled the requirements of the ASTM D-7250 test method, so that a Flexural Stiffness (EI) and Core Shear Modulus (G) could be computed using the calculations of the ASTM D-7250 test method.

All specimens were tested at a loading rate of 1 mm/min and the tests were finished when failure occurred in the sandwich either in the facings or in the core. Load and correspondent deflection were taken from the test, and results, such as stresses and bending modulus of elasticity, were obtained by application of the Timoshenko simplified beam theory. The machine used was an Instron 3369 electromechanical testing machine, with a 10kN loading cell, as shown in Figure 21.

Figure 21 - Instron 3369 Testing Machine

3.5.3. Test results and discussion

Figure 22 and Figure 23 represent the behavior of the specimens with the gel coating working in compression in the bending tests under the ASTM C-393 test method.

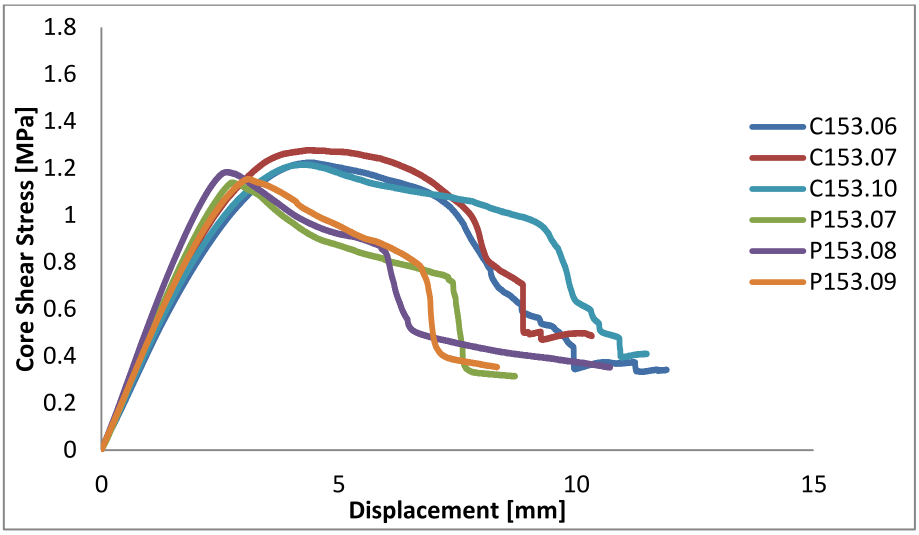


Figure 22 – Core stress-Displacement curves displaying the different behavior between PVC and cork composite cores 70 mm span

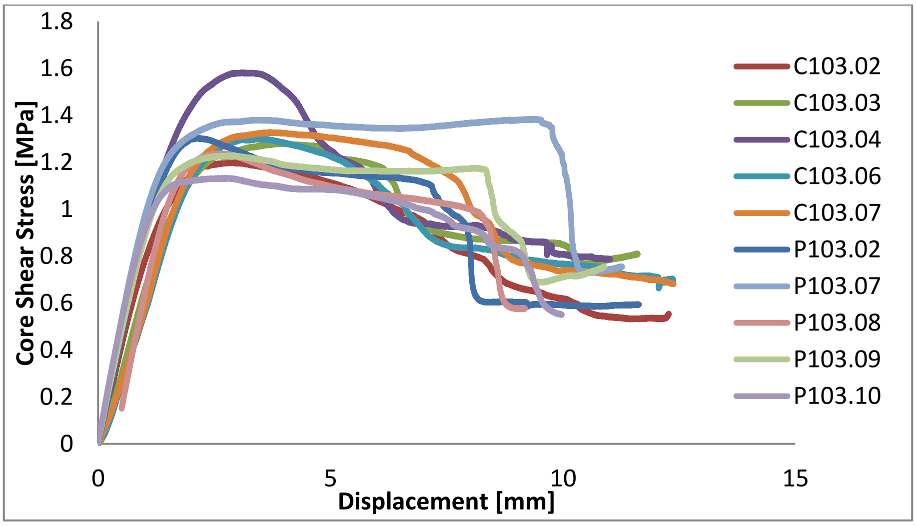


Figure 23 - Core stress-Displacement curves displaying the different behavior between PVC and cork composite cores 50 mm span

As the figure of the 70 mm span tests there is a notable difference between the PVC and cork composite behavior. The PVC cores exhibit a notable peak in shear stress followed by quick drop in core stress due to crushing of the core. The Cork Cores exhibit a less inclined slope until the crack formed due to core stress reaches the lower facing (Figure 32). The 50 mm span tests specimens behave somewhat differently, since in both core

types the slope after maximum core stress is small, retaining shear stress values close to the maximum shear stress for much longer.

Figure 24 and Figure 25 represent the behavior of the specimens with the gel coating working in tension in the bending tests under the ASTM C-393 test method.

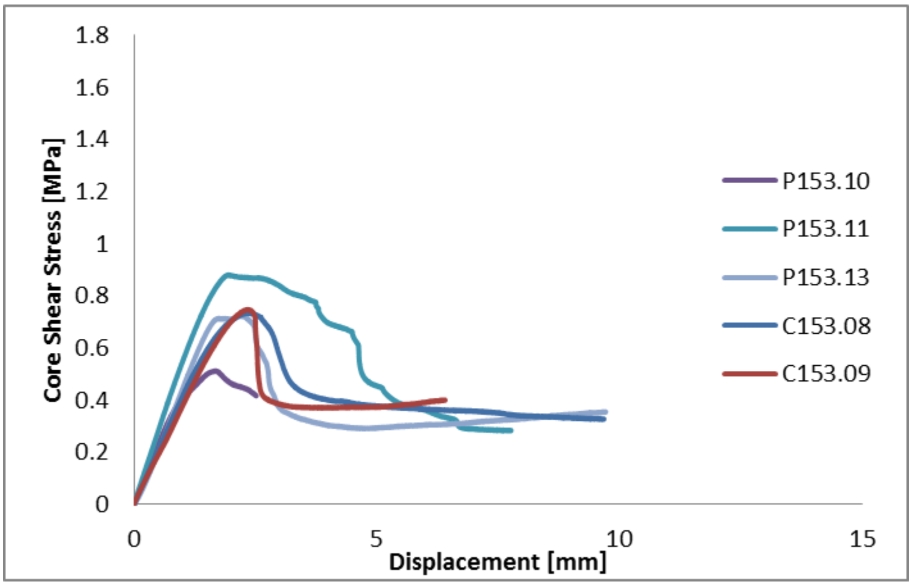


Figure 24 - Core shear stress-Displacement curves displaying the different behavior between PVC and cork composite cores 70 mm span

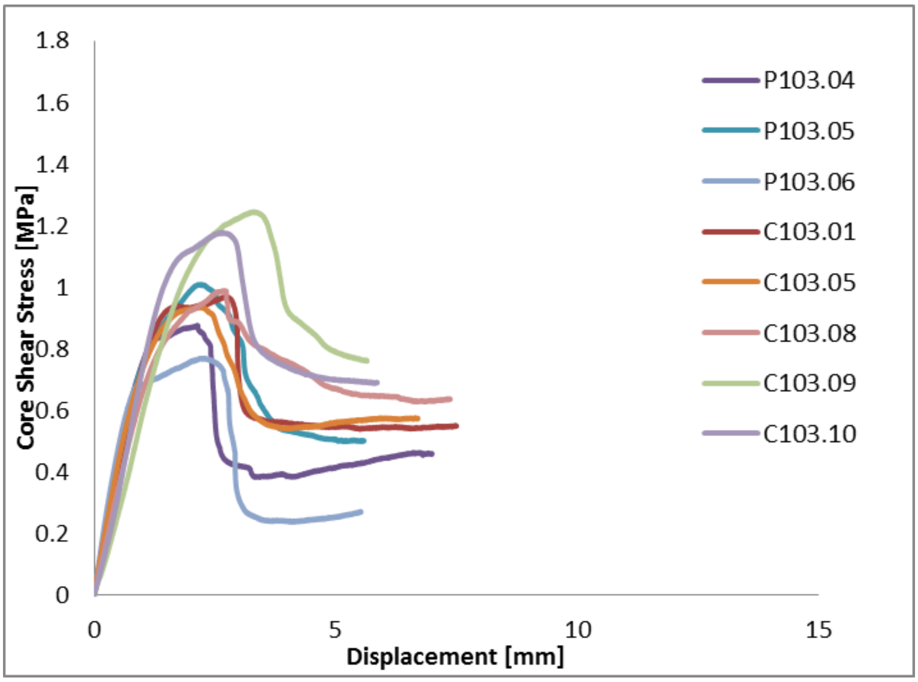


Figure 25 - Core shear stress-Displacement curves displaying the different behavior between PVC and cork composite cores 50 mm span

With the Gelcoating working in tension it was found that the upper facings failed prematurely in every test performed (see 3.5.5), which means that the Gelcoating added some compressive strength to the facings. With a peak core stress around the same values for both cork composite cores and PVC cores, the maximum values of stress are about 30% lower when compared to specimens in which the Gelcoating was working in compression and with greater variability between tests. The behavior is significantly different to the one shown in Figure 22 and Figure 23, since after maximum stress there is an immediately sharp drop in stress values due to the complete failure of the facing in compression.

Figure 26 and Table 7 show the average Core shear stress (7 specimens per test), the Standard Deviation and the Coefficient of variation, with the Gelcoat facing working in compression.

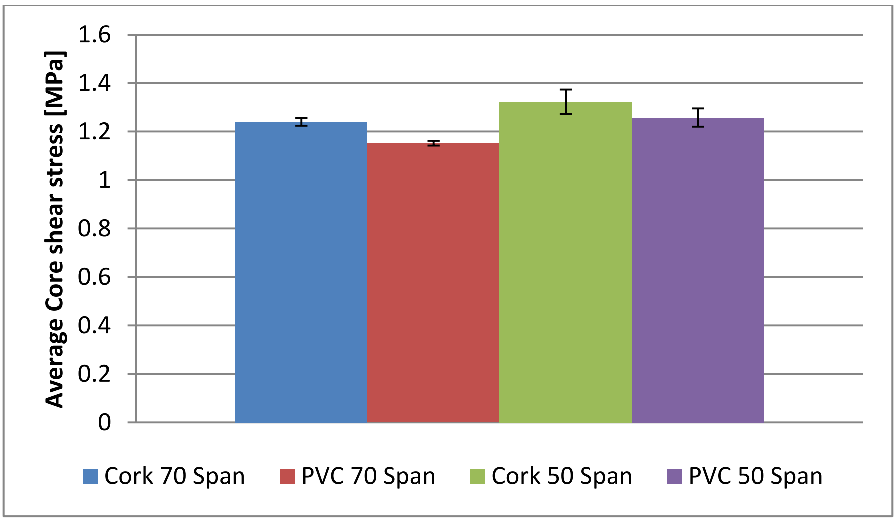


Figure 26 – Average core shear stress by core and by span length

Table 7 - Average core shear stress by core and by span length

Core material	Cork		PVC	
Span	70 mm	50 mm	70 mm	50 mm
Average Shear Stress [MPa]	1.24	1.30	1.15	1.26
Std Dev	0.015	0.05	0.01	0.037
Coef. Var	1.2%	3.8%	0.9%	2.9%

Cork Composite cores exhibit a higher core stress in both 70 mm and 50 mm span tests with the core stress 6% higher than PVC cores. Some scale effects can be observed, with the 50mm span with higher shear values than the 70mm span tests. However, the Standard deviation calculated implies a higher degree of variability on the 50 mm span tests, actually making the difference between both cores insignificant statistically, which coupled with the specimens behavior shown in Figure 25, point to a somewhat different behavior of the whole specimen when compared with the 70 mm tests.

Since one of the objectives is to compare between the behavior of these sandwich structures, it was decided to also calculate the sandwich shear stress of the specimens. Figure 27 and Table 8 show the average sandwich shear stress, standard deviation and coefficient of variation, with the gelcoat facing working in compression.

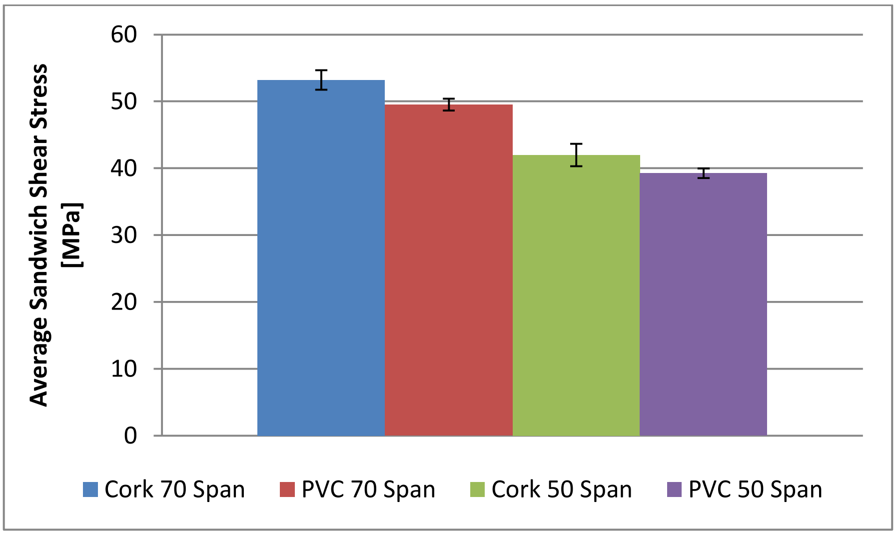


Figure 27 - Average sandwich shear stress by core and by span length gelcoat compression

Table 8 - Average sandwich shear stress by core and by span length gelcoat compression

Core material	**Cork**		**PVC**	
Span	70 mm	50 mm	70 mm	50 mm
Average Shear Stress [MPa]	53.22	41.99	49.50	39.26
Std Dev	1.456	1.668	0.898	0.716
Coef. Var	2.7%	4.0%	1.8%	1.8%

As anticipated from the core stress analysis, the cork composite core specimens have a higher value of Average shear stress than PVC cored specimens with a 6% difference.

To cross-check the assumption that all the specimens with the gel coating working in tension failed due to facing failure, Figure 28 and Table 9 show the average shear stress, standard deviation and coefficient of variation, with the gelcoat facing working in tension.

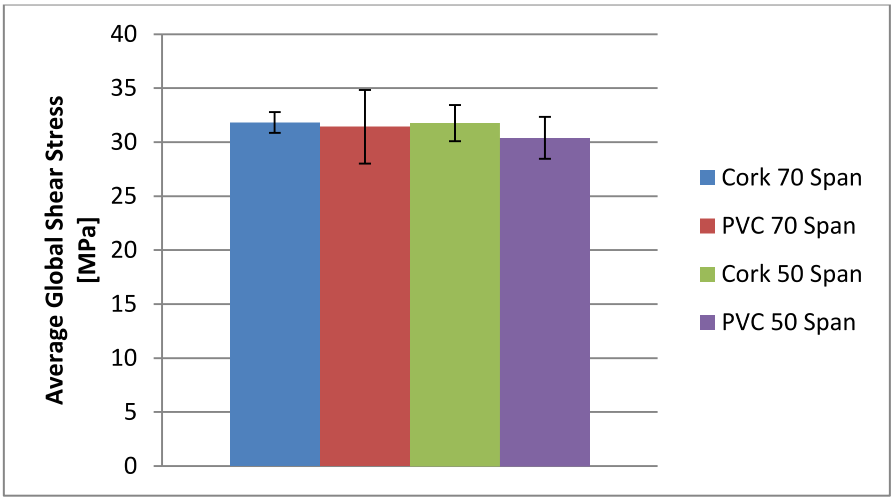


Figure 28 – Average global shear stress by core and by span length gelcoat tension

Table 9- Average global shear stress by core and by span length gelcoat tension

Core material	Cork		PVC	
Span	70 mm	50 mm	70 mm	50 mm
Average Stress [MPa]	31.82	31.77	31.42	30.39
Std Dev	0.964	1.670	3.404	1.932
Coef. Var	3.0%	5.3%	10.8%	6.4%

There is indeed a high degree of similarity in the values of global Stress in the sandwich structures with the gel coating working in tension, pointing out to the same type of behavior in all the specimens tested, with the small differences in shear stress inside the Standard Deviation measured for all the specimens.

The standard deviation in itself is much higher than in the tests where the cores were responsible for failure, and that can be attributed to differences in the facings tested,

since, as stated earlier, the specimens were taken from the production line using wet-layup, a labor intensive manufacturing process, with a high degree of variability compared to the Core materials which are produced in bulk by mechanical means.

All the values of the total shear stress are at least 9 MPa lower than the tests where the coating was working in compression, further reinforcing the notion that the cores were not responsible for failure in these tests.

Figure 29 and Table 10 show the average core shear modulus G, the standard deviation and coefficient of variation by core type, using all test specimens.

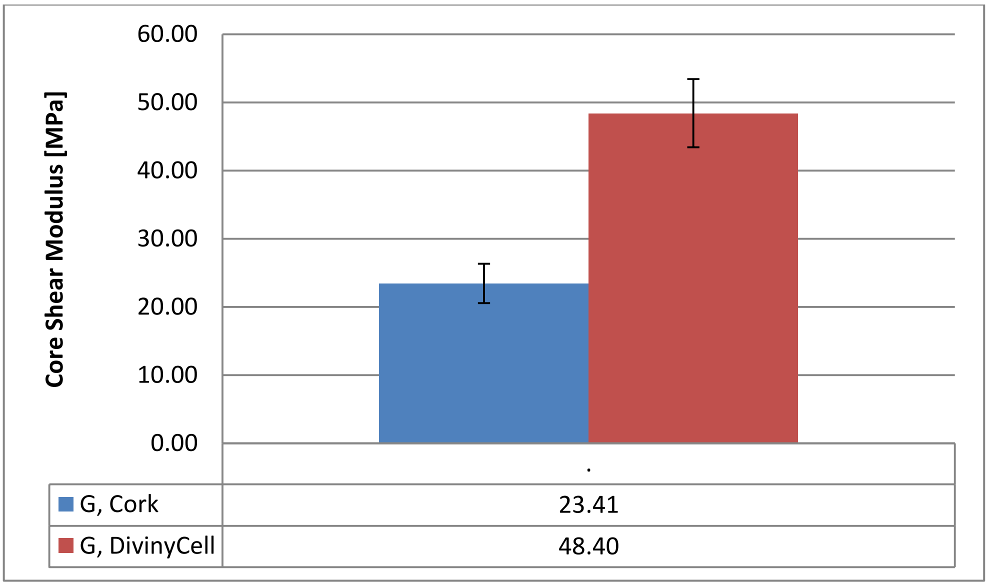


Figure 29 – Core Shear Modulus by core type

Table 10 – Core Shear Modulus by core type

Core Shear Modulus (MPa)		
G	Cork	DivinyCell
Average	23.41	48.40
STDev	2.89	5.01
CV	12%	10%

Figure 30 and Table 11 show the average Flexural stiffness (EI), the Standard Deviation and Coefficient of Variation by core type, using all test specimens.

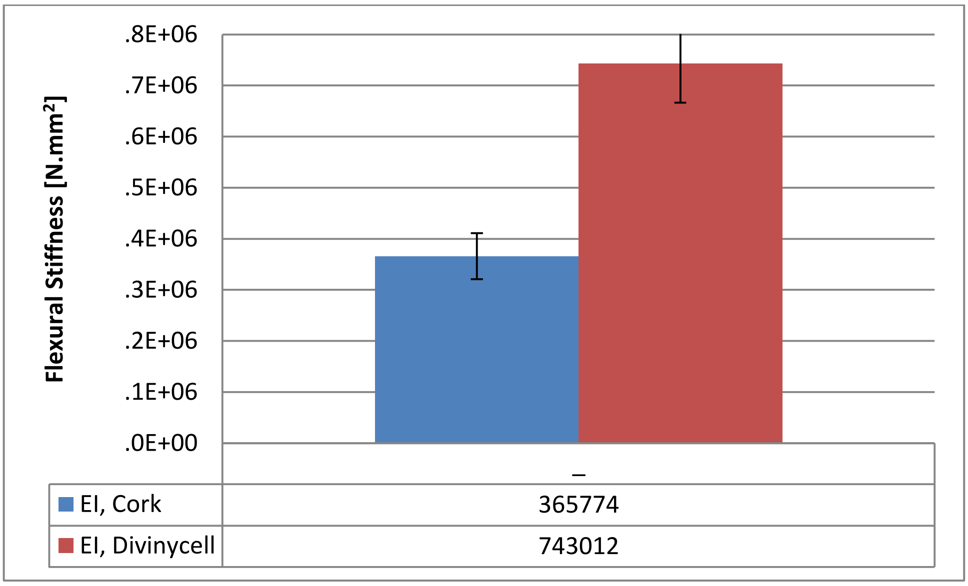


Figure 30 – Average Flexural stiffness (EI) by core type

Table 11 – Average Flexural stiffness (EI) by core type

flexural stiffness, (N.mm^2)		
EI	Cork	DivinyCell
Average	365774	743012
STDev	45142	76701
CV	12%	10%

The PVC cored sandwich specimens exhibit a higher shear modulus and higher flexural stiffness, 51% in both cases or more than double the values of the cork composite core sandwich specimens, due to the higher deflection measured at mid-point of the latter. Observed in all core types was a somewhat high value of the coefficient of variation. This may be mostly due to errors in measured spans (since the span values are generally squared or cubed, even small errors turn into a large difference) and some dimensional differences in specimens. It must be noted that the boards were produced by hand lay-up at NELO specifically for these tests, and a tight dimensional control was not possible during manufacturing, which means that there is some dimensional differences between boards. Given that almost all of the boards have at least one specimen in these tests contributes to a high variation measured.

In regards to the shear modulus the fact that the measured values are much higher than the values stated by the manufacturers of the core materials (for cork composites 5 MPa stated versus 23MPa measured and for PVC cores 27MPa stated versus 48 MPa measured), show that the facings carry much of the shear.

Note: All of the specimens not discarded, see subsection 3.5.4 were used for the calculation of both core shear modulus and flexural stiffness. Since the formula for obtaining these values in the ASTM D 7250 test method take into account the results of 2 bending tests at 2 different span lengths, with approximately 30 odd tests per core type at 3 different span lengths and 10 loading values per specimen tested resulted in about 3000 values calculated per core type and per property totaling 12000 calculations.

3.5.4. Discarded tests

Unfortunately some tests were not considered valid for various reasons. The bending tests with support span of 100 mm were not considered due to the fact that the number of tests was not enough for a significant statistical analysis in regards to loads and stresses, given premature failure in most specimens. In the calculation of both Core Shear Modulus and Flexural stiffness however, the number of specimens tested in both cases (with the gel coating in tension or compression) were enough for an analysis to be made. In any case the tests were usable for failure mode analysis as can be seen below.

Some specimens with 50 mm width were also discarded due to a problem with the test fixtures in one test batch. In those tests the supports possessed a rotating joint half-way up which allowed for some degree of rotation. Unfortunately the screws that fixed the joint could not be tightly screwed and in every test when the load value was in proximity of 50N, the joint gave way approximately ¼ of a millimeter, which introduced an error that was not deemed small enough to bypass, and thus were not used in calculations. This effect can be seen in Figure 31.

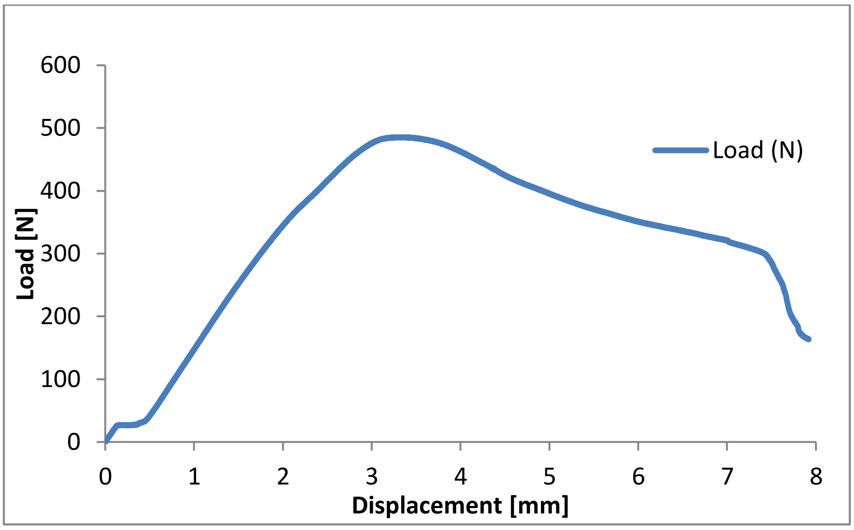


Figure 31 – Load displacement curve typical of the 50mm width specimen tests

3.5.5. Failure modes

Two failure modes were identified during the tests: core failure and facing failure in compression. In all the tests with the gel coating action in compression the failure was due to the cores.

In the case of cork composite cores the failure was due to core shear failure, with crack or cracks developing in the core and propagating until they become macroscopic in size, with the maximum shear stress occurring before the crack becomes macroscopic. After this point the crack propagates until reaching the interface with the facings progressing between the core material and the adhesive (see Figure 32).

The PVC foam cores present localized crushing due to compression stresses. What this means is that the PVC foam cores fail not by shear stresses, but by the compressive stresses during the test, as can be seen in Figure 33.

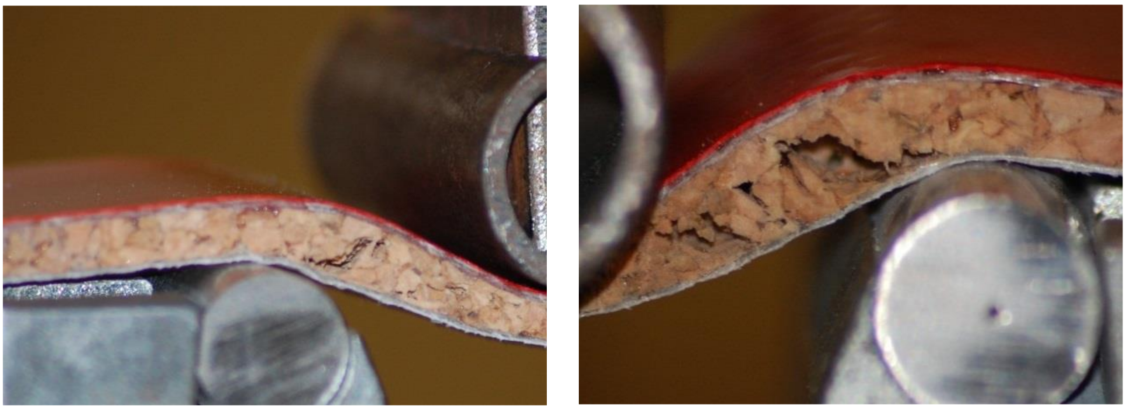


Figure 32 – Crack development and progression (Cork Composite Cores)

Figure 33 – Local Crushing (PVC foam cores)

In all the tests with the gel coating acting in tension the failure was due to the facings, since, as Figure 34 shows, independent of the core type, width or span, all facings with a pronounced indentation forming under the loading fixture.

Figure 34 – Facing failures in testing, Cork Cores left and Divinycell Cores Right

3.5.6. Conclusions

The specimens with Cork Composite cores have average core and total stress values between 5 to 7% higher than PVC cored specimens but at a higher deflection.

The shear modulus in the specimens with PVC cores is 51% higher than those with Cork composite Cores.

The flexural stiffness in the specimens with PVC cores is 51% higher than those with Cork composite Cores.

The relatively small thickness of the cores has an impact on the results, with the facings also carrying shear stresses.

No discernable scale effects were observed when the width was increased from 30 mm to 50 mm.

The Gel coating in the facings in compression serves to reinforce those facings, therefore preventing the specimen failure by facing failure, visible in those specimens tested with the coating working in tension.

3.6. Impact Test

The goal was to determine the impact strength of both sandwich structures to an impact event that could occur with the kayak, typically by the paddle hitting the front of the kayak when in motion or small impacts when docking the kayak.

3.6.1. Specimen production and dimensions

The test specimens were obtained from the production line at Mar Kayaks in boards of 1.0x0.25 m produced by wet/hand lay-up, and prepared at IST. All the specimens were sandwich structures with 2 layers of Glass fiber/epoxy multiaxial 0º/90º laminate with 240g/m^3 density. The core materials were either Cork composites Amorim CoreCork® NL10 or PVC foam cores Divinycell H80, both with 2.0 mm thickness. One of the skins was painted with Gelcoat Crystic 253PA, for protection and aesthetic purposes. The bonding agent between the materials used was Resoltech 1040 Epoxy resin. The boards were selected randomly and care was taken to insure that the specimen groups had samples from all the boards taken from production.

The boards were cut to 150X100 mm size as per the test method with sandwich thickness averaging 4.2 mm and 34 samples of each core material were tested, within a range of impact energies in order to ascertain the impact behavior of cork cores and its comparison with similar PVC cores.

3.6.2. Test methodology

The tests were carried out according to the ASTM D7136 Standard test method for measuring the damage resistance of a fiber-reinforced polymer matrix composite to a drop weight impact event.

A hemispherical ended cylindrical projectile was dropped from a known, variable height between guide rails onto clamped sandwich specimens. A variable mass was attached to the projectile and a piezoelectric load cell gave the variation of impact force with time. An optical gate gave the incident velocity of the impact head, and hence the velocity, displacement and the energy could be calculated from the measured force-time data by successive numerical integrations, knowing the impact mass.

The tests were performed using a fully instrumented Rosand IFW5 falling weight machine as seen in Figure 35.

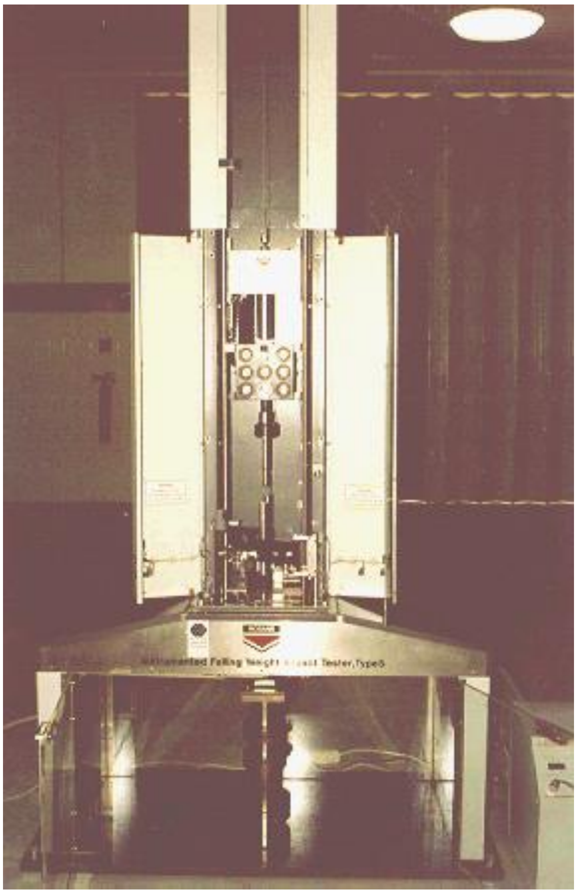


Figure 35 - Rosand IFW5 falling weight machine

The Rosand IFW 5HV allows carrying out impact tests within a high range of energies, since the impact mass could be varied between 2kg and 29kg, the velocities between 1.5 m/s and 21.5 m/s, and a maximum height of 2.2m, allowing for impact energies between 2 J and 1400 J. Given the physical configuration of the machine it is possible to perform a diverse set of impact tests, from universal testing to Charpy and Izod testing, just by changing the clamping fixtures. The test machine also possessed a Second Strike Preventer used in most of the specimen tests. The impactor selected for the tests had a diameter of 16 mm, and since the mass of the impactor could be modified, tests were performed with 24kg, 5kg, 3kg and 2kg, in order to be able to obtain both punctured specimens, in order to analyze the damage type on the lower face, and non-punctured specimens, for energy, force and Barely Visible Impact Damage (BVID) comparison.

3.6.3. Potential Impact energy

In order to study all of the impact effects, multiple potential impact energies were used during the tests. The test method determines a specific ratio of impact energy of 6.7

J/mm. However, the test method was designed with monolithic composite structures in mind which are more resistant than the sandwich composites tested. As such tests were performed with varying impact energies to determine the influence of the impact energy on the sandwich structures, see Table 12, with 100% being equal to the impact energy of 6.7 J/mm.

Table 12 – Potential impact Energies tested

Potential Energy			
E	100%	26.8	J
E	50%	13.4	J
E	33%	8.9	J
E	25%	6.7	J
E	16%	4.5	J
E	10%	2.6	J

The 68 specimens were divided as is shown in Table 13, with 34 tests with NL10 cores and 34 with Divinycell H80 Foam core, with 9 initial tests for tune up (SC01 through 04 and SP01 through 05). Followed by 5 tests at different potential energies, with the exception of the impact tests at $1/6^{th}$ the specific energy ratio, so that additional testing may be performed.

Table 13 – Specimen references, mass and drop height tested

Ref	Mass [kg]	Drop Height [m]	% Energy	Ref	Mass [kg]	Drop Height [m]	% Energy
SC01	24	0.121	100	**SP01**	24	0.120	100
SC02	24	0.120	100	**SP02**	24	0.120	100
SC03	24	0.010	10	**SP03**	24	0.059	50
SC04	24	0.015	10	**SP04**	24	0.010	10
Core05	5	0.271	50	**SP05**	24	0.010	10
Core06	5	0.569	100	**PVC06**	5	0.560	100
Core07	5	0.560	100	**PVC07**	5	0.559	100
Core08	5	0.560	100	**PVC08**	5	0.560	100
Core09	5	0.559	100	**PVC09**	5	0.558	100
Core10	5	0.559	100	**PVC10**	5	0.559	100
Core11	5	0.271	50	**PVC11**	5	0.270	50
Core12	5	0.271	50	**PVC12**	5	0.269	50
Core13	5	0.271	50	**PVC13**	5	0.271	50
Core14	5	0.270	50	**PVC14**	5	0.269	50
Core15	5	0.271	50	**PVC15**	5	0.270	50
Core16	3	0.303	33	**PVC16**	3	0.303	33
Core17	3	0.302	33	**PVC17**	3	0.303	33
Core18	3	0.302	33	**PVC18**	3	0.303	33
Core19	3	0.302	33	**PVC19**	3	0.303	33
Core20	3	0.302	33	**PVC20**	3	0.303	33
Core 26	3	0.228	25	**PVC26**	3	0.228	25
Core 27	3	0.226	25	**PVC27**	3	0.227	25
Core 28	3	0.228	25	**PVC28**	3	0.228	25
Core 29	3	0.227	25	**PVC29**	3	0.227	25
Core 30	3	0.228	25	**PVC30**	3	0.227	25
Core21	2	0.228	16	**PVC21**	2	0.228	16
Core22	2	0.227	16	**PVC22**	2	0.227	16
Core23	2	0.226	16	**PVC23**	2	0.227	16
Core24	2	0.228	16	**PVC24**	2	0.229	16
Core25	2	0.228	16	**PVC25**	2	0.226	16
Core31	2	0.228	16	**PVC31**	2	0.227	16
Core32	2	0.228	16	**PVC32**	2	0.227	16
Core33	2	0.228	16	**PVC33**	2	0.228	16
Core34	2	0.227	16	**PVC34**	2	0.228	16

3.6.4. Test results

Table 14 presents the results of the impact tests showing the impact velocities, the maximum impact force and the absorbed energy by the specimens.

Table 14 – Impact testing results

Ref	Impact V [m/s]	Fmax [N]	Abs Energy [J]	% Energy	Ref	Impact V [m/s]	Fmax [N]	Abs Energy [J]	% Energy
SC01	1.30	2278	17.91	100	**SP01**	1.40	2342	15.99	100
SC02	1.44	2261	18.41	100	**SP02**	1.42	2344	17.31	100
SC03	0.47	725	5.01	10	**SP03**	1.02	2060	14.15	50
SC04	0.40	1149	3.03	10	**SP04**	0.48	804	4.53	10
Core 05	2.15	1506	10.13	50	**SP05**	0.45	836	3.81	10
Core 06	3.14	1491	8.47	100	**PVC06**	3.12	1923	13.14	100
Core 07	3.14	1681	13.17	100	**PVC07**	3.12	1410	9.98	100
Core 08	3.14	2046	12.77	100	**PVC08**	3.14	1906	12.53	100
Core 09	3.14	1565	11.27	100	**PVC09**	3.14	1758	11.07	100
Core 10	3.12	1519	12.17	100	**PVC10**	3.14	1768	11.84	100
Core 11	2.13	1388	9.58	50	**PVC11**	2.12	1612	11.58	50
Core 12	2.12	1560	11.86	50	**PVC12**	2.11	1551	11.87	50
Core 13	2.12	1467	12.00	50	**PVC13**	2.11	1652	11.92	50
Core 14	2.12	1430	11.51	50	**PVC14**	2.12	1469	10.59	50
Core 15	2.12	1523	11.20	50	**PVC15**	2.13	1531	11.25	50
Core 16	2.28	1400	8.17	33	**PVC16**	2.29	1309	8.28	33
Core 17	2.29	1437	8.24	33	**PVC17**	2.29	1385	8.22	33
Core 18	2.29	1193	8.35	33	**PVC18**	2.28	1366	8.17	33
Core 19	2.29	1210	8.25	33	**PVC19**	2.28	1376	8.17	33
Core 20	2.29	1284	8.23	33	**PVC20**	2.28	1346	8.16	33
Core 26	1.95	1001	6.07	25	**PVC26**	1.95	1075	6.04	25
Core 27	1.94	1193	5.97	25	**PVC27**	1.95	1122	6.03	25
Core 28	1.95	1225	6.01	25	**PVC28**	1.95	1124	6.03	25
Core 29	1.95	1223	6.01	25	**PVC29**	1.95	976	6.06	25
Core 30	1.95	1193	6.05	25	**PVC30**	1.95	976	6.04	25
Core 21	1.93	1003	3.91	16	**PVC21**	2.03	1183	4.31	16
Core 22	2.01	1040	4.24	16	**PVC22**	2.02	1067	4.27	16
Core 23	2.01	1026	4.24	16	**PVC23**	2.02	1045	4.28	16
Core 24	2.01	1092	4.21	16	**PVC24**	2.02	981	4.29	16
Core 25	2.01	1119	4.24	16	**PVC25**	2.03	922	4.31	16
Core 31	2.02	1050	4.27	16	**PVC31**	2.01	1127	4.25	16
Core 32	2.01	1043	4.22	16	**PVC32**	2.01	956	4.25	16
Core 33	2.02	954	4.27	16	**PVC33**	2.03	956	4.31	16
Core 34	2.02	1043	4.27	16	**PVC34**	2.02	910	4.29	16

From Figure 36 to Figure 39 some examples of impact graphs obtained during the impact tests can be seen.

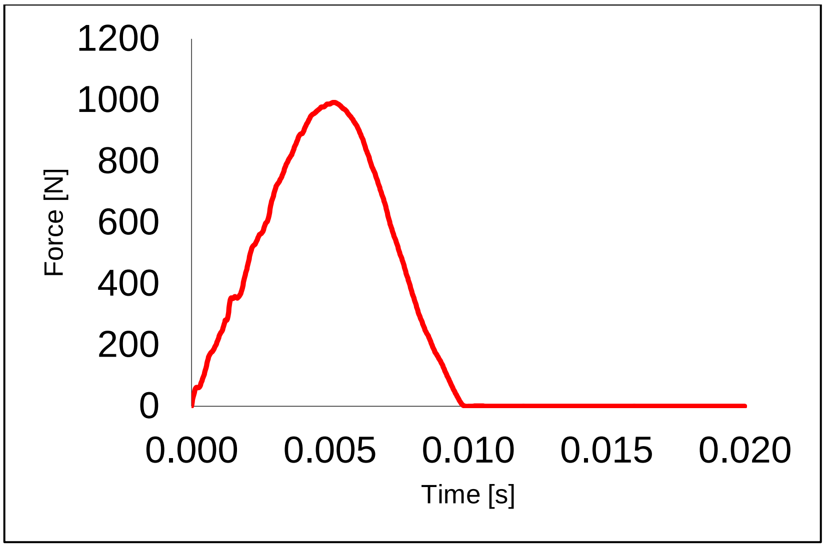


Figure 36 – Force vs. time for NL10 at 16% Potential impact energy

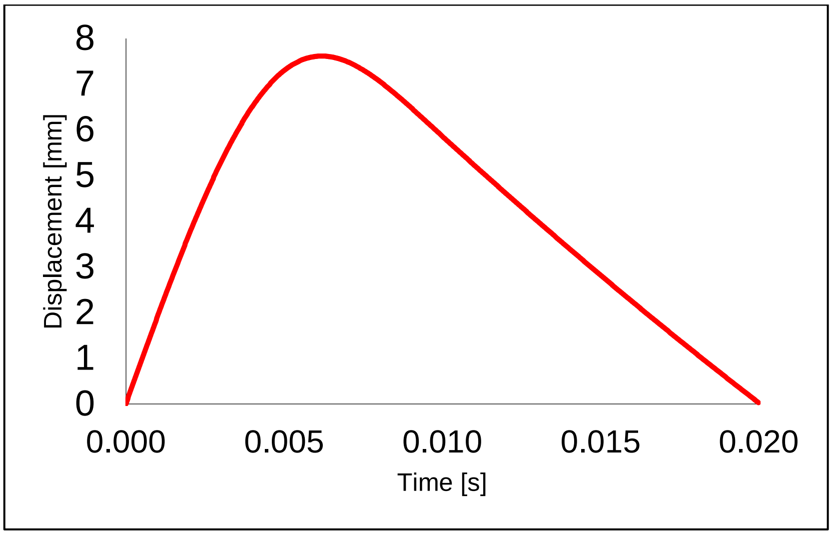


Figure 37 - Displacement vs. time for NL10 at 16% Potential impact energy

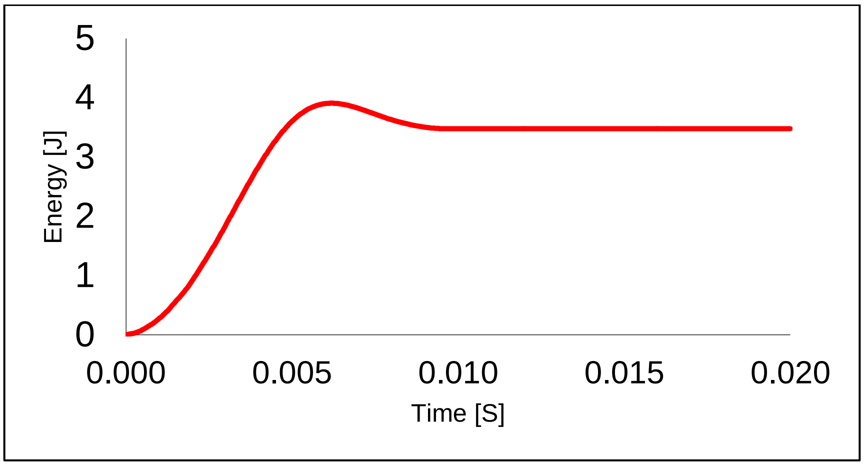


Figure 38 - Energy vs. time for NL10 at 16% Potential impact energy

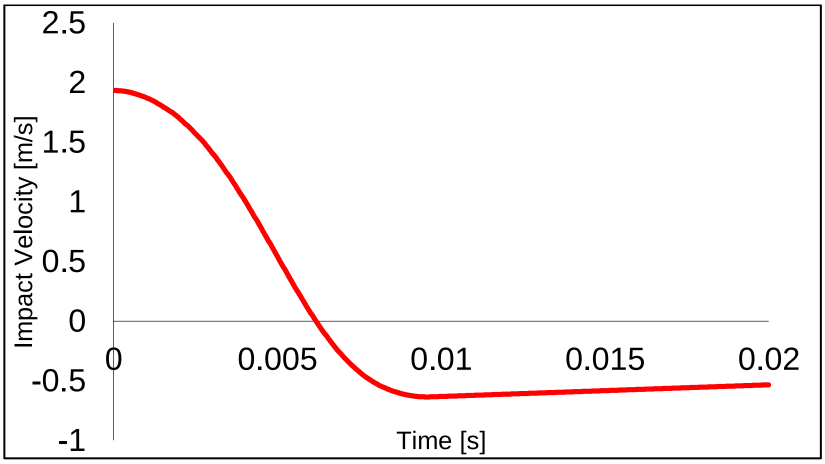


Figure 39 – Impact Velocity vs. time for NL10 at 16% Potential impact energy

From Table 15 to Table 19 are presented the Averages, standard deviation and coefficient of variation of force and absorbed energy from the specimens for each level of potential energy.

Table 15 - Average, Stdev and Coefficient of Variation of Force and Absorbed energy at 100% potential energy

100%	**Cork**		**PVC**	
Energy	Force	Abs Energy	Force	Abs Energy
Average	1660.5	11.6	1752.7	11.7
StdDev	203.4	1.7	184.4	1.1
CV [%]	12.3	14.5	10.5	9.5

Table 16 - Average, Stdev and Coefficient of Variation of Force and Absorbed energy at 50% potential energy

50%	Cork		PVC	
Energy	Force	Abs Energy	Force	Abs Energy
Average	1473.68	11.23	1562.92	11.44
StdDev	62.20	0.87	63.66	0.49
CV [%]	4.22	7.76	4.07	4.28

Table 17 - Average, Stdev and Coefficient of Variation of Force and Absorbed energy at 33% potential energy

33%	Cork		PVC	
Energy	Force	Abs Energy	Force	Abs Energy
Average	1305.07	8.25	1356.34	8.20
StdDev	98.42	0.06	27.02	0.04
CV [%]	7.54	0.68	1.99	0.54

Table 18 - Average, Stdev and Coefficient of Variation of Force and Absorbed energy at 25% potential energy

25%	Cork		PVC	
Energy	Force	Abs Energy	Force	Abs Energy
Average	1167.02	6.02	1054.60	6.04
StdDev	84.22	0.03	66.38	0.01
CV [%]	7.22	0.56	6.29	0.18

Table 19 - Average, Stdev and Coefficient of Variation of Force and Absorbed energy at 16% potential energy

16%	Cork		PVC	
Energy	Force	Abs Energy	Force	Abs Energy
Average	1041.13	4.21	1016.48	4.28
StdDev	44.77	0.11	89.54	0.02
CV [%]	4.30	2.57	8.81	0.52

Tables show some very interesting results; there is no statistical significant difference between the NL10 Cores and the Divinycell cores, since the differences in averages are below the standard deviation. There is no difference between the absorbed energy at 100% and 50% potential energy meaning that the specimens only begin to resist

perforation somewhere below the 50% potential energy of the carried out tests, and that the maximum energy absorption by these specimens is about 11 J.

3.6.4.1. 100% potential impact energy

Figure 40 and Figure 41 show the impact damage occurred in upper faces due to 100% impact energy in the Cork core sandwich and the Divinycell core sandwich.

Figure 40 – Impact damage on the face subjected to impact NL10 Core at 100% Potential Energy

Figure 41 - Impact damage on the face subjected to impact Divinycell Core at 100% Potential Energy

The damage on the upper faces is similar in both specimens with a circular indentation with penetration of the gel coating. The penetration of the impactor ruptures the glass fiber in a cruciform pattern coincident with the main orientation of the fibers. The indented area is similar for both types of specimens, since the penetrator entered fully into the specimen.

Figure 42 and Figure 43 show the impact damage occurred in lower faces due to 100% impact energy in the Cork core sandwich and the Divinycell core sandwich.

Figure 42 - Impact damage on the lower face NL10 Core at 100% Potential Energy

Figure 43 - Impact damage on the lower Divinycell Core at 100% Potential Energy

In the lower faces it can be seen a different behavior of the sandwich structure responses. In the Cork core the rupture takes a decidedly oval shape, while in the Divinycell cores the shape is circular. Analysis of both types of specimens seems to suggest that while the DivinyCell cores compress and rupture, due to the high stress concentrations upon impact, the NL10 Cores develop a crack in response to the stresses that propagates in one direction until the impactor passes through. This crack is formed along the Glass fiber plies and is dependent of the orientation, *i.e.*, the crack forms in either 0º or 90º depending on specimens, although its orientation is not dependent of the boundary conditions.

3.6.4.2. 50% potential energy

Figure 44 and Figure 45 show the impact damage occurred in upper faces due to 50% potential energy in the Cork core sandwich and the Divinycell core sandwich.

Figure 44 - Impact damage on the face subjected to impact NL10 Core at 50% Potential Energy

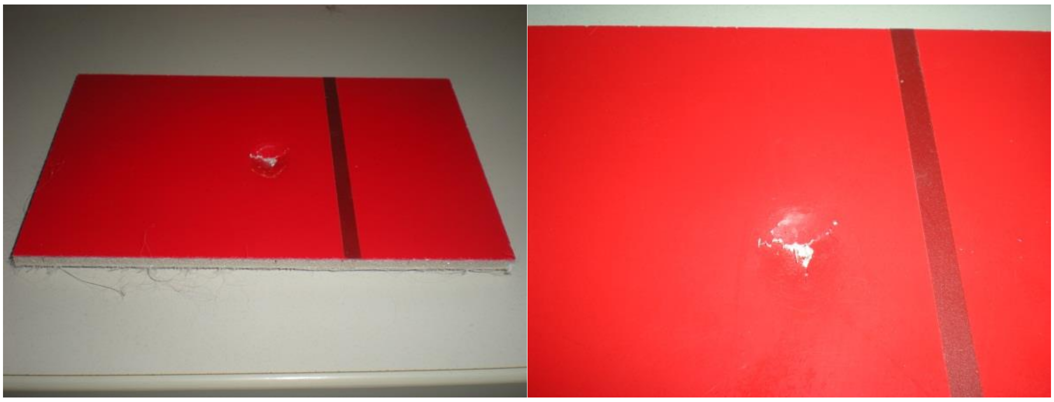


Figure 45 - Impact damage on the face subjected to impact Divinycell Core at 50% Potential Energy

At 50% impact energy the damage in the upper face appears somewhat milder, although the impactor passed through the top face of the specimen. In both cores the damage of the upper face presents a similar pattern with a cruciform pattern of rupture appearing coincident with the glass fibers orientation.

Figure 46 and Figure 47 show the impact damage occurred in lower faces due to 50% impact energy in the Cork core sandwich and the Divinycell core sandwich.

Figure 46 - Impact damage on the lower face NL10 Core at 50% Potential Energy

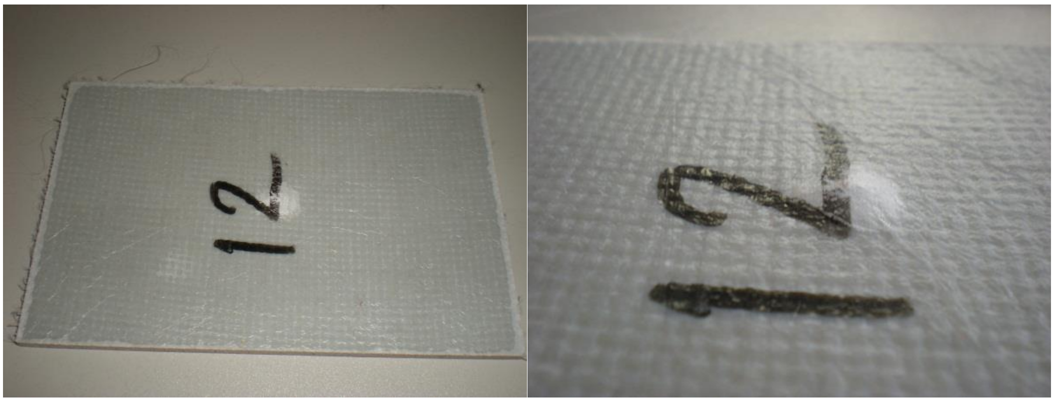


Figure 47 - Impact damage on the lower face Divinycell Core at 50% Potential Energy

In the lower faces, there is much more significant visible damage in the NL10 specimens with a larger area of damage and rupture of at least one layer of glass fiber in all specimens. On the Divinycell specimens, the visible damage area is smaller and there is no apparent penetration of the lower faces of the specimens.

3.6.4.3. 33% potential energy

Figure 48 and Figure 49 show the impact damage occurred in upper faces due to 33% potential energy in the Cork core sandwich and the Divinycell core sandwich.

Figure 48 - Impact damage on the face subjected to impact NL10 Core at 33% Potential Energy

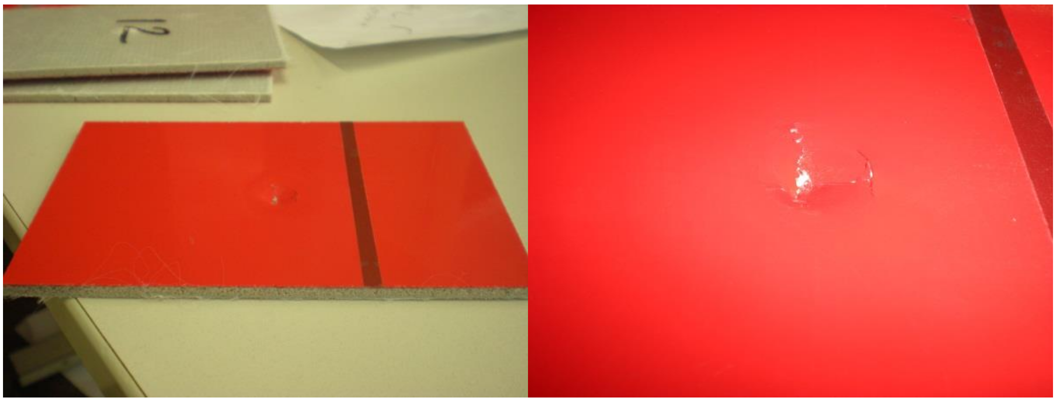


Figure 49 - Impact damage on the face subjected to impact Divinycell Core at 33% Potential Energy

At 33% potential energy the visible damage is still present with rupture of the top faces in both core specimens. Again present is the cruciform pattern of rupture oriented with the glass fiber orientation with gel coating damage mirroring the rupture and around the impactor edge.

Figure 50 and Figure 51 show the impact damage occurred in lower faces due to 33% impact energy in the Cork core sandwich and the Divinycell core sandwich.

Figure 50 - Impact damage on the lower face NL10 Core at 33% Potential Energy

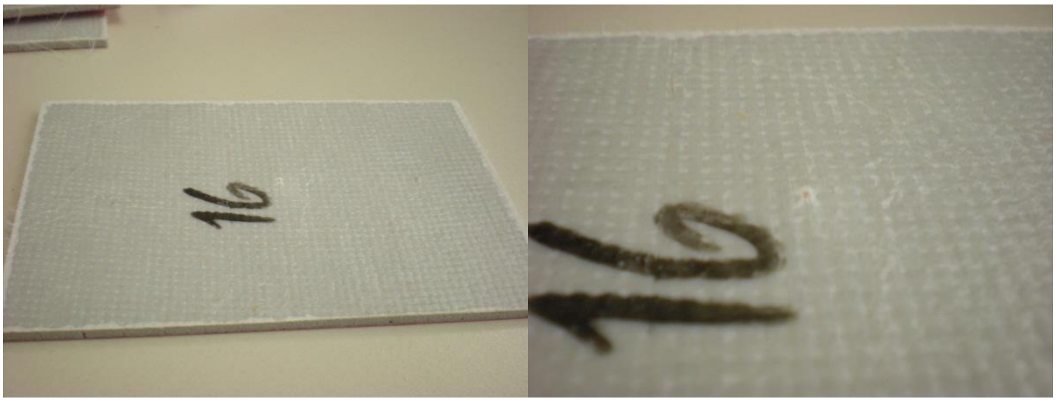


Figure 51 - Impact damage on the lower face Divinycell Core at 33% Potential Energy

On the lower faces there is a significant difference in visible damage between cores. In most cork specimens there is visible damage to the lower faces, with facing damage in at least one layer of glass fiber, and some debonding. On the Divinycell cores there is little if any visible damage, as can be seen on Figure 51.

3.6.4.4. 25% and 16% potential energy

Specimens impacted at 25% and 16% show damage on the upper face, with cracking on the gel coating and little ply damage at both energy levels. If not for the presence of gel coating the damage could be construed as BVID. In the lower faces there is no visual damage, and inspection of the faces after debonding shows no layer damage in any of the specimens. Given that only the 25% and 16% potential energy levels could be considered BVID, further analysis and testing was performed in both test specimens. Further tests were made at 10% potential impact energy although there was the fear that with drop heights lower than 20 mm the variation in drop height distance would be difficult to measure.

Figure 52 and Table 20 present the results of the maximum stress and Figure 53 and Table 21 show the average absorbed energy by energy level and by material.

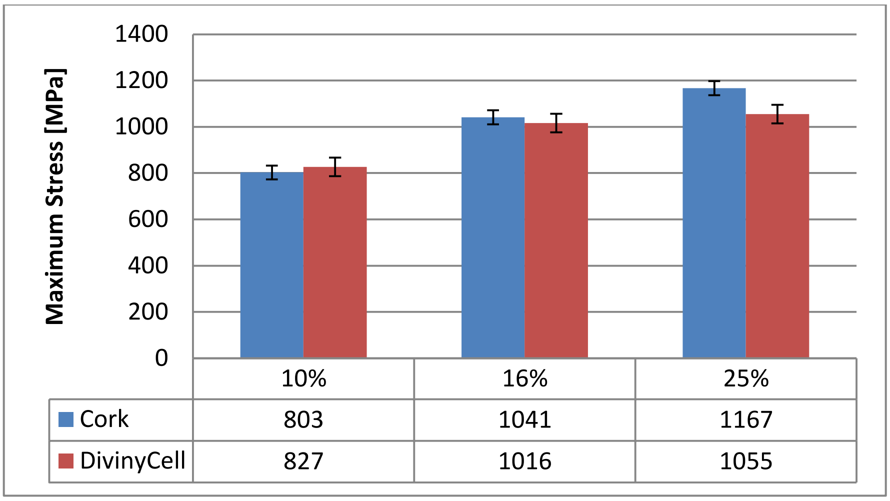


Figure 52 – Maximum stresses on impact per energy level.

Table 20-Maximum Stress on impact per energy level

Maximum Stress	10%		16%		25%	
	Cork	PVC	Cork	PVC	Cork	PVC
Average	803	827	1041	1016	1167	1055
StdDev	40	25	47.5	95	49.5	75
CV [%]	5.0%	3.0%	4.6%	9.4%	4.2%	7.1%

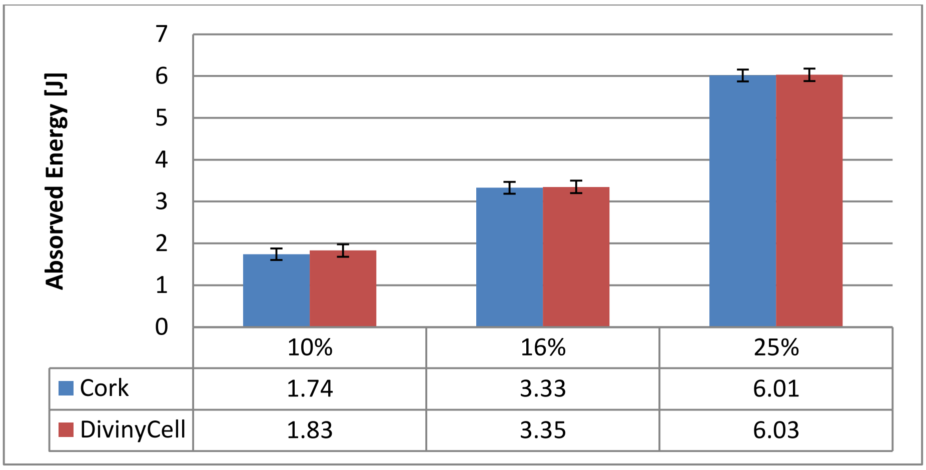


Figure 53 – Absorbed energy per energy level.

Table 21 - Absorbed energy on Impact per energy level

Absorbed Energy	10%		16%		25%	
	Cork	PVC	Cork	PVC	Cork	PVC
Average	1.74	1.83	3.33	3.35	6.02	6.04
StdDev	0.03	0.01	0.11	0.02	0.03	0.01
CV [%]	1.7%	0.5%	3.3%	0.6%	0.5%	0.2%

In terms of maximum stress the cork cored panels have the same values as the Divinycell cores at the 10% and 16% energy levels given the standard deviation measured. At 25% Energy cork cores sustain a higher stress than the Divinycell cores and at this level there is already visible damage on the facings. The absorbed energy, see Figure 53, shows that there is no discernible difference between cores which implies that almost all of the energy is absorbed by the faces of the sandwich structure. The 10% potential impact energy tests were not considered for the rest of the work, as doubts still lingered on the correct positioning of the impactor, *i.e.*, given that the drop height control mechanism had around 2 mm of play when positioning the impactor, a 10% difference in drop height distance was deemed too large a variation to obtain significant results.

3.6.5. C-SCAN

The C-Scan imaging proved to be a challenge since the sandwich is composed by materials with different densities that muddle the ultrasound signal as it passes through all the materials. The C-Scan Machine is presented in Figure 54.

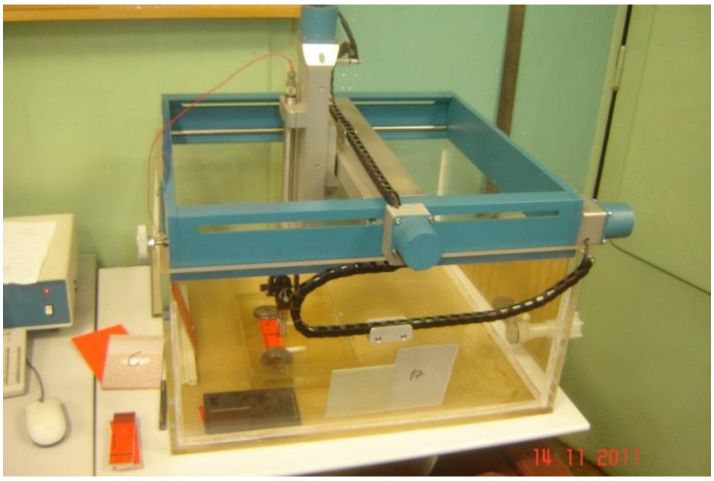


Figure 54 C-Scan Machine

As such, only a clear picture of the top layer was obtained. Figure 55 shows a typical C-Scan image of cork at 25% potential energy level, and Figure 56 the typical C-Scan energy of DivinyCell at 25% potential energy.

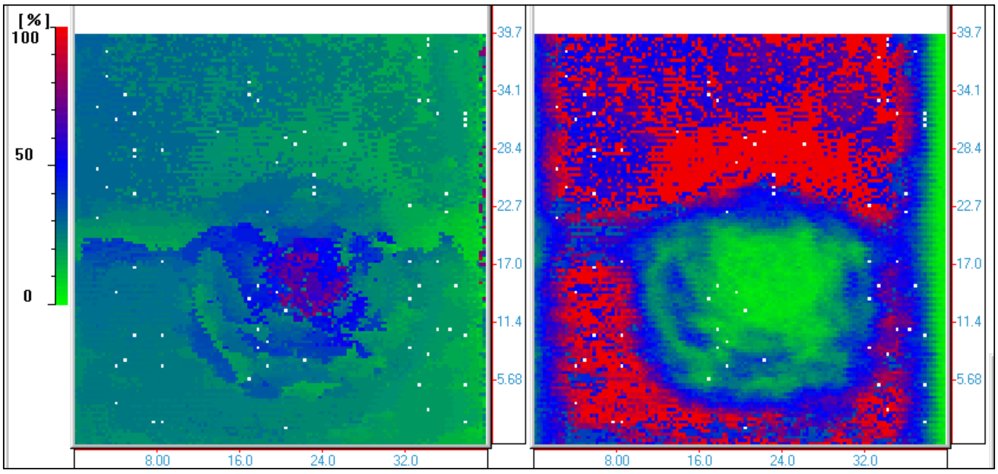


Figure 55- Time of flight and amplitude variations at 25% energy level Cork

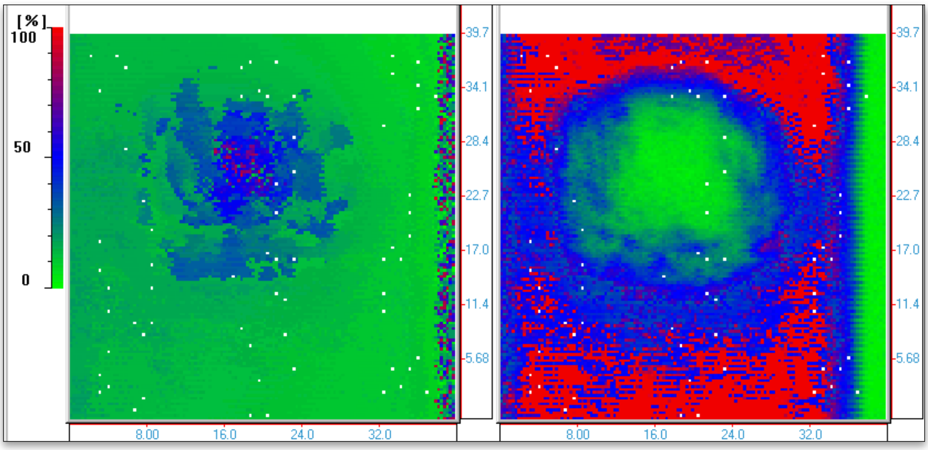


Figure 56 - Time of flight and amplitude variations at 25% energy level DivinyCell

The right side of Figure 55 and Figure 56 shows the indentation level of the impact, consistent between all tests at a determined energy level. The left side of Figure 55 and Figure 56 shows the inner damage in the glass fibers.

C-Scans were also performed at 16% potential energy level to determine the impact damage as seen in Figure 57 and Figure 58.

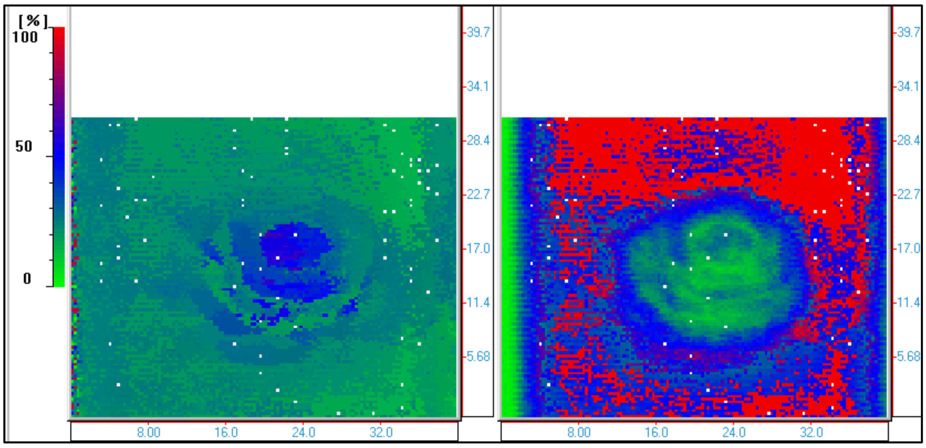


Figure 57 - Time of flight and amplitude variations at 16% energy level Cork

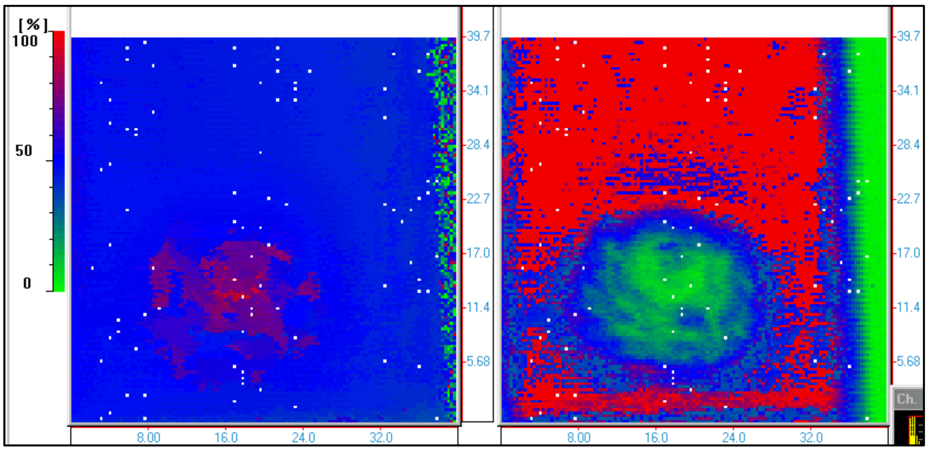


Figure 58 - Time of flight and amplitude variations at 16% energy level PVC

Once again the tests were consistent at the 16% energy level.

To better understand the damage incurred in the Sandwich structure, the delaminated area and maximum diameter of the impact area were measured According to the ASTM D 5824 test method. Those results are shown in Table 22 and Table 23.

Table 22 – Delaminated Area per Impact energy and per core material

Area Delaminated (mm^2)	**16% E**		**25% E**	
	Cork	PVC	Cork	PVC
Average	255.2	380	475.2	670
StdDev	35.53	51.55	34.77	59.56
CV [%]	13.9%	13.6%	7.3%	8.9%

Table 23 – Maximum Diameter of the impact area per impact energy and per core material

Max Diameter (mm)	16% E		25% E	
	Cork	PVC	Cork	PVC
Average	18.00	22.5	24.20	29.81
StdDev	1.22	1.33	1.10	1.55
CV [%]	6.8%	5.9%	4.5%	5.2%

The results of the delaminated area and the maximum diameter of the impact area show that given that the cork cores sustained about the same stresses at the same level of energy, it had to be expected that the area delaminated, *i.e.*, the area that effectively resists the impactor, would be equal to the delaminated area of the PVC. This means that, although at higher potential energy levels, between 50% and 33%, Divinycell cores are preferable to cork cores, given that at 33% there is no apparent penetration of the lower faces, at BVID levels of energy Cork cores are preferred since the cork cores absorb more energy than the DivinyCell Cores resulting in smaller impact areas simpler/cheaper to repair.

3.6.6. Conclusions

All of the specimens impacted at 100%, 50% and 33% impact energy show damage on the lower face with the first two impact energies showing complete perforation of the sandwich structure.

The amount of energy the specimens can absorb is in the vicinity of 11.5 J as can be depicted in tables of impact energy, since the absorbed impact energy from full Specific Energy to 50% Specific Energy is negligible.

The NL10 specimens have a high degree of variability. This variability has been observed in other tests and it is maybe due to the cork itself and the method of fabrication, since the NL10 sandwiches rely on natural materials separated by granule size and that epoxy has to completely permeate the core in the manufacturing process.

Another remark is that there is no statistical difference between the absorbed energy of the two cores, mostly due to the high standard deviation presented in the cork tests. This can mean that the cores have similar behavior when subject to impact or, more likely, that the thickness of the cores is too small to have any influence on the impact characteristics.

Below 33% the visible damage is only present on the faces impacted on both core types.

For potential impact energies of 16 and 25%, Cork cores suffer a higher Maximum stress, although statistically insignificant the lower the impact energy, and about the same energy is absorbed. Cork cores have less delaminated area after impact which means that the cork cores are able to absorb more impact energy that the Divinycell cores.

3.7. Bending after impact test

The goal in this case was to determine the behavior under BVID sandwich structures analyzed, and to determine what would be loss of global flexural modulus at the potential impact energies tested.

3.7.1. Specimen production and dimensions

The test specimens were obtained from the impact tests previously performed. The boards were cut from its 150X100 mm size as per the test method to a 90X50 mm size, with 6 specimens taken for each core type and for the 16% and 25% potential energy tests. Finally given this new geometry 7 new specimens of non-impacted specimens were also tested, for a total of 33 specimens.

3.7.2. Test methodology

The test methodology is the same as the one used in the first bending tests. Given the fact that the specimens had been impacted it was decided to test the specimens with the impact area 15 mm away from the loading point (using the center of impacted area as the other reference point) in order to avoid direct interactions between the loading point and the impacted area, with a support span area of 70 mm. In this case it was decided to calculate the flexural stiffness (EI) values instead of the bending modulus, since after impact, the shape of the composite would not be constant throughout the length of the specimens.

3.7.3. Test results

Figure 59 and Table 24 show the variation of EI with impact energy, and as well as the Standard Deviation and Coefficient of Variation.

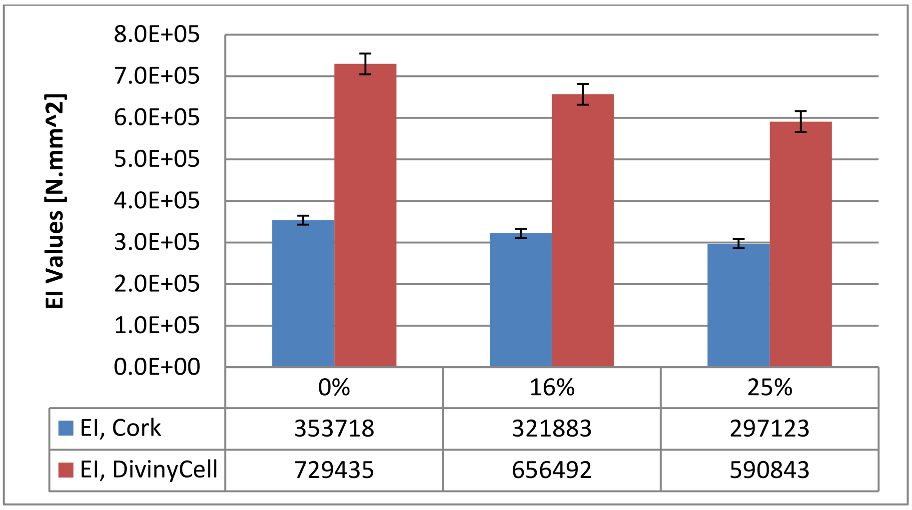


Figure 59- EI values in bending

Table 24 – EI values in Bending with Standard Deviation and Coefficient of Variation and loss of EI values in %

		Cork	DivinyCell
		EI N.mm^2	
0%	Average	353718	729435
	STDev	11106	56531
	CV [%]	3.14%	7.75%
	EI Variation	0%	0%
16%	Average	321883	656492
	STDev	14540	52540
	CV [%]	4.41%	7.87%
	EI Variation	-9%	-10%
25%	Average	297123	590843
	STDev	14541	24419
	CV [%]	4.89%	4.13%
	EI Variation	-16%	-19%

The values of the EI decrease with the increase of impact energy. All panel types experience a loss of EI with increased impact energy, since there is damage in the faces, although the DivinyCell cores drop in values is more than the cork cores.

Compared between them the DivinyCell cores have better values of EI in all impact energies (about double that of the Cork cores) although the gap tends to decrease

slightly from potential energy level to potential energy level, especially at 25% energy levels.

The Cork core Sandwich specimens, although with a much smaller value of EI experience a smaller loss of performance when compared to the DivinyCell Specimens, slightly shortening the distance between both core types.

There is a slight loss of flexural stiffness in these new batches of tests in the non-impacted specimens (Table 24) compared to the first non-impacted specimens tested (Table 11), of about 2%, well inside the Standard deviation of both tests. The biggest change between both un-impacted tests is the reduction in the Variation of the flexural stiffness value. The fact that these tests had less specimens coming from only two boards, compared to the 63 specimens from 6 boards from the first tests, could also explain the greater deviation.

3.7.4. Conclusions

Impact at certain levels cause damage to the composite structures that diminish the mechanical properties of the structures in bending even at BVID ranges. Both the maximum stress supported as the flexural stiffness decreased, especially on Divinycell cores, with the loss of flexural modulus at impact energy of 1.675 J/m (25% potential impact energy) of almost 20%. The cork cores, although starting with much smaller values of EI behave better with the impact, *i.e.* loses less performance, possibly due to the epoxy resin that permeated the existing voids of cork in the core prior the hand lay-up manufacturing, and/or to the ability of cork to absorb more impact energy and thus creating a smaller impact area on the specimens.

3.8. General Discussion and Conclusions

After all the results had been analyzed, several conclusions could be immediately reached.

Regarding compression, the difference in results of the cork cored specimens and the Divinycell specimens are statistically insignificant due to high result variability with the cork cored specimens having less variability than the DivinyCell cored specimens.

Regarding impact, both specimen types have an energy absorption capability of around 11.5J mostly due to the GFRP skins. Divinycell cored specimens have no perforation of the lower skin sooner than the Sandwich cored specimens (at 50% potential impact

energy). The force of impact is the same for both core types at a given impact energy (since it is a function of the test itself and not the specimens), as are the values of absorbed energy. The only other difference in specimens is the lower delaminated area of the Cork cored specimens at BVID levels, pointing to a better ability of the cork cores to absorb Energy.

In the first bending tests the cork cores had an average stress higher than the Divinycell cores, when considering only the cores and the entire specimens, but with a 50% lower value of flexural stiffness, due to the sandwich cores. In the bending after impact tests, the DivinyCell cores continue with much higher values of EI, but with a higher performance loss for higher impact energies when compared to the Cork cored Specimens.

After the rounds of test a meeting was scheduled with NELO to discuss how to proceed. With these results, the performance penalty of the sandwich cores was too high to apply in competition level kayaks, with a 0.5 kg increase in weight, when comparing similar levels of performance. For the Touring models NELO produces, a mid-level kayak for leisure activities, the weight penalty of the kayaks was considered less important than the cost reduction of the cork cores and NELO is currently producing some Touring models with Cork cores. Finally, although the Cork cores are potentially greener than the Divinycell cores, when analyzing all the materials used during the construction the possible environmental difference between the cores represent a small parcel of the total impact of the kayak Figure 61.

Figure 60 – Demonstration Kayak with CoreCork Core material [83]

This leads to an interesting question, what can be considered “green”? Using this case as an example, is the sandwich structure with cork cores “greener”? Possibly. But does the increase in material needed to equalize mechanical performance offset the smaller environmental impact of Cork? Does it still qualify as “green”? And what is a useful

measure of "green", especially now that "green" is such a marketing buzzword? *Reductio ad absurdum* the only true "green" materials, parts or processes would be those with no impact on the environment, which is an impossibility. But between that position and one that states that a reduction in 0.001% in environmental impact makes it "greener", a sentence that while true mathematically completely misses the point of environmental impact reduction, there is a lot of space to accurately and effectively measure the "green" improvement of a material, part or process.

For instance as Figure 61 shows, even if cork is a much "greener material" than Divinycell the fact is that by weight they represent a very small parcel of the economic impact

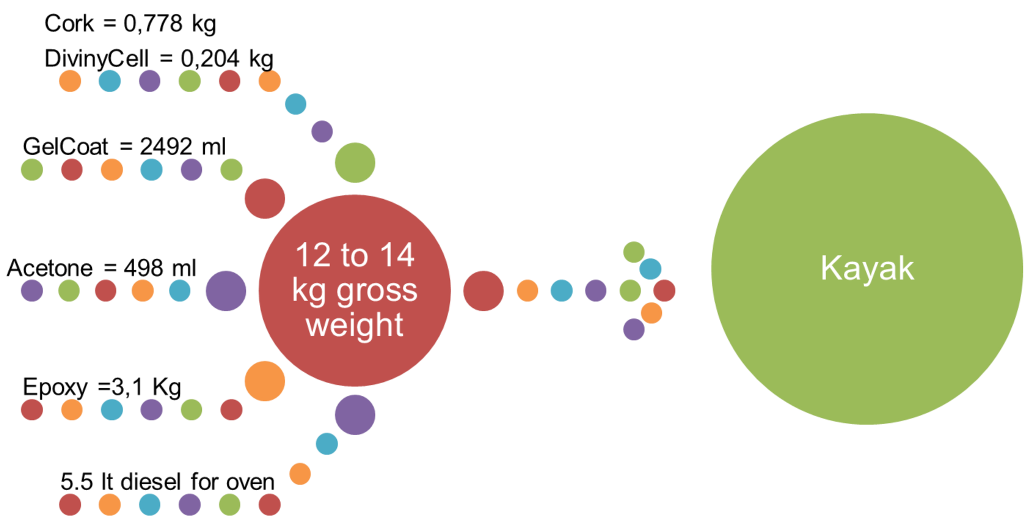


Figure 61 – Materials applied in a Viper 51 Kayak per quantity

3.8.1. Final Remarks

With the tests concluded several questions were raised. First, since the environmental impact of the cores was not a big parcel of the total environmental impact of the product, where else could the impacts be diminished; Second the limiting nature of purely mechanical tests should be recognized; and finally the decisions made during the meeting spurred an interest in material selection, and how could material selection methodologies help with decisions such as the ones taken by NELO. The next chapter deals with both these questions.

4. Developing a multiple analysis framework

In this chapter a multiple simultaneous performance analysis framework is discussed, taking advantage of the single performance metric study performed in chapter 3 and expanding on the subject of multi performance metric analysis. The material substitution problem, which this thesis also encompasses, will be addressed. The first subsection deals with the results of Chapter 3, specifically subsection 3.8, expanding on the remarks and conclusions presented in order to demonstrate the need for a more encompassing study of materials. Subsection 4.2 presents and develops the general makeup of a framework intended to study composite material selection for any given part taking into account more than just the mechanical properties. Subsection 4.3 delves into the concept of *Pareto optimality*. Sub-section 4.4 talks about the processes used in the manufacturing of composite materials and finally Sub-section 4.5 talks about composites including basalt fibers.

4.1. Limitations of the purely mechanical approach

Chapter three was a pure mechanical approach to the problem submitted. While mechanical performance is of course an important variable of any project, the sole focus on mechanical properties can be detrimental to a product.

First off, any approach of material substitution that does not take into account the cost of such substitution is, in an Industrial environment, frankly useless. Using a new material, however much lighter it may be, or how much better the mechanical performance is when compared with the incumbent material, but that in turn raises the product cost to a level above which the market is willing to pay is to doom a possible viable project to oblivion.

Environmental considerations and sustainable development, are also taking a much more relevant role since the turn of the millennium as mentioned throughout this work, which means that companies are fundamentally more aware of the impact that their new products have on the earth and its population, and are actively trying to diminish their activities footprint either through direct means, incorporating greener solutions in their designs, or indirectly, using the automotive industry as an example, by increasing gas mileage of the standard automobile. This is also extended to new and improved production processes, since a fair share of the environmental impact of a new product comes from its manufacturing

It must be taken into account that all of these parameters are also relative. If somehow the new material adds value to the product, by being able to be labelled green, or state of the art, or any other myriad terms for example, the increase in cost can be offset by the new “perceived value” of the product [84], [85].

Other considerations are also of import. As Leite showed on his thesis [86], when considering a product as part of a larger family maybe even if a new material beats the incumbent in all performance metrics, it may still be preferable to continue using the incumbent material given certain parameters (given certain conditions of economies of scale). Social issues of adopting new solutions must also be considered, as mentioned with the Corn based Ethanol example in Section 1.3.

The problem is of course not restricted to a purely mechanical focus but can be expanded to any problem where multiple conflicting objectives compete for attention to focus solely on one aspect in detriment of all other.

4.2. Framework discussion

In Chapter 3 a simple material substitution task was performed, in the sense that the only concerns were mechanical properties concerns, with the cost and environmental problems already set aside and with an incumbent material to compare to. Even with only mechanical concerns analyzed, the amount of tests required to validate the material selection was somewhat vast and time consuming. After the results of Chapter 3 questions were raised: What if the selection also focused on the cost aspect? What if environmental concerns were also raised? What if there was no incumbent material, so that instead of comparing materials to a baseline, the materials would have to be compared amongst themselves? And if all of these concerns were present how to develop them in tandem giving each part its true value? And most importantly, how to achieve any degree of automation on what could be an extremely time consuming problem? These questions, led to the development of the framework present in this thesis, which will be explained and discussed in this chapter and the next one.

4.2.1. Framework basis

To summarize, could a framework be created that analyzed multiple composites in multiple attributes with a high degree of automation? The answer is yes, since MCDM were created to solve multi criteria problems, so it is a question of developing a framework but regarding material selection, and such tools exist. The problem is that no

such framework has been developed for the specificity of composites, particularly the anisotropy present in most, if not all, composite materials.

Reductio ad absurdum, isotropic materials are simple to develop, given that the number of properties required to apply an isotropic material to a product are few and simple to determine. Composites, with its mix of resin and fibers, can have different properties depending on a high number of variables, including different resins and fibers, fiber weaving, fiber volume, number of layers, ply stacking orientation, void percentage, manufacturing processes etc., which increase the complexity of selecting the "best material" for an application by orders of magnitude, so the framework would have to deal with most of these variables, some being process specific.

Since some properties are process specific, for example, some resins are unsuitable for some processes, either by having a long or short gel time, and the costs of running different processes are different, that means that the framework also has to include a way to factor in the manufacturing process.

Regarding properties, what would be the most important to consider? Obviously that the mechanical performance is still important (no product has ever succeeding in the market without succeeding in its given task), so the composite materials would have to be able to sustain the required performance. There is no need for them to exceed this value of performance so we are considering Isoperformance, which means that the ability to carry the loads intended cannot be a selection variable, since if a certain stacking sequence/resin and fiber mix/number of plies does not perform it cannot be part of the general solution space, meaning that other variables must be found. Variables for consideration should be chosen carefully, since different markets/companies have different necessities. A *Mechanical Performance* and easy to measure variable should ideally be chosen, and *Weight* is, in most applications something that is to be minimized. Anecdotally, companies always go for the lowest cost possible, so *Economic Cost* is one general variable, *i.e.* suitable to most companies/products, to include. Finally *Environmental Cost* is a very important variable to track, as said in the first chapters.

Of course that the Engineer/practitioner using this framework might disagree with the variables chosen, or agree but could wish to add more variables, or change the way the

chosen variables are calculated so the framework also has to have a high degree of modularity, in order to be able to add/remove/change the way the tool might work.

As such, the framework must possess the following:

- Database or database hooks to obtain the properties of the materials one wishes to evaluate;
- A way to determine if the materials/stacking sequence/number of plies/manufacturing process combinations being evaluated are able to perform its duty, and comply with other constraints;
- A way to determine which of the materials/stacking sequence/number of plies/manufacturing process combinations that pass the Isoperformance test are the best solutions;
- A way to deploy this information to the engineer/practitioner in a suitable way.

4.2.2. Overview of the framework

With all of the above in mind, developing a framework to take multiple objectives into account, and rank them in order to determine the best materials for the requirements became the driving force of the thesis from that point onward for a number of reasons. It would allow the automation of the always cumbersome work of determining material orientation and number of layers for a given composite; it would allow for multiple composites to be analyzed concurrently and it would allow the analysis of more than one parameter in order to select the best possible materials for an application. By being mostly hands-off it would not allow a user to express material preferences until the final stage, *i.e.*, it would be difficult for a user to game the program into delivering the results the user wanted *a priori*, which would allow for new materials to surface as possible results, and not be discarded from the beginning by simply being new to the decision maker. By integrating environmental concerns right from the outset, they take on an equal footing with the usual concerns of cost and performance, a staple of Sustainable Design. With all of this in mind the framework goal could be codified as:

"A decision support framework to advise on the best possible composite layup for a part, depending on shape, loads, and other factors, by taking into account the Performance dimension, the Economical dimension and the Environmental dimension,

ensuring that the selected material is able to cope with the required scenario, while using the least amount of material necessary per composite".

Finally, by establishing a cohesive and strong backbone, the framework could be highly editable by an engineer or practitioner, allowing for performance models suitable to any particular case study.

4.3. Decision making in material selection

As seen on chapter 2 there are many Multi Criteria Decision Methods (MCDM) to choose from, from TOPSIS to VIKOR [61], [70]. The main issue with these methods, given the scope of the framework is the fact that they must be constructed either by or with, the decision maker. Since one of the frameworks goals is the suitability to multiple cases, a tailor made MCDM would be counter to the frameworks goals. Since a selection of the best materials would still have to be performed by the framework, this selection is made by using the concept of *Pareto Optimality*.

4.3.1. Pareto Optimality

Developed by Wilfred Pareto, it is a technique to optimize a system with multiple attributes without penalty to any of them. Initially developed for economic systems, Pareto proposed that, if the standards of living of any one could be improved without detriment to another these systems were not efficient, and thus could be improved [87].

In other words, if we have a space of possible solutions to a problem this space may fall into one of three categories; completely dominated, where one solution, is better than all of the other solutions, neither dominated nor dominating, where there are solutions with better values for some variables than others, but worse in others, and finally the non-dominated solutions, which are the solutions with the best trade-offs between values, with this last category also known as the *Pareto Front* [88].

Since in Engineering most problems have more than one variable, even the *Pareto Front* often have a big number of solutions, correlating exponentially with the number of variables being studied, that, although far smaller than the original solution space, may cause problems when choosing one of these alternatives. [89].

It is used in material selection problems in order to decrease the number of materials to a group of "best" alternatives taking into account all of the considered variables or constraints. One such use is done by Marco Leite in his Thesis [86].

4.4. Processes

Composite materials can be manufactured in several different ways, depending on performance requirements, initial investment, cycle time, production volume expected, part complexity and part size. Generally speaking, the two most used requirements in process ranking are performance and production volume (Figure 62).

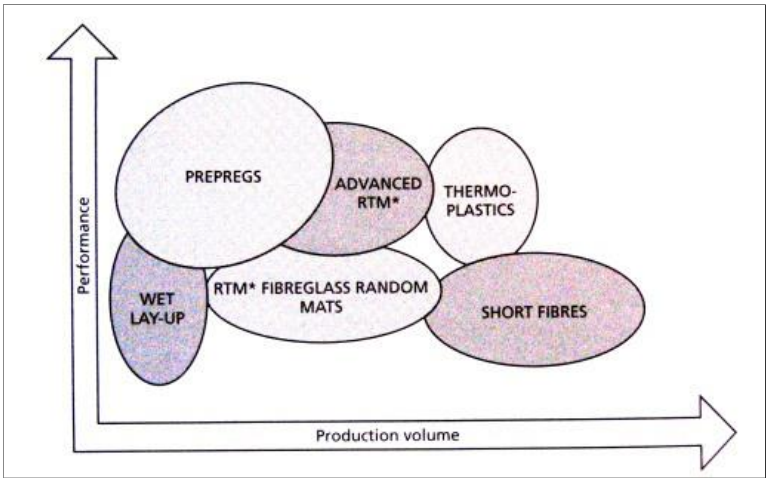


Figure 62 – Performance *vs* Production volume ranking of composite materials manufacturing processes [90]

There are more composite materials production processes than the ones shown on the figure and all of them would overlap in some way on Figure 62. They can be divided into open mold processes, such as Hand/Wet Lay-up and Spray up, and closed mold processes such as Resin Transfer Molding (RTM), Infusion and Wet/Hand Lay-up with vacuum bagging, all of them with advantages and disadvantages. For instance Hand Lay-up is a process with a small initial investment, able to produce some complex shapes, but it is unsuitable for large scale production due to the high cycle times. Conversely Compression molding has a very low cycle time, but a very high initial investment. Most of these methods, with the exclusion of spray-up, can be used with either woven or filament fibers and with prepegs (pre impregnated mats or filaments fibers).

The next paragraphs present an overview of some of the commonly used processes:

- **Spray Up** – Along with Hand Lay-up, it is an open mold process, used in very large parts and/or in low production volumes. The mold itself is inexpensive compared with closed molds, given than almost no pressure is applied to the mold. The

process itself, seen in Figure 63, begins with the application of a gel coat to the surface of the mold, to produce a smooth outer layer. Then a mixture of resin, resin catalyst and chopped strand are sprayed into the mold, and a roller is used to remove the air from the composite and equalize the thickness of the layer. This process is repeated until the required thickness is achieved, and in some cases, woven fiber is used to reinforce certain sections and add thickness to the part. The composite is then cured at room temperature. Although it is a comparatively inexpensive process it does have a few drawbacks, the two most important being low and uneven mechanical properties due to the use of short strand fibers sprayed into the mold cavity, and a high emission of pollutants into the atmosphere, during manufacturing and curing due to the open nature of the mold.

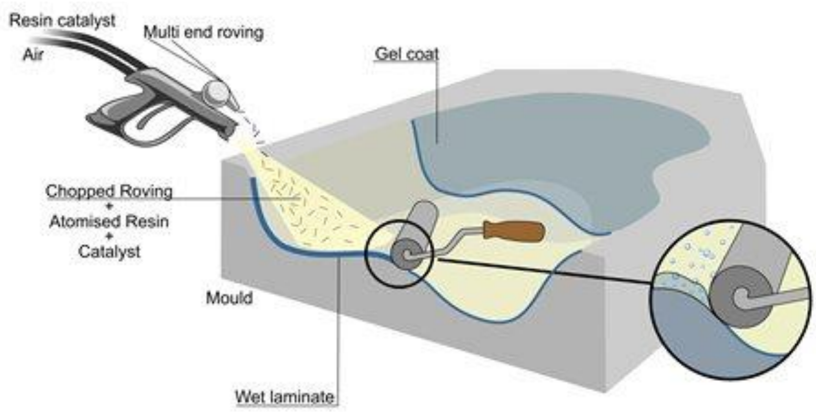


Figure 63 - Spray Lay Up Process [91]

- **Compression Molding** – Compression Molding is a closed mold process used in medium to high production volumes. It has a very large initial investment mainly due to the use of forge steel molds and heated presses capable of achieving over 250ºC and over 170 bars. It offsets this initial cost by the cycle time and the fact that, although the molds are expensive, their projected life time is generally around 200 000 parts. Fundamental to the process is the use of sheet molding compound (SMC), which is chopped fibers sandwiched between two layers of resin, and rolled to impregnate the fibers and remove excess air from it. After curing the SMC is easily handled. The process begins by placing the SMC inside the mold which is the clamped pressed and heat up to the temperatures and pressures mentioned above. As the temperature and pressure increases the SMC flows and fills the mold cavity as can be seen in Figure 64.

Figure 64 – Compression molding process [92]

- **Injection Molding** – Injection Molding is a closed mold process with a very low cycle time and used in high volume production (up to 2 000 units/hour). While it initially used an injection compound of resins and chopped glass fiber, as seen in Figure 65, Injection Molding has been taken over by the use of Bulk Molding Compounds (BMC). BMC is similar to SMC, and with a similar manufacturing method, although with a lower fiber percentage (30% vs 60%) and lower fiber length (12.5mm vs 25mm).

  The process of injection molding with BMC starts when a plunger forces the BMC through a heating channel and into the closed and heated mold at about 82 MPa, the heat and pressure fluidifying the BMC and allowing it to completely fill the mold cavity.

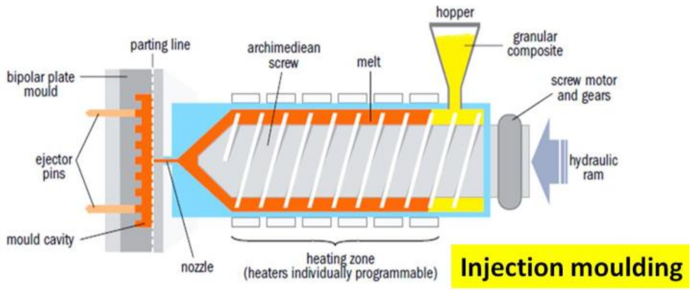


Figure 65 – Injection Molding process [93]

- **Resin Film Infusion** – Resin Film Infusion is a closed mold process, where Dry fabrics are laid up with layers of a resin film in multiple layers. The lay-up is vacuum bagged to remove air through the dry fabrics, and then heated to allow the resin to first melt and flow into the air-free fabrics, and then after a certain time, to cure, Figure 66.

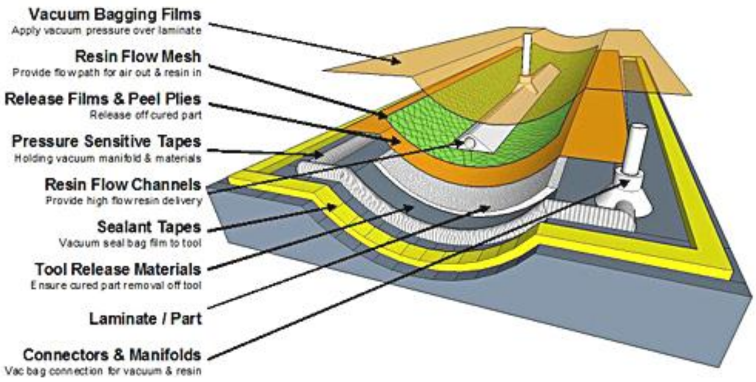


Figure 66 – Resin film infusion [94]

Finally there are new methods of manufacturing such as **Automated Fiber Placement** (AFP) and **Automated Tape Laying** (ATL), where a Computer Numerical Control (CNC) robot places prepeg fibers (AFP) and prepeg tape (ATL), and place them in an exact pattern and/or orientation according to the instructions of the programming. These new technologies allow for an increased processing speed and reduced costs (both labor and composite scrap), but more importantly, they increase part consolidation and uniformity, but at a very high initial investment cost.

Within the processes available, two were selected for inclusion in the framework, namely Wet/Hand Lay-up with Vacuum bagging (HLU) and Resin Transfer Molding (RTM). Both these methods are similar in part quality and part performance, allowing for a direct comparison of other variables other than pure mechanical performance, but differ in initial investment and production volume capabilities among others. These two processes will be discussed in the next two sub-sections.

4.4.1. Hand Lay-up

Hand Lay-up is an open or closed mold process, often considered the simplest of the composite processes, due to its low requirements in terms of materials and ancillary equipment, and its main advantage is the lowest initial investment out of all of the composite processes. Used for low volume production of parts (Figure 67) it is especially suited to the production of large parts such as kayaks, wind turbine blades, hulls and caravans. Although it is generally considered an open mold process, it can also be used as a closed mold process by using vacuum bagging similar to the Resin

Film Infusion Process above, and for the purposes of this work, when Hand Lay-up is mentioned it is always in the form of a closed mold process with vacuum bagging.

Figure 67 – Hand Lay-up built kayak [95]

The manufacturing process begins with the application of Gel-Coat in the face of the mold. When the gel coat has cured, a layer of fiber is placed in the mold, and then catalyzed resin is applied on the mold. A roller is then used to ensure that the fiber mat is wet, to remove entrapped air and to ensure the same thickness of the resin-fiber composite. This process is repeated the necessary number of times to ensure that the required thickness is achieved (Figure 68). Reinforcements in specific directions can also be applied during this stage to ensure that everything cures together and that a single, monolithic part is produced. After this process a plastic film is placed over the mold and sealed at the mold edges. Air is then removed, creating a vacuum, in a process known as vacuum bagging, and then placed in a curing oven at mild temperatures (45º to 60º Celsius), to increase the mechanical properties of the composite.

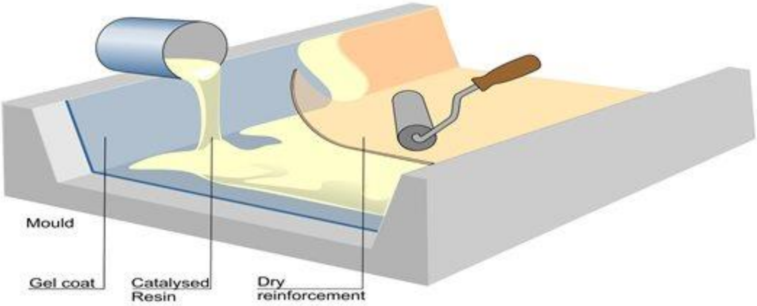


Figure 68 – Hand Lay-up process schematic [96]

The main advantage of Hand Lay-up is, as mentioned above, the low initial investment cost, given that, oversimplifying it; all you need is a mold. Other advantages include the fact that by being a widely used process for so long its variables are known by all. Finally, the process is well suited to various shapes, and sizes, practically all of the fibers in the market are usable as do the resins, as long as the resins have a medium-long gel time.

Its disadvantages include the long cycle time of the process that limits the feasibility of higher production volumes, and somewhat lower mechanical properties when compared to the same part using other processes. The latter disadvantage comes from the process itself. Since Hand Lay-up is a manual labor intensive process, much of the mechanical properties are dependent on the worker building the part, which means that repeatability is an issue, since by the very nature of the process, the layer orientation may be disturbed, including local distortions and scissoring effects, resulting in less than expected mechanical properties. Finally aspects of the final part such as final thickness, fiber volume and weight are difficult to control, limiting the process whenever the dimensional and geometrical tolerances are exacting.

4.4.2. RTM (Resin Transfer Molding)

Resin transfer molding is the general name of a few closed mold process, used for low to medium production volumes, with a higher investment cost than open mold processes but generally lower than other closed mold processes. This family of processes is composed of RTM, Vacuum Assisted RTM (VARTM) and Light RTM.

The RTM process itself, Figure 69, begins with the cutting of the woven fiber mats into the shaper required for the part, in the required number of layers, the next step is the placement of the fibers on the mold in the required orientations, Figure 70. Afterwards the mold is closed and placed in a heated press (with temperatures ranging between 35ºC and 100ºC and pressures between 1 bar and 6 bar, depending on parameters such as part geometry, part dimensions, fiber weaving method, and viscosity of the resin), until the whole mold is at the required temperature. The next step is the injection at constant pressure or flow of a pre catalyzed, very low viscosity resin, filling the mold and creating the composite. The part is then left to cure in the mold until it is removed from the press and the mold, generally almost cured [97], [98].

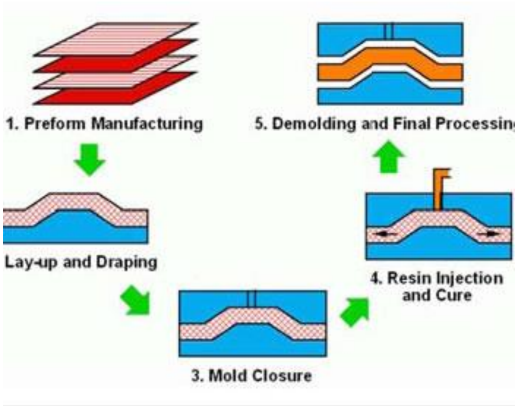


Figure 69 – RTM process schematics [99]

Figure 70 – RTM mold [100]

Regarding other closed mold processes RTM has some advantages. It does not require the use of pre-pegs, since the process can use dry fibers and resins that can be stored at room temperature, has little to none post fabrication work, a lower cost workforce than with other closed mold processes and finally the initial investment costs are lower. Its main drawback is the somewhat slow cycle time, that makes RTM an unfavorable choice for very large scale production.

Vacuum Assisted RTM (VARTM), is a variant of RTM, where instead of the resin being pumped into the mold it is instead drawn into it by the use of vacuum. It allows

for a very high fiber volume in a part (up to 70%) and the construction of very large parts in a single step, at a higher cost of mold production, since the molds are more complex and require significant work, due to the fact that there is generally more than one injection port on the part, and the resin feed channels are generally longer and in mold.

Light RTM, is a mix between RTM and VARTM, where low pressure injection is coupled with vacuum, allowing the use of different lighter, and cheaper molds to produce the parts, with similar quality and void content.

In this document the designation RTM refers the process of RTM proper and not VARTM or Light RTM.

4.5. New Composite Materials challenges

There are many materials that can be used in composite design from fibers to resins, with the possible combinations between them almost boundless, starting with the "regulars" like carbon fiber passing through aramids and glass fiber, and with resins ranging from the ever ubiquitous Epoxy resins to the esters family of resins up to resins such as Bismaleimide.

Unfortunately this vastness of choice is also the main issue with selecting composites as mentioned in chapter 1. Even if the problem is reduced to only one fiber/one resin, an engineer must select from the triumvirate number of plies, stacking sequence, fiber volume and others like what kind of fiber weave would suit the composite better, all with an impact in the global behavior of the composite. There are several ways to work around this problem, but these solutions are problem based. One example is the use of prepegs, with very specific instructions of use which yield similar results to the ones indicated by the companies producing these materials. Unfortunately prepegs are not suitable to all of the manufacturing processes mentioned above so the choice of prepegs ultimately limits the choice of manufacturing process to be used, and *vice-versa*, which may not be the "best one" for a specific application given production size or cycle time. If the prepegs are discarded most material companies tend to show the results of their fibers/resins using a composite with the best possible combination of fiber volume/number of plies/stacking/weave triumvirate for the tests performed. This methodology causes problems when comparing different composites since not only there is no global comparison baseline, there is no test report other than the results and

the fibers/resins used, (leaving out for instance composite lay-up, production method, and thickness) which means that if the engineer in the company that wishes to produce a new product, changes one of the parameters of the triumvirate, he cannot be certain that the results will be as expected.

The material companies themselves cannot test all possible combinations of resin/fiber since, as it will be seen in sub-section 4.5.2.1, the numbers of tests required for the determination of relevant mechanical properties can be quite large and assuming the minimum of 5 tests performed per test method (and some tests were performed twice, one for each direction of the fibers), means a minimum of 40 tests performed **per composite material composition**. Coupled with the necessary work to produce the test specimens, and as mentioned in subsection 3.3 the difficulty in producing good composite specimens, this characterization is time consuming and requires some specialized and expensive equipment to perform.

This also means that most companies that wish to build a new product also have no way of testing new materials, and that factor together with the risk-averse engineer mentioned in Chapter 1, means that companies rarely invest in new materials until they are a proven commodity.

Most material companies try to compensate this lack of information with contact request in order for them to determine the best way to use their materials in the new product, but this does not solve the issue that, in the beginning of a new project, there is no such thing as the final product, and as such no way to accurately gauge the performance of these new materials.

Even some dedicated sites, like Prospector Composites possesses little complete data for composites of a non prepeg nature, as it will be shown in Subsection 6.1.1 and a number of problems arise when attempting to fulfill the data gap.

Most of these issues are due to the analytical formulations developed specifically for composites. If talking about the possible properties of a composite the rule of mixtures can be used to obtain some relatively accurate data and several approximations can be used to derive other properties [101]. Although the data that can be derived from these formulations are generally enough to do some sort of part analysis, for instance when

the criterion is maximum deflection, there are some properties required for the use of some Failure Criteria that cannot be derived from these methods.

The failure criteria themselves need to be refined to produce accurate results, especially when the composites are working in compression. as Tan *et al.* [102] shows.

As such materials testing and the publishing of results (especially with a complete report about test conditions, test methods, apparatus, composite lay-up, production method, etc.) is possibly the best way that material R&D companies can make their products more appealing. It is not about testing all of the possible combinations of their new material, which would be prohibitively expensive, but to test the new fibers/resins in some globally accepted parameters, (using epoxy resins as the matrix for a new fiber or using carbon fiber as the material in a new resin, at certain fiber volumes, taking into account possible chemical bonding issues for example) that would make first pass comparisons easier. Showing the strengths **and** weaknesses of a new material, coupled with some real application studies, is, in the author's opinion, the best way to demonstrate the potential of a new material.

And if there are issues with the mechanical properties of the composites, the environmental properties are even more complicated to obtain. To alleviate the environmental issues, Bio-Resins and Natural Fibers have been studied intensely in these past few years and shall be discussed in the next sub section.

4.5.1. Natural Fibers and Resins General

As mentioned previously, although composites made with fibers such as carbon fibers and resins such as epoxy have very good properties when designed correctly, there is one unavoidable problem with them which is what to do with them at the End Of Life (EOL) stage. While recyclability is a possibility in some composites, most are simply burnt or buried, with the accompanying environmental problems related to those disposal processes [103]. In order to alleviate these issues, natural fibers and resins have been a very busy realm of study in this last decade, in order to obtain more environmental friendly composites.

The general definition of a "Natural" material is "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" [104]. The most studied "Natural" fibers are plant fibers from jute [80], ramie [105], sisal [106], among others. Bio resins study started at the same time as "natural" fibers, generally working together with them to provide true "green" composites [107], [108].

A good review of the current art in "natural" fibers and Bio resins can be found in the works of La Mantia *et al.* [109] and Koronis *et al.* [104].

Natural fibers have problems of their own. First of they have higher densities and lower mechanical behavior than other fibers (although recent studies have shown that these properties can be improved up to the level of Glass Fiber), and with quite variable mechanical properties depending on plantation location, seasonal weather patterns and all the problems associated with agricultural production. Additionally in wet environments the life time is much smaller than most composites with severe aging problems. Furthermore, although these fibers may decrease the environmental impact of the product as they leave production, the fact that the normally used resins are impregnated into the natural fibers make re-use after the EOL a tricky proposition at best. If coupled with Natural resins the EOL image would be better but Bio resins have problems of their own. Most are thermoplastic, which means that they are unsuitable to most composite material manufacturing processes. They are afflicted by the same aging problems as natural fibers, unless specifically prepared, trading the biodegradability for an extended lifespan. Finally, as mentioned in Chapter 3 there are problems in finding bio-resins with the necessary Gel-time for the Hand lay-up process, and for RTM.

There is also another "natural" fiber (although its status as a true natural fiber is debated, given the definition above), which is not plant based, basalt fibers. Given the work on the plant based "natural fibers" already done, basalt fibers were the ones selected for this study. The next subsection deals with those fibers.

4.5.2. Basalt fibers

Created and developed by the Moscow Research Institute of Glass and Plastic on the former Soviet Republic in the 1950's, Basalt Fibers, produced by the melting and extrusion of Basalt rocks, which themselves are a product of volcanism processes, is a Natural fiber with high mechanical properties and cost-effectiveness [110].

Although possessing properties close to, or better than Glass fibers, due to the possible military and aerospace applications of Basalt Fibers, the research made was deemed sensitive and thus classified until the arrival of Perestroika in the early 90's.

Nowadays, the main production method of basalt fibers is similar to Glass fiber, with the melting of washed and broken Basalt rocks at temperatures around 1500ºC. The material is then pushed through a bushing with hundreds of small holes which is then spun into a yarn, creating basalt fibers [111].

Initially studied from a civil engineering view, especially the reinforcement and strengthening of concrete structures, the properties of Basalt fibers soon caught the attention of the engineering community, and extensive studies have been performed on basalt fiber composites, as shown by Fiore *et al.* [112].

4.5.2.1. Basalt composite tests

Since it was chosen to use Basalt Fibers as the new "natural" material to be used, data would have to be collected on the mechanical behavior of Basalt Fiber in a composite.

For that purpose an IST Masters student Rafael Preto studied the mechanical properties of a 2/2 twill bi-axial 0º/90º basalt fiber with Unsaturated Polyester (UP) Resin composite material [113] with a fiber volume of 30%, manufactured by RTM, that would be fed into the Framework proposed above and expanded on in the next chapters.

The mechanical tests performed were as follows:

ASTM D 3039 - Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials

ASTM D 3410 - Standard Test Method for Compressive Properties of Polymer Matrix Composite Materials with Unsupported Gage Section by Shear Loading

ASTM D 3518 - Standard Test Method for In-Plane Shear Response of Polymer Matrix Composite Materials by Tensile Test of a ±45° Laminate

ASTM D 4255 - Standard Test Method for In-Plane Shear Properties of Polymer Matrix Composite Materials by the Rail Shear Method

The test results are shown in Table 25.

Table 25 – Basalt/UP composite Mechanical properties [113]

	Thickness (m)	E11 (Pa)	E22 (Pa)	E33 (Pa)	G12 (Pa)	G13 (Pa)	G23 (Pa)
Basalt	3.13E-04	1.4E+10	1.40E+10	1.40E+10	2.70E+09	2.70E+09	2.70E+09
	+S1 (Pa)	**+S2 (Pa)**	**-S1 (Pa)**	**-S2 (Pa)**	**S12 (Pa)**		
Basalt	4.60E+08	4.60E+08	-4.00E+08	-4.00E+08	4.20E+07		

4.5.3. Paddle blade

This case study was developed in conjunction with Master's student Rafael Preto who was working on his Master's thesis [113] studying the mechanical behavior of basalt fiber composites. Although the test specimens, tests and ABAQUS model were built in conjunction, the goal of the tests regarding Rafael Preto thesis was to determine if the data collected during the mechanical tests could be considered valid, the purpose of the tests for this thesis was to study a real-life application of the tool and to determine if the Basalt fiber/UP Composite was present in the solution space.

4.5.3.1. The Kayak paddle blade: Specimens

In this subsection the manufacturing of the kayak paddle blade specimens (Figure 71) is discussed.

Figure 71 – Kayak paddle blade

In order for the specimen to be manufactured by the Hand/Wet Layup method, a mold was designed in SOLIDWORKS where a 3D surface was created, with the dimensions shown in Figure 72.

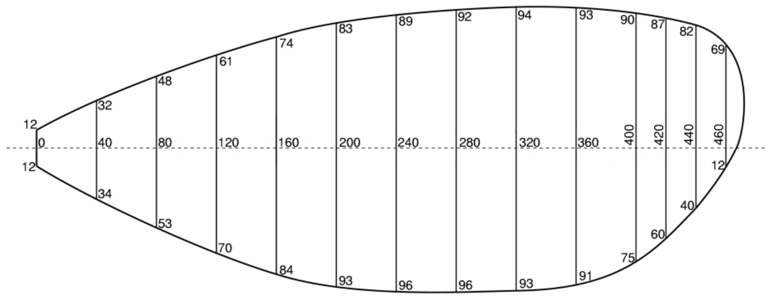


Figure 72 – Paddle Blade Dimensions [mm]

This surface was then used as the mold face, with the mold being produced in a CNC machine using polyurethane. This mold was then attached to a Medium Density Fiberboard (MDF) surface and coated with UP Resin, to seal and smooth the mold (Figure 73).

Figure 73 – Mold used in the manufacturing of the paddle blades

With this mold the specimens were then manufactured at IST using the Wet/Hand Layup manufacturing method as discussed in chapter 4 (Figure 74 and Figure 75).

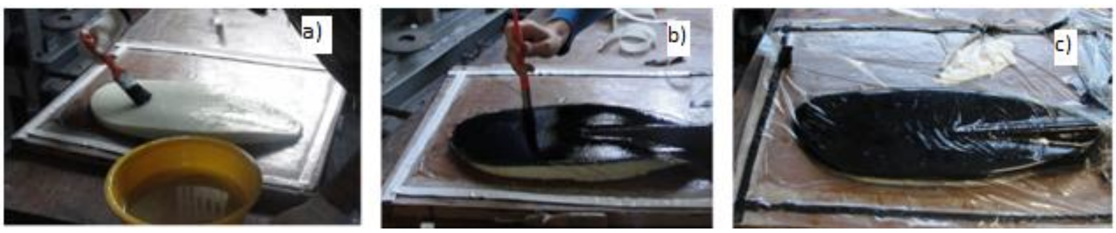


Figure 74 – Some hand/wet lay-up steps: a) initial resin coating; b) fiber wetting; c) vacuum bagging of the specimen [113]

Figure 75 – Vacuum sealed paddle blade specimen

Specifically, the specimen was created with 8 layers of a biaxial 2/2 twill of Basalt fiber aligned with the major axis using Unsaturated Polyester as the resin, and vacuum bagged. The mold was coated with a demolding agent, and a resin absorbent textile was used to absorb the excess resin. Two specimens were manufactured with this method, for redundancy and confirmation (Figure 76).

Figure 76 – Paddle blade specimens

The main difference between specimens was the handle length, with the first specimen having a longer handle. In terms of manufacturing there were a few problems with the first specimen during manufacture. This was due mainly to the fact that there were some problems maintaining a low vacuum in the first specimen, due to leaks near the end of the handle, and the unfortunate fact that one of the compressors malfunctioned during the vacuum process. In the second specimen the level of vacuum was much constant and lower, which resulted in a better surface finish with no delamination in any area, and presumably a better mechanical behavior. Finally the different thickness of the

paddle blade specimens when compared to the specimens tested in subsection 4.5.2.1 points to a higher fiber volume, which may have influence on the results.

4.5.3.2. The Kayak paddle Blade: Testing

- **Mechanical**

The paddle blades were fixed to a support structure, in order to allow no movement of the paddle handle as Figure 77 shows. Two digital probe indicators were placed on the test bed in contact with the paddle blade, one at the end of the aluminum rod and another 165mm from it and were used to measure deflections at those points on the axis line of the paddle handle. Loads were then placed at the edge of the blade, which could be increased in increments of 2N or 5 N, as in Figure 78.

Figure 77 – Test Bed

Figure 78 – End point load and digital probe indicators on the specimen

By increasing the load the deflection was measured in both probe indicator and the paired data load/deflection was then compared to the ABAQUS model shown in chapter 5. Figure 79 shows one of the specimens loaded and the corresponding deflection. Three

tests were performed with the first specimen being loaded twice (once in one face and once in the other) and the second specimen being loaded once.

Figure 79 – Mid test

- **Paddle blade test analysis**

As mentioned previously, the thickness of the paddle blade is somewhat lower than the thickness of the tested specimens which point to a different fiber volume content, and the quality of the first test specimen was lower than desirable. With that in mind after the tests were performed, an analysis was performed on the paddle specimens, specifically the first specimen to determine what problems a deficient HLU process could create.

Manufacturing problems

The first analysis was a visual inspection of the faces of the paddle blade to inspect for deficiencies. Figure 80 shows some of the defects found on the first paddle blade.

Figure 80 – Some manufacturing problems detected in the facings. Clockwise from the top left: Delamination of the topmost layer; wrinkling effect from insufficient vacuum/deficient bagging; insufficient wetting of the fibers; trapped air bubbles on the surface of the mold causing holes in the specimen

All of the problems shown on Figure 80 can be traced back to 3 main causes: insufficient wetting leading to areas with a lack of resin, with some delamination; Poor Vacuum bagging application leading to the wrinkles shown, and insufficient vacuum being applied due to deficient vacuum bag application and a problem with the compressor during the process.

In the second paddle blade specimen these problems were corrected leading to the faces shown in Figure 81 and Figure 82.

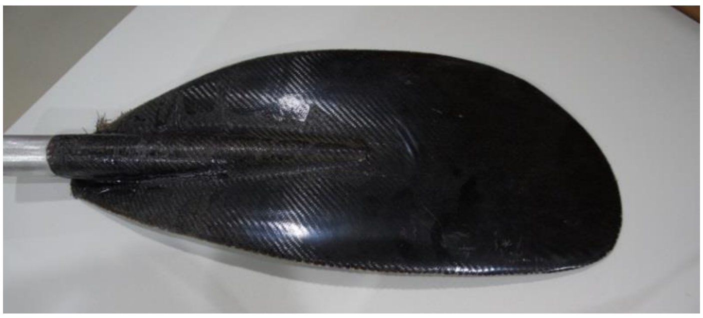


Figure 81 – top face of the second paddle blade specimen

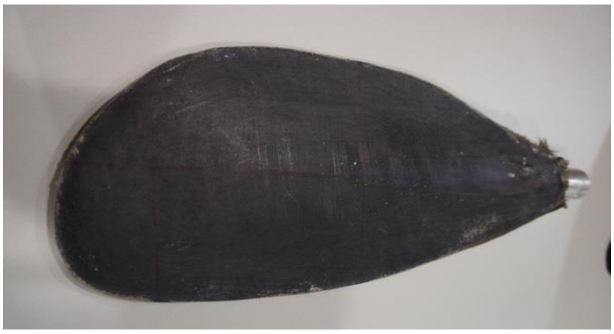


Figure 82 – Bottom face of the second paddle blade specimen

The only problem encountered in the second paddle blade specimen was a lack of resin in the topmost face, although with correct wetting of the fibers. The problem was due to an issue tamponing the top of the aluminum handle which led to some resin leaving the top of the paddle blade near the handle and subsequent pooling inside the handle as shown in Figure 83 and Figure 84.

Figure 83 – Lack of resin above the fibers near the aluminum handle

Figure 84 – Resin pooling inside the aluminum handle

To understand if the defects were also present on the inside of the paddle blade, and to determine the fiber volume of the paddle blade, the specimen was divided into 8 parts as Figure 85 shows. Visual inspection of the thickness of the paddle blade yielded the results shown in Figure 86.

Figure 85 – First paddle blade specimens

Figure 86 – inner defects of the first paddle blade clockwise from top left: Lack of resin and deficient contact between the composite material and the handle caused by insufficient vacuum; insufficient resin through the thickness of the specimen; voids and top layer delamination of the paddle blade.

As Figure 86 shows, there are a few problems with the inside of the composite paddle blade, due to the problems with establishing a good vacuum and a lack of resin as mentioned above. The problems with the vacuum are the main reason for the fact that there is little contact between the handle and the composite, and the resin.

Microscopic inspection

A microscope inspection of the paddle blade specimens confirmed the results of the visual inspection with some areas with little to no resin between layers, a product of

deficient resin depositing, and some voids and delamination being the product of insufficient resin and insufficient vacuum being created (Figure 87).

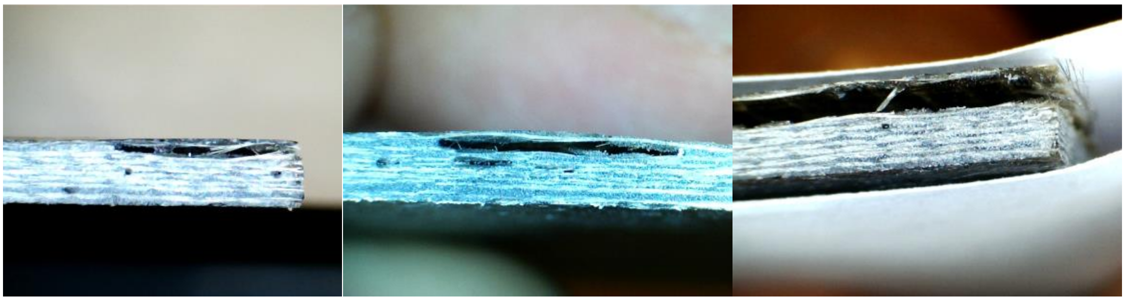


Figure 87 – Voids, resin deficit and delamination in the basalt fiber paddle specimens

Fiber Volume

Since the paddle blade was manufactured by RTM, there was the worry that the fiber volume percentage could be quite different from the specimens tested, which could invalidate the data, since different fiber volumes lead to different mechanical properties. To determine the Fiber volume, two specimens were cut from the first paddle blade created in two different areas, in order to determine the density of the composite, and use that value to compute the fiber volume, as seen on Table 26. Also measured was the Basalt fiber density since the density of the Basalt fiber used was given in kg/m^2, and compared with the tabled data for Basalt Fibers (Table 27).

Table 26 – Specimen density calculations and values

	graduated cylinder diameter [m]	Area [m^2]	water rise [m]	Volume [m^3]	Weight [kg]	Density [kg/m^3]
specimen 1	2.30E-02	4.15E-04	5.95E-03	2.47E-06	4.16E-03	1682.8
specimen 2	2.40E-02	4.52E-04	6.20E-03	2.8E-06	4.29E-03	1529.5

Table 27 – Expected Density *vs* Measured Density

Fiber Density [kg/m^3]	Expected	Measured
	2700	2483.4

Table 27 shows there is a difference between the expected fiber density and the measured density. There are a number of explanations: The tabled values for basalt fibers are not specific to the Basalt fiber used; the calculations performed to obtain the measured values are by necessity approximations; the value was calculated using the Composite density and the Resin density. There could be errors determining the Composite density (volume approximations mainly), and by calculation the Fiber density using only these two values, features such as voids on the composite (which exist in a fair number), would reduce the apparent density of the Composite which would in turn reduce the Calculated Fiber density.

Given what was said in the preceding paragraph, it was decided to calculate the fiber volume using the two values as the maximum and minimum % of Basalt fiber (Table 28).

Table 28 – Specimen Fiber Volume contents

	Composite Density [kg/m^3]	Fiber Density Expected [kg/m^3]	Fiber Density Measured [kg/m^3]	Resin Density [kg/m^3]	Fiber Volume Expected	Fiber Volume Measured
specimen 1	1682.79	2700	2483.37	1200	32%	37.7%
specimen 2	1665.41	2700	2483.37	1200	31%	36.4%

As the table shows, the difference in values between the two specimens is quite small which means that the paddle blade could be considered to have a uniform fiber volume. The difference between fiber volumes from the expected to the calculated are of about 5%, which, depending on what value is closer to the actual value of fiber volume percentage could have some impact on the mechanical properties.

5. The Heuristically Integrated Material Selection Framework [HIMSelF]

5.1. Development and Scope

5.1.1. Design

Since one of the goals would be the simultaneous analysis of the composites in terms of cost, performance and environment, indicators had to be chosen in order to evaluate all of the dimensions. A suitable means of determining what are the best combination of materials would have to be selected as well. The indicators chosen were Cost (€/unit), environment (kgCO_2/unit), and for performance the weight of the part (kg/unit). Cost was chosen since it is still the most important driver of any product, and for performance the choice relied on weight since all the composites that reached this level of analysis would have passed a mechanical performance test, *i.e.*, all of the composites analyzed would have to be able to carry the loads assigned, and weight savings is one of the most important factors that incited the use of composites we see today. For the environment indicator, the choice fell on kgCO_2/unit since it is easier to estimate and it is a value with a higher immediate impact than values of an eco-indicator, since even engineers are accustomed to think of environment as mainly greenhouse gases, although acknowledging that the CO_2 emissions presents a less complete picture of the environmental impact.

The CO_2 values were obtained from literature whenever possible, and when no data was found the data was based on the data on the CES EduPack Software database which determines CO_2 values as a percentage (8%) of the energy consumed during production. The main concern with this data is that it is an estimation with admittedly high variability, since the energy consumed by the processes to obtain a certain material is highly dependent of numerous factors, such as scale, equipment and general practices.

For the ranking of solutions, several MCDM were studied, but the decision relied on a Pareto Optimality Solution, where all of the non-dominated solutions of the Pareto front would be presented. From that point onward the ultimate choice of material is in the hands of the engineer or practitioner.

Given the task at hand, it was clear that in order to calculate the best stacking sequence and layer number for any given composite for any given part and for any given load that

the tool would have to be able to perform a vast number of calculations including Finite Element Analysis. Given the broad nature of parts that could be studied, the first choice for the FEA was the ABAQUS program, especially due to its python scripting capabilities, and in order to use the results of the ABAQUS program, and iterate it multiple times, the main coding program selected was MATLAB, given its, eventually, easy integration with the python script, the ability to export results in multiple formats and the ability, once programed, to automatically create figures and graphs. Finally within MATLAB it would be simpler to use the results from ABAQUS and feed them to a cost modelling and an environmental assessment, and rank the solutions by Pareto optimality, and the use of sub-functions allowed a "plug-and-play" style of programming where the main computational models share the same backbone and could be replaced without compromises to the main framework sequence.

Early in the development a modular approach to MATLAB programming was decided for the tool base. The decision was made taking into account three important factors. First the code for every different part of the tool would be constrained to that module, which meant cleaner code and more importantly all lines of code for a particular routine would be on a single file, easy to find and read. Secondly by modularizing the tool, debugging is facilitated, since each module could be tested independently, and allowed for a somewhat painless upgrade for each module since it didn't imply changes to the whole code, and only for that module. Finally that same modularity meant that it became possible to change modules for others, for instance when changing the cost model to suit a particular process, or updating the environmental model.

The modular approach also allowed the development of the tool in increments, *i.e.*, a simpler version of each module could be loaded into the program, tested, to determine, for instance, variable use and attribution, and then upgraded to the complete version.

Finally with a modular approach it is possible to maintain control variables along the program, such as number of composites being tested, and subsequently layer number and weight unchanged, and insures that these important variables cannot be changed by any calculations that exist in each module.

5.1.2. Manufacturing processes chosen for the test cases

The program would also analyze two different processes of creating the composites RTM and wet/hand lay-up, as shown in chapter 4. These two manufacturing processes

were selected since both processes work from the same base materials, which allows for a leaner comparison (they both use a resin and a matrix mixed during the manufacturing, unlike, for example, prepegs, which are already a mix of uncured resin and fiber). Production wise, these processes are the most alike in terms of part geometry, and in possible part complexity. RTM is a natural progression when going from the low volume / low costs that wet/hand lay-up allows, to a higher volume manufacturing process.

5.2. General Framework Overview and Modules

In order for the program to be able to calculate the best solution for any given part geometry, the initial data to be included by the user has to include, the ABAQUS data for that part, *i.e.*, the user has to draw the part, assign loads and boundary conditions, and determine what parameters to use as pass condition (Tsai-Hill Failure Criterion and/or max deflection at selected points, for example). The user then loads the tool and directs the program to the ABAQUS files, and includes the estimated annual unit production. From this point onwards the program runs through the ABAQUS file, and when it achieves solutions for all of the composites present in the database, it then runs through the Economic, Environmental and Performance modules, to determine the values of each indicator. Finally the tool determines the Pareto front of the solutions, and shows all of the non-dominated results to the user, allowing the user to select which Composite best suited to his needs.

Figure 88 shows the flowchart of the program execution.

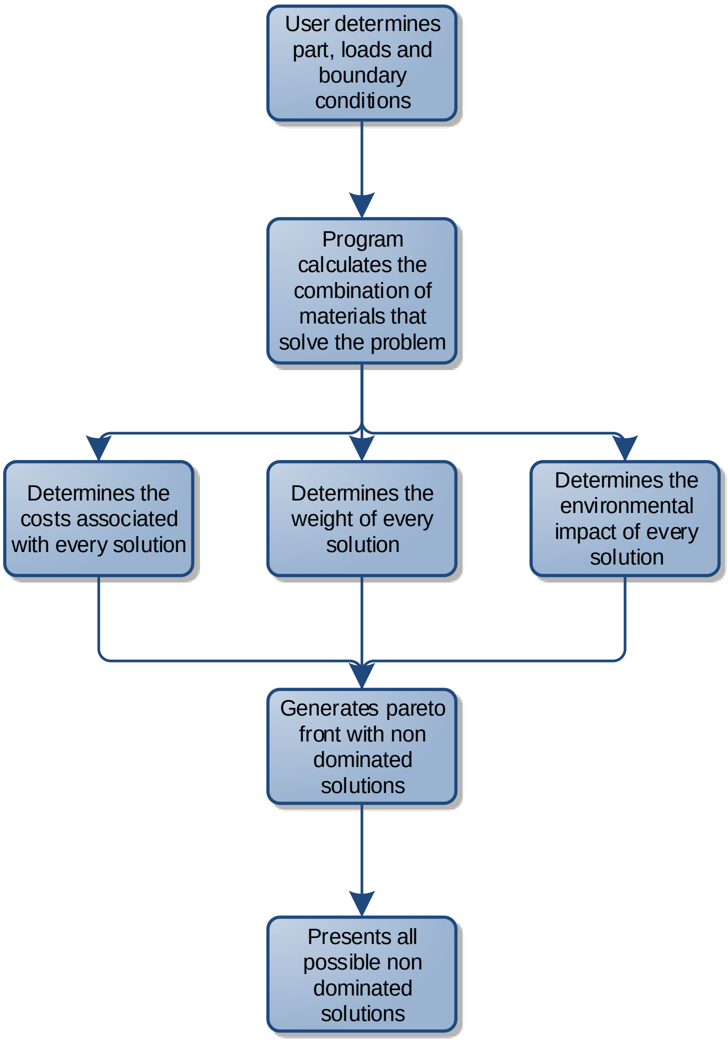


Figure 88 – General framework flowchart

5.2.1. Main Tree

The *Main tree* is the software routine responsible for calling different modules, and addressing and retrieving variables from module to module. It is also responsible for external user query (such as part surface area and estimated annual production) ABAQUS filename, results filename, and values not present in the Database. The *main tree* calls the module sequentially and only when the previous module has returned the requested values. The sequence begins with a database query that loads composite values from a database, including values from mechanical testing, density, environmental and economic costs of the fibers and the resins and the number of composites being studied. This first control variable is the most important one in the program since it is the limit variable to which most modules answer to. It then runs the FEA module, assigning variables for the mechanical properties necessary for the

module and a control variable and retrieves the necessary data for the next modules, *i.e.*, the number of layers of each composite. The next module in the sequence is the *weight (or performance) module*, where the weight of each composite is computed. Next is the *Cost module*, where taking into account the various costs associated with the production of the parts using the processes chosen (RTM and Hand/Wet Layup), and the estimated number of parts per year, the cost per unit is calculated. The *Environmental module* is similar in execution to the cost module but calculates the CO_2 emissions per unit in kg instead.

Then the *main tree* runs the *Ranking Module*, where all of the solutions are ranked according to Pareto optimality, and the Pareto front solutions are subjected to a final cost analysis to better help the user to understand the results.

Finally there is the *export module* where all of the data is exported to a folder and presents the user with the results.

Figure 89 shows the flowchart representative of the *main tree* execution.

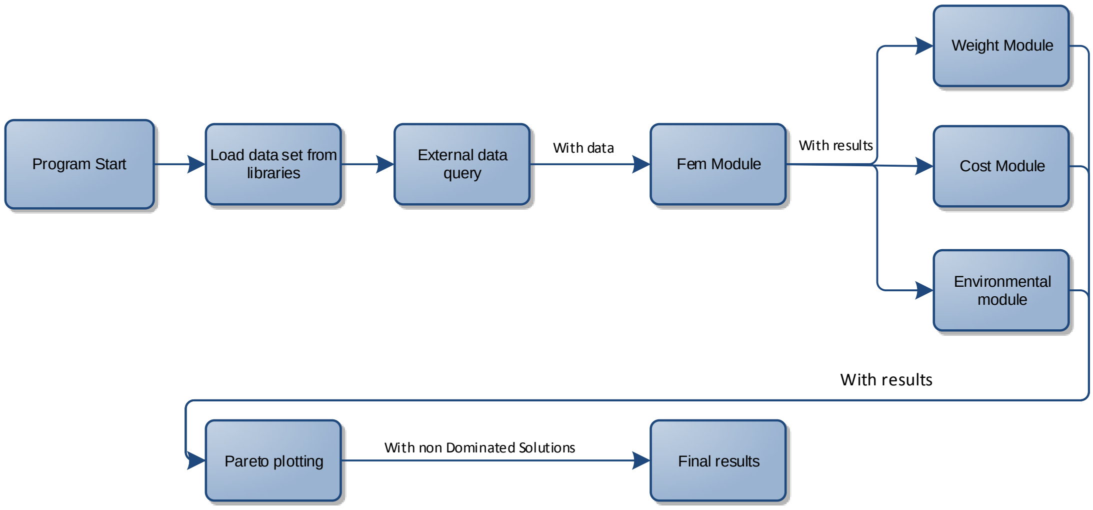


Figure 89 – Main tree flowchart

5.2.2. FEA Module

The first module is the *FEA Module*. It is in this module that all of the composites on the database are evaluated, by taking into account part geometry, loads, boundary conditions and material properties, to determine the best layer orientation and number of layers that withstand the loads imposed, while using the minimum amount of material necessary, according to selected failure criteria. The module achieves this goal by interacting iteratively with the ABAQUS FEA program. Receiving from the *main tree*

the values it needs for the calculations ($E_{11.}$ $E_{22.}$ $G_{12.}$ $G_{13.}$ G_{23}. ν, σ_{1T}, σ_{2T}, σ_{1C}, σ_{2C}, τ_{12} and Layer Thickness), and the control variable that specifies how many composites are being studied, the module selects the first composite. Starting with 2 symmetric layers the program then selects the orientation for the fibers and injects all of this data into the ABAQUS python file and runs it. When the module injects the data, it also reads the file for the type of analysis to be performed, *i.e.*, what is the failure criterion inputted in order to change the outputs file. After the ABAQUS program finishes the calculations, the program then runs a results/output ABAQUS Python script with the type of analysis required by the user. The MATLAB module then compares the output values with the failure criteria imposed and determines if the composite passes the criteria. If it does the module stores the layer number and layer orientation of the composite tested and goes to the next composite. If it does not pass the module defines a new orientation and re-runs the analysis and comparison sub-routines until either an orientation that passes is found, or there are no more layer orientation combinations for the number of layers defined. The program then increments the number of layers, and re-runs the orientation sub-routine until a solution is found. After the program finds a solution for the composite it is testing it then proceed to the next composite re-running the routines until all composites have been tested. This ensures that all of the composites are able to handle the established loads, with the minimum amount of material necessary, according to a selected failure criterion. Finally the program returns to the *main tree* the values of the number of layers and orientation for each composite.

Figure 90 shows the *FEA module* flowchart.

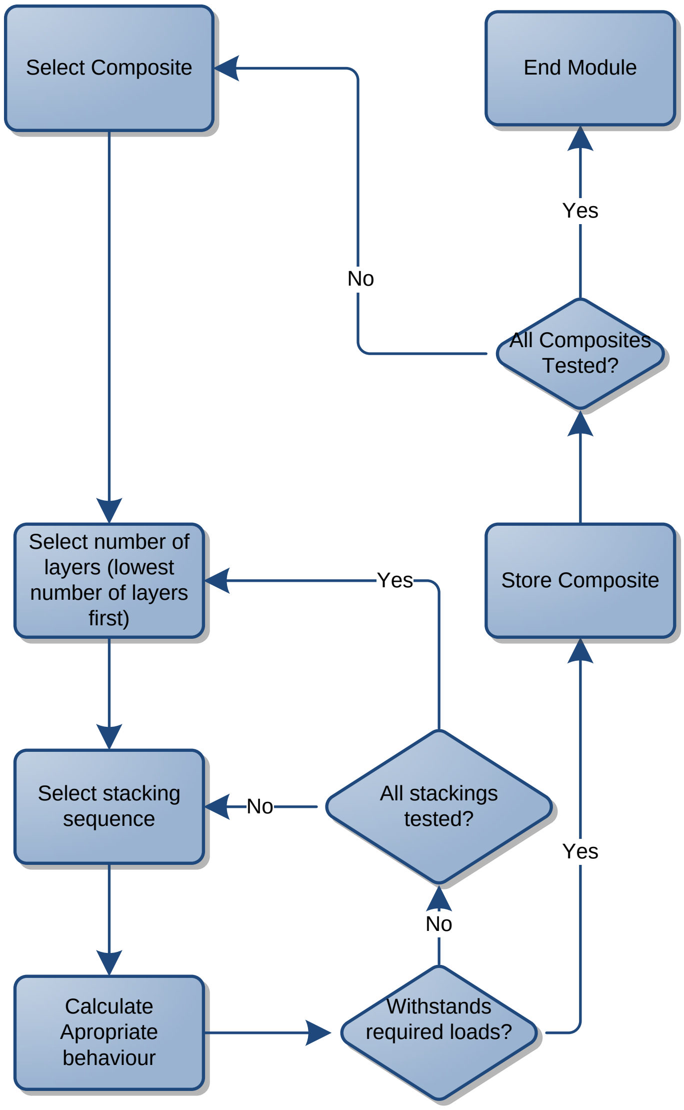


Figure 90 – FEA module flowchart

After the user indicates where the *jnl file is, the module loads the journal file into an array with each cell comprised of one line of text from the journal file. Since the ABAQUS scripting language is python it is of the utmost importance that the syntax of the original file is preserved, or else the scripting will not work. The next step is assigning the mechanical properties of the first composite in the database to variable in order to be injected into the array.

After obtaining the variables the module then scans the array for the line where the variables are to be inserted, and inserts them. Then the module scan for what orientation has been tested, starting from a $[0^{o}]^{n}$ with n being the number of layers. The module then copies the array into a *.py file, and orders the running of ABAQUS with the

created *.py file as the script. The information in the script file allows ABAQUS to define the part shape, loads and boundary conditions, mesh and executes the analysis of the part.

To extract results from this analysis, the module then runs another python script through ABAQUS, this one developed by the module itself, with instructions to calculate the significant results according to the loading applied, and the failure criterion selected. The module then compares the results with the criterion and if accepted stores this data in another array, generates the necessary figures, and selects another material from the database and begins anew. If the material does not meet the criterion, the tool first changes the ply orientation and retries the scripting part.

If all orientations have already been tested, the module adds another layer to the script by increasing the array size by one, moving the cell information one by one until it reaches the cell immediately before the cell where the cell with the layer information is. After finding this cell the tool then inserts a new line with the new layer information and re-runs the scripting information.

After all the materials in the database have been tested, the tool exports the results, focusing mainly in the number of layers and ply orientation per material, and stores it in an excel file ready to be used by the next modules.

5.2.2.1. ABAQUS program and composite definition

For all of the test cases the ABAQUS script written followed the same guidelines in order to minimize errors in the problem definition. All of the script files followed the same order of steps, described in Table 29.

Table 29 – ABAQUS Step Guide

ABAQUS	
STEP	Definition
Define Shape	Define part shape or import shape from another program. Shape must be 3d surface. Define sections
Define Material	Define Material. Composite Definition as Lamina. Mechanical properties attribution. Apply material to model
Define Layer	Determine initial layer, define symmetry, define orientation
Define orientation	Create Composite Coordinate System. Define orientation axis, Define 0º Axis. Define directions
Define loads	Define applied loads to part
Define Boundary conditions	Define the Boundary conditions applied to the part
Define Mesh	Define the mesh type, element shape, seed pattern and size.
Apply mesh	Apply mesh given mesh properties defined on the previous step.
Define output	Define results outputs. Define failure criteria, and appropriate data/graphics to export
save file	Save data file

These steps ensure that all of the scripts operate accordingly, while at the same time allowing the MATLAB module that handles all of the ABAQUS scripts to easily search and find the correct values which to change. These steps also create a simple step by step method for the user to construct its ABAQUS file in order to be handled by the tool with minimum problems.

One thing of note is that the layers of the composites studied were always considered symmetric in order to decrease the number of iterations of the program. The parts were always defined as surfaces and the tool only iterates in global thickness, *i.e.*, all of the part gets added another pair of plies if the part does not meet the failure criteria in an ABAQUS iteration, since in all of the parts considered the forces and stresses applied were generally consistent throughout the part geometry.

For the first three tests the failure criterion considered was the Tsai-Hill Failure Criterion, chosen for two reasons. First, the fact that only one calculation needs to be performed by the ABAQUS program would diminish the cycle time and secondly because the Tsai-Hill failure criterion is the most widely used in academia. For the real life test case the failure criterion chosen was one of deformation at two selected points, since by being a kayak paddle one seeks the minimum deformation possible so that no

rowing energy is wasted on deforming the paddle. It was this line of thought that also governed the experimental data, so the tests could be run against a tested case.

In both cases, after both ABAQUS scripts are run the tool compares the maximum value of the failure criterion in the ABAQUS analysis with the values predetermined, by scanning the results file created by the ABAQUS script.

ABAQUS also exports 3 images in TIFF format for each composite, to help visualize the results. The images printed are:

- The problem definition (Figure 91),
- The deformed shape with the values of the failure criterion plotted in the shape Figure 92.
- The values of the failure criteria chosen in each lamina across the part (Figure 93).

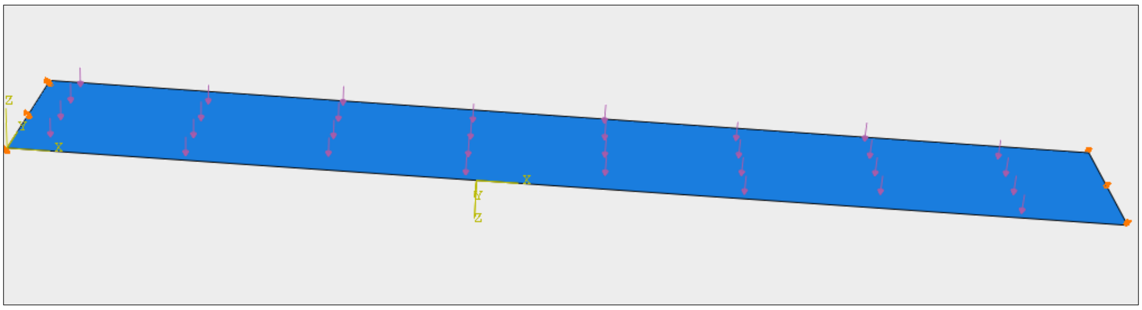


Figure 91 – Test Case load example (bending)

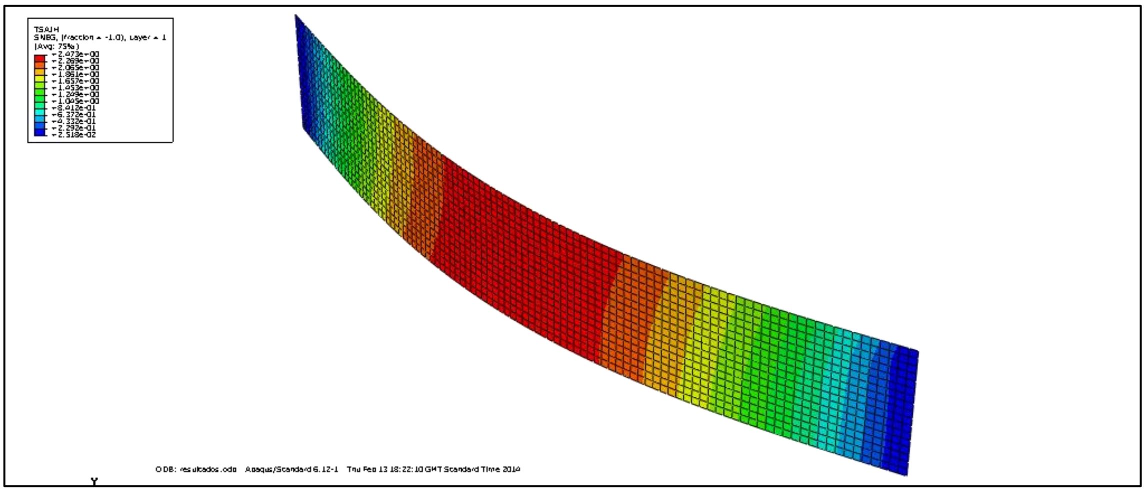


Figure 92 – Tsai-Hill values in Bending [0/45/90] Symmetric, note values higher than 1 (shown in red and orange). Bending example

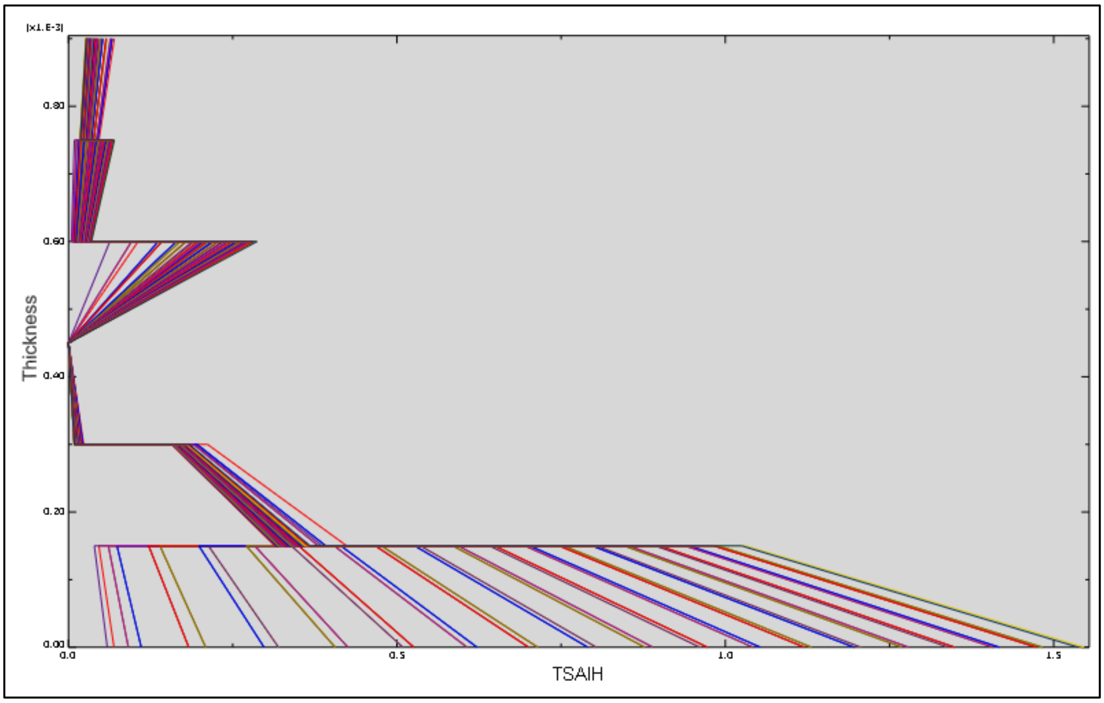


Figure 93- Tsai Hill values per layer [0/45/90] symmetric bending example

Figure 93 shows the values of the Tsai-Hill failure criterion for each layer on a 6 layer composite subjected to a bending loading, each line representing a series of nodes perpendicular to the span direction. Notice values above 1.0 in the x axis, meaning that according to the Tsai-Hill criterion, failure occurs in the part.

As mentioned before, with these results the MATLAB module then gives the Go/No Go decision of accepting this composite lay-up and ply number and either stores it, or discards the results and either changes ply orientation or, if all of the orientations for the given number of layers are exhausted, increases the number of layers. In the example from Figure 91 to Figure 93, the Tsai-Hill Criterion value is larger than 1 so this particular orientation would be discarded from the possible solutions.

5.2.3. Weight Module

The *weight module* is responsible for the calculations regarding the weight of the part being analyzed. The module receives from the *main tree* the number of layers, part surface area, and densities and then determines the part weight by determining the volume of the part and multiplying it by the lamina density for every composite that passed the load analysis module. The part weight, while being a performance indicator on its own is also a necessary value in order to determine the part costs and

environmental impact. Finally the module returns the values of the part weight to the *main tree*.

5.2.4. Cost and Environmental Module

In these modules the Cost per part and Environmental impact per part are calculated taking into account the part geometry, the composite lay-ups that passed the FEA module and the production methods chosen (RTM and Wet/Hand Lay-up). The cost and environmental models are divided in two parts, one for each process, and some of the variables taken into account are shown in Table 30.

Table 30 – General Cost Variables in both modules

Variables
Number of workers
Electricity
Fiber
Resin
Mold Cost
Demolding
Curing Oven
Adhesives
Curing Oven running
Geotextile
Vacuum Polymers
Compressor Costs
Storing Costs

The cost modeling part of the module is divided into two halves, one for the cost modelling of Hand/wet lay-up with vacuum bagging and the other half for Resin Transfer Molding. For both processes the cost model receives from the *main tree* the number of layers, the control variable, the cost per unit of lengths of the fibers, the cost per volume of the resin, the density, thickness and fiber volume of each composite lamina, surface area and projected area of the produced part and the Estimated Annual production of the part.

For the Hand/Wet Lay-up part of the cost model the variables in play are, the daily production rate (based on estimated annual production and curing time of the part, important for the calculation of the number of molds and number of workers), the total mold costs (number of required molds for the annual production plus replacement

molds if required), the worker cost (calculated using the size of the part to be produced, the number of layers, collaborator productivity and rates), material costs such as fiber costs and resin costs, production materials costs such as de-molding agents, absorbent material, polymers cover and adhesives for vacuum bagging, with the material cost already including production waste, production costs such as Oven costs, compressor costs (for vacuum bagging) and area costs (plant size) and finally the energy costs for the oven and the compressor.

For the RTM cost model, the module also calculates daily production rate, mold costs and material costs. For the material production costs the RTM cost model uses the de-molding agent required, for production costs the main cost is the RTM Machine cost, and the energy costs the running costs of the RTM Machine(s). Since this cost model is a comparative cost model, some costs considered equal were not added (such as water costs, general running costs, administrative personnel, etc.), since they are the same for both processes, and it was assumed that the plants were already running.

After determining the unit cost of all the composites using both manufacturing processes, the module presents the unit cost per composite given both processes and across the estimated production as shown in Figure 94. This helps to determine if there would be a process change if there was an overestimation or underestimation of the production values, since the production values have an effect on the costs and more importantly could have an impact on the production process chosen. Of note is the fact that, as Figure 94 shows, there is a significant drop in cost per unit from 1 unit to about 40 units. In order to better understand the costs development, for instance trade-off points, cost increases due to number of collaborators or machines, all figures will be represented from a certain value onwards, skipping the initial cost drop.

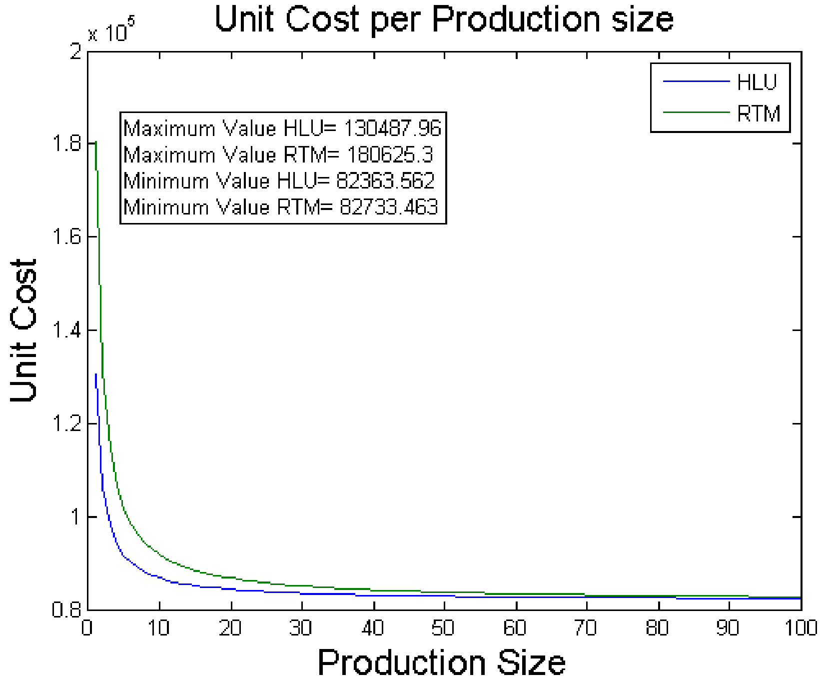


Figure 94 – Production Size (number of units) vs Unit Cost (€) Example

The program also determines the cost distribution according to the cost drivers, *i.e.*, how much does every cost driver contribute to the final cost, as Figure 95 shows.

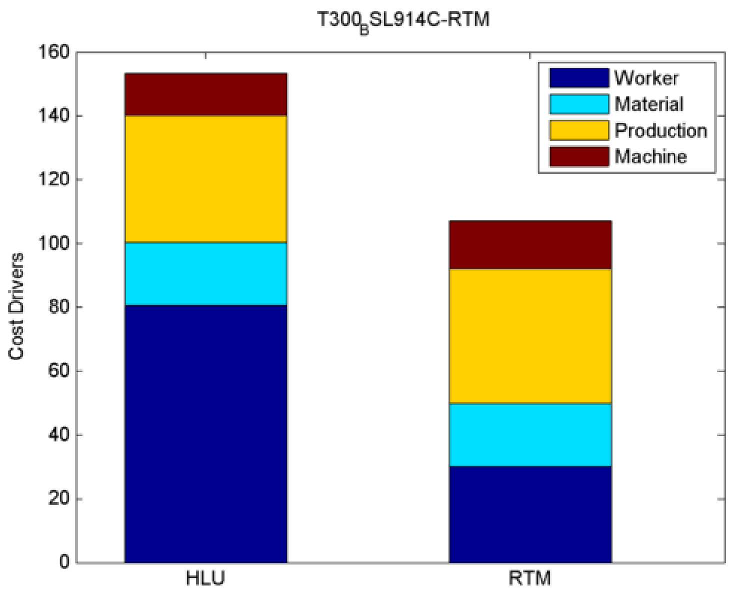


Figure 95 – Cost Drivers per unit cost example

The Environmental cost of the module is also divided into two parts, one for each process. The environmental metric used was CO_2 emissions per unit in kg (with data obtained from the literature), across the different inputs, due mainly to its easier readability, and ease of obtaining values, since when using the ECO99 indicators, studies would have to be performed for every material, and the final indicator, being a

composite result of a multitude of factors, is in itself undescriptive of the actual environmental impact of the part.

5.2.5. Decision Support Module

The final step of the tool is the decision support module. After all of the composites have been characterized (part weight, cost and CO_2 emissions per unit by Hand/Wet Lay-up and cost and CO_2 emissions per unit by Resin Transfer Molding, see Table 31), they are subjected to a pairwise comparison in order to determine non-dominated, *i.e.*, with at least one indicator better than the other material being compared to, solutions, also known as a Pareto front.

Table 31 – Example solutions pre-pairwise comparisons

Material	Weight	Env Cost HLU	Env Cost RTM	Economic cost HLU	Economic Cost RTM	Layers
1800_510A-40	0.069	0.659	0.648	304.42	267.81	2
1854_510A-40	0.069	0.557	0.546	247.57	210.96	2
AS4_890RTM*	0.050	0.949	0.941	206.07	169.42	2
AS4_PR520	0.043	0.762	0.755	206.94	170.29	2
AS6-5245c*	0.091	2.023	2.008	1170.35	1133.68	2
EGLASS4-7740*	0.027	0.181	0.177	174.58	137.97	2
EGLASS8-7740*	0.027	0.182	0.177	174.78	138.17	2
T300-4901A*	0.017	0.357	0.354	148.08	111.42	2
T300-4901B*	0.017	0.351	0.349	150.57	113.91	2
T300_BSL914C*	0.015	0.306	0.304	148.80	112.13	2
T500_R914*	0.019	0.362	0.359	154.86	118.18	2
T650-35_2237*	0.022	0.544	0.540	1161.40	1124.69	2
T700_510A-40	0.050	1.090	1.082	219.88	183.12	2
T700-4901A*	0.018	0.373	0.370	151.78	115.02	2
T700-4901B*	0.023	0.446	0.443	165.76	129.00	2

All of the solutions in the Pareto front are “Best” Solutions for the problem and as such are displayed to the user which will then make the final decision, Table 32.

Table 32 – Example Solution space (best results bolded)

Material	Weight	Environmental Cost	Economical Cost	Layers
EGLASS4-7740-RTM	0.027	**0.177**	137.97	2
T300-4901A-RTM	0.017	0.354	**111.42**	2
T300_BSL914C-RTM	**0.015**	0.304	112.13	2

5.3. Tool interface and usage: Example

In this section a small example of the usage of the tool is presented, along with notes and the required steps for the use of the tool. The tool in itself was designed to be as hands-off as possible¸ *i.e.*, once running there are no other inputs other than the initial.

5.3.1. Before running

Since the tool uses the ABAQUS program to obtain the minimum number of layers per composite, the user has to create an ABAQUS file, where the user specifies, among other part geometry, material orientation, loads and boundary conditions and meshes. In other words the creation of this file is somewhat similar to any other ABAQUS analysis. The main differences are: the user must use the general variables presented by ABAQUS, the element type must be shell or surface, the thickness is given by the section and on the composite mode, the layers must be defined as symmetric, with only one layer chosen, and its name must be *layer1*. Finally the user must save to a file. A summary of each step is provided in Table 33.

Table 33 – ABAQUS model construction

ABAQUS	
STEP	Actions
Define Shape	**Accept general variables given by ABAQUS for all steps unless noted**
Define Material	**Define thickness from section not from geometry, in the appropriate text box**
Define Layer	**Use only one layer, define symmetry, layer must be named layer1**
Define orientation	
Define loads	
Define Boundary conditions	
Define Mesh	
Apply mesh	
Define output	**A set named monitor must be created in order for the tool to be able to determine the composite layup functions**
save file	

The user also has the option to edit the database by opening the accompanying excel file

5.3.2. Running the tool

When the user runs the tool, the first input requested is the location of the .jnl file created when the ABAQUS file was first saved (it is in the same directory as the .cae file). The tool then copies the file to its working directory and changes the file extension in order to be read by the tool and inserted into ABAQUS (Figure 96).

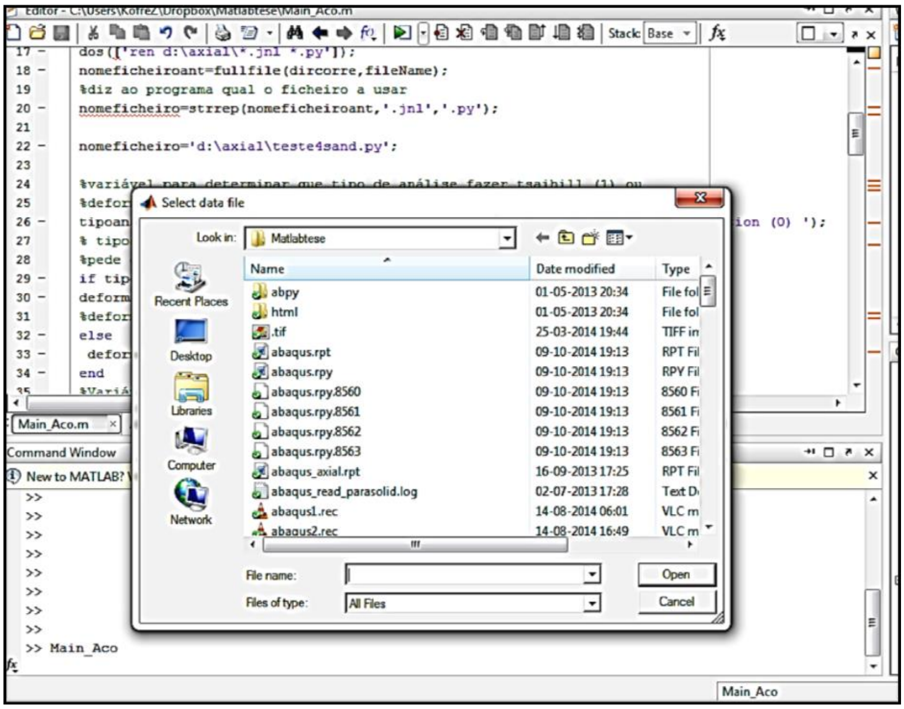


Figure 96 – File selection pop up box

The second input requested is the type of analysis to be performed. The tool was designed to analyze the composite part either by the Tsai-Hill Failure Criterion, or by Maximum Deformation failure criterion in a given area of the part. Given that the field output request is different in each case the tool has to know which analysis is to be performed. If Maximum Deformation is selected the tool then requests what is the maximum deformation allowed. These are the required inputs for the FEA part of the tool.

The final inputs required for the cost modules of the tool (Economic Cost, Environmental cost and Weight) are the Expected Annual Production, the part surface and part projected area, and if the part is a sandwich structure (Figure 97).

```
 Determine the analysis type: Tsai-hill (1) or max deformation (0) 1
Enter the estimated annual production Un 1000
Enter the surface area of the part m2 0.2
Enter the projected area of the part m2 0.28
Is it a sandwich structure? yes(1)/no(0)1
```

Figure 97 – Additional information request

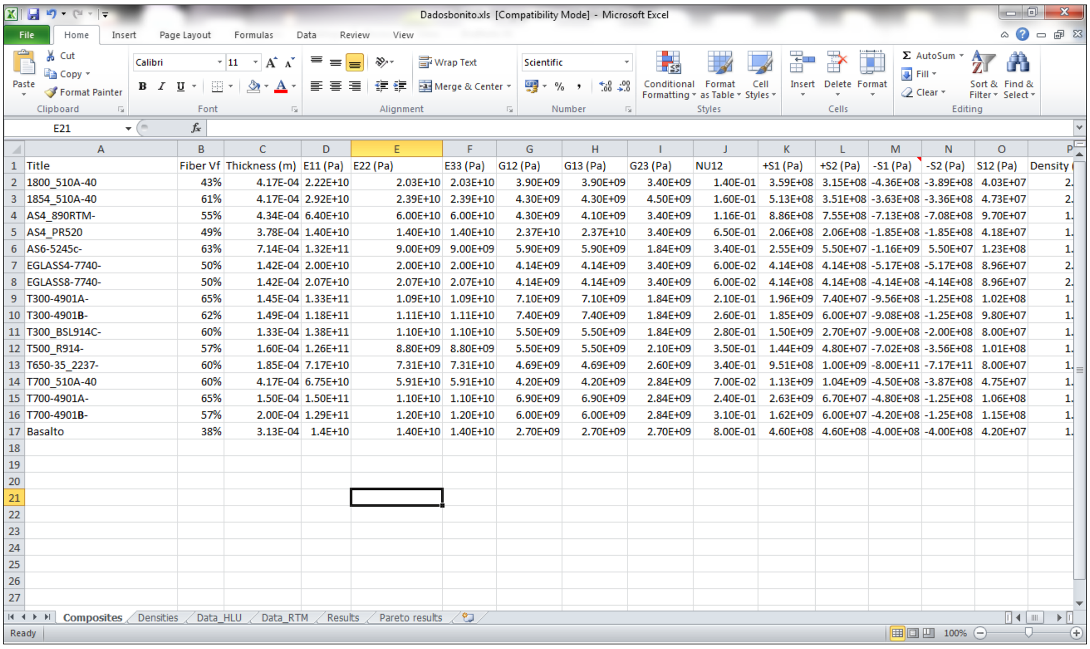
From this point onward the tool executes the necessary steps, and when finished presents the results.

5.3.3. Results file

The tool outputs two types of results files. Image files with the unit cost per production size and the unit cost breakdown by cost drivers of the non-dominated solutions, and an .xls file with a sheet with the results for all materials and all production methods, a sheet with only the solution space, and a sheet with the material orientation of each result.

5.3.4. Miscellaneous

In the .xls results file is also the database that the tool uses, regarding composite material properties, and cost model costs for both types of production methods. This means that the user is free to edit both these sheets, by introducing or removing composite materials, edit prices and properties of the composite materials, Figure 98, and change values on the cost model base.



	Title	Fiber Vf	Thickness (m)	E11 (Pa)	E22 (Pa)	E33 (Pa)	G12 (Pa)	G13 (Pa)	G23 (Pa)	NU12	+S1 (Pa)	+S2 (Pa)	-S1 (Pa)	-S2 (Pa)	S12 (Pa)	Density (
2	1800_510A-40	43%	4.17E-04	2.22E+10	2.03E+10	2.03E+10	3.90E+09	3.90E+09	3.40E+09	1.40E-01	3.59E+08	3.15E+08	-4.36E+08	-3.89E+08	4.03E+07	2.
3	1854_510A-40	61%	4.17E-04	2.92E+10	2.39E+10	2.39E+10	4.30E+09	4.30E+09	4.50E+09	1.60E-01	5.13E+08	3.51E+08	-3.63E+08	-3.36E+08	4.73E+07	2.
4	AS4_890RTM-	55%	4.34E-04	6.40E+10	6.00E+10	6.00E+10	4.30E+09	4.10E+09	3.40E+09	1.16E-01	8.86E+08	7.55E+08	-7.13E+08	-7.08E+08	9.70E+07	1.
5	AS4_PR520	49%	3.78E-04	1.40E+10	1.40E+10	1.40E+10	2.37E+10	2.37E+10	3.40E+09	6.50E-01	2.06E+08	2.06E+08	-1.85E+08	-1.85E+08	4.18E+07	1.
6	AS6-5245c-	63%	7.14E-04	1.32E+11	9.00E+09	9.00E+09	5.90E+09	5.90E+09	1.84E+09	3.40E-01	2.55E+09	5.50E+07	-1.16E+09	5.50E+07	1.23E+08	1.
7	EGLASS4-7740-	50%	1.42E-04	2.00E+10	2.00E+10	2.00E+10	4.14E+09	4.14E+09	3.40E+09	6.00E-02	4.14E+08	4.14E+08	-5.17E+08	-5.17E+08	8.96E+07	2.
8	EGLASS8-7740-	50%	1.42E-04	2.07E+10	2.07E+10	2.07E+10	4.14E+09	4.14E+09	3.40E+09	6.00E-02	4.14E+08	4.14E+08	-4.14E+08	-4.14E+08	8.96E+07	2.
9	T300-4901A-	65%	1.45E-04	1.33E+11	1.09E+10	1.09E+10	7.10E+09	7.10E+09	1.84E+09	2.10E-01	1.96E+09	7.40E+07	-9.56E+08	-1.25E+08	1.02E+08	1.
10	T300-4901B-	62%	1.49E-04	1.18E+11	1.11E+10	1.11E+10	7.40E+09	7.40E+09	1.84E+09	2.60E-01	1.85E+09	6.00E+07	-9.08E+08	-1.25E+08	9.80E+07	1.
11	T300_BSL914C-	60%	1.33E-04	1.38E+11	1.10E+10	1.10E+10	5.50E+09	5.50E+09	1.84E+09	2.80E-01	1.50E+09	2.70E+07	-9.00E+08	-2.00E+08	8.00E+07	1.
12	T500_R914-	57%	1.60E-04	1.26E+11	8.80E+09	8.80E+09	5.50E+09	5.50E+09	2.10E+09	3.50E-01	1.44E+09	4.80E+07	-7.02E+08	-3.56E+08	1.01E+08	1.
13	T650-35_2237-	60%	1.85E-04	7.17E+10	7.31E+10	7.31E+10	4.69E+09	4.69E+09	2.60E+09	3.40E-01	9.51E+08	1.00E+09	-8.00E+11	-7.17E+11	8.00E+07	1.
14	T700_510A-40	60%	4.17E-04	6.75E+10	5.91E+10	5.91E+10	4.20E+09	4.20E+09	2.84E+09	7.00E-02	1.13E+09	1.04E+09	-4.50E+08	-3.87E+08	4.75E+07	1.
15	T700-4901A-	65%	1.50E-04	1.50E+11	1.10E+10	1.10E+10	6.90E+09	6.90E+09	2.84E+09	2.40E-01	2.63E+09	6.70E+07	-4.80E+08	-1.25E+08	1.06E+08	1.
16	T700-4901B-	57%	2.00E-04	1.29E+11	1.20E+10	1.20E+10	6.00E+09	6.00E+09	2.84E+09	3.10E-01	1.62E+09	6.00E+07	-4.20E+08	-1.25E+08	1.15E+08	1.
17	Basalto	38%	3.13E-04	1.4E+10	1.40E+10	1.40E+10	2.70E+09	2.70E+09	2.70E+09	8.00E-01	4.60E+08	4.60E+08	-4.00E+08	-4.00E+08	4.20E+07	1.

Figure 98 – View of the composites database in Excel

Figure 99 shows the spreadsheet tabs, in the .xls file. Composites is the tab where the composite data is stored. The densities tab is a calculation tab so that the cost model accurately determines the resin cost and fiber cost of a composite. The Data_HLU and Data_RTM tabs are used for the economic and environmental cost model, and can be subbed by data in other file, *i.e.*, when plugging in another cost model these tabs can remain unused by the new cost models. Finally, the Results tab that shows the results for ALL of the composites tested in both RTM and HLU production, and finally the Pareto Results tabs shows only the non-dominated solutions.

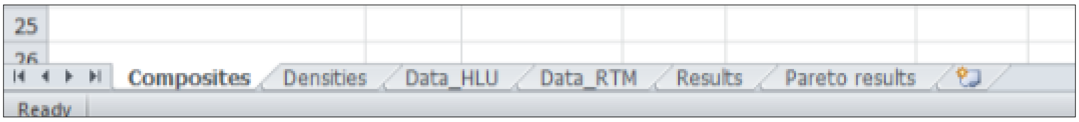


Figure 99 – Spreadsheet tabs

6. HIMSelF tool performance

6.1. Test cases

Before any tests were performed, a thorough analysis of the tool was performed and no syntax or semantic errors were discovered in the programming. However some unexpected interactions between variables could occur (such as divide by zero equations, infinite iterations, automation errors, among others). Thus in order to test the tool, 4 test cases were studied starting with a simple tension test to a plate/beam, a simply supported plate subjected to a distributed load (simple bending), a sandwich beam subjected to bending, and finally a real-life test case of a kayak paddle. The purpose of the first three tests was to determine if the program was performing all of the calculations correctly, and to determine some of the tool properties. Among other things, the goals were to determine if the best candidate varied with the inputs or if not what was the reason for it and if the best process varied or not. The tests also would help review the FEA, Economic and Ecological modules. In order to determine the behavior of the tool, the tests were designed in order to test the tool results when the estimated production and the loads applied to the part varied. The tables and figures with the values tested for both variables are presented in each test case sub chapter.

The last test was used to test the validity of the tool in a real-life scenario, in which a kayak paddle, with 8 layers of a biaxial 2/2 twill of Basalt fiber with Unsaturated Polyester as the resin with a 30% Fiber Volume manufactured by the Hand-Lay Up vacuum bagging process was built and experimentally tested. The validity of the FEA module of the tool will then be tested by comparing the values of displacement of the Basalt composite against its experimental value, and, by run with all of the materials in the database and the data obtained from the mechanical testing of the Basalt fiber Composites, would give an idea of the competitiveness of the Basalt composites.

In this last test the tool results would also allow to study the sensitivity of the tool to surfacing new materials: With the basalt fibers, performing here the function of a new material, being compared with other materials to determine its ranking among them.

6.1.1. Tested Materials and test parts

All of the tests were performed using the same material database, shown in Table 34. The composites chosen represent a good cross-section of composite materials, with two main types of fibers, with several woven and unidirectional styles, and four types of resin. Most of the data was retrieved from several databases, namely from the ProspectorComposites website [114]. The full data was generally present although some data values (such as σ_{1C}, σ_{2C}, density and thickness) were missing, and thus had to be calculated/estimated, mostly by comparison with similar composite lay-ups.

Table 34 – Materials database

Title	Fiber Vf	Fiber	Fiber type	Resin
1800_510A-40	43%	Glass	Plain Weave	Vinyl Ester
1854_510A-40	61%	Glass	Plain Weave	Vinyl Ester
AS4_890RTM*	55%	Carbon	5-Harness Satin weave	Epoxy
AS4_PR520	49%	Carbon	Biaxial Braid	Epoxy
AS6-5245c*	63%	Carbon	Unidirectional	Bismaleimide
EGLASS4-7740*	50%	Glass	4-Harness Satin weave	Epoxy
EGLASS8-7740*	50%	Glass	8-Harness Satin weave	Epoxy
T300-4901A*	65%	Carbon	Unidirectional	Epoxy
T300-4901B*	62%	Carbon	Unidirectional	Epoxy
T300_BSL914C*	60%	Carbon	Unidirectional	Epoxy
T500_R914*	57%	Carbon	Unidirectional	Epoxy
T650-35_2237*	60%	Carbon	8-Harness Satin weave	Polyimide
T700_510A-40	60%	Carbon	Plain weave	Vinyl Ester
T700-4901A*	65%	Carbon	Unidirectional	Epoxy
T700-4901B*	57%	Carbon	Unidirectional	Epoxy

For the first three tests the parts considered were always flat plates subjected to the different loads, from simple tension to a Multi loading case. This would simplify the data although most loading situation will be somewhat based in possible real life cases.

For the final test, and as mentioned in section 4.5, a Kayak paddle (Figure 100) was chosen as the real life scenario to study.

Figure 100 – Kayak paddle blade

Finally due to the amount of test result data of all test cases (a total of 47 tables, see Annex A), the results are presented in graphical form, with the results for the weight, the economic cost and the environmental cost normalized to each highest value, so that lower percentages mean a better solution. This also means that, in order to keep the figures readable, the results for the 1 unit produced tests were omitted, since the values of economic and environmental costs, for all material solutions, at that production level would be so high as to never be used as a basis for production.

6.1.2. Test Case 1 - Simple tension

6.1.2.1. Introduction

For this first test case of simple tension, the simulated specimen is a rectangular flat plate with dimensions of $0.25m \times 0.15m$ as shown in Figure 101. The plate is fixed at the top edge and a loading is applied at the bottom edge.

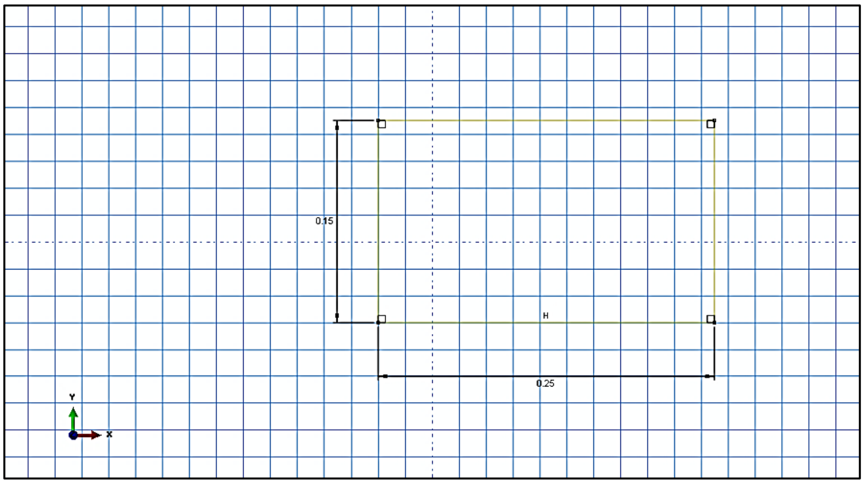


Figure 101 – Test case dimensions (m)

To determine the behavior of the tool four load values and four production values were combined as shown in Table 35, for a total of 16 simulations for this test case.

Table 35 – Test values for loads and Production

Test variables	Value	Value	Value	Value
Loads	10 kN/m	100 kN/m	500 kN/m	1 000 kN/m
Production	1 unit	250 units	500 units	1000 units

6.1.2.2. Test Loads and Boundary conditions

The model was fixed on its top edge (allowing for no rotation or displacement), and 4 different load values were applied in its bottom edge, (Figure 102) in order to determine the tool behavior, *i.e.*, if the tool was sensitive to changes in loads.

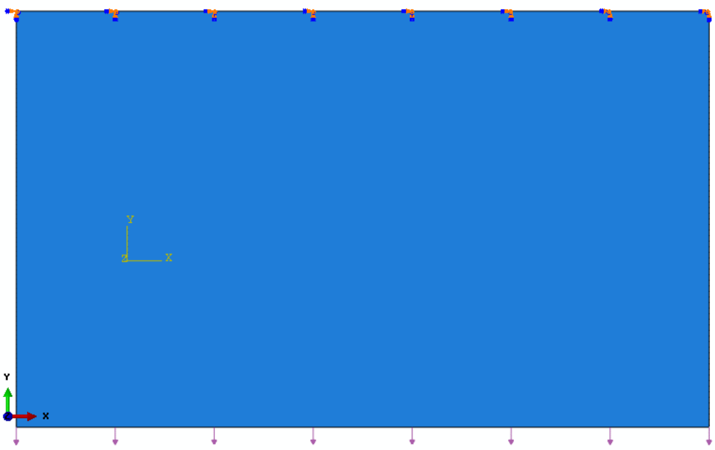


Figure 102 – Boundary conditions and loads

6.1.2.3. Results and discussion

Table 36 shows the results of the FEA module regarding the number of layers necessary per composite material to withstand the required loads.

Table 36 – Number of layers per composite material per load

Material	Layers			
	10kN/m	100kN/m	500kN/m	1000kN/m
1800_510A-40	2	2	6	10
1854_510A-40	2	2	4	6
AS4_890RTM*	2	2	2	4
AS4_PR520	2	4	14	20
AS6-5245c*	2	2	2	2
EGLASS4-7740*	2	2	10	18
EGLASS8-7740*	2	2	10	18
T300-4901A*	2	2	4	6
T300-4901B*	2	2	4	6
T300_BSL914C*	2	2	4	8
T500_R914*	2	2	4	6
T650-35_2237*	2	2	6	10
T700_510A-40	2	2	2	4
T700-4901A*	2	2	2	4
T700-4901B*	2	2	2	4

As Table 36 shows, the first two load values considered were conservative since no material required more than the two initial layers, with the exception of AS4-PR520 Carbon Fiber-Epoxy composite. To note that since only tension was considered, there are no dimensional instability concerns, which is another reason why the composite material are so thin.

For the third and fourth cases, the load values are high enough to require more layers, although some materials still retain the original two layers.

Figure 103 shows the Pareto results for the materials in the tension test from 250 units produced to 1000 units produced, with the Test case loads.

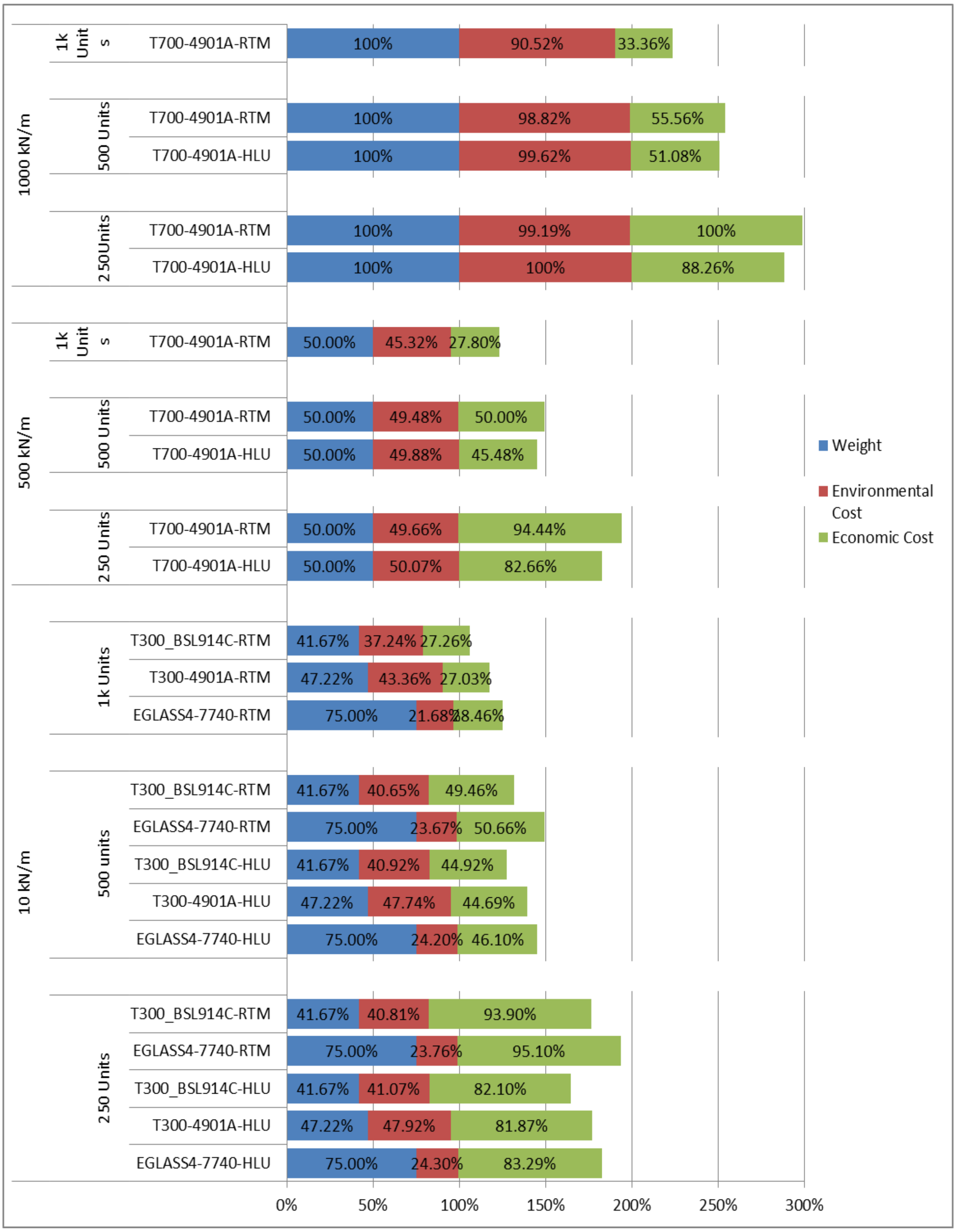


Figure 103 – Results for the various tests performed for the Tension test case (lower is better)

- **10kN/m Load**

As Figure 101 shows, the composite materials selected are the 4-harness satin weave Fiber-Glass Epoxy EGlass-7740, the Unidirectional Carbon-Fiber Epoxy T330-4901A and the Unidirectional Carbon-Fiber Epoxy T300-BSL914C. The Economic cost per part decrease with the number of units produced, since, except for the material costs, all of the other costs are distributed among more parts. Environmental costs also decrease since there is an economy of scale related to transportation. On the other hand Weight remains the same since weight is a function of the number of layers, which remain constant given the same load.

Up to 500 units, there is a mix of composite materials produced by RTM and Hand/Wet-Layup, given the fact that the HLU produced composites have a lower Economic Cost that the RTM composites, but a higher Economic cost. The exception being the T300-4901A Composite material only appearing in the solution space as a HLU produced Composite. At 1000 Units only the RTM produced composites appear in the solution space given that at a point between 500 and 1000 Units the RTM production method Economic Cost per unit decreased below that of the HLU Economic cost. To illustrate this point Figure 104 shows the Economic cost per estimated production size of the Carbon-Fiber Epoxy T300-BSL914C Composite material.

As mentioned in Subsection 5.2.4, the fact that the unit cost drops precipitously from 1 unit produced to 50 units produced does not reveal much information on the evolution of part cost for higher batch sizes. As such Figure 104 shows the cost per part from 200 units to 1000 units.

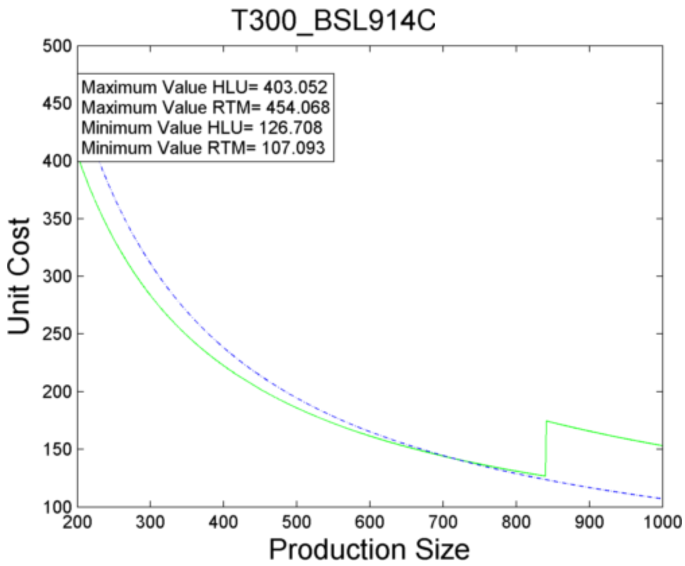


Figure 104 - Cost per part per unit production T300-BSL914C Composite material (truncated)

As Figure 104 shows, although the initial cost per part of RTM is much higher than HLU, the cost per part decreases faster in RTM, achieving the trade point at around 715 units. Another thing of note in the figure is that around 850 units the cost per part of HLU increases by about 50€, due to the need to have more workers in order to keep up with the production. To understand how these cost vary, Figure 105 through Figure 107 show the cost drivers of the Carbon-Fiber Epoxy T300-BSL914C Composite material for 250, 500 and 1000 units.

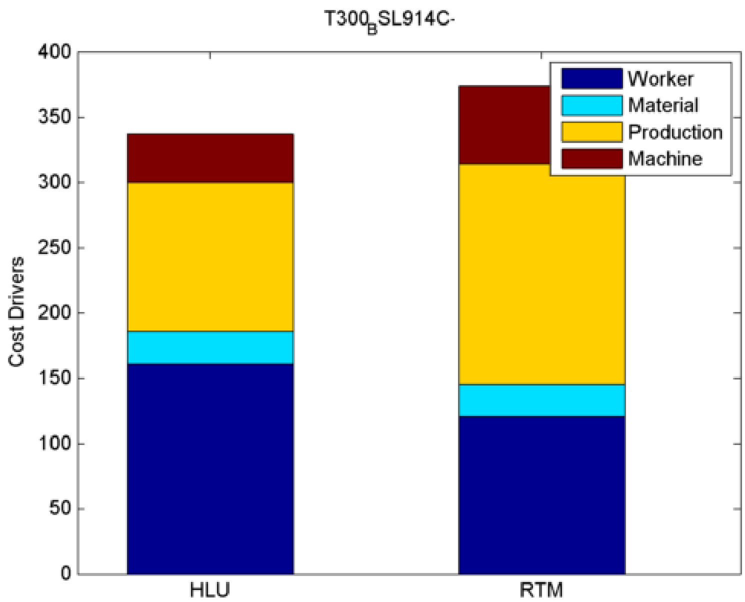


Figure 105 – Cost drivers per part, 250 units production

For 250 units HLU has an advantage over RTM, due mainly to the much lower initial costs as the Machine cost Driver shows, and smaller Production costs, including molds,

energy, and associated operations. At this stage the Worker costs are higher in HLU, and the material costs are about the same.

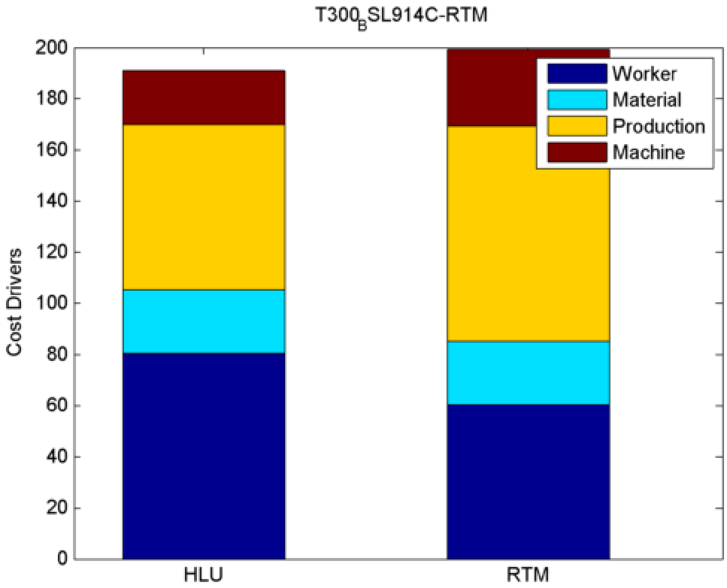


Figure 106 - Cost drivers per part, 500 units production

At an estimated production of 500 units both production methods have decreased the total costs. Material costs decreases as well as all of the other costs, with special emphasis on worker costs and production costs on RTM, which enables RTM to close the gap to HLU.

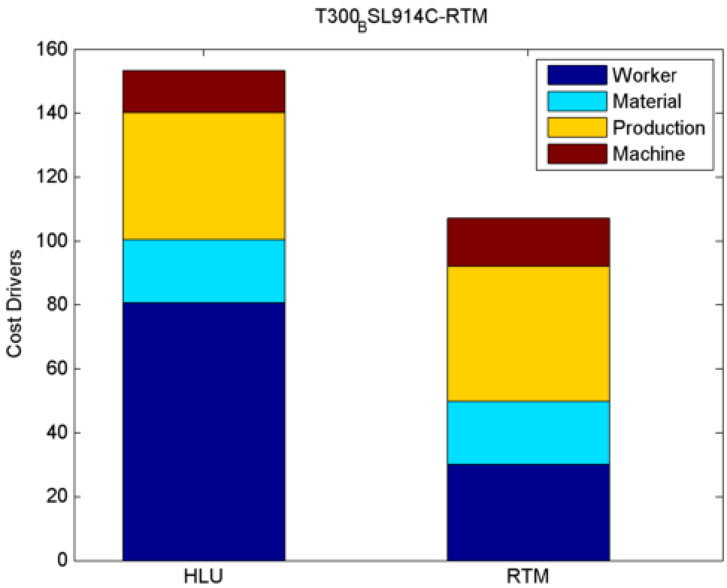


Figure 107 - Cost drivers per part, 1000 units production

At 1000 units RTM has lower total costs than HLU, especially due to the fact that HLU has more than double the Worker costs when compared to RTM. In fact the cost of

Workers and Material costs is almost as high as all the RTM cost drivers combined, due to the increase in number of workers required at about an estimated production of 850 units.

- **100 kN/m**

Only one material saw its number of layers increase and, since it was not part of the initial solution space, it remains unaltered from the 10kN/m load case.

- **500 kN/m and 1000 kN/m**

Given the results of the 500kN/m loading case and the 1000kN/m loading case, they will be discussed together. As Figure 104 shows, the material chosen for 500kN/m and 1000kN/m is the Unidirectional Carbon Fiber Epoxy T700-4901 Composite material. As with the loading cases of 10kN/m and 100kN/m, HLU remains a viable option up to 500 units. There are a number of results worth discussing. The weight of the part doubles from 500kN/m to 1000kN/m due to the number of layers required to withstand the loads double, but the same cannot be said of the Environmental and Economic Cost, since both costs are different for the resin and the fiber.

Another result is that if the T700-4901 Carbon-Epoxy composite is the best material for the higher load cases studied, why is it not the best material for the lower load cases? Simply put, T700-4901 is just too good for the lower load cases, *i.e.*, the small premium in Economic cost and weight offsets the higher mechanical performance of this particular composite, meaning that for loads that other materials can handle at the same number of layers, it is dominated by other solutions.

Table 37 shows the Material selection per load case, production method and production size.

Table 37 – Material Selection per load case/production method/production size

Nº units		kN/m	1800 510A-40	1854 510A-40	AS4 890	AS4 PR 520	AS65 245	EGLA SS4 7740	EGLA SS8 7740	T300 4901A	T300 4901B	T300 BSL914C	T500 R914	T650 2237	T700 510A-40	T700 4901A	T700 4901B
1 Unit	RTM	10						X		X		X					
		100						X		X		X					
		500														X	
		1000														X	
	HLU	10						X				X					
		100						X				X					
		500														X	
		1000														X	
250 Units	RTM	10						X		X		X					
		100						X		X		X					
		500														X	
		1000														X	
	HLU	10						X				X					
		100						X				X					
		500														X	
		1000														X	
500 Units	RTM	10						X		X		X					
		100						X		X		X					
		500														X	
		1000														X	
	HLU	10						X				X					
		100						X				X					
		500														X	
		1000														X	
1000 Units	RTM	10						X				X					
		100						X				X					
		500														X	
		1000														X	
	HLU	10															
		100															
		500															
		1000															

As Table 37 shows, there is a clear difference between the 10kN/m and the 100kN/m tests and the 500kN/m and the 1000kN/m Load tests. With the increase from 100kN/m to 500kN/m the number of layers increases in all of the Pareto Front materials of the 100kN/m composite materials, which increases the costs and weight, while the T700-4901 Composite Material maintains the same number of layers, which causes it to surface as “The” Material for those loads.

With these tests, the material changed according to the loads considered which means that there is no “super-material” in the database. Although in the 500kN/m and 1000kN/m only one Composite material appeared, it does not mean that it would be the only material chosen for even higher load cases. The Economic cost varied with production size, due to the Economies of scale, and both costs varied with the load cases, since higher loads imply higher material volumes which impact negatively on the costs. In all test cases the main cost driver depended on the production method, with the main Cost driver in RTM being the production costs, and the main cost driver in HLU being the worker costs, although with the Material cost driver rising with the number of layers. One thing to consider with the Material cost driver is that the surface area of the part was relatively small, only $0.0375m^2$, which decreases the Material cost impact for this test case. It is expected (and confirmed in the next test case), that higher material surface areas will lead to a higher impact of the Material costs in the total costs. All of what was said tentatively means that the tool is not is not driven by one single variable, which would mean that the tool had not been properly designed, but is instead driven by a combination of variables with impact on the final solution space.

6.1.3. Test Case 2 Bending

6.1.3.1. Introduction

For the second test case, bending of a sandwich plate, the simulated specimen is a square flat plate with dimensions of 1m X 1m as shown in Figure 108. The plate is simply supported at its right and left edges and a distributed load is applied to the area of the plate.

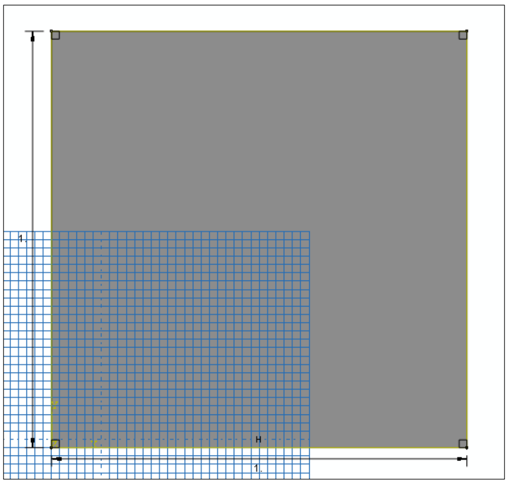


Figure 108 – Test specimen dimensions (m)

To determine the behavior of the tool three loadings and four production quantities were considered as shown in Table 38, for a total of 12 simulations for this test case.

Table 38 – Load Values and unit production tested

Test variables	Value	Value	Value	Value
Loadings	0.5 kPa	5 KPa	25 kPa	
Production	1 unit	250 units	500 units	1000 units

6.1.3.2. Test Loads and Boundary conditions

The model (Figure 109) was simply supported on its left and right edges (allowing only rotation along the y axis), and three different pressures were applied in its surface in order to determine the tool behavior, *i.e.*, if the tool was sensitive to changes in loadings.

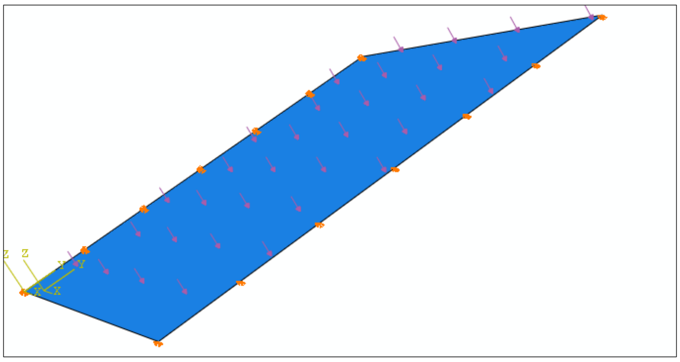


Figure 109 – Test loads and boundary conditions, bending test

6.1.3.3. Results

Table 39 shows the results of the FEA module regarding the number of layers necessary per composite material to withstand the required loads.

Table 39 - Number of Layers per composite material

Material	Layers		
	0.5kPa	**5kPa**	**25kPa**
1800_510A-40	**4**	**8**	**18**
1854_510A-40	**4**	**8**	**18**
AS4_890RTM*	**2**	**6**	**14**
AS4_PR520	**6**	**16**	**20**
AS6-5245c*	**2**	**4**	**6**
EGLASS4-7740*	**8**	**22**	**48**
EGLASS8-7740*	**8**	**22**	**48**
T300-4901A*	**6**	**14**	**32**
T300-4901B*	**6**	**14**	**32**
T300_BSL914C*	**6**	**16**	**36**
T500_R914*	**6**	**16**	**34**
T650-35_2237*	**4**	**12**	**26**
T700_510A-40	**4**	**8**	**16**
T700-4901A*	**6**	**20**	**44**
T700-4901B*	**6**	**16**	**36**

As Table 39 shows the load values considered represent a good spectrum of layers being considered, with all materials requiring more layers as the loads increase, and with some composites requiring more than double the number of layers for the given load. Figure 110 shows an example result for the FEA module regarding the Tsai-Hill Failure Criterion along the thickness of the specimen.

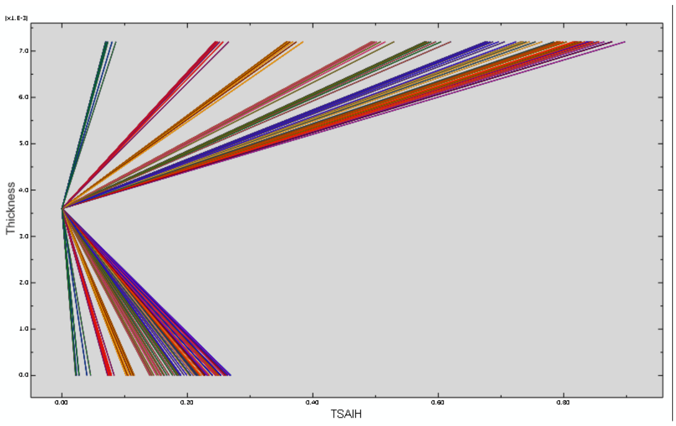


Figure 110 – Tsai Hill test results per lamina, 25kPa, T700-4901B Composite

Figure 111 shows the Pareto results for the materials in the bending test from 250 units to 1000 units with all the test case loads.

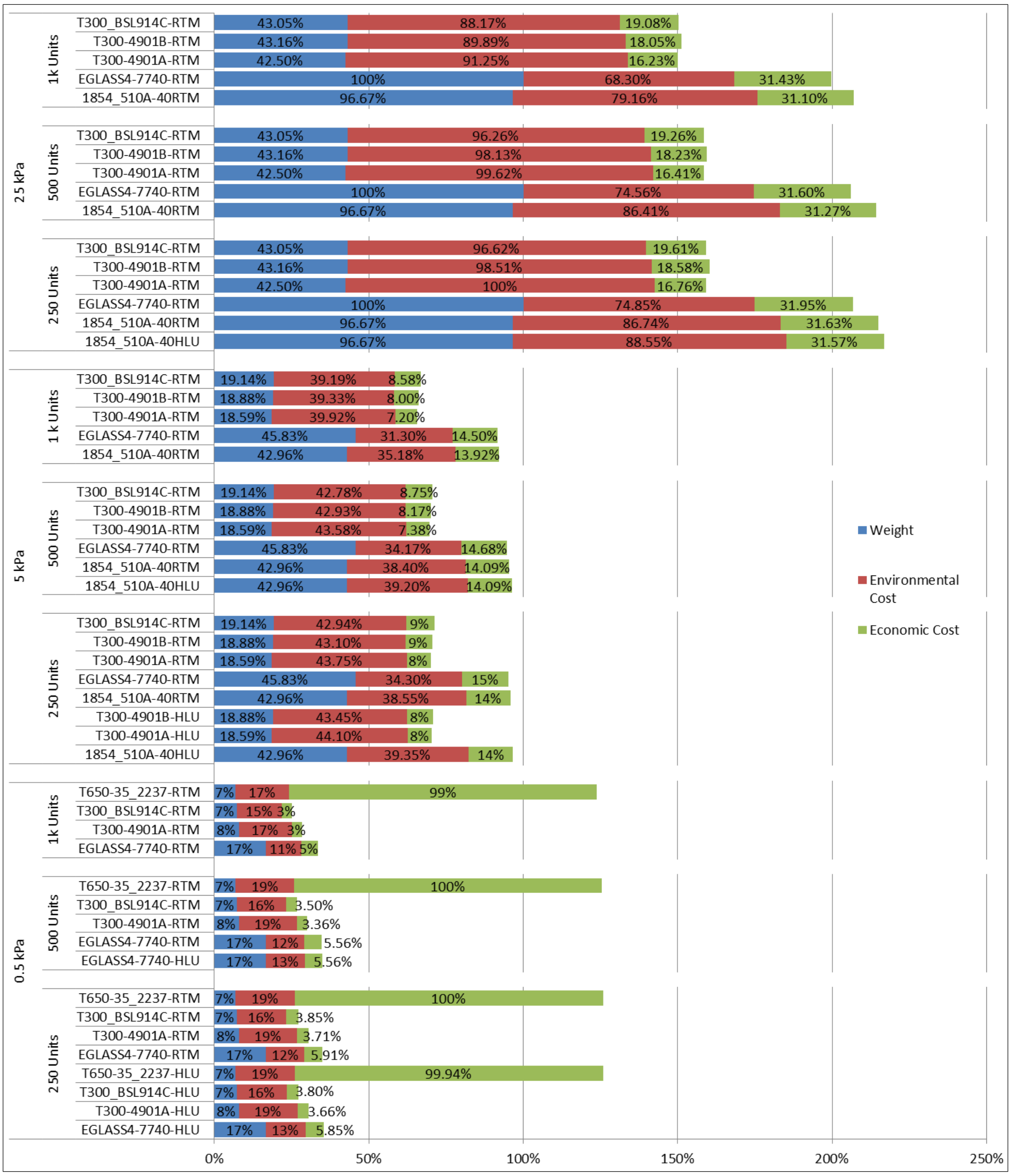


Figure 111 - Results for the various tests performed for the Bending test case (lower is better)

- **0.5 kPa Loading case**

As Figure 111 show, the composite materials selected are the 4-harness satin weave Fiber-Glass Epoxy EGlass-7740, the Unidirectional Carbon-Fiber Epoxy T300-4901A and the Unidirectional Carbon-Fiber Epoxy T300-BSL914C, and the 8-Harness Satin weave-Polymide T650-35_2237. The Economic cost per part decrease with the number of units produced, since, except for the material costs, all of the other costs are distributed among more parts. On the other hand Weight remains the same since the weight is a function of the number of layers, which remain constant given the same load. Up to 500 units, there is a mix of composite materials produced by RTM and Hand/Wet-Layup, given the fact that the HLU produced composites have a lower Economic Cost that the RTM composites, but a higher Economic cost. At 500 units almost all of the composites selected are produced by RTM, with the exception of the composite EGlass-7740, due to the fact that it is still cheaper to produce that the equivalent composite produced by RTM and with a smaller environmental impact than all of the other composites. At 1000 Units only the RTM produced composites appear in the solution space given that at a point between 500 and 1000 Units the RTM production method Economic Cost per part decreased below that of the HLU Economic cost, for the EGlass-7740 composite. Figure 112 shows the estimated cost per part for the Eglass-7740 Composite material, from 200 units to 1000.

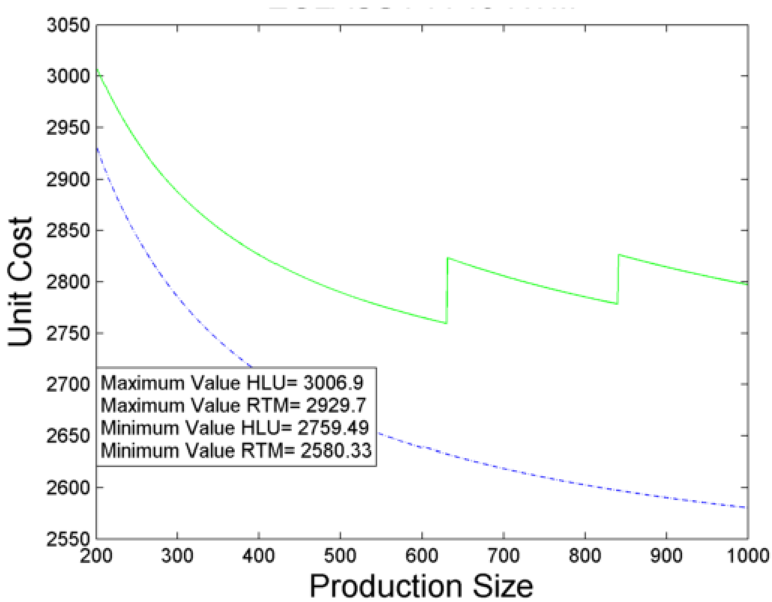


Figure 112 - Cost per part per unit production size E-GLASS 7740 Composite material (truncated)

As Figure 112 shows, the estimated cost pert part drops much faster in this test than in the tension test (see Figure 104), due to a number of factors, namely, the fact that by being a bigger part (with an area of $1.0m^2$ versus $0.0375m^2$), there are more ancillary production costs in the HLU process, such as a higher volume of plastic sheet, tacky tape and gaffer tape necessary for vacuum bagging per part, which decreases the costs in a much slower rate than the RTM process which suffers less from such ancillary costs, which means that the cut-off point between HLU and RTM is below 200 units per year (in contrast to the 750 units per year of the first test case), regardless of composite material chosen. The two jumps in unit cost in the HLU curve are due to two different situations. The first jump, at about 630 units, is due to the need of expanding the curing oven, in order to meet the number of units required. The second jump, at around 850 units is due to the need of more Wet/Hand lay-up workers required to meet the expected production, and occurs slightly sooner than the first test case.

To understand how these costs vary, Figure 113 to Figure 115 shows the cost drivers of the Glass-Fiber Epoxy 7740 Composite material for 250, 500 and 1000 units.

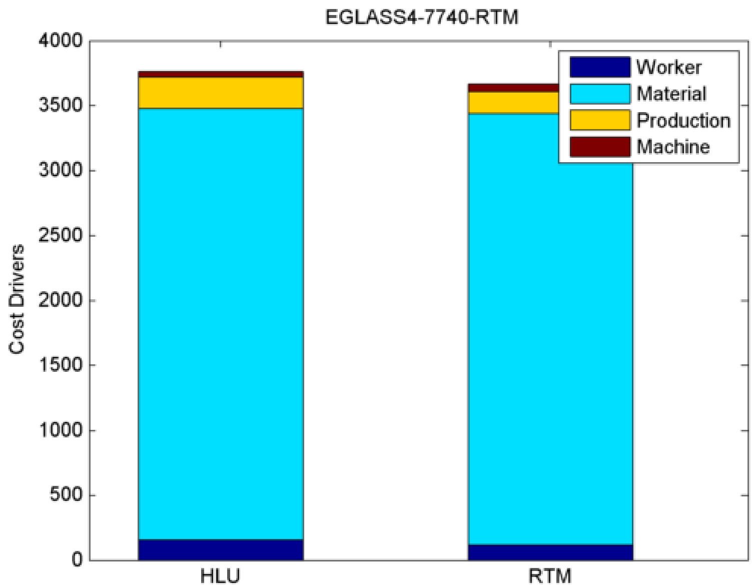


Figure 113 – Cost drivers per unit, 250 units production

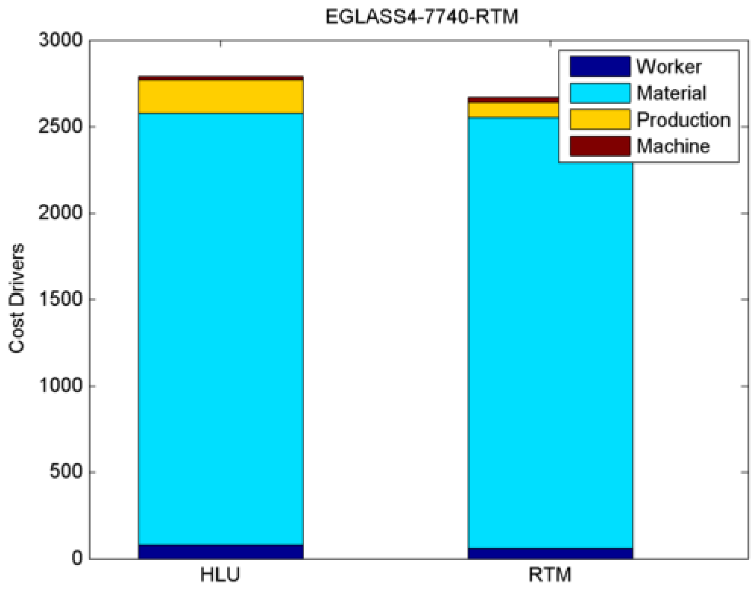


Figure 114 - Cost drivers per part, 500 units production

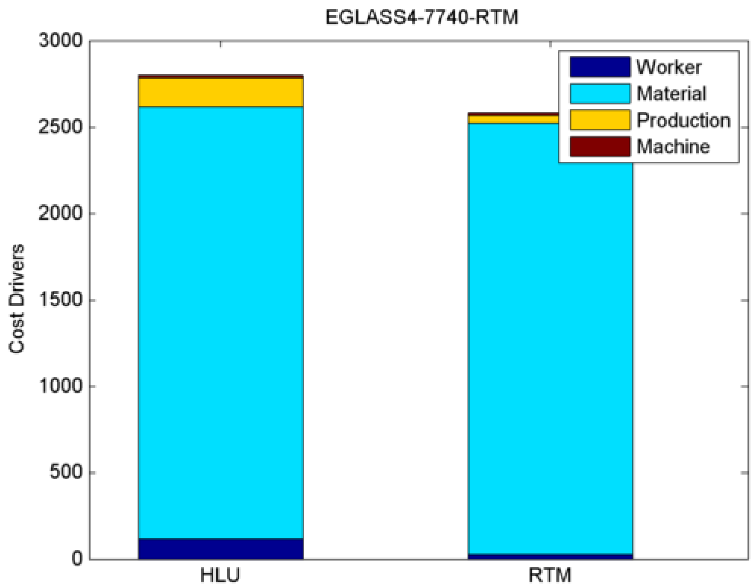


Figure 115 - Cost drivers per part, 1000 units production

In all of the cases the material cost is the dominant cost driver, responsible for between 75% and 95% of the part cost, depending on composite material, due to the number of layers required to produce the part, in contrast to the first test case where the material cost was one of the smallest cost drivers. Due to the ancillary costs mentioned above, the unit cost produced by HLU remains somewhat constant (with a fluctuation of about 60€/per part given production size) after a production above 400 units, which means that the unit cost is already close to the minimum possible by the process, *i.e.*, no further saving can be made by up scaling the production, and are actually detrimental to the unit cost. The RTM costs keep diminishing, and further up scaling should drive the price

further down. The differences in cost between processes are, of course, due to differences in process costs, as in the first test case.

- **5 kPa and 25kPa Loading cases**

Given that the same material was chosen the 5kPa and 25kPa load cases will be treated together.

As Figure 111 shows, the composite materials selected are satin weave Glass fiber, Vinylester 1854_510A-40, the 4-harness satin weave Fiber-Glass Epoxy EGlass-7740, the Unidirectional Carbon-Fiber Epoxy T300-4901A and T300-4901B, and the Unidirectional Carbon-Fiber Epoxy T300-BSL914C. As in the first case, trade point between HLU and RTM is below 200 units with the exception being the 1854_510A-40 composite, with a trade point of 265 units. From that point onward all of the solutions are RTM with the same composites being part of the solution space for both load values. The part cost increases tremendously due to the amount of raw material being used, a combination of big part size and a high number of layers, with the difference in cost for the same unit production with different loads correlates with the huge increase to more than double of the number of layers. As an example the T300-4901 Composite requires 32 layers to withstand the loads, which means that a single part requires a minimum of $32m^2$ of cloth plus resin. Since no economies of scale were considered for the materials, the costs rise in accordance to the number of layers.

Table 40 shows the Material selection per load case, production method and production size.

Table 40 - Material Selection per load case/production method/production size

	1 Unit						250 Units						500 Units						1000 Units					
Process	RTM			HLU			RTM			HLU			RTM			HLU			RTM			HLU		
kPa	0.5	5	25	0.5	5	25	0.5	5	25	0.5	5	25	0.5	5	25	0.5	5	25	0.5	5	25	0.5	5	25
1800 510A-40																								
1854 510A-40		X	X		X	X		X	X		X	X		X	X		X			X	X			
AS4 890																								
AS4 PR520																								
AS6 5245c																								
EGLASS4 7740	X	X	X	X	X		X	X	X	X			X	X	X	X			X	X	X			
EGLASS8 7740																								
T300 4901A		X	X	X	X	X	X	X	X	X	X		X	X	X				X	X	X			
T300 4901B		X			X	X		X	X		X			X	X					X	X			
T300 BSL914C	X	X	X	X	X	X	X	X	X	X			X	X	X				X	X	X			
T500 R914																								
T650 35_2237	X			X			X			X			X						X					
T700 510A-40																								
T700 4901A																								
T700 4901B																								

With the exception of the 8-Harness Satin weave Carbon Fiber-Polyimide T650-35_2237 all of the materials in the 0.5kPa load case are present in the 5 kPa and 25 kPa. One possible explanation is that, given the low number of layers of the T650-35_2237 composite when compared with the other composites selected, each layer can withstand higher loadings. This can mean that a 5kPa and the 25kPa loads are sub-optimal for this composite when compared to the other alternatives in the solution space, *i.e.*, that the number of layers required for the load cases are capable of supporting a higher load than the one imposed, which could, coupled with a possible increase in number of layers for the composites in the solution space, return the T650-35_2237 composite to the solution space. The reasoning behind this line of thought is based on the fact that while the composites in the solution space go from one load case to the next with an increase in

layer number of around 2.3x, the T650-35_2237 composite goes from load case to load case with a layer increase factor of 3x.

With this test case, the dominant cost driver is the material cost, given the size of the part being produced. Once again the model shows sensitivity to multiple variables which increases the confidence on the performance of the tool.

6.1.4. Test Case 3 - Sandwich structures in Bending

6.1.4.1. Introduction

For this third test case, and to demonstrate the suitability of the framework towards sandwich structures, a sandwich structure was tested. The part selected for this case was a 0.1m x 0.015m flat plate as shown in Figure 116.

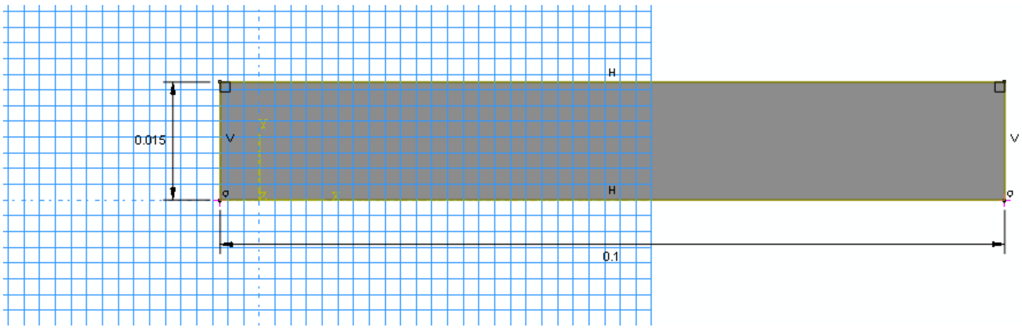


Figure 116 – Test specimen dimension (m)

The dimensions were selected in order to respect the 16:1 span to depth ratio of the ASTM C393 bending test method, with the maximum deflection set at half that value or 2.5mm at mid-span.

In this test case instead of using the Tsai-Hill failure criterion, the Maximum Deflection failure criterion was used, to test the framework response to such a failure criterion.

The core material for the sandwich structure was the CoreCork® NL10 material with 5.0mm thickness and the mechanical properties are shown in Table 41.

Table 41- CoreCork® NL10 Mechanical Properties

Elastic Modulus MPa	Shear Modulus MPa	Poisson Ratio	Density kg/m^3
5.1	5.9	0.3	120

To determine the behavior of the framework three loadings and four production quantities were considered as shown in Table 42, for a total of 12 simulations for this test case.

Table 42 - Load Values and unit production tested.

Test variables	Value	Value	Value	Value
Loads	50kPa	100kPa	250kPa	
Production	1 unit	250 units	500 units	1000 units

6.1.4.2. Test Loadings and Boundary conditions

The model was fixed at both edges (allowing no rotation or motion at either end), and three different loadings were applied on the top facing of the sandwich, (Figure 117) in order to determine the tool behavior, *i.e.*, if the tool was sensitive to changes in loads, and if, by using a loading type similar to the last case study, if the tool would return similar solution spaces.

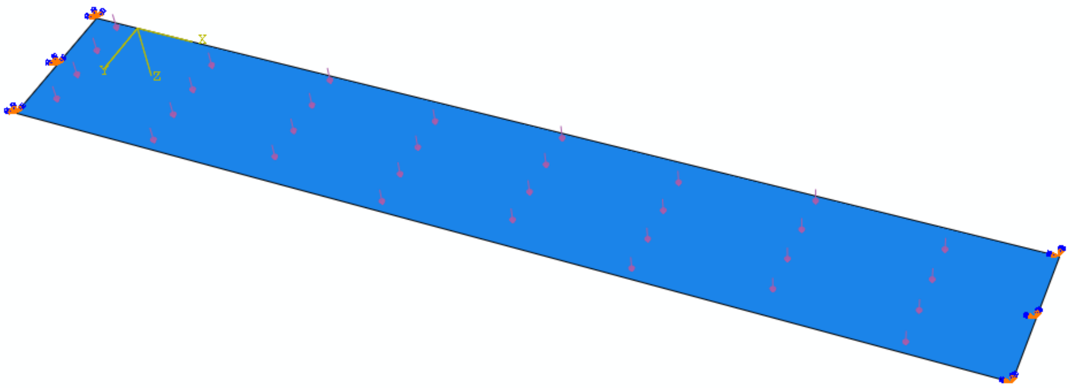


Figure 117 - Test loads and boundary conditions, sandwich test

6.1.4.3. Results

Table 43 shows the results of the FEA module regarding the number of layers necessary per composite material (with each skin possessing half of the number of layers required) to withstand the required loads.

Table 43 - Number of Layers per composite material

Material	Layers		
	50kPa	100kPa	250kPa
1800_510A-40	2	4	10
1854_510A-40	2	4	8
AS4_890RTM*	2	2	4
AS4_PR520	2	2	8
AS6-5245c*	2	2	2
EGLASS4-7740*	2	10	32
EGLASS8-7740*	2	10	30
T300-4901A*	2	2	6
T300-4901B*	2	2	8
T300_BSL914C*	2	2	8
T500_R914*	2	2	6
T650-35_2237*	2	4	10
T700_510A-40	2	2	4
T700-4901A*	2	2	6
T700-4901B*	2	2	6

As Table 43 shows the first load case was not particularly demanding on the sandwich structure with all of the composites tested needing only the two starter layers to stay below the 2.5 mm maximum deflection at mid-span required. In the second load case, 100kPa some composite materials start increasing the number of layers, especially the 4 and 8 harness satin weave glass-fiber composites. In the last loading case, all of the materials have increased the number of layers, with the exception of the AS6-5245c biaxial braid carbon fiber- epoxy composite material.

Figure 118 shows the Pareto results for the materials in the sandwich bending test.

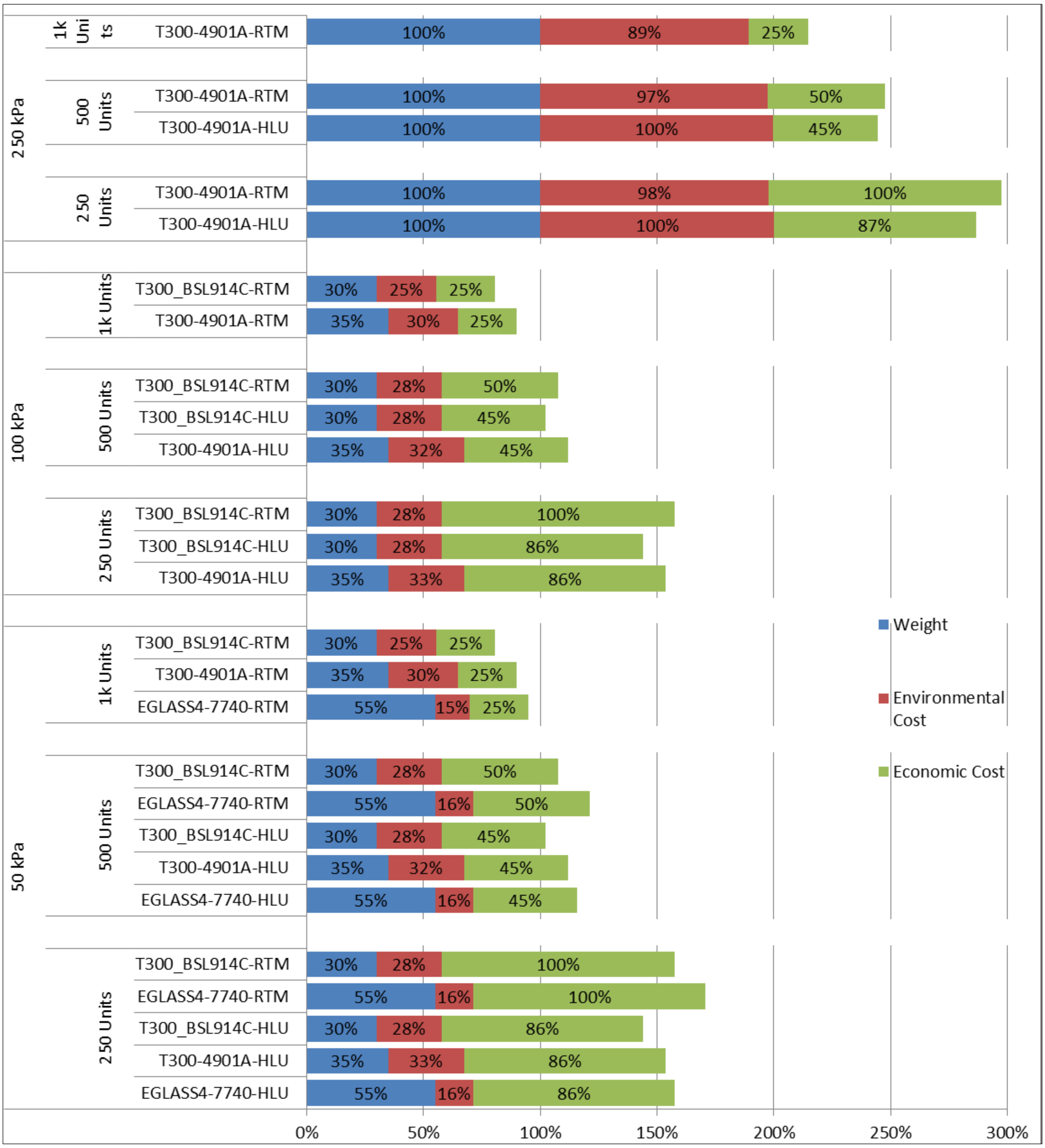


Figure 118 - Results for the various tests performed for the Sandwich test case (lower is better)

- **50kPa Loading case**

As Figure 118 shows, the composite materials selected are the 4-harness satin weave Fiber-Glass Epoxy EGlass-7740, the Unidirectional Carbon-Fiber Epoxy T300-4901A and the Unidirectional Carbon-Fiber Epoxy T300-BSL914C. As it happened in the previous cases, the Economic cost per part decreases with the number of units produced, and the weight remains constant. Up to 1000 units, there is a mix of composite materials

produced by RTM and Hand/Wet-Layup, given the fact that the HLU produced composites have a lower Environmental Cost that the RTM composites, but a higher Economic cost.

At 1000 units no HLU produced part appears in the solution space since somewhere between 500 and 1000 units the unit cost of the HLU parts overtakes the unit cost of the RTM produced parts. Figure 119 shows the estimated cost per unit for the Eglass-7740 Composite material, from 200 units to 1000, for this test case.

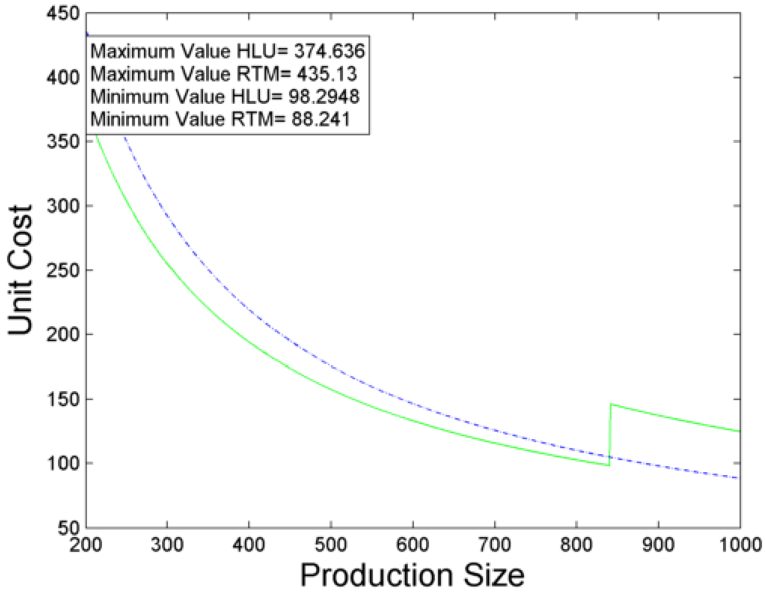


Figure 119 – Cost per part per unit production size E-GLASS 7740 Composite material (truncated)

As Figure 119 shows the trade-off point between HLU and RTM happen at the 841 estimated unit production mark, coincident with the jump in cost per unit of the HLU part due to the increase in workers in order to produce the number of units required. The overall shape of both curves are similar to the first test case, due to the fact that although the load type changes, the number of layers and part dimensions are similar, which translates into similar costs in both test cases. Again the RTM solution decreases in cost faster than the HLU solution, mostly due to the fact that the rate of growth of the number of molds is slower rate in RTM than in HLU, as are the ancillary costs mentioned in the second test case.

To understand how these costs vary, Figure 120 to Figure 122 show the cost drivers of the Glass-Fiber Epoxy 7740 Composite material for 250, 500 and 1000 units.

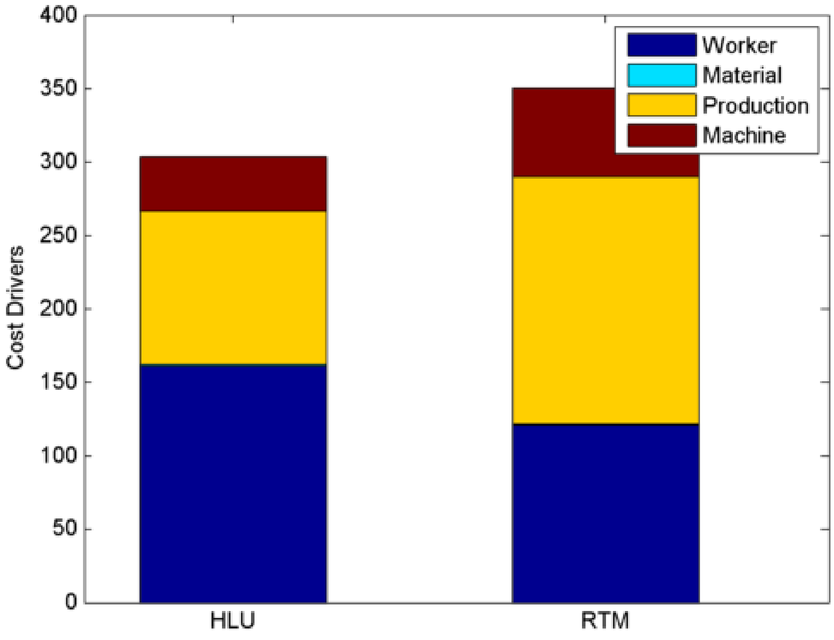


Figure 120 – Cost drivers per part, 250 units production

For 250 units HLU has an advantage over RTM, due mainly to the much lower initial costs as the Machine cost Driver shows, and smaller Production costs, including molds, energy, and associated operations. The only advantage that RTM possesses in terms of economic costs at this stage is due to the lower workers costs, since RTM requires a lower number of workers at this point. Of note is the fact that, due to the size of the part, the material costs are almost irrelevant to the final cost.

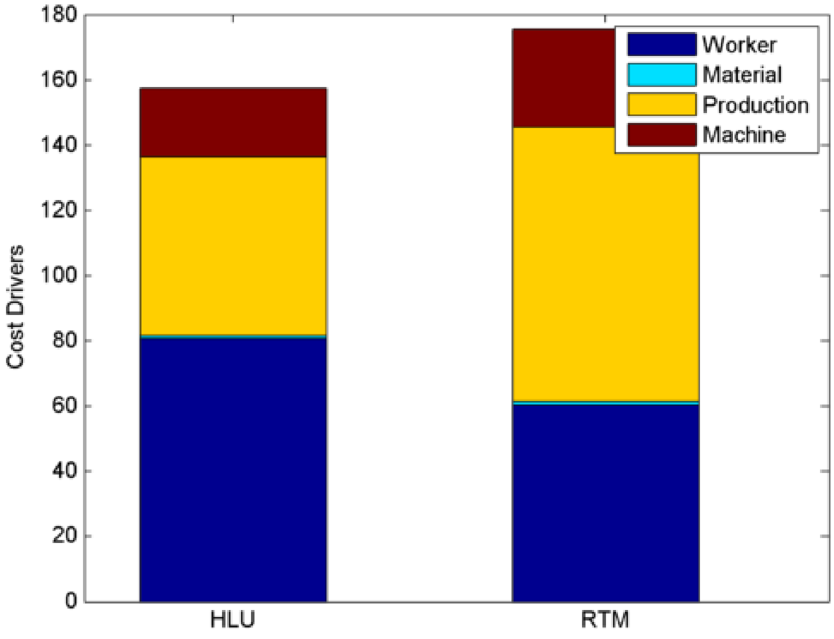


Figure 121 - Cost drivers per part, 500 units production

At an estimated production of 500 units both production methods have decreased the total costs to slightly more than half of the costs for the 250 unit production. Material costs remain static, and will remain so, only showing as a bigger part of the total costs due to the fact that all of the other costs have decreased, with special emphasis on material costs and production costs on RTM, which enables RTM to close the gap to HLU.

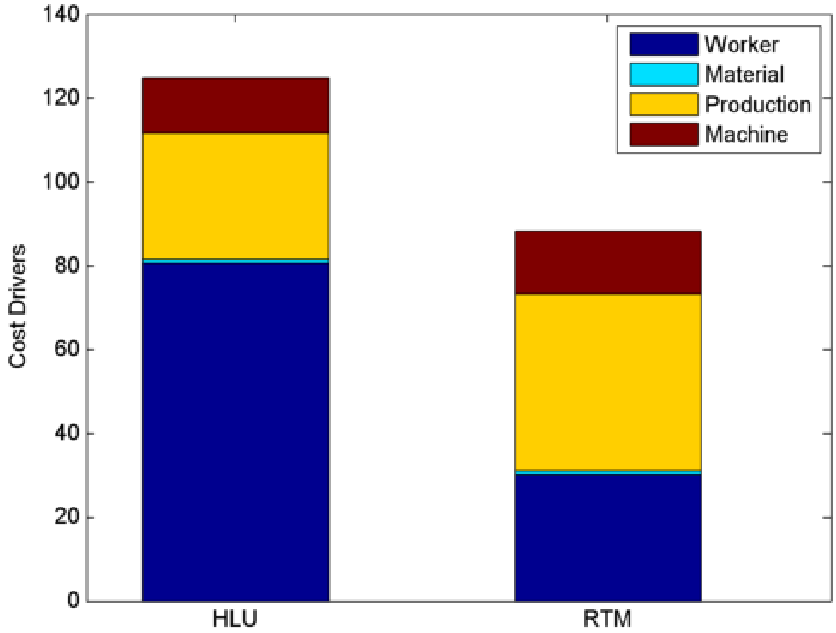


Figure 122 - Cost drivers per part, 1000 units production

At 1000 units RTM has lower total costs than HLU, especially due to the fact that HLU has more than double the Worker costs when compared to RTM, a similar state as seen on the first test case. These costs are so much higher that the worker costs in the HLU part is almost on par with the **total** cost of the parts produced by RTM.

- **100kPa Loading case**

As Figure 118 shows, the composite materials selected are the Unidirectional Carbon-Fiber Epoxy T300-4901A and the Unidirectional Carbon-Fiber Epoxy T300-BSL914C, with the 4-harness satin weave Fiber-Glass Epoxy EGlass-7740, dropping from the solution space owing to the big increase in the number of layers required to withstand the loads given.

- **250kPa Loading case**

As Figure 118 shows the only material chosen for the 250 kPa load case is the Unidirectional Carbon-Fiber Epoxy T300-4901A Composite material. As in the first two load cases the HLU produced part is still a possible solution up to 840 units, the point where the RTM produced part becomes cheaper than its HLU counterpart. This does not mean however that the Carbon-Fiber Epoxy T300-4901A composite material becomes the only choice from 250kPa and up load values. Although at 250kPa the Carbon-Fiber Epoxy T300-BSL914C requires two more layers than the chosen material, there might be load cases where once again both materials have the same number of layers, which means that the T300-BSL914C composite material would once again surface in the solution space. Table 44 shows the material selection per load case, production method and production size.

Table 44 - Material Selection per load case/production method/production size

	1 Unit						250 Units						500 Units						1000 Units					
Process	RTM			HLU			RTM			HLU			RTM			HLU			RTM			HLU		
kPa	**50**	**100**	**250**	**50**	**100**	**250**	**50**	**100**	**250**	**50**	**100**	**250**	**50**	**100**	**250**	**50**	**100**	**250**	**50**	**100**	**250**	**50**	**100**	**250**
1800 510A-40																								
1854 510A-40																								
AS4 890																								
AS4 PR520																								
AS6 5245c																								
EGLASS 4 7740	X			X			X			X			X			X			X					
EGLASS 8 7740																								
T300 4901A			X	X	X	X			X	X	X	X			X	X	X	X	X	X	X			
T300 4901B																								
T300 BSL914 C	X	X		X	X		X	X		X	X		X	X		X	X		X	X				
T500 R914																								
T650 35_223 7																								
T700 510A-40																								
T700 4901A																								
T700 4901B																								

As Table 44 shows, the solution space is quite small for this test case with only 3 materials being chosen in the first load case and progressively diminishing the higher the applied load.

As in the first two test cases the main cost driver depended on the production method, with the main Cost driver in RTM being the production costs, and the main cost driver in HLU being the worker costs, with the Material cost driver increasing with the number of layers. Given the test case small surface area of the part the material costs have almost no expression in the unit cost, which could signify that the production method in the cost model might not be the most suitable for test cases with small part dimensions.

6.1.5. Test Case 4 – Case study, rowing paddle blade

6.1.5.1. Introduction

For this final test case, the manufacturing of a rowing paddle blade using the Hand/Wet Layup manufacturing technique was selected. This test case was used to determine the suitability of the tool to a real life scenario, in addition to determine the relative ranking of the Basalt-Unsaturated Polyester composite material studied in chapter 4, to understand how this new material would rank among the database composite materials.

- **ABAQUS**

An ABAQUS model of the paddle blade was developed, in order to determine if the values obtained by the mechanical tests were in good correlation regarding the behavior of the Basalt Composites, and to test a suitable ABAQUS model for use in the tool.

The model developed in ABAQUS was a paddle blade with the dimensions shown in Figure 72 affixed to an aluminum rod with a 1.5mm wall thickness and a diameter of 30mm, as a representation of the specimens of Figure 76. Figure 123 shows the ABAQUS 3d model of the paddle blade.

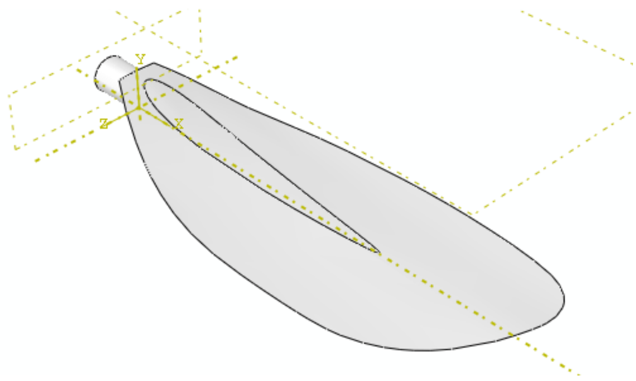


Figure 123 – 3D Model of the paddle blade

This model was then loaded in two different ways. In one, a variable end load was applied, as to mimic the mechanical tests performed previously and the data pair load/deflection at nodes placed at the same distance as the digital probe indicators were placed in the experimental tests. Three tests were made with the same configuration as the mechanical tests.

Of particular note are the second and third tests (the tests performed on the front side of both blades), where the difference in deformation from the mechanical tests to the ABAQUS tests were of 24% and for the point near the aluminum handle, and 34% for the point near the edge. For the third test the results were 63% and 12% respectively. Given the problems encountered when producing the first specimen, the differences in results were probable, although the values of 63% on the second specimen were somewhat larger.

In both tests the values for deformation on the first point of the experimental test were higher on the ABAQUS tests than on the mechanical tests, which, when combined with the 63% difference in deformation for the second test, may point to a problem in the ABAQUS model in the zone where the aluminum handle meets the composite paddle blade.

On the second point on the experimental tests the results were more in line with a lower value of deformation in the ABAQUS model, given that the ABAQUS model assumes a perfect lamina with no voids or local issues with the composite laminate. With these results, the ABAQUS model was considered a good representation of the real paddle blade, since there was a good correlation between the ABAQUS values for deformation and the real paddle blade. In addition, the possible problems detected on point one (on

the end of the aluminum rod) in both tests were deemed irrelevant since the tool would search for the maximum value of deflection, which occurs on the blade edge.

The second test was run as a pressure on the face of the blade to simulate the paddling motion, as in service, and was done for the express purpose of the real-life test of the tool, as can be seen in the next sub-section.

6.1.5.2. Test Loads and Boundary conditions

The ABAQUS model was fixed on the edge of the aluminum handle, and a distributed load was applied on the paddle blade face as shown in Figure 124.

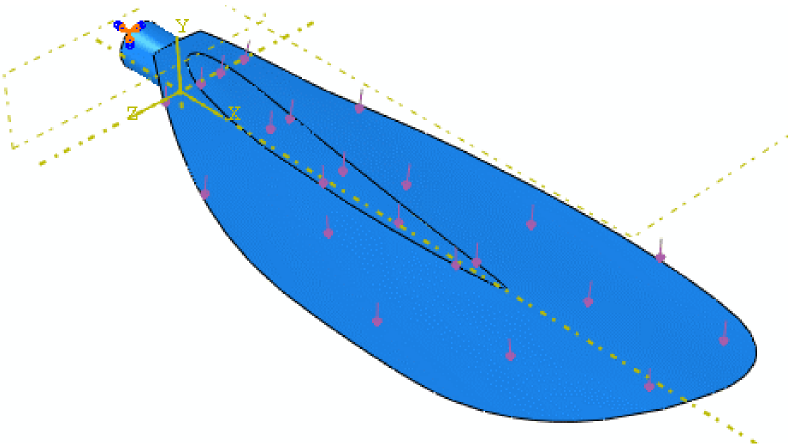


Figure 124 – Loads and Boundary conditions (paddle blade)

The loading value considered was of a 50N load distributed along the whole face of the paddle blade.

The model was then meshed as Figure 125 shows and ran to determine where the maximum deflection would occur (Figure 126).

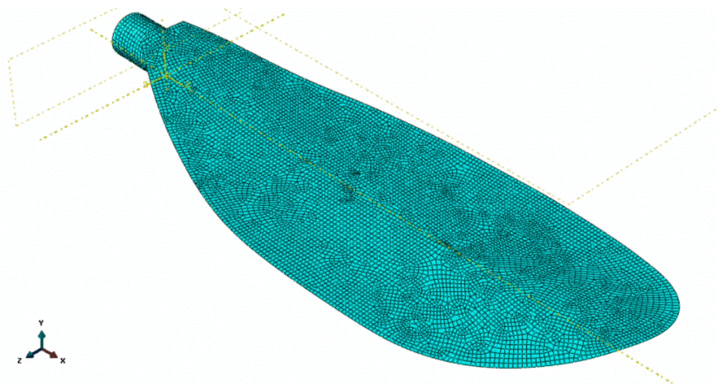


Figure 125 – paddle blade Abaqus mesh

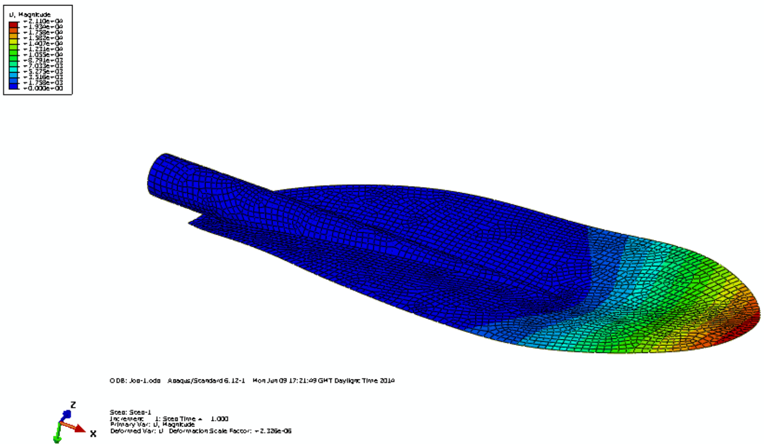


Figure 126 – Sample test results, top of the paddle blade

Knowing where the maximum deflection would occur, several nodes were selected along the edge of the paddle blade subjected to the highest deformation as seen on Figure 127. This was done to reduce the computing time, given that the tool was instructed to query the results from these nodes only, and not from all nodes of the mesh.

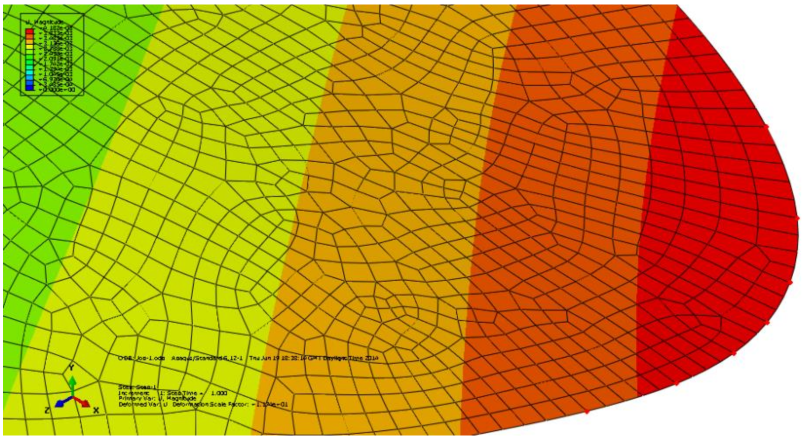


Figure 127 – Nodes selected (red dots) for the displacement of the paddle blade

6.1.5.3. Results

The first tests were run using the values obtained for the mechanical properties of the Basalt fiber/UP composite material (Figure 128).

Table 45 shows the deformation values of the selected nodes of the Basalt fiber/UP composite paddle blade.

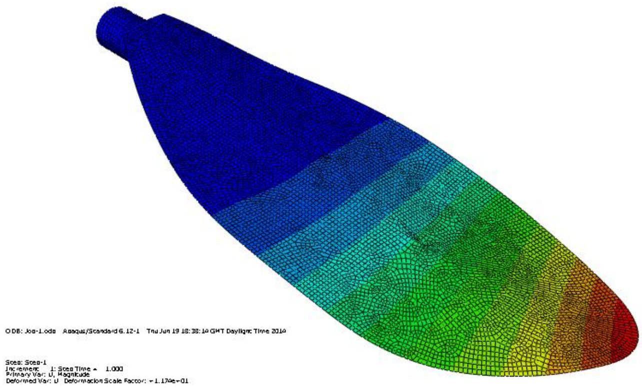


Figure 128 – Test results Basalt fiber/UP composite paddle blade

Table 45 – Displacement results at the end nodes Basalt-UP composite material

_U:Magnitude PI:	
Node	Deformation [m]
PART-1-1 N: 417	3.73E-03
PART-1-1 N: 422	3.92E-03
PART-1-1 N: 426	4.05E-03
PART-1-1 N: 429	4.12E-03
PART-1-1 N: 432	4.17E-03
PART-1-1 N: 436	4.18E-03
PART-1-1 N: 441	4.08E-03

These values were applied to determine the range of deflections used in the tests. By setting the values of deflection of each simulated test at 3.0mm, 5.0mm and 8.0mm, we could compare the results with the Basalt fiber/UP composite. Given that the test paddle blade supported 4.2mm with 8 layers, it would mean that, if the tool was working correctly, the number of layers for the 3.0mm of deflection would have to be higher than 8, and for the 8.0mm deflection the number of layers would have to be lower than 8. As such, and taking into account production values similar to those of the first test cases considered, a total of 12 combined simulations cases were made for this test case as shown in Table 46.

Table 46 – Maximum deflection and unit production tested

Test variables	Value	Value	Value	Value
Max. deflection	3 mm	5 mm	8 mm	
Production	1 unit	250 units	500 units	1000 units

Table 47 shows the results of the FEA module regarding the number of layers necessary per composite material to withstand the maximum deflection specified.

Table 47 – Number of layers per composite material

Material	Layers		
	3.0mm	5.0mm	8.0mm
1800_510A-40	8	6	4
1854_510A-40	8	6	4
AS4_890RTM*	6	4	4
AS4_PR520	8	6	4
AS6-5245c*	4	4	2
EGLASS4-7740*	26	16	12
EGLASS8-7740*	24	16	12
T300-4901A*	14	8	6
T300-4901B*	14	8	6
T300_BSL914C*	14	10	8
T500_R914*	12	8	6
T650-35_2237*	10	8	6
T700_510A-40	6	4	4
T700-4901A*	12	8	6
T700-4901B*	10	6	6
Basalt-UP	12	8	6

The results shown reinforce the notion that the tool is working correctly, since, as predicted the number of layers of the Basalt Fiber UP resin composite material decreased with the increase in maximum deflection allowed, with the values for 5 mm in accordance to the previous tests performed (which predicted 4.18 mm of maximum deflection of the paddle blade with 8 layers of composite material).

Figure 129 shows the Pareto optimal results for all thicknesses from one unit production to 1000 unit production of maximum deflection.

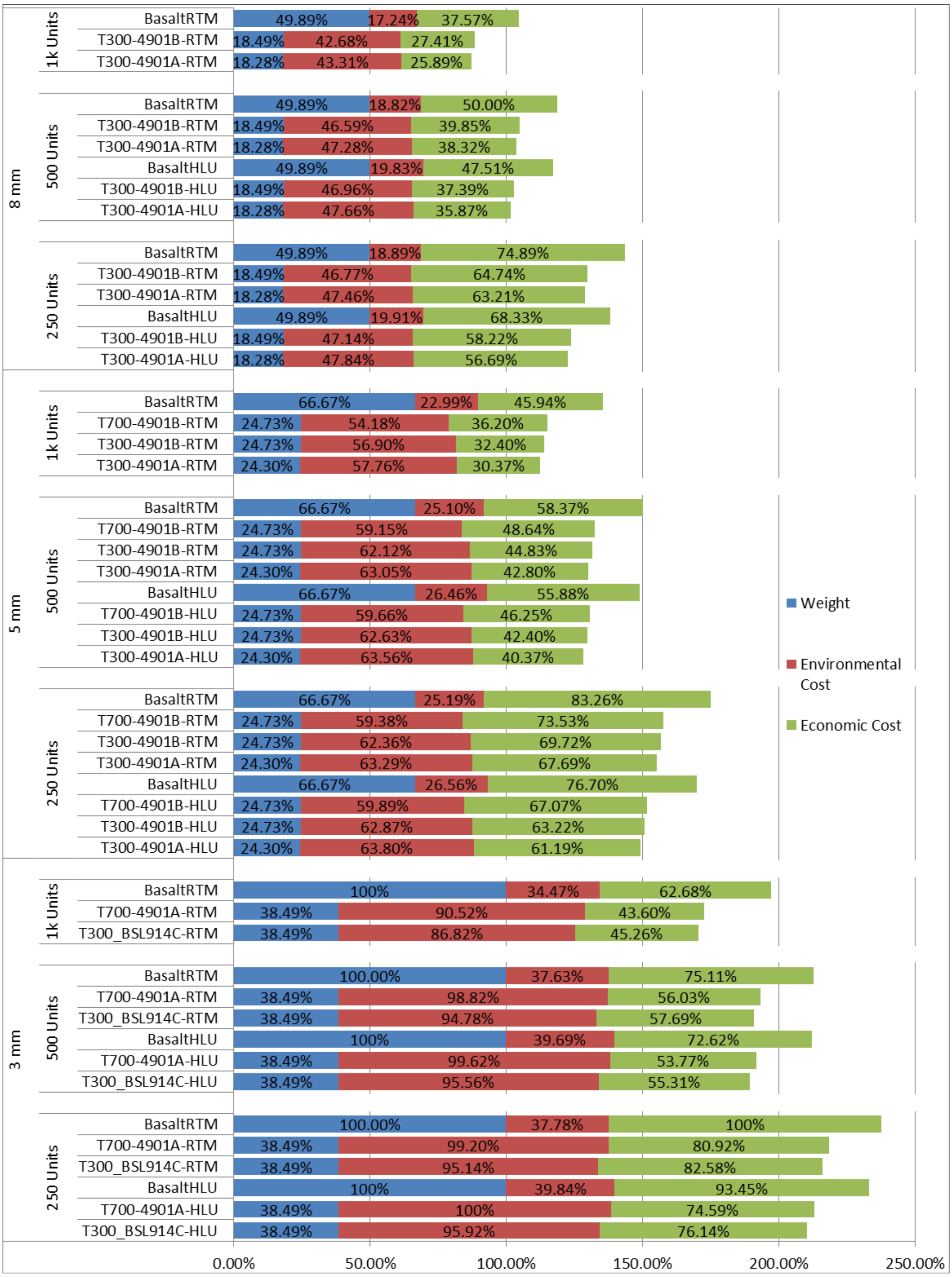


Figure 129 - Results for the various tests performed for the paddle blade test case (lower is better)

- ### 3.0mm deflection case

As Figure 129 shows the selected composite materials are the Unidirectional Carbon-Fiber Epoxy T300-BSL914C, the Unidirectional Carbon Fiber Epoxy T700-490, and

the biaxial 2/2 twill Basalt fiber Unsaturated Polyester composite material. As in the former test cases the RTM produced units have a lower environmental impact than the HLU parts, with the same weight which means that HLU produced units only show up in the solution space for as long as the price is lower than the RTM produced units. The trade-off between HLU and RTM occurs at around 550 units (see also Figure 130), after which the price of the HLU solutions rise above the RTM solutions and afterwards all solutions are RTM produced parts. In this first test with Basalt Fibers, they appear in the solution space due to its much lower environmental impact than the other solutions, although at a cost and weight penalty. It should be noted that in this test case the weight has no impact on the environmental performance, *i.e.*, no fuel savings from a lower weight part, which could have changed the final results. The weight penalty comes mainly from the basalt fibers themselves, as well as the resin used given the lower mechanical properties of Unsaturated Polyester vs the Epoxy Resin of most solutions. The cost of all solutions decrease with the number of expected production due to the cost of tooling up being distributed by more units. Figure 130 shows the price development from 200 units to 1000 units for the Basalt-UP composite material.

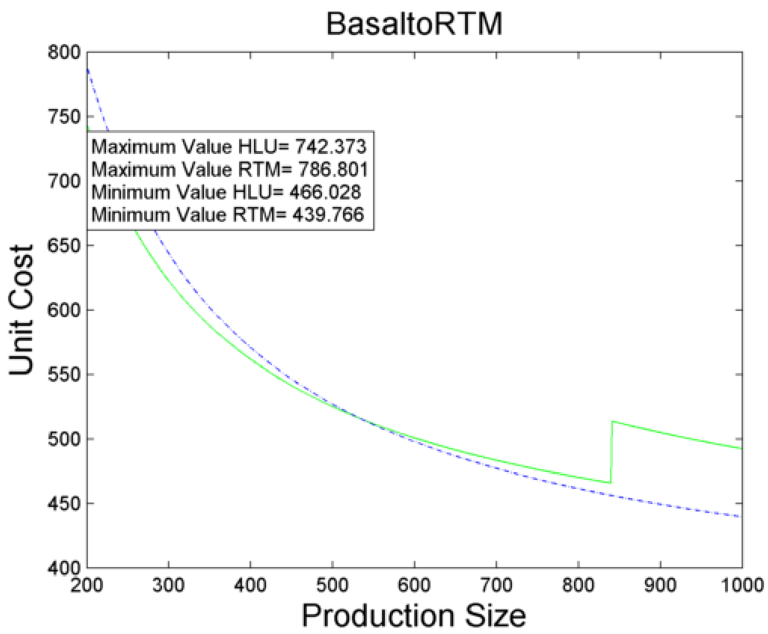


Figure 130 - Cost per part per unit production size Basalt fiber- Unsaturated Polyester Composite material (truncated)

As Figure 130 shows, HLU is a viable option up to 550 units, after which it becomes more expensive than RTM. Given that the only metric keeping parts produced by HLU in the solution space is cost per part, RTM produced parts are the only ones present in the solution space after 550 units. As in the other test cases there is a cost hike in HLU,

in this case related to the increase in workers needed to fulfill the production expectation. To understand why these costs vary Figure 131 to Figure 133 show the cost drivers of the Basalt-UP composite material, from 250 unit production to 1000 unit production.

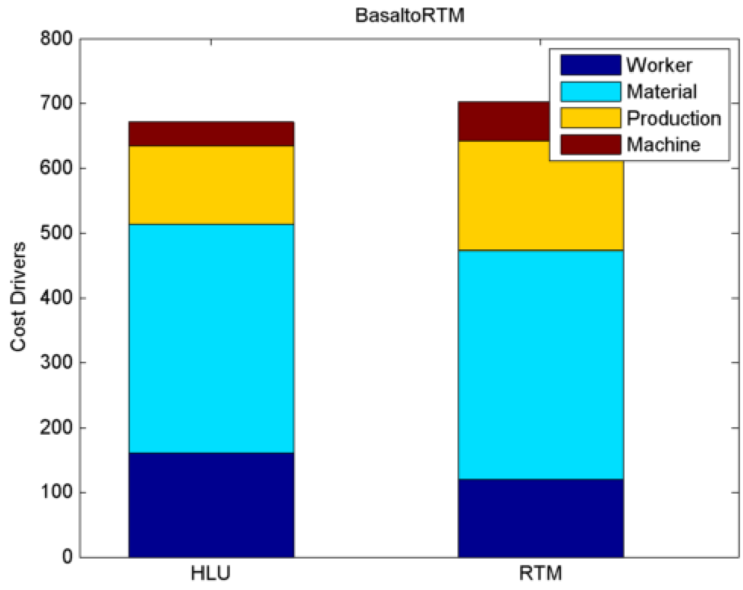


Figure 131 - Cost drivers per part, 250 units production

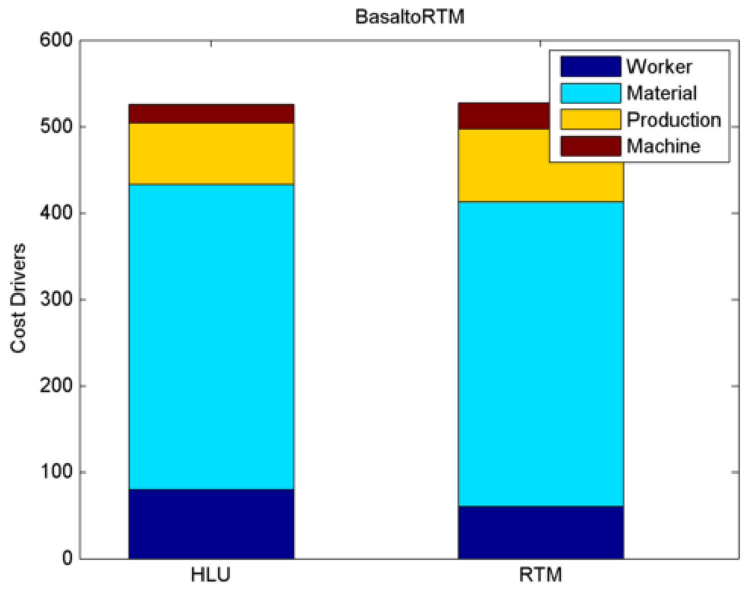


Figure 132 - Cost drivers per part, 500 units production

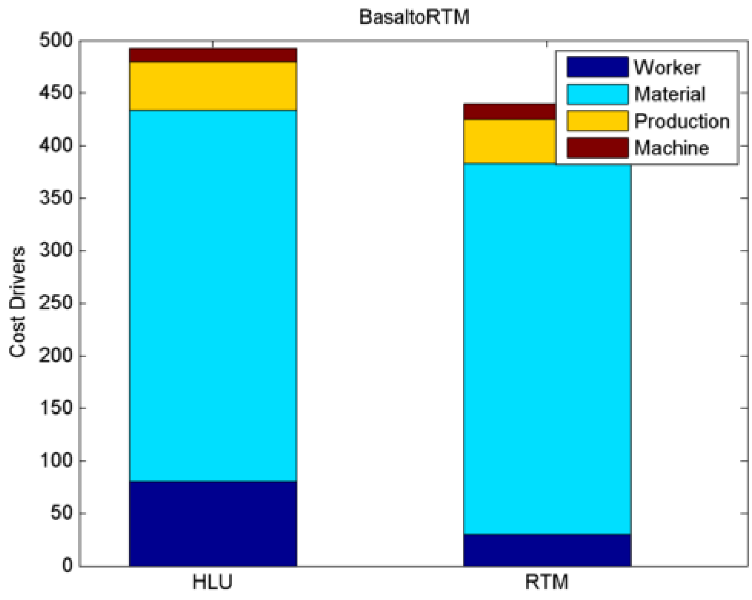


Figure 133 - Cost drivers per part, 1000 units production

In all of the cases the material cost is again the predominant cost driver accounting for roughly 55% of the total cost at 250 units and raising to 80% at 1000 units. The rest of the costs again subscribe to economies of scale with the cost per part of the worker costs, production costs and machine costs diminishing. The exception is the worker cost for HLU between 500 and 1000 units which remain at the same value, explained by the fact that the number of workers doubles, but so does the expected production. It is this increase in number of workers, coupled with the smaller effects of scale of the production cost driver, which makes HLU a costlier alternative to RTM at 1000 units.

- **5.0mm deflection case**

As Figure 129 shows the selected composite materials are the Unidirectional Carbon-Fiber Epoxy T300-4901 at two different fiber volumes, the Unidirectional Carbon Fiber Epoxy T700-490, and the biaxial 2/2 twill Basalt fiber Unsaturated Polyester composite material. In comparison with the 3.0mm test case the main difference is the replacement of the T300-BSL914C, for the T300-4901 at two different fiber volumes, due to the fact that the number of layers of these new Carbon fiber composites is smaller than the T300-BSL914C in this test case, while in the 3.0mm test case the number of layers was the same.

- **8.0mm deflection case**

As Figure 129 shows the selected composite materials are the Unidirectional Carbon-Fiber Epoxy T300-4901 Resin at two different fiber volumes and the biaxial 2/2 twill Basalt fiber Unsaturated Polyester composite material. The difference in terms of solution space, when compared with the 5.0mm max deflection test case, is the exclusion of the Unidirectional Carbon Fiber Epoxy T700-490, due to the fact that it maintains the same number of layers, while the 8.0mm max deflection test materials present in the solution space decrease the number of layers (see Table 47). Given this decrease the weight, environmental cost and economic cost also decrease. Again as in the first two test cases, the Basalt-UP composite material is part of the solution space due to its lower environmental impact but again at a cost and weight penalty.

Table 48 shows the Material Selection per load case/production method/production size.

Table 48 - Material Selection per load case/production method/production size

	1 unit						250 units						500 units						1000 units					
Process	RTM			HLU			RTM			HLU			RTM			HLU			RTM			HLU		
mm	**3**	**5**	**8**	**3**	**5**	**8**	**3**	**5**	**8**	**3**	**5**	**8**	**3**	**5**	**8**	**3**	**5**	**8**	**3**	**5**	**8**	**3**	**5**	**8**
1800 510A-40																								
1854 510A-40																								
AS4 890																								
AS4 PR520																								
AS6 5245c																								
EGLASS4 7740																								
EGLASS8 7740																								
T300 4901A		X	X		X	X		X	X		X	X		X	X		X	X		X	X			
T300 4901B		X	X		X	X		X	X		X	X		X	X		X	X		X	X			
T300 BSL914C	X			X			X			X			X			X			X					
T500 R914																								
T650 35_2237																								
T700 510A-40																								
T700 4901A	X			X			X			X			X			X			X					
T700 4901B		X			X			X			X			X			X			X				
Basalt UP	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X			

As Table 48 shows the only solutions in all of the tests are the carbon fiber composites materials due to their lower weight and higher mechanical properties, and the basalt fiber composite, due to its smaller environmental impact.

6.2. Discussion

Cost is dependent on process, material, production size, part size and number of layers so everything indicates that the tool functions correctly. It also helps in understanding how part costs vary, and in selecting the best process for a given part, load and production size.

The cost model was developed from NELO company so it is not adequate for small parts, since the cost model assumes one mold per part, when with small enough parts several can be made in the same mold, which would decrease costs (mold numbers, workforce size and curing oven size). It is also not a suitable cost model for large volumes of production (bigger than 1000 units), given that NELO works with small yearly volumes and as such has a cost profile adjusted to their production. Consequently the costs skyrocket past 1000 units in the HLU case.

The sandwich test case could have used also different core materials at different thicknesses to determine the overall best sandwich structure but at a significant cost in computing time.

As mentioned in chapter 4, one of the main problems was access to complete data for composites, and the lack of a good rule of thumb for missing values. As such the use of Failure criteria methods based on equations (such as the Tsai-Hill failure criterion used in the first two test cases) presents an issue. As such, criteria based on measurable properties, such as the maximum deflection used in the fourth test case will remain the norm until better behavior prediction can be made.

The test cases show that the tool is working as intended since it shows sensitivity to:

- Production size, with the cost decreasing with the increase in production size;
- Loading values, in the first test cases the different load values return different solution spaces, due to the fact that the changes in the number of layers are not constant for the materials, *i.e.*, due to the different properties of the materials being tested, the same increase in load values produced a different increase in the number of layers for each material;

- Deflection, similar to the previous bullet point, since, for example, decreasing the maximum deflection allowed is functionally similar to an increase in load values;
- Loading type, the materials chosen show some sensitivity to loading type, since, for instance the satin weave Glass fiber-Vinyl ester 1854_510A-40 Composite material only shows in the solution space of the bending test case, while the 4-harness satin weave Fiber-Glass Epoxy EGlass-7740 does not show up in the kayak paddle blade solution space;
- Part size, since the dominant material cost varies with part size. If the first two test cases are compared, we see that the dominant cost driver changes from the production costs in the first test case with an area of $0.0375m^2$, to the material costs in the second test case with a part area of $1m^2$.

The environmental cost decreases with the number of layers, since the environmental cost is a function both process and materials, although for smaller parts the main environmental impact is the production impact. Of note is that the environmental cost module created does not take into account vehicles of any kind, *i.e.*, the model does not consider the fuel saving from using lighter parts, or in other words, it considers that all of the parts produced are not to be part of a system with a propulsion system.

Regarding the Basalt Composites, it is worth noting that the Basalt Fiber composite appears in the solution space of all of the paddle blade tests. With that in mind it was decided to re-run the first three test cases to determine if the Basalt Fiber composites would always surface as a possible solution. The results are presented in sub-section 6.2.1.

One thing of note in the final test case is the fact that while basalt fibers have the lowest environmental impact per weight unit, the fact that carbon fibers have a much better mechanical performance, offsets this impact by using much less material than the Basalt fiber solution. This means that environment impact studies MUST be coupled with mechanical performance studies, in order to guarantee the minimum impact possible.

Finally the reduction of possible materials to a small subset of the initial database (from the initial 32 possibilities to at most 8 solutions), while simultaneously determining number of layers, layer orientation, process, weight, economic and environment cost represents a leap forward in composite design.

6.2.1. Basalt Results in the first three test cases

As mentioned previously, the basalt fiber composites were present in all of the paddle blade tests, and so, it was decided to re-run the first three test cases. Table 49 shows the results of the basalt fibers in the first three test cases.

Table 49 – Basalt results in the first three test cases

Test Case 1	**Axial Load**	**10 kN/m**	**100kN/m**	**500 kN/m**	**1000 kN/m**
	Nº of layers	2	4	18	36
	Appears as solution	yes	no	no	no
	Replaces	none	N/A	N/A	N/A
Test Case 2	**Flexural Load**	**0.5 kPa**	**5 kPa**	**25 kPa**	
	Nº of layers	6	18	38	
	Appears as solution	yes	yes	yes	
	Replaces	none	none	none	
Test Case 3	**Sandwich Load**	**50 kPa**	**100 kPa**	**250 kPa**	
	Nº of layers	2	6	18	
	Appears as solution	yes	no	no	
	Replaces	none			

As Table 49 shows the Basalt fiber composites do appear as a possible solution in some of the tests:

When the Basalt fiber composites appear in the solution space, they do not replace any material present in the solution space prior to the introduction of the Basalt fiber composites. This is due to the fact that, although the Basalt fiber composites have one of the lowest environmental impacts, the values of the economic cost and weight are high enough that no composite materials present before are dominated by its appearance.

In cases where the number of layers of basalt is similar to the composites in the former solution space, Basalt fiber composites always appear as part of the solution space given their comparatively low environmental impact.

With the exception of the flexural loading case, where the Basalt fiber composites show up in all of the loading values tests, all of the other cases show the Basalt fiber composites appearing in the solution space of the first loading case and subsequently disappear from it. This is due to two main factors: The first one is mentioned in the

preceding paragraph, when the number of layers in the Basalt fiber composite is similar to other composites, they will always appear due the low environmental impact. The second factor is due to the fact that the Basalt fiber composites increase in number of layers with the increase in load values at a much higher rate than the solution space composite materials.

This means that the low environmental impact of the Basalt fiber composites is not enough to keep it as a possible solution, since the increased number of layers of the Basalt fiber composites, when compared to the materials in the solution space, offsets this initial advantage.

There are some changes to the first test case. The 100kN/m flexural test was not analyzed in detail, since the results were equal to the 10kN/m loading value. When the Basalt Fiber composites are introduced to the database the results are somewhat different since the Basalt fiber composites show as a solution in the 10kN/m loading case, but not in the following cases.

The results tables for the introduction of Basalt fiber composites in the first three test cases can be found in Annex B.

6.2.2. General tool discussion

The shape of the curves of the unit cost vs estimated production is similar in all test cases, since the cost model is the same for all of the test methods. If we add the fact that the cost model does not account for economies of scale when purchasing materials, means that what changes in the graphics is the relative positions of the curves regarding one another (as in test cases 1, 3 and 4), and the exact points of the jumps in the unit cost for the HLU solutions (with test case 2 being an extreme example of "curve compression", since the first jump occurs much sooner than in the other test cases due to the tremendous material and ancillary costs of the parts).

6.2.2.1. Tool limitations

The cost model used in this tool and for these test cases was designed taking into account the NELO production, which means that it may not be suitable for other applications. Fortunately due to the way the framework was designed it is possible to plug other cost models better suited for the analysis to be performed.

No economies of scale are considered in the cost model, so the material cost remains the same per unit, although it is possible to change the cost model to include such parameters.

The model only increases the number of layers in the whole part, *i.e.*, it is not able to determine where in the part are the highest solicitations, and what areas need not be further reinforced, which means that depending on load type some areas of a part might be thicker than need be, which leads to an increase in costs and weight.

There is not a great degree of optimization in the way the ABAQUS model is run, *i.e.*, if a material requires 8 layers to withstand the loads required the tool will calculate results from 2 layers (the minimum amount of layers) up to the solution with 8 layers including all possible fiber stacking sequence. The issue is one of convergence for a fixed number of layers. Given the loading type some fiber orientations are better than other withstanding the loads applied, (0º for axial loading, ±45º when torque is applied, etc.), the results for each layer orientation may vary wildly from orientation sequence to orientation sequence, which means that it becomes a global optimization problem to solve the best orientation sequence, to which no suitable solution was found.

Due to the lack of optimization and the way ABAQUS runs, the runtime is consequently high. The next subsection studies the runtime of the program.

6.2.2.2. Tool runtime analysis

As mentioned the run time of the program tends to increase dramatically with the number of layers. This subsection aims to understand why this happens. Table 50 shows the nº of cycles per test, the total time per test and the cycle time of the program, and Figure 134 the cycle time per test.

Table 50 – Number of cycles, Total time and Cycle time of the program

Test	Nº of Cycles	Total Time (s)	Cycle Time (s)
Axial 10 kN	16	230	14.37
Axial 100 kN	26	473	18.19
Axial 500 kN	141	2619.58	18.58
Axial 1MN	278	4835.13	17.39
Bending 500N	122	2163.94	17.74
Bending 5kN	393	6803	17.31
Bending 25kN	887	15844.73	17.86
Sandwich 50kN	16	367	22.94

Sandwich 100kN	58	1240	21.38
Sandwich 250kN	286	6032.28	21.09
Paddle 3mm	335	11353	33.89
Paddle 5mm	215	7382	34.33
Paddle 8mm	155	5590	36.06

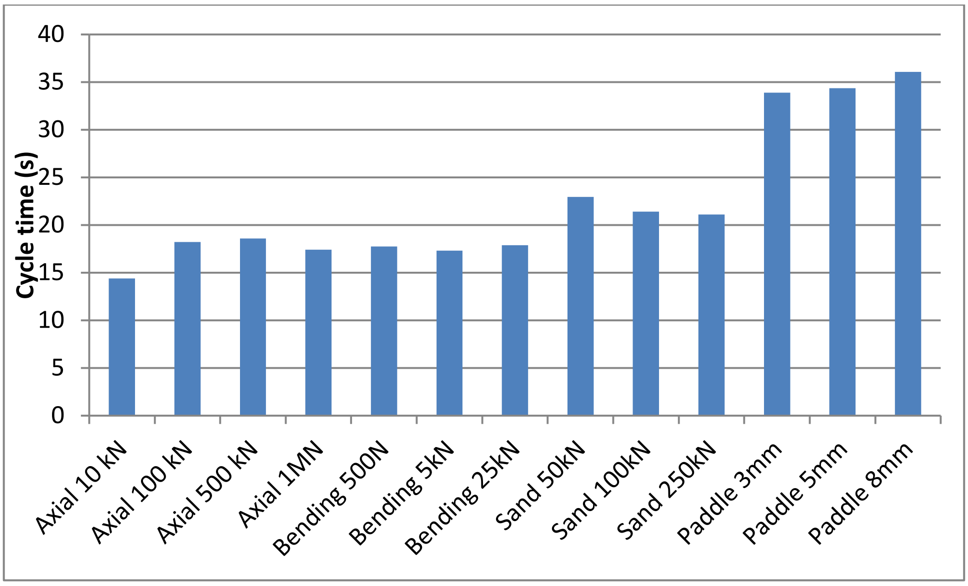


Figure 134 – Cycle time per test

Regarding the number of cycles, and their high value, the problem is that, as mentioned before, the program runs all of the possible combinations until it finds one combination of nº of layers/orientation that withstand the applied loads starting from two layers up, which means that we can express the minimum number of calculations per material required as thusly:

$$Minimum\ number\ of calculations = \sum_{x=1}^{n/2-1} 5^x \quad (1)$$

With n being the layer number at which the composite being tested is able to sustain the applied loads, which means that there is an exponential growth in the number of operations that the program has to do until it reaches a solution, *i.e.*, for a high number of layers, the total time the program runs increases tremendously.

Regarding the cycle time/total time we can see that it increases with an increase in complexity of the mesh/load case. The first two test cases have a simple load profile with a relatively large mesh size, which means that the cycle time is the same in the first two test cases between 17 and 18 seconds, with the exception of the first loading case of

the first test case with a 14s cycle time. In the third test case, with a smaller mesh, a statically indeterminate beam and a sandwich structure, the cycle time increases (to about 21.5 seconds), and finally for the paddle blade test case with the smallest mesh size the cycle time increases to about 34 seconds.

One thing of note is that the main reason for the long cycle time in all of the test cases is the fact that each time that the program call upon ABAQUS to perform a calculation, ABAQUS has to read the license file, which takes, depending on computer load, between 5 and 8 seconds, and ABAQUS is called twice per cycle. This means that in most cases, just the license file reading can take up to 50% of the cycle time.

One final note regarding total time and cycle time: All of these cycle times are valid for the computer on which the simulations were performed. Since the reading of the License file is dependent on disk reading speed, a computer equipped with a fast hard drive (like a Solid State Drive for example), would diminish the cycle time and consequently the total time of a test case.

7. Conclusions and Future Work

7.1. Conclusions

This thesis aims to answer a very complex issue, *i.e.*, the way designers and practitioners treat and apply knowledge to design. In this sense the work carried out proposes an integrated approach to composite engineering design considering economic, environmental and mechanical inputs.

One of the main aspects to consider regarding the design is the material selection process. Such selection was carried out between an incumbent material, namely Divinicell H80 as part of the core of a sandwich structure with glass fiber-epoxy facings, and a new material, Amorim CoreCork NL10 as the new core material.

The study showed that the new material has somewhat lower mechanical properties in some cases (particularly flexural stiffness, core shear modulus) and carried a weight penalty, while information provided by NELO and Amorim companies showed a lower cost and better environmental properties. This raised several questions, as shown in subsection 3.8 of this document.

There was also research done presented in the first two chapters of this document focusing on the state of materials selection, and determined that a gap existed in composites material selection regarding both environmental concerns and a proper method for evaluating multiple composite materials given their specificity.

These questions and this research led to the identification of two particular issues as the most important: first, the inclusion of environmental impacts on material selection is of the utmost importance in the present, given the current impact of human activity in the environment and how to minimize it. Second, the material selection process in composites is of a higher degree of difficulty, given it peculiarities in terms of mechanical properties, that can be somewhat tailor made to a specific set of goals.

With those questions in mind a framework was designed and built to tackle the problem of material selection in composites.

A tool based on the principles of the framework was developed and thoroughly tested, and showed promise tackling the composite material design problem.

What follows are the relationships between the research questions and the main achievements of this body of work.

When a new material is introduced in the market, specifically a composite material, one of the goals was to understand how to make new materials visible to be used by practitioners. The conclusions are that the companies producing these new materials must, first of all, perform the necessary tests to ascertain the mechanical properties of the materials, although with changes to the way the tests are performed. As discussed in Chapter 4 a compromise must be achieved between the material production companies to develop baseline composite materials in a way that these new materials can be compared to.

The data must be more complete than generally presented, since most data can only be used when using deflection as the failure criterion.

Regarding the issue of resource scarcity and environmental concerns, and in regards into determining a good method to choose from an enormous material database, the framework developed is of both use to the practitioners and the companies since, by easy integrating and computing the best possible solutions to any given product it simplifies the work done by practitioners immensely, while at the same time, allowing new materials to surface if they are a part of the solution space.

The tool developed works as a first pass approach to new material selection during R&D of a new product, especially due to; the modularity, enabling the practitioner to change/add parameters more suitable to each individual product; the fact that every material in the solution must comply with the loading and boundary conditions envelope settled by the practitioner.

Finally, and as mentioned before, by allowing a part analysis with a significant number of incumbent materials and processes and reducing the number to a small subset of the initial database, while simultaneously determining the number of layers, layer orientation, process, weight, economic and environment cost, coupled with less iterative but more specific tools, such as Dassault Systemes Composites Modeler, should guarantee the best possible composite design for any given task.

Other conclusions of this work are as follows.

As presented in chapter 3, when looking through a purely mechanical perspective, Cork incurs in a significant penalty regarding its mechanical properties, especially given its values of both flexural stiffness (EI) and core shear modulus (G). If we consider also the economic cost and the environmental cost, Cork becomes a better material for some applications, given that according to information provided by NELO and Amorim companies, the cost is lower and the environmental impact is smaller, although the difference in the total environmental impact of a kayak is somewhat negligible. This result comes from the set of studies performed in the framework of this thesis.

The tests performed on basalt fibers during this work give us a better understanding of the properties of Basalt fiber composites, information that, at the time of the tests was scarce.

With these tests performed the data can then be used in material libraries, which can be accessed either by the practitioners directly, or by a program used by the practitioners.

Finally by making the framework available to practitioners, it would help disseminate the importance of environmental concerns as a design parameter of equal importance to the cost/performance metrics used.

On a personal level the internship at MAR-KAYAKS company, served as a very good experience, fundamental to understanding the manufacturing processes of composite materials by Hand Lay-Up, process workflow in the industrial environmental, and data collection to assess engineering, environmental and economic values.

7.2. Future Work

Only two processes were evaluated RTM and HLU, due to the fact that these are the most comparable in terms of unit production capability, although there are a number of variations of these that could influence the obtained results and could be added. The framework is open to include additional processes that should be studied and inserted into the tool.

Although the idea of achieving test parity between different materials is quite a good one, tests must be performed to determine which should be the baseline fibers and resins taking into account the possible interactions between new materials with the current

ones, and take special care in determining them in order not to bottleneck future material research into materials that **have** to be compatible with at least one baseline material.

The numerical tool (the FEA module) is only able to increase thickness globally (in terms of dimensions), *i.e.*, if only one very small area is over the failure criterion imposed, all areas of the part will have additional layers of material. For now the tool can only deal with shells, which means that reinforcements like ribs cannot be designed into the Abaqus file. Although the main scope of this work was not heading to the numerical area, the tool can be improved according to the designer's purpose. Research into methods of increasing the scope of the tool should be performed, in order for the FEM module to be able to handle other configurations. This means changing the shape of the base part and dealing with fixed and free edges.

Optimization methods for both layer number and orientation would significantly decrease the number of calculations required, and thus the total runtime, and should be improved by recent developments in the field.

Environmental impact determination programs such as SimaPro are of great help in the study of materials/processes. Research should be performed in incorporating SimaPro functionality or hooks into the tool. A new project for the collaboration in this area is suggested.

References

1. WCED, *Our Common Future* 1987: Oxford University Press.
2. Malthus, *An Essay On The Principle Of Population* 1798, Penguin Classics.
3. Meadows DH, M.D., Randers J, Behrens WW III. , *The Limits to Growth* 1972, New York: Universe Books.
4. Turner, G.M., *A comparison of The Limits to Growth with 30 years of reality.* Global Environmental Change, 2008. **18**(3): p. 397-411.
5. Huang, G.O., *Design for X — concurrent engineering imperatives*, ed. G.O. Huang. Vol. 17. 1996: Chapman & Hall.
6. Jeswiet, J. and M. Hauschild, *EcoDesign and future environmental impacts.* Materials & Design, 2005. **26**(7): p. 629-634.
7. Luttropp, C. and J. Lagerstedt, *EcoDesign and The Ten Golden Rules: generic advice for merging environmental aspects into product development.* Journal of Cleaner Production, 2006. **14**(15–16): p. 1396-1408.
8. Karlsson, R. and C. Luttropp, *EcoDesign: what's happening? An overview of the subject area of EcoDesign and of the papers in this special issue.* Journal of Cleaner Production, 2006. **14**(15–16): p. 1291-1298.
9. Wanyama, W., Ertas, A.Zhang, H. C.Ekwaro-Osire, S, *Life-cycle engineering: Issues, tools and research.* International Journal of Computer Integrated Manufacturing, 2003. **16**(4-5): p. 307-316.
10. Jeswiet, J.A., *Definition of life cycle engineering.* Proceedings of the 36th CIRP international seminar on manufacturing systems. , 2003: p. (pp. 17-20).
11. Hauschild, M., J. Jeswiet, and L. Alting, *From Life Cycle Assessment to Sustainable Production: Status and Perspectives.* CIRP Annals - Manufacturing Technology, 2005. **54**(2): p. 1-21.
12. Jiang, R., W.J. Zhang, and P. Ji, *Selecting the best alternative based on life-cycle cost distributions of alternatives.* International Journal of Production Economics, 2004. **89**(1): p. 69-75.
13. Ljungberg, L.Y., *Materials selection and design for development of sustainable products.* Materials & Design, 2007. **28**(2): p. 466-479.
14. Liu, H.-C., L. Liu, and J. Wu, *Material selection using an interval 2-tuple linguistic VIKOR method considering subjective and objective weights.* Materials & Design, 2013. **52**(0): p. 158-167.
15. Anojkumar, L., M. Ilangkumaran, and V. Sasirekha, *Comparative analysis of MCDM methods for pipe material selection in sugar industry*. Expert Systems with Applications.
16. Ashby, M.F., *Materials Selection in Mechanical Design* 1999, Burlington, Massachusetts: Butterworth-Heinemann.
17. Kou, G., Y. Shi, and S. Wang, *Multiple criteria decision making and decision support systems — Guest editor's introduction.* Decision Support Systems, 2011. **51**(2): p. 247-249.
18. 2013; Available from: http://www.footprintnetwork.org/en/index.php/GFN/.
19. Simon, J.L., *Resources, population, environment: An oversupply of false bad news.* Technological Forecasting and Social Change, 1981. **19**(3): p. 207-225.
20. Seidl, I. and C.A. Tisdell, *Carrying capacity reconsidered: from Malthus' population theory to cultural carrying capacity*. Ecological Economics, 1999. **31**(3): p. 395-408.
21. Markert, J., *The Malthusian fallacy: Prophecies of doom and the crisis of Social Security*. The Social Science Journal, 2005. **42**(4): p. 555-568.

22. Elwell, F.W. *Reclaiming Malthus*. 2001 [cited 2011 May 19]; Available from: http://www.faculty.rsu.edu/users/f/felwell/www/Theorists/Malthus/reclaim.htm.
23. Borucke, M., Moore, D., Cranston, G., Gracey, K., Iha, K., Larson, J., Lazarus, E., Morales, J., Wackernagel, M. , Galli, A. ,, *Accounting for demand and supply of the biosphere's regenerative capacity: The National Footprint Accounts' underlying methodology and framework.* Ecological Indicators, 2013. **24**(0): p. 518-533.
24. Buttel, F.H., A.P. Hawkins, and A.G. Power, *From limits to growth to global change. Constraints and contradictions in the evolution of environmental science and ideology*. Global Environmental Change, 1990. **1**(1): p. 57-66.
25. Costanza, R., *Limits to growth: The 30-year update.* Ecological Economics, 2006. **59**(3): p. 397-399.
26. Cole, H.S.D., Freeman, C., Jahoda, M., Pavitt, K.L.R., *Models of Doom: A Critique of the Limits to Growth.*1973, New York: Universe Books.
27. Turner, G.M., *On the Cusp of Global Collapse? Updated Comparison of The Limits to Growth with Historical Data.* GAIA - Ecological Perspectives for Science and Society, 2012. **21**(2): p. 116-124.
28. Ayres, R.U., *Cowboys, cornucopians and long-run sustainability*. Ecological Economics, 1993. **8**(3): p. 189-207.
29. Gorobets, A., *Eco-centric policy for sustainable development.* Journal of Cleaner Production, 2014. **64**(0): p. 654-655.
30. Liu, H.,Zhou, G., Wennersten, R., Frostell, B., *Analysis of sustainable urban development approaches in China.* Habitat International, 2014. **41**(0): p. 24-32.
31. Deakin, M. and A. Reid, *Sustainable urban development: Use of the environmental assessment methods.* Sustainable Cities and Society, 2014. **10**(0): p. 39-48.
32. Gaigalis, V. and R. Skema, *Sustainable economy development and transition of fuel and energy in Lithuania after integration into the European Union.* Renewable and Sustainable Energy Reviews, 2014. **29**(0): p. 719-733.
33. Seuring, S. and M. Müller, *From a literature review to a conceptual framework for sustainable supply chain management.* Journal of Cleaner Production, 2008. **16**(15): p. 1699-1710.
34. Shen, L., K. Muduli, and A. Barve, *Developing a sustainable development framework in the context of mining industries: AHP approach.* Resources Policy, (0).
35. Guan, J., A. Zhang, and M.M. Aral, *An optimization approach for sustainable development planning of savanna systems.* Journal of Arid Environments, 2013. **98**(0): p. 60-69.
36. Milutinović, S. and V. Nikolić, *Rethinking higher education for sustainable development in Serbia: an assessment of Copernicus charter principles in current higher education practices.* Journal of Cleaner Production, 2014. **62**(0): p. 107-113.
37. Müller-Christ, G., Sterling, S., van Dam-Mieras, R., Adomßent, M., Fischer, D., Rieckmann, M., *The role of campus, curriculum, and community in higher education for sustainable development – a conference report.* Journal of Cleaner Production, 2014. **62**(0): p. 134-137.
38. Adomßent, M., Fischer, D., Godemann, J., Herzig, C., Otte, I., Rieckmann, M., Timm, J., *Emerging areas in research on higher education for sustainable development – management education, sustainable consumption and*

perspectives from Central and Eastern Europe. Journal of Cleaner Production, 2014. **62**(0): p. 1-7.
39. Lozano, F.J. and R. Lozano, *Developing the curriculum for a new Bachelor's degree in Engineering for Sustainable Development.* Journal of Cleaner Production, 2014. **64**(0): p. 136-146.
40. Dimitrova, E., *The 'sustainable development' concept in urban planning education: lessons learned on a Bulgarian path.* Journal of Cleaner Production, 2014. **62**(0): p. 120-127.
41. Bravo, G., *The Human Sustainable Development Index: New calculations and a first critical analysis.* Ecological Indicators, 2014. **37, Part A**(0): p. 145-150.
42. Rinne, J., J. Lyytimäki, and P. Kautto, *From sustainability to well-being: Lessons learned from the use of sustainable development indicators at national and EU level.* Ecological Indicators, 2013. **35**(0): p. 35-42.
43. [cited 2014 January]; Available from: epi.yale.edu.
44. Mansoor, M., Mariun, N., Ismail, N., Wahab, N., Izzri A., *A guidance chart for most probable solution directions in sustainable energy developments.* Renewable and Sustainable Energy Reviews, 2013. **24**(0): p. 306-313.
45. Kharrazi, A., Kraines, S., Hoang, L., Yarime, M., *Advancing quantification methods of sustainability: A critical examination emergy, exergy, ecological footprint, and ecological information-based approaches.* Ecological Indicators, 2014. **37, Part A**(0): p. 81-89.
46. Dahlén, P. and G.S. Bolmsjö, *Life-cycle cost analysis of the labor factor.* International Journal of Production Economics, 1996. **46–47**(0): p. 459-467.
47. Roy, P., Nei, D.,Orikasa, T., Xu, Q., Okadome, H., Nakamura, N., Shiina, T., *A review of life cycle assessment (LCA) on some food products.* Journal of Food Engineering, 2009. **90**(1): p. 1-10.
48. Berkhout, F. and R. Howes, *The adoption of life-cycle approaches by industry: patterns and impacts.* Resources, Conservation and Recycling, 1997. **20**(2): p. 71-94.
49. Joshi, S., *Product Environmental Life-Cycle Assessment Using Input-Output Techniques.* Journal of Industrial Ecology, 1999. **3**(2-3): p. 95-120.
50. Daniel, S.E. and C.P. Pappis, *Application of LCIA and comparison of different EOL scenarios: The case of used lead-acid batteries.* Resources, Conservation and Recycling, 2008. **52**(6): p. 883-895.
51. Sousa, I. and D. Wallace, *Product classification to support approximate life-cycle assessment of design concepts.* Technological Forecasting and Social Change, 2006. **73**(3): p. 228-249.
52. Ribeiro, I., Peças, P., Silva, A., Henriques, E., *Life cycle engineering methodology applied to material selection, a fender case study.* Journal of Cleaner Production, 2008. **16**(17): p. 1887-1899.
53. Ashby, M.F., *Multi-objective optimization in material design and selection.* Acta Materialia, 2000. **48**(1): p. 359-369.
54. Dori, D. and M. Shpitalni, *Mapping Knowledge about Product Lifecycle Engineering for Ontology Construction via Object-Process Methodology.* CIRP Annals - Manufacturing Technology, 2005. **54**(1): p. 117-122.
55. Duflou, J., Dewulf, W., Sas, P., Vanherck, P., *Pro-active Life Cycle Engineering Support Tools.* CIRP Annals - Manufacturing Technology, 2003. **52**(1): p. 29-32.
56. Gu, P. and S. Sosale, *Product modularization for life cycle engineering.* Robotics and Computer-Integrated Manufacturing, 1999. **15**(5): p. 387-401.

57. Kara, S., *Life cycle engineering: Applying life cycle knowledge to engineering solutions.* CIRP Journal of Manufacturing Science and Technology, 2009. **1**(4): p. 213.
58. Peças, P., Ribeiro, I., Folgado, R., A., Henriques, E., *A Life Cycle Engineering model for technology selection: a case study on plastic injection moulds for low production volumes.* Journal of Cleaner Production, 2009. **17**(9): p. 846-856.
59. Poll, G.W., *Life cycle engineering and virtual product development — The role of tribology*, in *Tribology and Interface Engineering Series*, M.P.G.D. D. Dowson and A.A. Lubrecht, Editors. 2005, Elsevier. p. 15-28.
60. Züst, R., G. Caduff, and B. Schumacher, *Life-Cycle Modelling as an Instrument for Life-Cycle Engineering.* CIRP Annals - Manufacturing Technology, 1997. **46**(1): p. 351-354.
61. Pohekar, S.D. and M. Ramachandran, *Application of multi-criteria decision making to sustainable energy planning—A review.* Renewable and Sustainable Energy Reviews, 2004. **8**(4): p. 365-381.
62. Ashry, G.A., *On globally convergent multi-objective optimization.* Applied Mathematics and Computation, 2006. **183**(1): p. 209-216.
63. Ozernoy, V.M., *Some issues in mathematical modelling of multiple criteria decision-making problems.* Mathematical Modelling, 1987. **8**(0): p. 212-215.
64. Ananda, J. and G. Herath, *The use of Analytic Hierarchy Process to incorporate stakeholder preferences into regional forest planning.* Forest Policy and Economics, 2003. **5**(1): p. 13-26.
65. Bana e Costa, C.A. and J.-C. Vansnick, *A critical analysis of the eigenvalue method used to derive priorities in AHP.* European Journal of Operational Research, 2008. **187**(3): p. 1422-1428.
66. Govindan, K., Rajendran, S., Sarkis, J., Murugesan, P., *Multi criteria decision making approaches for green supplier evaluation and selection: a literature review.* Journal of Cleaner Production, (0).
67. Ishizaka, A. and A. Labib, *Review of the main developments in the analytic hierarchy process.* Expert Systems with Applications, 2011. **38**(11): p. 14336-14345.
68. Kurttila, M., Pesonen, M., Kangas, J.,Kajanus, M., *Utilizing the analytic hierarchy process (AHP) in SWOT analysis — a hybrid method and its application to a forest-certification case.* Forest Policy and Economics, 2000. **1**(1): p. 41-52.
69. Zanakis, S.H., Solomon, A., Wishart, N., Dublish, S., *Multi-attribute decision making: A simulation comparison of select methods.* European Journal of Operational Research, 1998. **107**(3): p. 507-529.
70. Rao, R.V., *Decision Making in the Manufacturing Environment*2007: Springer.
71. Ananda, J. and G. Herath, *A critical review of multi-criteria decision making methods with special reference to forest management and planning.* Ecological Economics, 2009. **68**(10): p. 2535-2548.
72. Stewart, T.J., *A critical survey on the status of multiple criteria decision making theory and practice.* Omega, 1992. **20**(5–6): p. 569-586.
73. García-Cascales, M.S. and M.T. Lamata, *On rank reversal and TOPSIS method.* Mathematical and Computer Modelling, 2012. **56**(5–6): p. 123-132.
74. Wang, Y.-M. and Y. Luo, *On rank reversal in decision analysis.* Mathematical and Computer Modelling, 2009. **49**(5–6): p. 1221-1229.

75. Çalışkan, H., Kurşuncu, B., Kurbanoğlu, C., Güven, Ş. Y., *Material selection for the tool holder working under hard milling conditions using different multi criteria decision making methods.* Materials & Design, 2013. **45**(0): p. 473-479.
76. E. Triantaphyllou, S.H.M., *An Examination of the Effectiveness of Multi-Dimentional Decision-Making Methods: A Decision-Making Paradox.* International Journal of Decision Support Systems, 1989(nº 5): p. 303-312.
77. Raju, K.S. and C.R.S. Pillai, *Multicriterion decision making in performance evaluation of an irrigation system.* European Journal of Operational Research, 1999. **112**(3): p. 479-488.
78. Noticias, D.d. *Empresas nacionais "ganham" Olimpíadas*. 2013 30-12-2013]; Available from: http://www.dn.pt/inicio/economia/interior.aspx?content_id=3607829.
79. Stringer, L.G., *Optimization of the wet lay-up/vacuum bag process for the fabrication of carbon fibre epoxy composites with high fibre fraction and low void content.* Composites, 1989. **20**(5): p. 441-452.
80. Alves, C., Ferrão, P. M. C., Silva, A. J., Reis, L. G., Freitas, M., Rodrigues, L. B., Alves, D. E., *Ecodesign of automotive components making use of natural jute fiber composites.* Journal of Cleaner Production, 2010. **18**(4): p. 313-327.
81. Sinha Ray, S. and M. Bousmina, *Biodegradable polymers and their layered silicate nanocomposites: In greening the 21st century materials world.* Progress in Materials Science, 2005. **50**(8): p. 962-1079.
82. Mamalis, A.G., Manolakos, D. E., Ioannidis, M. B., Papapostolou, D. P., *On the crushing response of composite sandwich panels subjected to edgewise compression: experimental.* Composite Structures, 2005. **71**(2): p. 246-257.
83. Composites, A.C., *CoreCork*, 2010.
84. Yee, C.J., N.C. San, and C.n.H. Khoon, *Consumers' perceived quality, perceived value and perceived risk towards purchase decision on automobile.* American Journal of Economics and Business Administration, 2011. **3**(1): p. 47.
85. Saif Ullah, M., *Customer Satisfaction, Perceived Service Quality and Mediating Role of Perceived Value.* International Journal of Marketing Studies, 2012. **4**(1).
86. Leite, M.A.O., *Techno economic evaluation in materials selection for multiple parts under OEM-Tier relations*, 2012.
87. Mathur, V.K., *How Well Do We Know Pareto Optimality?* The Journal of Economic Education, 1991. **Vol. 22**(No. 2): p. 172-178.
88. Chauhan, A. and R. Vaish, *Hard coating material selection using multi-criteria decision making.* Materials & Design, 2013. **44**(0): p. 240-245.
89. Das, I., *A preference ordering among various Pareto optimal alternatives.* Structural optimization, 1999. **18**(1): p. 30-35.
90. Hoa, D.G.S.V., *Composite Materials: Design and Application*2006: CRC Press.
91. Nuplex.com. [cited 2013 December]; Available from: http://www.nuplex.com/Composites/processes/spray-up.
92. www.catocci.com. [cited 2013 December]; Available from: http://catoci.com/the-company/technologies/.
93. http://www.intechopen.com/. [cited 2014 April]; Available from: http://www.intechopen.com/.
94. http://www.tygavac.co.uk/. [cited 2014 April]; Available from: http://www.tygavac.co.uk/process/resin-infusion.html.
95. http://kayaks4life.blogspot.pt/. [cited 2014 October]; Available from: http://kayaks4life.blogspot.pt/p/autoconstrucao-de-kaiaks.html.

96. http://www.nuplex.com/. [cited 2014 October]; Available from: http://www.nuplex.com/Composites/processes/hand-lay-up.
97. HILLER, G.R.F.J., J. L.; SCHMIDT, T. M. e AMICO, S. C.; (2006) Influência das, C.d.M.p.T.d.R.R.n.C.M. de, and B. Compósitos Poliméricos. LAPOL/Escola de Engenharia – UFRGS.
98. Restrepo, O., Hsiao, K.-T., Rodriguez, A., Minaie, B., *Development of adaptive injection flow rate and pressure control algorithms for resin transfer molding.* Composites Part A: Applied Science and Manufacturing, 2007. **38**(6): p. 1547-1568.
99. http://www.jjmechanic.com/. [cited 2014 July]; Available from: http://www.jjmechanic.com/process/images/rtm.jpg.
100. http://www.fiber-techinc.com/. [cited 2014 July]; Available from: http://www.fiber-techinc.com/capabilities/processes/resin-transfer-molding/.
101. Thomason, J.L., *The Influence of Fibre Properties on the Properties of Glass-Fibre-Reinforced Polyamide 6,6.* Journal of Composite Materials, 2000. **34**(2): p. 158-172.
102. Tan, P., L. Tong, and G.P. Steven, *Modelling for predicting the mechanical properties of textile composites—A review.* Composites Part A: Applied Science and Manufacturing, 1997. **28**(11): p. 903-922.
103. Herrmann, A.S., J. Nickel, and U. Riedel, *Construction materials based upon biologically renewable resources—from components to finished parts.* Polymer Degradation and Stability, 1998. **59**(1–3): p. 251-261.
104. Koronis, G., A. Silva, and M. Fontul, *Green composites: A review of adequate materials for automotive applications.* Composites Part B: Engineering, 2013. **44**(1): p. 120-127.
105. Gu, Y., Tan, X., Yang, Z., li, M., Zhang, Z., *Hot compaction and mechanical properties of ramie fabric/epoxy composite fabricated using vacuum assisted resin infusion molding.* Materials & Design, 2014. **56**(0): p. 852-861.
106. Sangthong, S., T. Pongprayoon, and N. Yanumet, *Mechanical property improvement of unsaturated polyester composite reinforced with admicellar-treated sisal fibers.* Composites Part A: Applied Science and Manufacturing, 2009. **40**(6–7): p. 687-694.
107. Deka, H., M. Misra, and A. Mohanty, *Renewable resource based "all green composites" from kenaf biofiber and poly(furfuryl alcohol) bioresin*. Industrial Crops and Products, 2013. **41**(0): p. 94-101.
108. Bakare, F.O., Åkesson, D., Skrifvars, M., Bashir, T., Ingman, P., Srivastava, R., *Synthesis and characterization of unsaturated lactic acid based thermoset bio-resins.* European Polymer Journal, (0).
109. La Mantia, F.P. and M. Morreale, *Green composites: A brief review.* Composites Part A: Applied Science and Manufacturing, 2011. **42**(6): p. 579-588.
110. Morova, N., *Investigation of usability of basalt fibers in hot mix asphalt concrete.* Construction and Building Materials, 2013. **47**(0): p. 175-180.
111. Lopresto, V., C. Leone, and I. De Iorio, *Mechanical characterisation of basalt fibre reinforced plastic.* Composites Part B: Engineering, 2011. **42**(4): p. 717-723.
112. Fiore, V., Scalici, T., Di Bella, G., Valenza, A., *A review on basalt fibre and its composites.* Composites Part B: Engineering, 2015. **74**(0): p. 74-94.
113. Preto, R., *Estudo experimental do comportamento mecânico de compósitos em fibras de basalto*, Master thesis in Mechanical Engineering 2013, Instituto Superior Técnico.

114. [cited 2012 March 11]; Available from: http://composites.ides.com/.

ANNEX A – Tool results

Test case 1

10 kN/m and 100 kN/m

Table 51 – Material, Weight, Environmental and Economic cost of the solutions 10kN/m (1 part)

Material	Weight (kg)	Environmental Cost (kg CO_2 per part)	Economic Cost (€ per part)
EGLASS4-7740-HLU	0.027	0.1991	73075.96
T300-4901A-HLU	0.017	0.3927	**73070.41**
T300_BSL914C-HLU	**0.015**	0.3366	73071.29
EGLASS4-7740-RTM	0.027	**0.1947**	87326.77
T300_BSL914C-RTM	0.015	0.3344	87322.04

Table 52 - Material, Weight, Environmental and Economic cost of the solutions 10kN/m (250 parts)

Material	Weight (kg)	Environmental Cost (kg CO_2 per part)	Economic Cost (€ per part)
EGLASS4-7740-HLU	0.027	0.1983	327.24
T300-4901A-HLU	0.017	0.3912	**321.68**
T300_BSL914C-HLU	**0.015**	0.3353	322.56
EGLASS4-7740-RTM	0.027	**0.1940**	373.67
T300_BSL914C-RTM	**0.015**	0.3331	368.94

Table 53 - Material, Weight, Environmental and Economic cost of the solutions 10kN/m (500 parts)

Material	Weight (kg)	Environmental Cost (kg CO_2 per part)	Economic Cost (€ per part)
EGLASS4-7740-HLU	0.027	0.1976	181.15
T300-4901A-HLU	0.017	0.3897	**175.60**
T300_BSL914C-HLU	**0.015**	0.3341	176.48
EGLASS4-7740-RTM	0.027	**0.1932**	199.06
T300_BSL914C-RTM	**0.015**	0.3319	194.33

Table 54 - Material, Weight, Environmental and Economic cost of the solutions 10kN/m (1000 parts)

Material	Weight (kg)	Environmental Cost (kg CO_2 per part)	Economic Cost (€ per part)
EGLASS4-7740-RTM	0.027	**0.177**	111.82
T300-4901A-RTM	0.017	0.354	**106.21**
T300_BSL914C-RTM	**0.015**	0.304	107.09

$500\ kN/m$

Table 55 – Material, Weight, Environmental and Economic cost of the solutions 500kN/m (1 part)

Material	Weight (kg)	Environmental Cost (kg CO_2 per part)	Economic Cost (€ per part)
T700-4901A-HLU	**0.018**	0.4103	**73073.50**
T700-4901A-RTM	**0.018**	**0.4070**	87324.16

Table 56 – Material, Weight, Environmental and Economic cost of the solutions 500kN/m (250 parts)

Material	Weight (kg)	Environmental Cost (kg CO_2 per part)	Economic Cost (€ per part)
T700-4901A-HLU	**0.018**	0.4087	**324.78**
T700-4901A-RTM	**0.018**	**0.4055**	371.06

Table 57 – Material, Weight, Environmental and Economic cost of the solutions 500kN/m (500 parts)

Material	Weight (kg)	Environmental Cost (kg CO_2 per part)	Economic Cost (€ per part)
T700-4901A-HLU	**0.018**	0.4072	**178.70**
T700-4901A-RTM	**0.018**	**0.4039**	196.45

Table 58 – Material, Weight, Environmental and Economic cost of the solutions 500kN/m (1000 parts)

Material	Weight (kg)	Environmental Cost (kg CO_2 per part)	Economic Cost (€ per part)
T700-4901A-RTM	0.018	0.370	109.21

$1000\ kN/m$

Table 59 - Material, Weight, Environmental and Economic cost of the solutions 1000kN/m (1 parts)

Material	Weight (kg)	Environmental Cost (kg CO_2 per part)	Economic Cost (€ per part)
T700-4901A-HLU	**0.036**	0.8195	**73095.52**
T700-4901A-RTM	**0.036**	**0.8129**	87346.01

Table 60 - Material, Weight, Environmental and Economic cost of the solutions 1000kN/m (250 parts)

Material	Weight (kg)	Environmental Cost (kg CO_2 per part)	Economic Cost (€ per part)
T700-4901A-HLU	**0.036**	0.8164	**346.80**
T700-4901A-RTM	**0.036**	**0.8098**	392.91

Table 61 - Material, Weight, Environmental and Economic cost of the solutions 1000kN/m (500 parts)

Material	Weight (kg)	Environmental Cost (kg CO_2 per part)	Economic Cost (€ per part)
T700-4901A-HLU	**0.036**	0.8133	**200.71**
T700-4901A-RTM	**0.036**	**0.8067**	218.31

Table 62- Material, Weight, Environmental and Economic cost of the solutions 1000kN/m (1000 parts)

Material	Weight (kg)	Environmental Cost (kg CO_2 per part)	Economic Cost (€ per part)
T700-4901A-RTM	0.036	0.739	131.07

Test case 2

0.5 kPa Load Case

Table 63 - Material, Weight, Environmental and Economic cost of the solutions 0.5kPa (1 part)

Material	Weight (kg)	Environmental Cost (kg CO_2 per part)	Economic Cost (€ per part)
EGLASS4-7740-HLU	2.847	21.2333	75993.10
T300-4901A-HLU	1.361	31.3852	**74896.26**
T300_BSL914C-HLU	1.226	26.9665	74966.51
T650-35_2237-HLU	**1.169**	31.9220	123124.04
EGLASS4-7740-RTM	2.847	**20.7163**	90717.14
T300_BSL914C-RTM	1.226	26.7432	89686.55
T650-35_2237-RTM	**1.169**	31.7097	137844.08

Table 64 - Material, Weight, Environmental and Economic cost of the solutions 0.5kPa (250 parts)

Material	Weight (kg)	Environmental Cost (kg CO_2 per part)	Economic Cost (€ per part)
EGLASS4-7740-HLU	2.847	21.1529	2929.32
T300-4901A-HLU	1.361	31.2663	1832.48
T300_BSL914C-HLU	1.226	26.8644	**1902.73**
T650-35_2237-HLU	**1.169**	31.8011	50060.26
EGLASS4-7740-RTM	2.847	**20.6378**	2961.25
T300-4901A-RTM	1.361	31.0198	1860.41
T300_BSL914C-RTM	1.226	26.6419	1930.66
T650-35_2237-RTM	**1.169**	31.5896	50088.19

Table 65 - Material, Weight, Environmental and Economic cost of the solutions 0.5kPa (500 parts)

Material	Weight (kg)	Environmental Cost (kg CO_2 per part)	Economic Cost (€ per part)
EGLASS4-7740-HLU	2.847	21.0724	2782.60
EGLASS4-7740-RTM	2.847	**20.5594**	2785.03
T300-4901A-RTM	1.361	30.9018	**1684.20**
T300_BSL914C-RTM	1.226	26.5406	1754.45
T650-35_2237-RTM	**1.169**	31.4695	49911.98

Table 66 - Material, Weight, Environmental and Economic cost of the solutions 0.5kPa (1000 parts)

Material	Weight (kg)	Environmental Cost (kg CO_2 per part)	Economic Cost (€ per part)
EGLASS4-7740-RTM	2.847	**18.833**	2697.79
T300-4901A-RTM	1.361	28.307	**1596.96**
T300_BSL914C-RTM	1.226	24.312	1667.21
T650-35_2237-RTM	**1.169**	28.827	49824.74

5 kPa and 25kPa Load case

Given that the same materials were chosen the 5kPa and 25kPa load cases will be treated together. Table 67 through Table 70 shows the Pareto results for the materials in the bending test with a 5 kPa load and Table 71 through Table 75 shows the Pareto results for the materials in the bending test from 1 part produced to 1000 parts produced, with a 25 kPa load.

Table 67 - Material, Weight, Environmental and Economic cost of the solutions 5kPa (1 part)

Material	Weight (kg)	Environmental Cost (kg CO_2 per part)	Economic Cost (€ per part)
1854_510A-40HLU	7.339	65.3543	80267.96
EGLASS4-7740-HLU	7.829	58.3902	80562.02
T300-4901A-HLU	**3.176**	73.2314	76914.90
T300-4901B-HLU	3.225	72.1567	**77313.68**
T300_BSL914C-HLU	3.269	71.9092	77606.89
1854_510A-40RTM	7.339	64.0222	94992.00
EGLASS4-7740-RTM	7.829	**56.9690**	95282.56
T300-4901A-RTM	**3.176**	72.6550	91626.94
T300-4901B-RTM	3.225	71.5715	92025.72
T300_BSL914C-RTM	3.269	71.3163	92316.93

Table 68 - Material, Weight, Environmental and Economic cost of the solutions 5kPa (250 parts)

Material	Weight (kg)	Environmental Cost (kg CO_2 per part)	Economic Cost (€ per part)
1854_510A-40HLU	7.339	65.1067	7204.18
T300-4901A-HLU	**3.176**	72.9540	3851.12
T300-4901B-HLU	3.225	71.8834	4249.90
1854_510A-40RTM	7.339	63.7797	7236.11
EGLASS4-7740-RTM	7.829	**56.7532**	7526.68
T300-4901A-RTM	**3.176**	72.3798	**3871.05**
T300-4901B-RTM	3.225	71.3004	4269.83
T300_BSL914C-RTM	3.269	71.0462	4561.05

Table 69 - Material, Weight, Environmental and Economic cost of the solutions 5 kPa (500 parts)

Material	Weight (kg)	Environmental Cost (kg CO_2 per part)	Economic Cost (€ per part)
1854_510A-40HLU	7.339	64.8592	7057.47
1854_510A-40RTM	7.339	63.5372	7059.90
EGLASS4-7740-RTM	7.829	**56.5374**	7350.46
T300-4901A-RTM	**3.176**	72.1046	**3694.83**
T300-4901B-RTM	3.225	71.0293	4093.61
T300_BSL914C-RTM	3.269	70.7760	4384.83

Table 70 - Material, Weight, Environmental and Economic cost of the solutions 5 kPa (1000 parts)

Material	Weight (kg)	Environmental Cost (kg CO_2 per part)	Economic Cost (€ per part)
1854_510A-40RTM	7.339	58.202	6972.66
EGLASS4-7740-RTM	7.829	**51.790**	7263.22
T300-4901A-RTM	**3.176**	66.050	**3607.59**
T300-4901B-RTM	3.225	65.065	4006.37
T300_BSL914C-RTM	3.269	64.833	4297.59

Table 71 - Material, Weight, Environmental and Economic cost of the solutions 25 kPa (1 part)

Material	Weight (kg)	Environmental Cost (kg CO_2 per part)	Economic Cost (€ per part)
1854_510A-40HLU	16.513	147.0469	88875.06
T300-4901A-HLU	**7.260**	167.3870	**81456.83**
T300-4901B-HLU	7.372	164.9285	82368.33
T300_BSL914C-HLU	7.354	161.7957	82887.66
1854_510A-40RTM	16.513	144.0505	103596.60
EGLASS4-7740-RTM	17.082	**124.2967**	103761.22
T300-4901A-RTM	**7.260**	166.0692	96150.87
T300_BSL914C-RTM	7.354	160.4614	97577.70

Table 72 - Material, Weight, Environmental and Economic cost of the solutions 25 kPa (250 parts)

Material	Weight (kg)	Environmental Cost ($kg\ CO_2$ per part)	Economic Cost (€ per part)
1854_510A-40HLU	16.513	146.4899	15811.28
1854_510A-40RTM	16.513	143.5049	15840.72
EGLASS4-7740-RTM	17.082	**123.8259**	16005.33
T300-4901A-RTM	**7.260**	165.4402	**8394.99**
T300-4901B-RTM	7.372	162.9712	9306.48
T300_BSL914C-RTM	7.354	159.8536	9821.82

Table 73 - Material, Weight, Environmental and Economic cost of the solutions 25 kPa (500 parts)

Material	Weight (kg)	Environmental Cost ($kg\ CO_2$ per part)	Economic Cost (€ per part)
1854_510A-40RTM	16.513	142.9592	15664.50
EGLASS4-7740-RTM	17.082	**123.3551**	15829.11
T300-4901A-RTM	**7.260**	164.8111	**8218.77**
T300-4901B-RTM	7.372	162.3516	9130.27
T300_BSL914C-RTM	7.354	159.2458	9645.60

Table 74 - Material, Weight, Environmental and Economic cost of the solutions 25 kPa (1000 parts)

Material	Weight (kg)	Environmental Cost ($kg\ CO_2$ per part)	Economic Cost (€ per part)
1854_510A-40RTM	16.513	130.955	15577.26
EGLASS4-7740-RTM	17.082	**112.997**	15741.87
T300-4901A-RTM	**7.260**	150.972	**8131.53**
T300-4901B-RTM	7.372	148.719	9043.03
T300_BSL914C-RTM	7.354	145.874	9558.36

Test case 3

50kPa

Table 75 - Material, Weight, Environmental and Economic cost of the solutions 50 kPa (1 part)

Material	Weight (kg)	Environmental Cost (kg CO_2 per part)	Economic Cost (€ per part)
EGLASS4-7740-HLU	0.011	**0.0077**	73035.72
T300-4901A-HLU	0.007	0.0154	**73035.49**
T300_BSL914C-HLU	**0.006**	0.0132	73035.53
EGLASS4-7740-RTM	0.011	**0.0077**	87274.34
T300_BSL914C-RTM	**0.006**	0.0132	87274.16

Table 76 - Material, Weight, Environmental and Economic cost of the solutions 50 kPa (250 parts)

Material	Weight (kg)	Environmental Cost (kg CO_2 per part)	Economic Cost (€ per part)
EGLASS4-7740-HLU	0.011	**0.0077**	303.13
T300-4901A-HLU	0.007	0.0153	**302.91**
T300_BSL914C-HLU	**0.006**	0.0132	302.95
EGLASS4-7740-RTM	0.011	**0.0077**	350.07
T300_BSL914C-RTM	**0.006**	0.0132	349.88

Table 77 - Material, Weight, Environmental and Economic cost of the solutions 50 kPa (500 parts)

Material	Weight (kg)	Environmental Cost (kg CO_2 per part)	Economic Cost (€ per part)
EGLASS4-7740-HLU	0.011	**0.0076**	157.08
T300-4901A-HLU	0.007	0.0153	**156.86**
T300_BSL914C-HLU	**0.006**	0.0131	156.90
EGLASS4-7740-RTM	0.011	**0.0076**	175.53
T300_BSL914C-RTM	**0.006**	0.0131	175.34

Table 78 - Material, Weight, Environmental and Economic cost of the solutions 50 kPa (1000 parts)

Material	Weight (kg)	Environmental Cost (kg CO_2 per part)	Economic Cost (€ per part)
EGLASS4-7740-RTM	0.011	**0.007**	88.29
T300-4901A-RTM	0.007	0.014	**88.06**
T300_BSL914C-RTM	**0.006**	0.012	88.10

100kPa

Table 79 - Material, Weight, Environmental and Economic cost of the solutions 100 kPa (1 part)

Material	Weight (kg)	Environmental Cost (kg CO_2 per part)	Economic Cost (€ per part)
T300-4901A-HLU	0.007	0.0154	**73035.49**
T300_BSL914C-HLU	**0.006**	**0.0132**	73035.53
T300_BSL914C-RTM	**0.006**	**0.0132**	87274.16

Table 80 - Material, Weight, Environmental and Economic cost of the solutions 100 kPa (250 parts)

Material	Weight (kg)	Environmental Cost (kg CO_2 per part)	Economic Cost (€ per part)
T300-4901A-HLU	0.007	0.0153	**302.91**
T300_BSL914C-HLU	**0.006**	**0.0132**	302.95
T300_BSL914C-RTM	**0.006**	**0.0132**	349.88

Table 81 - Material, Weight, Environmental and Economic cost of the solutions 100 kPa (500 parts)

Material	Weight (kg)	Environmental Cost (kg CO_2 per part)	Economic Cost (€ per part)
T300-4901A-HLU	0.007	0.0153	**156.86**
T300_BSL914C-HLU	**0.006**	**0.0131**	156.90
T300_BSL914C-RTM	**0.006**	**0.0131**	175.34

Table 82 - Material, Weight, Environmental and Economic cost of the solutions 100 kPa (1000 parts)

Material	Weight (kg)	Environmental Cost (kg CO_2 per part)	Economic Cost (€ per part)
T300-4901A-RTM	0.007	0.014	**88.06**
T300_BSL914C-RTM	**0.006**	**0.012**	88.10

250kPa

Table 83 - Material, Weight, Environmental and Economic cost of the solutions 250 kPa (1 part)

Material	Weight (kg)	Environmental Cost (kg CO_2 per part)	Economic Cost (€ per part)
T300-4901A-HLU	**0.020**	0.0473	**73037.01**
T300-4901A-RTM	**0.020**	**0.0462**	87275.63

Table 84 - Material, Weight, Environmental and Economic cost of the solutions 250 kPa (250 parts)

Material	Weight (kg)	Environmental Cost (kg CO_2 per part)	Economic Cost (€ per part)
T300-4901A-HLU	**0.020**	0.0471	**304.42**
T300-4901A-RTM	**0.020**	**0.0460**	351.36

Table 85 - Material, Weight, Environmental and Economic cost of the solutions 250 kPa (500 parts)

Material	Weight (kg)	Environmental Cost (kg CO_2 per part)	Economic Cost (€ per part)
T300-4901A-HLU	**0.020**	0.0469	**158.38**
T300-4901A-RTM	**0.020**	**0.0459**	176.81

Table 86 - Material, Weight, Environmental and Economic cost of the solutions 250 kPa (1000 parts)

Material	Weight (kg)	Environmental Cost (kg CO_2 per part)	Economic Cost (€ per part)
T300-4901A-RTM	0.020	0.042	89.57

Test case 4

3 mm

Table 87 – Material, Weight, Environmental and Economic cost of the solutions 3mm (1part)

Material	Weight (kg)	Environmental Cost (kg CO_2 per part)	Economic Cost (€ per part)
T300_BSL914C-HLU	**0.179**	3.9325	73294.15
T700-4901A-HLU	**0.179**	4.0997	**73283.31**
Basalt HLU	0.465	1.6335	73415.61
T300_BSL914C-RTM	**0.179**	3.9006	87552.57
T700-4901A-RTM	**0.179**	4.0667	87540.91
Basalt RTM	0.465	**1.5488**	87674.77

Table 88 – Material, Weight, Environmental and Economic cost of the solutions 3mm (250 parts)

Material	Weight (kg)	Environmental Cost (kg CO_2 per part)	Economic Cost (€ per part)
T300_BSL914C-HLU	**0.179**	3.9176	534.21
T700-4901A-HLU	**0.179**	4.0842	**523.37**
Basalt HLU	0.465	1.6273	655.67
T300_BSL914C-RTM	**0.179**	3.8858	579.45
T700-4901A-RTM	**0.179**	4.0513	567.79
Basalt RTM	0.465	**1.5429**	701.65

Table 89 – Material, Weight, Environmental and Economic cost of the solutions 3mm (500 parts)

Material	Weight (kg)	Environmental Cost (kg CO_2 per part)	Economic Cost (€ per part)
T300_BSL914C-HLU	**0.179**	3.9027	388.11
T700-4901A-HLU	**0.179**	4.0686	**377.26**
Basalt HLU	0.465	1.6211	509.57
T300_BSL914C-RTM	**0.179**	3.8711	404.80
T700-4901A-RTM	**0.179**	4.0359	393.15
Basalt RTM	0.465	**1.5371**	527.01

Table 90 – Material, Weight, Environmental and Economic cost of the solutions 3mm (1000 parts)

Material	Weight (kg)	Environmental Cost (kg CO_2 per part)	Economic Cost (€ per part)
T300_BSL914C-RTM	**0.179**	3.546	317.56
T700-4901A-RTM	**0.179**	3.697	**305.91**
Basalt RTM	0.465	**1.408**	439.77

5 mm

Table 91 – Material, Weight, Environmental and Economic cost of the solutions 5mm (1 part)

Material	Weight (kg)	Environmental Cost (kg CO_2 per part)	Economic Cost (€ per part)
T300-4901A-HLU	**0.113**	2.6158	**73189.28**
T300-4901B-HLU	0.115	2.5773	73203.52
T700-4901B-HLU	0.115	2.4552	73230.57
Basalt HLU	0.310	1.0890	73298.11
T300-4901A-RTM	**0.113**	2.5949	87448.07
T300-4901B-RTM	0.115	2.5564	87462.32
T700-4901B-RTM	0.115	2.4343	87489.02
Basalt RTM	0.310	**1.0329**	87557.32

Table 92 – Material, Weight, Environmental and Economic cost of the solutions 5mm (250 parts)

Material	Weight (kg)	Environmental Cost (kg CO_2 per part)	Economic Cost (€ per part)
T300-4901A-HLU	**0.113**	2.6059	**429.34**
T300-4901B-HLU	0.115	2.5675	443.59
T700-4901B-HLU	0.115	2.4459	470.63
Basalt HLU	0.310	1.0849	538.17
T300-4901A-RTM	**0.113**	2.5851	474.95
T300-4901B-RTM	0.115	2.5467	489.20
T700-4901B-RTM	0.115	2.4251	515.90
Basalt RTM	0.310	**1.0290**	584.20

Table 93 – Material, Weight, Environmental and Economic cost of the solutions 5mm (500 parts)

Material	Weight (kg)	Environmental Cost (kg CO_2 per part)	Economic Cost (€ per part)
T300-4901A-HLU	**0.113**	2.5960	**283.24**
T300-4901B-HLU	0.115	2.5578	297.48
T700-4901B-HLU	0.115	2.4366	324.53
Basalt HLU	0.310	1.0808	392.07
T300-4901A-RTM	**0.113**	2.5752	300.31
T300-4901B-RTM	0.115	2.5370	314.55
T700-4901B-RTM	0.115	2.4159	341.26
Basalt RTM	0.310	**1.0251**	409.55

Table 94 – Material, Weight, Environmental and Economic cost of the solutions 5mm (1000 parts)

Material	Weight (kg)	Environmental Cost (kg CO_2 per part)	Economic Cost (€ per part)
T300-4901A-RTM	**0.113**	2.359	**213.07**
T300-4901B-RTM	0.115	2.324	227.31
T700-4901B-RTM	0.115	2.213	254.02
Basalt RTM	0.310	**0.939**	322.31

8 mm

Table 95 – Material, Weight, Environmental and Economic cost of the solutions 8mm (1 part)

Material	Weight (kg)	Environmental Cost (kg CO_2 per part)	Economic Cost (€ per part)
T300-4901A-HLU	**0.085**	1.9613	**73157.74**
T300-4901B-HLU	0.086	1.9327	73168.42
Basalt HLU	0.232	0.8162	73239.36
T300-4901A-RTM	**0.085**	1.9459	87416.66
T300-4901B-RTM	0.086	1.9173	87427.34
Basalt RTM	0.232	**0.7744**	87498.59

Table 96 – Material, Weight, Environmental and Economic cost of the solutions 8mm (250 parts)

Material	Weight (kg)	Environmental Cost (kg CO_2 per part)	Economic Cost (€ per part)
T300-4901A-HLU	**0.085**	1.9539	**397.80**
T300-4901B-HLU	0.086	1.9254	408.48
Basalt HLU	0.232	0.8131	479.43
T300-4901A-RTM	**0.085**	1.9385	443.54
T300-4901B-RTM	0.086	1.9100	454.22
Basalt RTM	0.232	**0.7715**	525.47

Table 97 – Material, Weight, Environmental and Economic cost of the solutions 8mm (500 parts)

Material	Weight (kg)	Environmental Cost (kg CO_2 per part)	Economic Cost (€ per part)
T300-4901A-HLU	**0.085**	1.9464	**251.70**
T300-4901B-HLU	0.086	1.9181	262.38
Basalt HLU	0.232	0.8100	333.32
T300-4901A-RTM	**0.085**	1.9312	268.89
T300-4901B-RTM	0.086	1.9028	279.58
Basalt RTM	0.232	**0.7685**	350.83

Table 98 – Material, Weight, Environmental and Economic cost of the solutions 8mm (1000 parts)

Material	Weight (kg)	Environmental Cost (kg CO_2 per part)	Economic Cost (€ per part)
T300-4901A-RTM	**0.085**	1.769	**181.65**
T300-4901B-RTM	0.086	1.743	192.34
Basalt RTM	0.232	**0.704**	263.59

ANNEX B - Tool Results with Basalt composites in the first three tests

Test Case 1

Table 99 – Material, Weight, Environmental and Economic cost of the solutions including Basalt-UP composite in the database10kN/m (1 part)

Material	Weight	Environmental Cost	Economical Cost
EGLASS4-7740-HLU	0.0267	0.1991	73075.96
T300-4901A-HLU	0.0170	0.3927	**73070.41**
T300_BSL914C-HLU	**0.0153**	0.3366	73071.29
Basalt HLU	0.0465	0.1628	73086.73
EGLASS4-7740-RTM	0.0267	0.1947	87326.77
T300_BSL914C-RTM	**0.0153**	0.3344	87322.04
Basalt RTM	0.0465	**0.1551**	87337.55

Table 100 - Material, Weight, Environmental and Economic cost of the solutions including Basalt-UP composite in the database10kN/m (250 parts)

Material	Weight	Environmental Cost	Economical Cost
EGLASS4-7740-HLU	0.0267	0.1983	327.24
T300-4901A-HLU	0.0170	0.3912	**321.68**
T300_BSL914C-HLU	**0.0153**	0.3353	322.56
Basalt HLU	0.0465	0.1622	338.01
EGLASS4-7740-RTM	0.0267	0.1940	373.67
T300_BSL914C-RTM	**0.0153**	0.3331	368.94
Basalt RTM	0.0465	**0.1545**	384.45

Table 101 - Material, Weight, Environmental and Economic cost of the solutions including Basalt-UP composite in the database10kN/m (500 part)

Material	Weight	Environmental Cost	Economical Cost
EGLASS4-7740-HLU	0.0267	0.1976	181.15
T300-4901A-HLU	0.0170	0.3897	**175.60**
T300_BSL914C-HLU	**0.0153**	0.3341	176.48
Basalt HLU	0.0465	0.1616	191.93
EGLASS4-7740-RTM	0.0267	0.1932	199.06
T300_BSL914C-RTM	**0.0153**	0.3319	194.33
Basalt RTM	0.0465	**0.1539**	209.84

Table 102 - Material, Weight, Environmental and Economic cost of the solutions including Basalt-UP composite in the database10kN/m (1000 part)

Material	Weight	Environmental Cost	Economical Cost
EGLASS4-7740-RTM	0.0267	0.177	111.82
T300-4901A-RTM	0.0170	0.354	**106.21**
T300_BSL914C-RTM	**0.0153**	0.304	107.09
Basalt RTM	0.0465	**0.141**	122.60

100 kN/m

Only one material saw its number of layers increase and, since it was not part of the initial solution space, it remains unaltered from the 10kN/m load case.

This is not the case when we consider the basalt fiber composites since it does not show in the solution space form 100kN/m onward.

Test Case 2

Table 103 - Material, Weight, Environmental and Economic cost of the solutions including Basalt-UP composite in the database 0.5kPa (1 part)

Material	Weight	Environmental Cost	Economical Cost
EGLASS4-7740-HLU	2.847	21.2333	75993.10
T300-4901A-HLU	1.361	31.3852	**74896.26**
T300_BSL914C-HLU	1.225	26.9665	74966.51
T650-35_2237-HLU	**1.169**	31.9220	123124.04
Basalt HLU	3.718	13.0680	76202.23
EGLASS4-7740-RTM	2.847	20.7163	90717.14
T300_BSL914C-RTM	1.226	26.7432	89686.55
T650-35_2237-RTM	**1.169**	31.7097	137844.08
Basalt RTM	3.718	**12.3926**	90927.21

Table 104 - Material, Weight, Environmental and Economic cost of the solutions including Basalt-UP composite in the database 0.5kPa (250 part)

Material	Weight	Environmental Cost	Economical Cost
EGLASS4-7740-HLU	2.847	21.1529	2929.32
T300-4901A-HLU	1.361	31.2663	**1832.48**
T300_BSL914C-HLU	1.225	26.8644	1902.73
T650-35_2237-HLU	**1.169**	31.8011	50060.26
Basalt HLU	3.718	13.0185	3138.45
EGLASS4-7740-RTM	2.847	20.6378	2961.25
T300-4901A-RTM	1.361	31.0198	1860.41
T300_BSL914C-RTM	1.226	26.6419	1930.66

T650-35_2237-RTM	**1.169**	31.5896	50088.19
Basalt RTM	3.718	**12.3457**	3171.32

Table 105 - Material, Weight, Environmental and Economic cost of the solutions including Basalt-UP composite in the database 0.5kPa (500 part)

Material	Weight	Environmental Cost	Economical Cost
EGLASS4-7740-HLU	2.847	21.0724	2782.60
Basalt HLU	3.718	12.9690	2991.74
EGLASS4-7740-RTM	2.847	20.5594	2785.03
T300-4901A-RTM	1.361	30.9018	**1684.20**
T300_BSL914C-RTM	1.225	26.5406	1754.45
T650-35_2237-RTM	**1.169**	31.4695	49911.98
Basalt RTM	3.718	**12.2987**	2995.11

Table 106 - Material, Weight, Environmental and Economic cost of the solutions including Basalt-UP composite in the database 0.5kPa (1000 part)

Material	Weight	Environmental Cost	Economical Cost
EGLASS4-7740-RTM	2.847	18.833	2697.79
T300-4901A-RTM	1.361	28.307	**1596.96**
T300_BSL914C-RTM	1.225	24.312	1667.21
T650-35_2237-RTM	**1.169**	28.827	49824.74
Basalt RTM	3.718	**11.266**	2907.87

Table 107 - Material, Weight, Environmental and Economic cost of the solutions including Basalt-UP composite in the database 5kPa (1 part)

Material	Weight	Environmental Cost	Economical Cost
1854_510A-40HLU	7.339	65.3543	80267.96
EGLASS4-7740-HLU	7.829	58.3902	80562.02
T300-4901A-HLU	**3.176**	73.2314	**76914.90**
T300-4901B-HLU	3.225	72.1567	77313.68
T300_BSL914C-HLU	3.269	71.9092	77606.89
Basalt HLU	11.15	39.2029	81842.14
1854_510A-40RTM	7.339	64.0222	94992.00
EGLASS4-7740-RTM	7.829	56.9690	95282.56
T300-4901A-RTM	**3.176**	72.6550	91626.94
T300-4901B-RTM	3.225	71.5715	92025.72
T300_BSL914C-RTM	3.269	71.3163	92316.93
Basalt RTM	11.15	**37.1778**	96564.99

Table 108 - Material, Weight, Environmental and Economic cost of the solutions including Basalt-UP composite in the database 5kPa (250 part)

Material	Weight	Environmental Cost	Economical Cost
1854_510A-40HLU	7.339	65.1067	7204.18
T300-4901A-HLU	**3.176**	72.9540	**3851.12**
T300-4901B-HLU	3.225	71.8834	4249.90
Basalt HLU	11.155	39.0544	8778.36
1854_510A-40RTM	7.339	63.7797	7236.11
EGLASS4-7740-RTM	7.829	56.7532	7526.68
T300-4901A-RTM	**3.176**	72.3798	3871.05
T300-4901B-RTM	3.225	71.3004	4269.83
T300_BSL914C-RTM	3.269	71.0462	4561.05
Basalt RTM	11.155	**37.0370**	8809.10

Table 109 - Material, Weight, Environmental and Economic cost of the solutions including Basalt-UP composite in the database 5kPa (500 part)

Material	Weight	Environmental Cost	Economical Cost
1854_510A-40HLU	7.339	64.8592	7057.47
1854_510A-40RTM	7.339	63.5372	7059.90
EGLASS4-7740-RTM	7.829	56.5374	7350.46
T300-4901A-RTM	**3.176**	72.1046	**3694.83**
T300-4901B-RTM	3.225	71.0293	4093.61
T300_BSL914C-RTM	3.269	70.7760	4384.83
Basalt RTM	11.155	**36.8962**	8632.89

Table 110 - Material, Weight, Environmental and Economic cost of the solutions including Basalt-UP composite in the database 5kPa (1000 part)

Material	Weight	Environmental Cost	Economical Cost
1854_510A-40RTM	7.339	58.202	6972.66
EGLASS4-7740-RTM	7.829	51.790	7263.22
T300-4901A-RTM	**3.176**	66.050	**3607.59**
T300-4901B-RTM	3.225	65.065	4006.37
T300_BSL914C-RTM	3.268	64.833	4297.59
Basalt RTM	11.155	**33.798**	8545.65

Table 111 - Material, Weight, Environmental and Economic cost of the solutions including Basalt-UP composite in the database 25kPa (1 part)

Material	Weight	Environmental Cost	Economical Cost
1854_510A-40HLU	16.513	147.0469	88875.06
T300-4901A-HLU	**7.260**	167.3870	**81456.83**
T300-4901B-HLU	7.372	164.9285	82368.33
T300_BSL914C-HLU	7.354	161.7957	82887.66
Basalt HLU	23.550	82.7618	91241.98
1854_510A-40RTM	16.513	144.0505	103596.60
EGLASS4-7740-RTM	17.082	124.2967	103761.22
T300-4901A-RTM	**7.260**	166.0692	96150.87
T300_BSL914C-RTM	7.354	160.4614	97577.70
Basalt RTM	23.550	**78.4872**	105961.29

Table 112 - Material, Weight, Environmental and Economic cost of the solutions including Basalt-UP composite in the database 25kPa (250 part)

Material	Weight	Environmental Cost	Economical Cost
1854_510A-40HLU	16.513	146.4899	15811.28
1854_510A-40RTM	16.513	143.5049	15840.72
EGLASS4-7740-RTM	17.082	123.8259	16005.33
T300-4901A-RTM	**7.259**	165.4402	**8394.99**
T300-4901B-RTM	7.371	162.9712	9306.48
T300_BSL914C-RTM	7.354	159.8536	9821.82
Basalt RTM	23.550	**78.1899**	18205.40

Table 113 - Material, Weight, Environmental and Economic cost of the solutions including Basalt-UP composite in the database 25kPa (500 part)

Material	Weight	Environmental Cost	Economical Cost
1854_510A-40RTM	16.513	142.9592	15664.50
EGLASS4-7740-RTM	17.082	123.3551	15829.11
T300-4901A-RTM	**7.259**	164.8111	**8218.77**
T300-4901B-RTM	7.3717	162.3516	9130.27
T300_BSL914C-RTM	7.354	159.2458	9645.60
Basalt RTM	23.550	**77.8926**	18029.19

Table 114 - Material, Weight, Environmental and Economic cost of the solutions including Basalt-UP composite in the database 25kPa (1000 part)

Material	Weight	Environmental Cost	Economical Cost
1854_510A-40RTM	16.513	130.955	15577.26
EGLASS4-7740-RTM	17.082	112.997	15741.87
T300-4901A-RTM	**7.259**	150.972	**8131.53**
T300-4901B-RTM	7.371	148.719	9043.03
T300_BSL914C-RTM	7.354	145.874	9558.36
Basalt RTM	23.55	**71.352**	17941.95

Test Case 3

Table 115 – Material, Weight, Environmental and Economic cost of the solutions including Basalt-UP composite in the database 50kPa (1 part)

Material	Weight	Environmental Cost	Economical Cost
EGLASS4-7740-HLU	0.011	0.0077	73035.72
T300-4901A-HLU	**0.007**	0.0154	**73035.49**
T300_BSL914C-HLU	0.006	0.0132	73035.53
Basalt HLU	0.019	**0.0066**	73036.15
EGLASS4-7740-RTM	0.011	0.0077	87274.34
T300_BSL914C-RTM	**0.007**	0.0132	87274.16
Basalt RTM	0.019	**0.0066**	87274.78

Table 116 - Material, Weight, Environmental and Economic cost of the solutions including Basalt-UP composite in the database 50kPa (250 part)

Material	Weight	Environmental Cost	Economical Cost
EGLASS4-7740-HLU	0.011	0.00767	303.13
T300-4901A-HLU	0.007	0.01534	**302.91**
T300_BSL914C-HLU	**0.006**	0.01315	302.95
Basalt HLU	0.019	**0.00658**	303.56
EGLASS4-7740-RTM	0.011	0.00767	350.07
T300_BSL914C-RTM	**0.006**	0.01315	349.88
Basalt RTM	0.019	**0.00658**	350.50

Table 117 - Material, Weight, Environmental and Economic cost of the solutions including Basalt-UP composite in the database 50kPa (500 part)

Material	Weight	Environmental Cost	Economical Cost
EGLASS4-7740-HLU	0.011	0.00764	157.08
T300-4901A-HLU	0.007	0.01528	**156.86**
T300_BSL914C-HLU	**0.006**	0.01310	156.90
Basalt HLU	0.019	0.00655	157.51
EGLASS4-7740-RTM	0.011	0.00764	175.53
T300_BSL914C-RTM	**0.006**	0.01310	175.34
Basalt RTM	0.019	**0.00655**	175.96

Table 118 - Material, Weight, Environmental and Economic cost of the solutions including Basalt-UP composite in the database 50kPa (1000 part)

Material	Weight	Environmental Cost	Economical Cost
EGLASS4-7740-RTM	0.011	0.007	88.29
T300-4901A-RTM	0.007	0.014	**88.06**
T300_BSL914C-RTM	**0.006**	0.012	88.10
Basalt RTM	0.019	**0.006**	88.72