Economic comparison of new fibre placement methods – Dry Fibre Placement and Tailored Fibre Placement

João Miguel Mendes Carvalho Monteiro Cravidão

Thesis to obtain the Master of Science Degree in

Mechanical Engineering

Supervisors: Prof. Inês Esteves Ribeiro
Prof. Bruno Alexandre Rodrigues Simões Soares

Examination Committee

Chairperson: Prof. Rui Manuel dos Santos Oliveira Baptista
Supervisor: Prof. Inês Esteves Ribeiro
Members of the Committee: Dr. Jörg Kaufmann
Prof. Paulo Miguel Nogueira Peças

January 2021

Acknowledgements

Firstly, I would like to acknowledge the supervision given by Prof. Inês Ribeiro and Prof. Bruno Soares, who provided me with the pleasure of working in this master thesis, for all the support, either in research or writing, for always guiding me through all the steps of this work and for all the knowledge shared with me.

Moreover, this thesis would not be possible without the guidance provided by Prof. Marc Fleischmann and Dr. Jörg Kaufmann from the Chemnitz University of Technology, who always provided me with very fast, extremely detailed, and helpful information.

I am very thankful to my girlfriend, Mónica, who was always by my side and kept me going, from the ups and downs and through all the important decisions.

My appreciation to all of my friends that I met during the past five years and that I was lucky to have by my side through this quite intense journey, that supported me regardless and that provided me with more support that I could have ever anticipated.

Finally, I would like to thank my parents and sister for all the love and continuous support given throughout this incredible journey.

There are no words that can express my gratitude to you all.

Resumo

Tem-se assistido a um crescimento substancial da investigação e uso de novos métodos de fabrico de peças reforçadas com fibra de carbono, considerando as excelentes características que este tipo de material compósito proporciona. No entanto, o alto custo inerente, ainda se apresenta como um grande obstáculo. Assim, importa reduzir os custos de produção de cada peça, para que possam ser tomadas decisões relativamente à viabilidade de um investimento.

No presente estudo, foram desenvolvidos Modelos de Custo Baseados no Processo que permitem, com o cálculo e análise do custo de produção de uma peça, o estudo de melhorias relativas ao processo e à própria peça. Para compreender a influência dos diferentes parâmetros incluídos e de modo a identificar os principais *inputs* com mais peso no custo final foi, também, realizada uma análise de sensibilidade.

Utilizando dois tipos de métodos de infusão de resina, *Vacuum-Assisted Resin Infusion* (VARI) e *Resin Transfer Moulding* (RTM), foram selecionados dois tipos de métodos de produção, o *Dry Fibre Placement* (DFP) e o *Tailored Fibre Placement* (TFP), por serem inovadores e com oportunidade de crescimento, quando comparados com processos já comprovados, como o *Automatic Fibre Placement* (AFP), ou o *Automatic Tape Layup* (ATL).

Os resultados do estudo indicam que DFP e TFP apresentam uma significativa redução de custos, para peças de pequenas dimensões, quando comparados com AFP e ATL, algo com maior impacto quando se consideram pequenos volumes de produção, o que pode representar uma mais-valia nas indústrias automóvel e aeroespacial, gerando poupanças elevadas.

Palavras-Chave: Fibra de Carbono, Compósitos, Modelos de Custo Baseados no Processo, *Dry Fibre Placement*, *Tailored Fibre Placement*,

Abstract

There has been substantial growth in the research and use of new methods of manufacturing carbon fibre reinforced parts, considering the outstanding characteristics that this type of material provides. Nevertheless, the high inherent cost still presents itself as a major obstacle. It is therefore important to reduce the production costs of each piece, so that decisions can be taken regarding the viability of an investment.

Process-Based Cost Models were then developed in this study, which allows, with the calculation and analysis of the production cost of a part, the study of improvements regarding the process and the part itself. To understand the influence of the different parameters included and to identify the main inputs with more influence in the final cost, a sensitivity analysis was also performed.

Using two types of resin infusion methods, Vacuum-Assisted Resin Infusion (VARI) and Resin Transfer Moulding (RTM), two types of production methods were selected, Dry Fibre Placement (DFP) and Tailored Fibre Placement (TFP), for being innovative and having significant growth opportunity, when compared to already proven processes, such as Automatic Fibre Placement (AFP) or Automatic Tape Layup (ATL).

The results of the study indicate that DFP and TFP present a significant cost reduction, for small parts, when compared with AFP and ATL, something with greater impact when considering small production volumes, which can represent an added value in the automotive and aerospace industries, generating large savings.

Keywords: Carbon Fibre, Composite, Process-Based Cost Model, Dry Fibre Placement, Tailored Fibre Placement

Contents

Chapter 1 – Introduction 15

Chapter 2 – State of Art 17

- 2.1 Carbon Fibre Reinforced Polymers 17
- 2.2 Carbon fibre laying methods 19
  - 2.2.1 AFP and ATL 19
  - 2.2.2 DFP and TFP 20
- 2.3 Curing methods - RTM and VARI 22
- 2.4 Cost Models 22

Chapter 3 – Description of Processes 24

- 3.1 Carbon fibre laying methods 24
  - 3.1.1 Automatic Tape Laying 24
  - 3.1.2 Automated Fibre Placement 25
  - 3.1.3 Dry Fibre Placement 27
  - 3.1.4 Tailored Fibre Placement 28
  - 3.1.5 Comparison of manufacturing methods 30
- 3.2 Resin Infusion Methods 31
  - 3.2.1 Resin Transfer Moulding 31
  - 3.2.2 Vacuum-Assisted Resin Infusion 32

Chapter 4 – Methodology 33

Chapter 5 – Application of the Cost Models 36

- 5.1 Process-Based Cost Models 36
- 5.2 PBCM Development Technique 36
- 5.3 Models Development 37
  - 5.3.1 Main Costs 38
  - 5.3.2 Production Time 39
  - 5.3.3 Processes Steps 39
  - 5.3.4 Inputs 41
  - 5.3.5 Costs Breakdown 44

Chapter 6 – Results and Discussion 50

- 6.1 Test Case 50
  - 6.1.1 Exogenous Variables 50
  - 6.1.2 Materials Information 51
  - 6.1.3 Placement Information 52
- 6.2. Model validation and analysis to major cost drivers 53
  - 6.2.1 Analysis per step 53
  - 6.2.2 Production volume analysis for DFP and TFP 57

6.2.3 Production volume analysis for AFP and ATL 61
6.2.4 Comparing DFP, TFP; AFP and ATL 63
6.3 Sensitivity Analysis on the inputs 64
3.1 DFP inputs Sensitivity Analysis 65
6.3.2 TFP inputs Sensitivity Analysis 66
Chapter 7 – Conclusions and Future Work 69

Bibliography 71

Annex A 78

Inputs 78
DFP 78
TFP 79

List of Figures

Figure 1 - The Future Of Carbon Fibre Composites by Lux Research [68] 18
Figure 2 - The BMW i3 carbon fibre frame [69] 18
Figure 3 - The ratio of material used in the Boeing 787 [14] 19
Figure 4 - Audi A8 CFRP rear wall [70] 21
Figure 5 - Schematic of an ATL layup head, according to Åström [71] 24
Figure 6 - Part Width vs Layup rate of ATL using a tape 12 inches (≈300mm) wide [46] 25
Figure 7 - Part Width vs Scrap percentage of ATL using a tape 12 inches wide [46] 25
Figure 8 - Schematic of an AFP head [47] [72] 26
Figure 9 - *Electroimpact's* AFP head in a transfer cart [49] 26
Figure 10 - Fibre tow being placed by a DFP machine (Provided by TU Chemnitz) 27
Figure 11 - Relative strength and of a CFRP laminate with unidirectional fibre orientation depending on the angle of the applied load direction [73] 28
Figure 12 - Basic principle of the TFP process [74] 29
Figure 13 - FE-Analysis of optimization fibre direction for TFP [75] 29
Figure 14 - Adapted photograph of the designed TFP-reinforcement [76] 30
Figure 15 - RTM Schematics [59] 31
Figure 16 - Schematics of the VARI Process [60] 32
Figure 17 - VARI Variant: Seeman's composite resin infusion moulding (SCRIM) [77] 32
Figure 18 - Methodology 35
Figure 19 - Process-Based Cost Model decomposition [64] 37
Figure 20 - DFP Process Operation 39
Figure 21 - DFP Machine (Provided by TU Chemnitz) 40
Figure 22 - TFP Process Operation 40
Figure 23 - TFP machine (Provided by TU Chemnitz) 41
Figure 24 - Total epoxy cost schematics 44
Figure 25 - Binder Cost Flowchart 46
Figure 26 - VARI and RTM schematics 49
Figure 27 - *UrbanSAX* urban concept car [3] 50
Figure 28 - DFP Process Operation 53
Figure 29 - TFP Process Operation 54
Figure 30 - DFP Reception and Storage Step (price per part at 50 parts/year) 54
Figure 31 - TFP Reception and Storage Step (price per part at 50 parts/year) 54
Figure 32 - DFP Binder and Fibre Placements Step (price per part at 50 parts/year) 54
Figure 33 - TFP Core, Carrier, and Fibre Placements Step (price per part at 50 parts/year) 54
Figure 34 - DFP Infusion and Heat Step (price per part at 50 parts/year) 55
Figure 35 - TFP Infusion and Heat Step (price per part at 50 parts/year) 55
Figure 36 - TFP Curing Step (price per part at 50 parts/year) 55
Figure 37 - DFP Curing Step (price per part at 50 parts/year) 55

Figure 38 - DFP Demoulding, Trimming and Finishing Step (price per part at 50 parts/year) 56
Figure 39 - TFP Demoulding and Finishing Step (price per part at 50 parts/year) 56
Figure 40 - TFP vs DFP w/ VARI Variable Costs (costs per part at 50 parts/year) 56
Figure 41 - TFP vs DFP w/ VARI Fixed Costs (costs per part at 50 parts/year) 56
Figure 42 - TFP vs DFP w/ VARI (costs per part at 50 parts/year) 57
Figure 43 - TFP with VARI and RTM for low production volumes (1 to 50 parts/year) 57
Figure 44 - DFP with VARI and RTM for low production volumes (1 to 50 parts/year) 57
Figure 45 - DFP with VARI and RTM for larger production volumes (50 to 250 parts/year) 58
Figure 46 - TFP with VARI and RTM for larger production volumes (50 to 250 parts/year) 58
Figure 47 - Mould storage analysis for the TFP Curing Step 59
Figure 48 - DFP Production evolution 250-5000 pieces/year 60
Figure 49 - TFP Production evolution 250-5000 pieces/year 60
Figure 50 - TFP vs DFP with VARI 60
Figure 51 - TFP vs DFP with RTM 60
Figure 52 - TFP vs DFP with VARI or RTM 60
Figure 53 - Low production volume analysis for both AFP and ATL (1-20 parts/year) 61
Figure 54 - Larger production volume analysis for both AFP and ATL (20-250 parts/year) 61
Figure 55 - Significant production volume analysis for both AFP and ATL (250-5000 parts/year) 62
Figure 56 - Percentage of material-technical scrap as a function of the part area [36] 63
Figure 57 - DFP vs TFP vs AFP vs ATL 63
Figure 58 - DFP Carbon Fibre Sensitivity Analysis 65
Figure 59 - DFP Binder and Epoxy Sensitivity Analyses 65
Figure 60 - DFP Sandwich Core Sensitivity Analysis 65
Figure 61 - DFP Placement Sensitivity Analysis 66
Figure 62 - TFP Carbon Fibre Sensitivity Analysis 66
Figure 63 - TFP Sandwich Core Sensitivity Analysis 67
Figure 64 - TFP Carrier and Epoxy Sensitivity Analyses 67
Figure 65 - TFP Placement Sensitivity Analysis 67

Tables Index

Table 1 - Comparison between processes 30
Table 2 - Main Costs 38
Table 3 - Exogenous Variables 42
Table 4 - Specific Process Variables 42
Table 6 - RTM Model Variables 49
Table 5 - VARI Model Variables 49
Table 7 - Exogenous Variables used 50
Table 8 - Carbon Fibre Roving used in DFP 51
Table 9 - Binder Material used in DFP 51
Table 10 - Sandwich Core used in DFP 51
Table 11 - Epoxy used in DFP 51
Table 12 - Carbon Fibre Roving used in TFP 52
Table 13 - Carrier used in TFP 52
Table 14 - Carbon fibre placement in DFP 52
Table 15 - Carbon fibre placement in TFP 53
Table 16 - Costs for a 50 parts/year production with DFP with VARI or RTM and TFP with VARI or RTM 53
Table 17 - Numbers of Moulds needed by production volume for TFP 59
Table 18 - Production volume per numbers of moulds for TFP 59
Table 19 - Number of tows needed for ATL production. 62

Nomenclature

AFP - Automated Fibre Placement

ATL - Automated Tape Laying

CFRP - Carbon Fibre Reinforced Polymer

DFP - Dry Fibre Placement

KPI - Key Performance Indicator

NDT - Non-Destructive Tests

OoA - Out of Autoclave

PBCM - Process-Based Cost Models

Prepreg - Resin pre-impregnated carbon fibre material

RTM - Resin Transfer Moulding

TFP - Tailored Fibre Placement

VARI - Vacuum-Assisted Resin Infusion

Chapter 1 – Introduction

Ever since the development of carbon fibre, there has been a tireless search for the best type of carbon fibre reinforced polymer (CFRP) that, using this high-strength, high-stiffness, and lightweight material, would have the best properties possible for the task in hand. Over the years, carbon fibre composites have become the leading advanced composites in several industries, such as aerospace, automobile and sporting goods [1].

For applications that require high-temperature exposure resistance, such as in the aerospace industry, carbon-carbon composites have become the foremost material used and, with the increased interest and production of these composites over the years and with extensive research and development, the prices have been declining in a way that other industries now have the capacity to expand its usage, for example with the use of carbon fibres to reinforce concrete in the construction industry [2].

Contemplating that the most important aspects in the manufacturing industry are quality, price, and time to produce a part, in order to create carbon fibre composites that consider with this set of needs, there has been substantial research and development concerning the creation of various ways to automate fibre placement.

With this rapid creation of several kinds of automating the creation of CFRP, a need emerged: how to estimate, compare and analyse different types of designs of a part, identifying the critical aspects of design which drive up the cost. So, cost models were created to help the designers achieve the premium way to drive down the price of a part while maintaining the physical properties needed.

Cost estimating is a crucial component of the manufacturing process and especially in the composites area since the composite product needs to compete with well-developed metal technologies. In recent years, composite products that often were not selected for an application, as they were not cost-competitive, are now gradually being produced using new composite technologies. For example, in the automotive industry, where the market is very cost-sensitive, product cost plays a vital role in selecting technology and so everything is being done to investigate all the possible ways to lower the costs.

The present thesis consists in the economic comparison between four different types of production processes of carbon fibre reinforced composites with the focus on the doors of the *Fortis Saxonia* prototype, *Chemnitz University of Technology*'s urban hydrogen-powered concept car that has efficiency as its focus [3]. With the purpose of comparison, two process-based cost models (PBCM) for two types of processes of CFRP production were created in order to compare their results with the ones of two other PBCM that have already been developed [4].

The PBCM that had already been developed in a recent thesis [4] regards Automated Fibre Placement (AFP) and Automate Tape Layup (ATL) and the processes that will be developed in this thesis will be Dry Fibre Placement (DFP) and Tailored Fibre Placement (TFP). Since there is no standardised approach to machine architecture of DFP [5], this thesis will focus on the machine that exists at TU

Chemnitz. For DFP and TFP, two Out of Autoclave methods are employed, Vacuum-Assisted Resin Infusion (VARI) and Resin Transfer Moulding (RTM), which are also studied and compared economically in detail.

In Chapter 2, this thesis starts with a brief overview of CFRP and their usage, the creation and evolution of the automated processes studied in the thesis and their usage in the automotive and aerospace industry and, later, why they came to light in recent years. Along with the state of art of cost modelling.

AFP, ATL, DFP and TFP are presented and compared in Chapter 3, followed by the main differences between them, with special interest given to the processes studied, along with the description of both RTM and VARI methods.

In Chapter 4, the methodology used as a mean to create the PBCM for DFP and TFP with RTM and VARI is explained in detail.

With the methodology explained, in Chapter 5, the cost models are applied, and every calculation thoroughly explained for both processes.

In Chapter 6, the results are shown, discussed, and compared for the four PBCM, with special interest given to the test part, the doors of the race car that has been developed by TU Chemnitz. Model validation is completed with the intention of identifying if cost models are accurate, also identifying the major cost factors by doing a sensitivity analysis. Finally, the results are shown, examined, and evaluated.

Ultimately, in Chapter 7, the conclusions are displayed, and possible future work is explored and discussed.

Chapter 2 – State of Art

A composite material is comprised of the combination of two materials that have different properties, that brought together have superior qualities to those found on the elements when separated [6]. In order to create a carbon fibre reinforced composite, there is a need for a matrix and a reinforcement, with the reinforcement being the carbon fibre which provides the strength needed and the matrix, that is often a thermoset (usually a polymer resin, such as epoxy) [7].

In this chapter, the state of art of Carbon Fibre Reinforced Polymers (CFRP) is explained on section 2.1, followed by the carbon fibre laying methods studied on 2.2, in 2.3 the state of art of the curing methods used and on 2.4 the cost models.

2.1 Carbon Fibre Reinforced Polymers

In recent years, composite materials have been in the spotlight, for their greater acceptance into the transportation sector, creating drastic improvements in the aerospace and the automotive industries [8]. With the increased usage of this type of materials, some challenges had to be resolved so that they could compete with other proven metal materials. The main problems that arose were related to material behaviours under different conditions, manufacturing processes, assembly, joining methods, recycling or the material cost (when comparing to steel parts, CFRP parts can supply up to 75% of weight reduction, but associated with higher costs [9]).

Having to face these tough challenges and with an ever-increasing demand for lightweight parts for industries, CFRP have been used more and more often and have been the promising alternatives for the metal counterparts, since they generally have higher strength and stiffness to weight ratio, improved corrosion resistance and fatigue resistance [10].

Since the beginning of the development of CFRP, it was soon acknowledged that the costs and difficulty associated with manual layup were a major obstacle due to their high costs and low productivity, which sparked the creation and publication of the first US patents for what is recognisably Automated Tape Laying (ATL) [11] and Automated Fibre Placement (AFP) [12]. The machines created would replace manual labour, reduce labour hours, the learning curve, lead time and the bottleneck caused by the extreme need of skilled labour, while improving the quality, reliability, and kg/h, whilst also bringing down material wastage and costs.

Demand for CFRP has seen a huge growth in several industries like aerospace or automotive and the tendency is that the demand for carbon composites continues to grow at a very high pace as it can be seen in the figure 1, showing that its potential benefits have been proven and will continue to be improved drastically over the next few years.

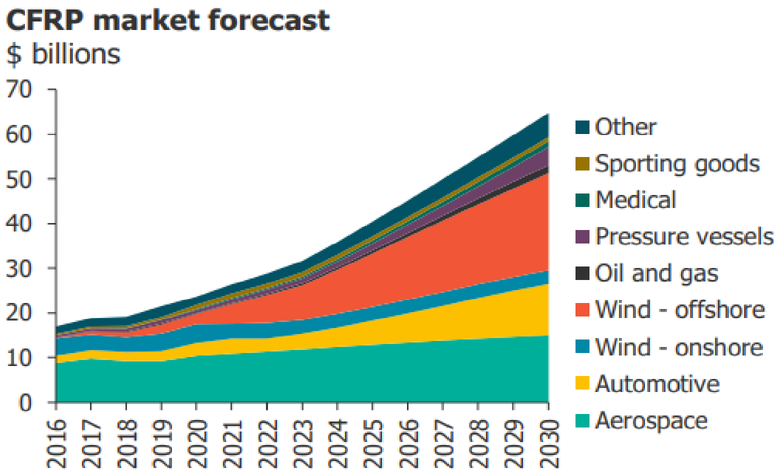


Figure 1 - The Future Of Carbon Fibre Composites by Lux Research [79]

The change towards the use of CFRP in mass-produced cars was first seen with BMW launching its i3, providing the weight reduction that effectively neutralizes the heft of the car's battery pack [13]. This small electrical model, i3 has been ground-breaking in delivering a glimpse into what can be achieved through the use of composite material and has launched numerous possibilities.

Figure 2 - The BMW i3 carbon fibre frame [80]

Composite materials allow for the production of parts which are more complex than metal parts and have a higher lifespan and so composites began to also be used in the aerospace industry. One of the most predominant effective usages of composites on an aircraft can be seen on the Airbus 787 (figure 3), in which 50% of its airframe consists of CFRPs, which, when compared to a standard aluminium design, has led to a weight reduction of 20% [14].

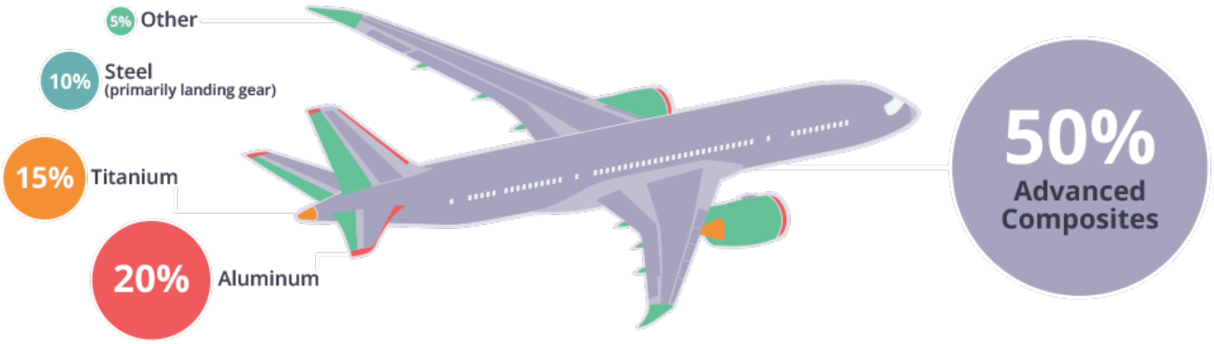


Figure 3 - The ratio of material used in the Boeing 787 [14]

2.2 Carbon fibre laying methods

On this chapter, the state of art for the carbon fibre laying methods studied in this thesis is shown. On 2.2.1, AFP and ATL techniques are presented and, on 2.2.2, the dry fibre methods are displayed.

2.2.1 AFP and ATL

The development of AFP at the end of the 1980s [15] and increased use of AFP machines for the layup of primary structures in aerospace have been a major driver of work to understand manufacturability. Substantial academic work has been produced in Europe and the USA [16], with this effort being used to identify major limitations of AFP (especially in terms of geometry and defects).

Comparable to ATL, AFP is a type of additive manufacturing with the significant variation being the material being laid down. Where ATL usually operates unidirectional tape of widths from 75 to 300 mm, modern AFP systems apply unidirectional composite tows of widths from 6.35 mm to 38.1 mm [17]. Thanks to the small tow width, AFP machines support multiple tows in parallel with each other simultaneously, with some systems capable of delivering up to 32 tows [18].

In the past few years, there have been quite a few innovations that will further help the expansion of these types of processes. One of these innovations is the small dual-process work cells, which perform both ATL and AFP, but that is much smaller than the AFP/ATL systems that are used to produce aircraft primary structures, which helps in terms of space since they can fit in most existing factories without major facility adjustments [19]. Another novelty that surfaced in this area is the software that helps with the programming, simulation, inspection, and edition of AFP/ATL tool-paths, bringing in smart manufacturing of the new Industry 4.0, further improving production and bringing digitalization on today's manufacturing operations [20].

Nowadays, AFP is emerging as one of the advanced methods toward fabrication of polymer matrix based composite structures. This automated technique focuses on polymer composite manufacturing for use in a broad variety of automotive and aerospace applications. This process presents a high level of customization through the possibility of placing every single tow on customizable paths [21].

Recently and parallel to that work, there has been an interest in applying dry fibre carbon-reinforced plastics for large structural elements in newer commercial aircraft programs. Dry fibre carbon-reinforced plastics can present some of the identical benefits that current prepreg material (resin pre-impregnated carbon fibre material) has on aluminium and provide additional advantages over prepreg itself [17] [22].

2.2.2 DFP and TFP

Even though safety is a big factor when new material is presented, undergoing an arduous process before it can be qualified and accepted for the aerospace industry, new ways of producing CFRP are always under development since aircraft have to be able to be operational for at least few decades, as they have a lifespan of over 30 years [23]. Since the demand for CFRP is projected to increase substantially over the next decade, in particular for use in the aerospace industry [24], any new material advancements which can help maximise lifespan and time in the air, at the lowest fuel usage and emissions, are welcomed and strived for.

Dry fibre methods such as DFP or TFP have the ability to follow a certain geometry, where other conventional wet prepreg fibre placement methods cannot. Through this ability to guide fibres, these can be steered in the direction of the load, with only the correct quantity of material being placed on the airframe so that less material and weight are required on the aircraft when compared to AFP or ATL [25].

In 2019, *Carbon ThreeSixty* took a great step for industrializing TFP technology, creating a proof of concept along with National Composites Centre, bringing to life a machine that achieved what was most needed for the parts created within the company. With TFP this company got something that only this type of technology was capable of achieving: complexity, weight, stiffness and strength, that which be accomplished by the optimisation of the reinforcing fibres, being placed in specific orientations [26].

In another hand, DFP has been thoroughly studied and one of the main problems found was the need for an out-of-plane impregnation, for example, an RTM process, which would reduce cycle times and quality of impregnation. However, further improvements are required to apply DFP-preforming methods in serial production [9].

One company that stands out on DFP production is *Voith*. Having developed the Voith Roving Applicator which allows for a “whole new digital 4.0 production line” that sets “new standards producing carbon fibre parts for high-volume automotive serial production”, capable of being included in a smart factory that “allows the automated production of CFRP components in almost any shape and individual lot sizes” [27].

This *Voith* machine has the ability to be in a high-volume production line, producing the rear panel for the new Audi A8 which contributes highly to the stiffness of the overall vehicle. This part includes localized load paths, which enables the finished part to provide 33% of the drive cell’s torsional stiffness at 50% of the weight when compared to an assembly of three to five welded aluminium parts [28].

Figure 4 - Audi A8 CFRP rear wall [29]

Back in 2015 in the aerospace industry *Irkut Corporation*, a Russian aircraft manufacturer, decided to use dry fibre technology in order to produce some of the primary components of its prototype MS-21 (which flew for the first time in 2017 and is prospected to start deliveries in 2021) [30][31]. This company chose DFP as the process to produce the aeroplane’s CFRP parts, as it started to be noticed in the industry for its great potential at reducing costs (avoiding the expensive autoclave curing and decreasing resin and dry material costs) [31].

Another type of method that uses dry fibres is TFP. This method is a type of technical embroidery, where dry fibres tows are computer place and then sewed onto a base material.

A lot of work is still under development on this very recent type of CFRP production, but one of the certainties that make this technique so attractive to researchers is its ability to reinforce with absolute freedom of positioning, cutting waste from the usual 30-70% on a typical automotive component, to a mere 3% [32].

ZSK is a company that has used TFP in other ways besides reinforcement. Since this technology can produce the composite pre-form with a mix of different fibres, such as optical or metallic materials (delivering particular properties for example electrical continuity or impedance). RFID components have already been made, by combining naked antenna wires and isolated feed wires with the use of TFP [33].

Another use of this method by *ZSK* is to incorporate polymers mixed with the carbon fibre, that during the moulding stage are melted forming the matrix, circumventing the need for a resin filler, fasttracking the manufacture of complex parts and improving the resin-to-fibre distribution, particularly in the extremities of the mould [34].

2.3 Curing methods - RTM and VARI

Whilst curing prepregs on AFP and ATL is done on an autoclave (a pressure chamber employed to execute industrial processes that involve elevated pressures and temperatures), RTM and VARI/VARTM use dry fibres, which do not make use of an autoclave.

With the elevated pressures and temperatures, the composites cure and remove the air voids, increasing the fibre volume fraction, that enhances its performance where weight and mechanical properties take precedence over cost [35]. But, since the usage of an autoclave is known to be very expensive and time-consuming (which in turn increases drastically the power consumption and production rate, further growing the costs), Out of Autoclave (OoA) processes (which do not require an autoclave for curing), have seen great development.

RTM process is used in the production of the structure of aircraft and cars, for example, powertrain components or exterior components [36], with a variant of RTM being used for the production of the BMW i3 show on the picture 2.

2.4 Cost Models

Product cost modelling can be used to evaluate potential future costs linked with the production of a product. Early cost estimates when production new parts can be used to support decision making involving which production methods are the most profitable and which parts are worth producing. In order to make precise cost models, there is a requirement to have a firm grasp on the technical expertise, but also the financial side of a production. The PBCM is a model that addresses a way to produce estimates with higher precision, by taking all of the steps of the process into account [37].

Whenever there is a production method that might be beneficial on the manufacture of a new part, experienced firms create a PBCM and this way all of the available methods can be compared to bring up the most cost-effective means to produce the part. Manipulating design specifications or process operating conditions also creates consequences not only on product performance, but also on production costs and these changes must be studied in advance using cost modelling [38].

This way costs must be considered when evaluating any change to product or process, because, ultimately, they establish the profit margin which a firm can realize and so, multiple cost models have been produced over the years with this intent [39].

Now considering the production methods explored throughout this thesis, there has been extensive study regarding the cost comparison between AFP and ATL [40], with a fantastic example being “A composite cost model for the aeronautical industry: Methodology and case study” that in 2015, published a paper on a production cost estimation model and evaluated the costs of a generic aeronautical wing [41].

Besides this study, others were also produced, but comparing hand-layup with AFP with prepreg versus dry infusion processes [42]. This paper, published for the SAMPE conference that occurred in Stuttgart in 2017, also puts a spotlight on the production and understanding of the creation of detailed cost models. By investigating the cost of relatively simple flat component over a variety of processes, the paper aims for a better understanding and identification of the risks in manufacturing and material choice.

Only not long ago, dry fibre tapes suitable to be used in standard AFP machines were produced as a low cost and OoA solution. This technology is in its early development stage and due to the novelty of the process, very limited research has been conducted and published [42] [43].

These dry fibre production types (e.g., DFP and TFP) have shown to be so recent that few studies have been conducted on their feasibility compared to proven technologies and therefore published cost models cannot seem to be found online.

Chapter 3 – Description of Processes

In the following chapter, a brief overview is presented on each one of the processes studied.

Starting with AFP and ATL, which have been the aerospace and automotive go-to processes when producing large CRFP parts using prepreg material. These have been around ever since the first designs of ATL and AFP machines which can be traced back to the 1970s [44], but new technologies have since been created and further developed, particularly automated placement of dry fibres.

The prominent technologies that use this type of dry fibres are DFP and TFP, which can be used to manufacture intricate preform structures which can then be resin-infused in several types of liquid moulding or resin infusion production methods [45], such as RTM and VARI.

3.1 Carbon fibre laying methods

The carbon fibre manufacturing processes studied were ATL, AFP, DFP and TFP, each presented on the following sections.

3.1.1 Automatic Tape Laying

Invented in the 1970s, ATL is now one of the most used CFRP producing techniques in existence [46]. With ATL, wide unidirectional tapes of prepreg material are placed on a mould using a loaded roller structure, as it can be seen on figure 5 that, depending on the complexity of the part under construction, presents different degrees of articulation. This method reproduces the manual layup of UD tape, but with the ability to have a higher deposition rate, producing larger parts and with greater control over the process. Modern machines present the capability of starting, orienting and cutting the tapes automatically, allowing for parts with higher complexity with tapes on locations that have with different requirements [47].

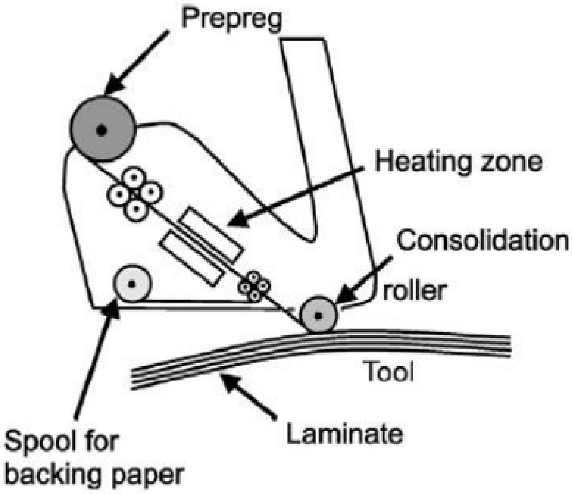


Figure 5 - Schematic of an ATL layup head, according to Åström [48]

Investigators claim that the lay-up rate of an ATL system can vary between 10 and 150 kg/h for flat and mildly contour components [49]. When this technology is used in smaller geometries there is the need for decelerating and accelerating instead of laying tape at an optimum speed, which lowers its efficiency and makes it unfeasible compared to other production methods when producing small components. The higher layup rate is achievable for huge flat components, stated as significant as 288 m^2 [49] and geometries that are smaller than 2.5 m^2 are produced with the smallest layup rate of roughly 12 kg/h (≈35m^2/h) [41]. This difference in layup rate base on the length and width of a part can be seen in figure 6.

Another indicator of the practicality concerning the production of a part is the scrap rate and ATL has a scrap rate of about 2% to 10%, but strongly depend on the tape length/width ratio along with the outlines' shape of the part [50]. As shown in figure 7, it is possible to deduce that it will be a bigger scrap percentage for small parts, but with the tendency to reach a constant value on bigger parts [51].

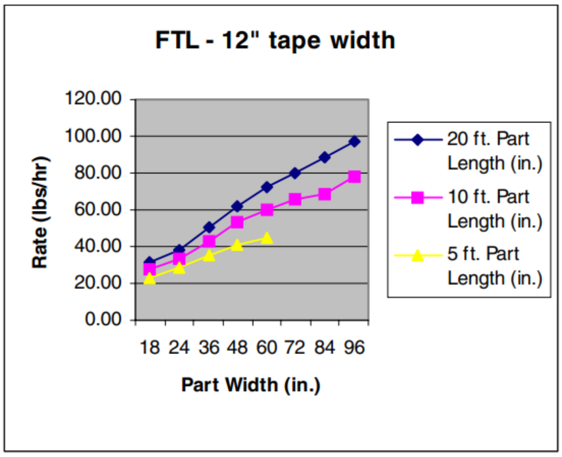


Figure 6 - Part Width vs Layup rate of ATL using a tape 12 inches (≈300mm) wide [51]

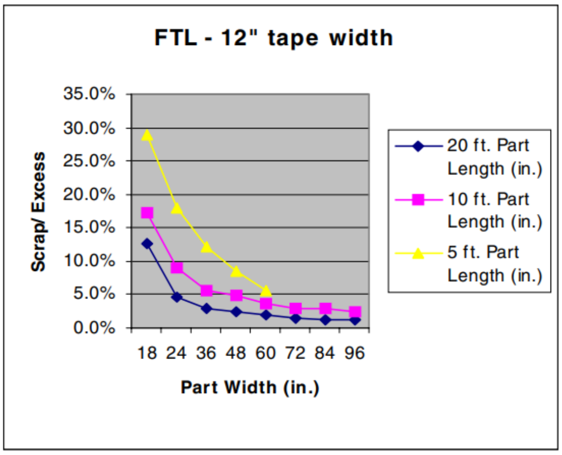


Figure 7 - Part Width vs Scrap percentage of ATL using a tape 12 inches wide [51]

3.1.2 Automated Fibre Placement

AFP was developed in the early 1980s in order to solve the limitations of the filament winding and ATL processes [52]. Since then, both processes have been refined and both are thoroughly used, with AFP being regularly used in the aircraft industry.

As shown on the figure 8, this process involves computer-controlled laying of prepreg tow, allowing for an automated high-speed production of laminates by laying down up to 32 parallel tows at the same time, with widths ranging from 3.2 to 12.7 mm at a rate of 2 to 150 kg/h depending on size and part complexity [41].

Using a loaded compaction roller, the tows are compressed and then heat is supplied by a heater in the AFP head. As the tows are laid, the collective action of heating and compaction causes merging and bonding of the plies.

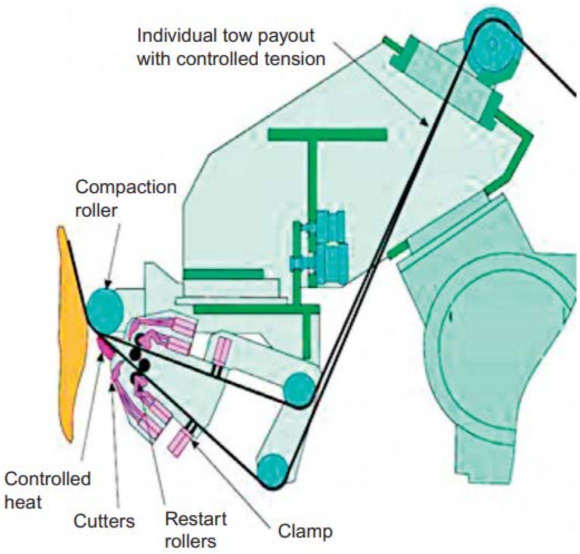


Figure 8 - Schematic of an AFP head [52] [53]

The AFP head is able to stop, cut and restart individual tows while in motion. This is an advantage of AFP, as this creates a possibility to do door or window cut-outs or layup various sizes of ply doublers with close tolerance accuracy on the ply boundaries [54].

It is also possible to lay up tows in any orientation, and several of the machines currently available will do simultaneous bidirectional lay up of material as for example the *Electroimpact*'s modular head that can be connected to a robotic arm which is seen below on figure 9 [55], but this technology isn't limited to this type of usage. There are four types of AFP machines to date: Winding Platform Configuration, the moving Column Configuration, the High Rail Gantry Configuration and the Robotic Arm Configuration [56].

Figure 9 - *Electroimpact's* AFP head in a transfer cart [55]

AFP presents some specific advantages when compared to other processes. It involves reduced labour related to manufacturing, decreased demand for in-process examination, and a substantial decrease in scrap when compared to ATL (AFP has a low scrap rate percentage of about 3% to 5%

[50]). This cost advantages vary according to the size of the part being developed, being significant on larger parts than on smaller parts, since that small parts require the machine to run at slow operating speeds, instead of the top/optimal speed [52].

3.1.3 Dry Fibre Placement

In order to produce complex part shapes, technologies that use fabric draping in a mould involve large waste and variable final mechanical properties due to inconsistency in the fabric structure and the amount of local fibre volume fraction. With these problems in mind and understanding that efficiency and cost are of great importance on the production of parts, automated dry fibre placement for preform manufacturing was created [57]. This approach allows for the integration of many functions in a complex part thanks to the ability of the robot to steer fibre tows at specific locations.

After the placement of the fibre tows (as it can be seen in the figure 10) and since this process does not involve pre-impregnated material and instead places dry fibres, the final part is created by using a resin infusion method such as RTM or VARI.

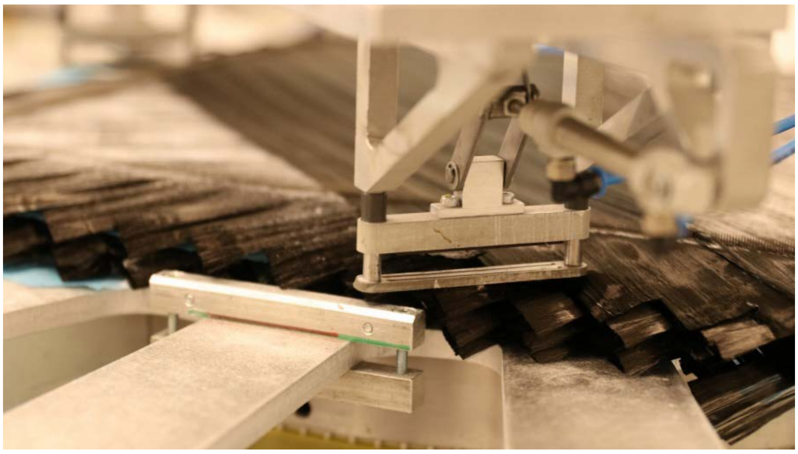


Figure 10 - Fibre tow being placed by a DFP machine (Provided by TU Chemnitz)

As there is a lack of resin, this significantly reduces resin accumulation, which allows for longer maintenance intervals and better reliability by reducing or eradicating the challenges connected with this build-up, which decreases equipment use by 25% to 30% [17].

DFP utilizes fast response time and controlled emissions of heating systems. This advantage considerably decreases undesirable heat on adjacent areas and increases the performance of the method [17].

With the intent of providing high bending stiffness with total low density, a sandwich core might be applied to the construction of a part. Cores used in the production of CFRP, have special properties, as these do not compress under vacuum pressure and they include canals that help with resin flow to act as an internal flow for resin infusion.

3.1.4 Tailored Fibre Placement

As shown in the figure 11, the angle between the load and the fibre direction greatly influence the behaviour that a placed fibre will have under stress. For example, when the angle between the load direction and the fibre is 10 degrees, then the strength is reduced to about 20% of the maximum, showing the great influence that placing the fibres on the ideal trajectories has on the part's performance.

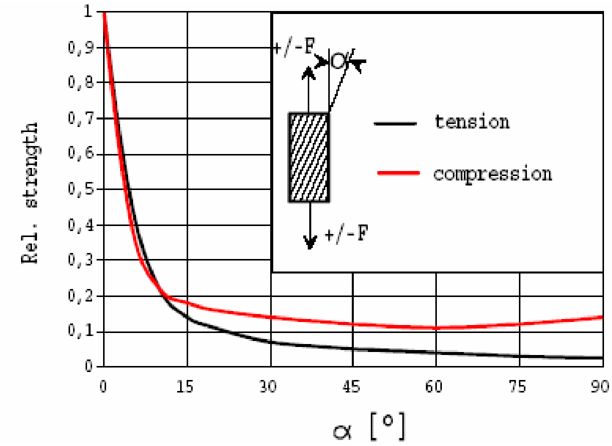


Figure 11 - Relative strength and of a CFRP laminate with unidirectional fibre orientation depending on the angle of the applied load direction [58]

Taking this into consideration, there is the opportunity of exploring the loads and having tailored preforms that are perfected for a particular part, which will create the lightest composite structure possible, creating a great advantage towards the usage of TFP.

This CFRP production method was created by the Institute for Polymer Research Dresden in the early 1990s [59]. Originally, before automation was introduced, the reinforcement structures were handmade stitched with a curvilinear pattern and later in the mid-1990s, an adaptation of this method was introduced with industrial sewing machines, which computerized the embroidery process.

As seen in figure 12, the roving is deposited following a pre-defined path by rotating the roving pipe and moving the base material in two perpendicular directions. The roving is fixated by zigzag stitches along its path and it can be made out of carbon, glass, or other types of fibre. The base material can be either fabric or nonwovens (a type of fabric that is not knitted or weaved but instead made from fibres that are bonded together mechanically, thermally, or chemically [60]).

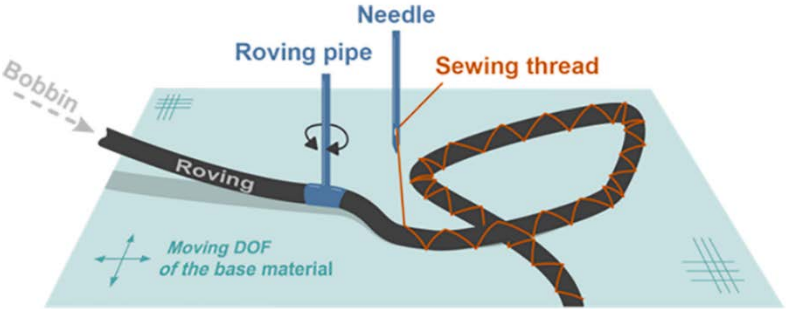


Figure 12 - Basic principle of the TFP process [61]

TFP can be used for local reinforcements of bigger parts or full preforms for smaller parts. One of the main advantages of TFP today is its usage for reinforcement according to the part's application [62]. The local tensions and deformations are calculated using the fibre optimization procedure shown below.

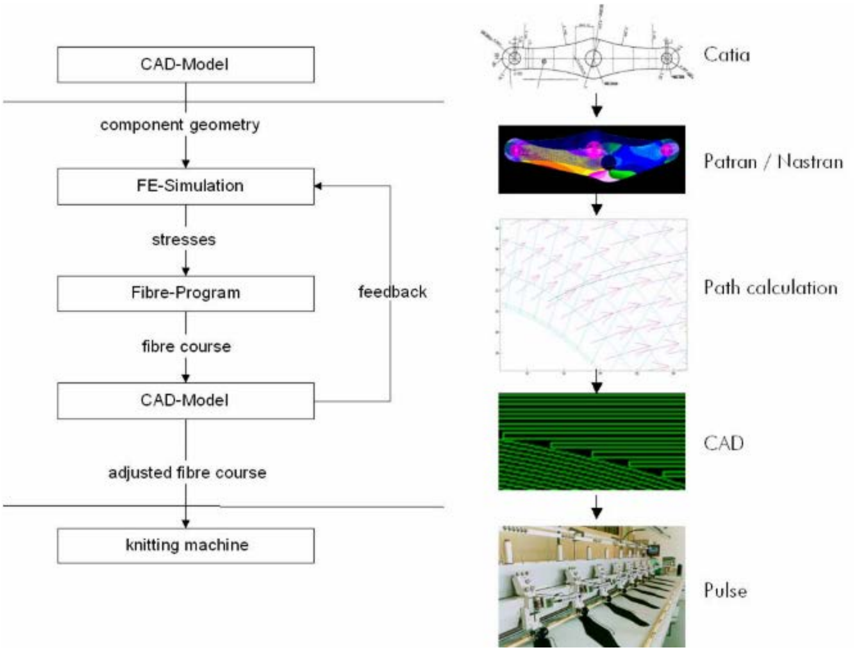


Figure 13 - FE-Analysis of optimization fibre direction for TFP [63]

One of the most interesting applications of TFP reinforcement is done on stress concentrated holes in notched parts. A study was done in 2002 in the Institute of Polymer Research Dresden, where a hole (as seen on the figure 14) is reinforced using finite element analysis. With this, a reference plate without a hole reached a specific failure load of 90 kN, which, due to the hole, this value decreases to 55 kN. After the application of the TFP reinforcement, the value increased to 85 kN, with the fracture occurring outside of the reinforcement, showing that the notch effect due to the hole is completely eliminated displaying the promising usage of this technology on the reinforcement of notched parts [64].

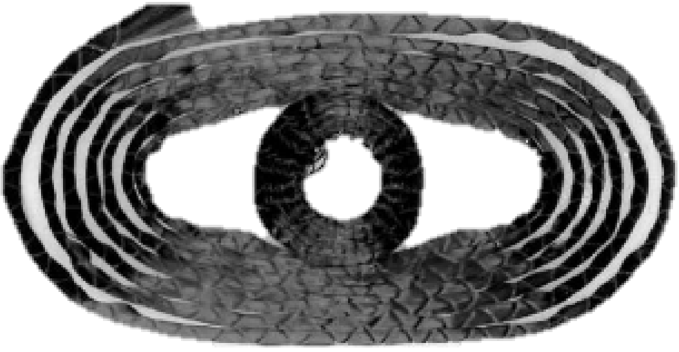


Figure 14 - Adapted photograph of the designed TFP-reinforcement [65]

3.1.5 Comparison of manufacturing methods

The table 1 represents a summarised comparison between ATL, AFP, DFP and TFP. It was produced by gathering data from the bibliography and laboratory information provided by TU Chemnitz since DFP and TFP information is scarce.

Table 1 - Comparison between processes

	ATL	AFP	DFP	TFP
Type of Part	- Large and flat	- Medium to large - Complex with curvature	-Limited in terms of placement to 2D or low curvature surfaces	- Small - Reinforcements of any size
Scrap Rate	2% to 10% [50]	2% to 5% [66]	Similar to AFP	Close to 0%
Scrap cost	Low	Low	Low	Close to 0
Productivity	High	High	Medium	Medium
Investment	Large	Large	Low	Low
Material Width	75, 150 or 300mm	3,2 to 12,7mm	25 to 50mm	1 to 12,5mm (up to 25mm in new types of TFP machines)
Additional Auxiliary Material	Usually, none: Matrix already included	Usually, none: Matrix already included	Binder	Sewing thread/base material
Freedom of material choice	Requires very specific prepreg material	Requires very specific prepreg material	More flexibility on types and widths of tows	Very flexible: the raw-rovings do not need any specific pre-treatment A lot of options for sewing threads and base materials

3.2 Resin Infusion Methods

The resin infusion methods examined were RTM and VARI, each are explained in the following sections.

3.2.1 Resin Transfer Moulding

Resin Transfer Moulding (RTM) is an OoA process that is mainly used to produce components with large surface areas, complex shapes and smooth finishes, being one of the best methods for large scale production of parts [67].

Fabric is placed inside the cavity in the middle of two matched moulds with their internal surfaces having the form of the final component. Fabric plies are stacked to the necessary orientation and thickness inside the mould, which is then sealed and clamped. Using a pump, liquid resin (with a low enough viscosity so to flow through the very small gaps among the fibres of the fabric) is injected into the mould. With the resin flowing through the open spaces of the fabric until the mould is entirely filled. Following injection, the mould is heated in order to cure the matrix which forms the part [68].

This process can be seen in the figure 15 below.

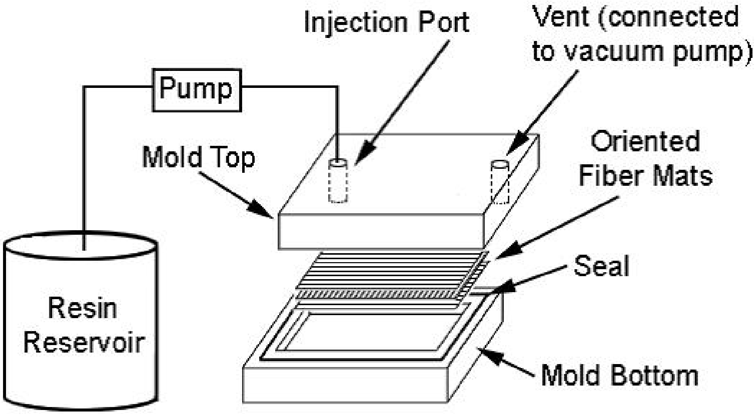


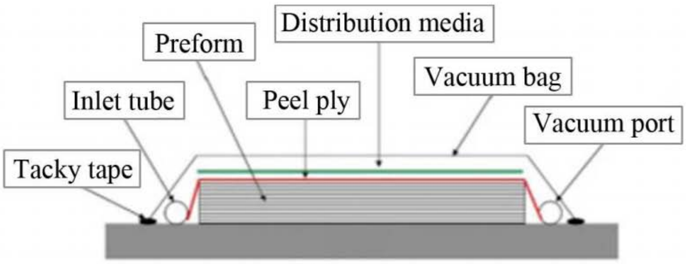
Figure 15 - RTM Schematics [69]

This RTM process can create parts which have high fibre volume content (up to 65%), making them suitable for primary aircraft structures that require high stiffness, strength, and fatigue performance. In this process and with the mould closed and sealed the air is extracted from the mould using a vacuum-pump system and attract the resin throughout the fabric [69].

Some types of fabric are challenging to infuse with resin, which leave dry spots or voids in the cured composite and the way the fibre is laid can be disrupted by the high flow pressures needed to force the resin through some fabrics. To reduce the effect of these problems, a variant of the RTM process called Vacuum-Assisted Resin Infusion (VARI) is used [68].

3.2.2 Vacuum-Assisted Resin Infusion

Instead of having the resin injected under pressure into the mould cavity as in conventional RTM, in VARI, the resin is pulled into the mould under the pressure differential created by the vacuum. As seen on the figure 16, after the resin progresses between the fibres and tows of the fabric until the single-sided rigid mould is filled, the infusion process stops and the part is then cured at an elevated temperature, producing parts with less porosity than those produced using RTM [67].



(a) Lay up

(b) Pre-filling (c) Filling (d) Post-filling

Figure 16 - Schematics of the VARI Process [71]

This figure illustrates the consumables and the equipment required for this process and its different stages. First, layers of fibrous reinforcement are laid on the mould, which has already been coated with a release agent, to form the preform.

To get a simple separation of the consumables from the part and to create a relatively good surface finish, peel ply is placed over the preform and in order to speed up the flow of the resin, distribution medium can be placed over the peel ply (as stated in the figure 17).

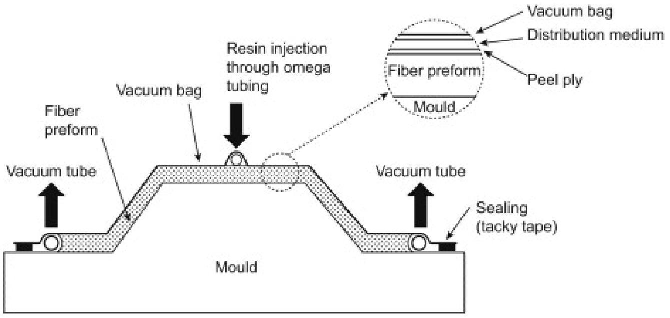


Figure 17 - VARI Variant: Seeman's composite resin infusion moulding (SCRIM) [70]

Once inlet and vent tubes are positioned, the mould is closed using a vacuum bag sealed with sealant tape (also known as tacky tape). After the cavity is sealed, the inlet is clamped, and vacuum is applied to the vents. This stage is referred here as “pre-filling” and at the end of it, the inlet is opened and the resin flows through the preform, representing the “filling” stage.

The “post-filling” stage involves removal of excess resin and allows resin pressure and laminate thickness to equilibrate within the cavity [71].

Chapter 4 – Methodology

The current chapter is aimed at covering the methodology used on how to compare and analyse the economic performance of both production methods that were studied.

Considering the focus of this study and the results that needed to be shown and discussed, Process-Based Cost Models were the best method to provide an accurate and feasible process to achieve the main aim of this thesis.

This thesis is incorporated on a research project between Instituto Superior Técnico and TU Chemnitz. This thesis was created after extensively understanding the usage and work done with the two production methods that Chemnitz University Composites Laboratory has been working on (TFP and DFP) and with the same approach taken with the AFP and ATL, other two possible CFRP production that, were described on the previous chapter.

With this knowledge on the subject, the approach taken was, with the data gathered from the processes, to understand what are the main drivers related to the cost models, what are the inputs needed, how to differentiate between them and what needs to be bright and clear to create a better final analysis and conclusions.

One of the analyses needed between DFP and TFP was related to the resin infusion technologies used in both methods. Vacuum-Assisted Resin Infusion and Resin Transfer Moulding were the two technologies in question, as VARI is the one currently used in the university, with RTM existing as well, but only used sometimes depending on the availability of the machine since there was no proper knowledge on at what time one process is better/cheaper than the other.

Due to COVID-19, several meetings were held online with these four teachers and with no possibility to be able to go to the Chemnitz University's labs for the first few months to observe the processes in action. All the data provided by the Prof. Marc Fleischmann was crucial in the development and gradual refinement of the PBCMs.

With Microsoft Excel, two PBCMs were created from scratch and another two were largely adapted to create a comparison between them all. DFP and TFP have a lot in common and AFP and ATL are very similar as well.

At the beginning of the design of a cost model, the relevant costs must be thoroughly defined. These costs were divided into two different types: Variable and Fixed Costs, studying how the costs vary according to the number of pieces produced.

After the costs were defined for this problem, a process tree was created, decomposing the costs into process blocks with smaller inputs which there was more information about. Data was then gathered with the help of the Chemnitz University's researchers (as it can be seen in on the Annex) and simplified equations helped to make sense of so ample and varied information.

To create a PBCM with a minimum margin of error regarding the real values that would be measured in a real production scheme, everything needs to be well-defined. Boundaries and limitations need to be correctly specified so that the values given throughout all the blocks are very close to reality. In this thesis, none of the PBCMs includes the non-destructive test (NDT) to give clearance of the piece for it to be used in a real-life situation and the assembly of the part on the car. This study is focused on the usage of processed material from a third party until the final piece produced before its NDTs.

During the creation of the PBCMs, sensitivity analyses were done to all inputs given, on a regular basis, so as to the final models provide accurate results. A test case, the door of the race car from the German University, was used, compared, and showed to the researchers to confirm the validity of the final models.

With the results on the table, the findings were questioned and studied on several angles, a comparison between the four cost models was created, major cost drivers were observed and identified according to their impact on the final result. Since the process was split into different blocks, several graphics and charts were then created highlighting the important information needed for a visual appealing understanding of the conclusions.

On the next page, a simple figure is shown, which clarifies all the steps taken until the analysis of the results.

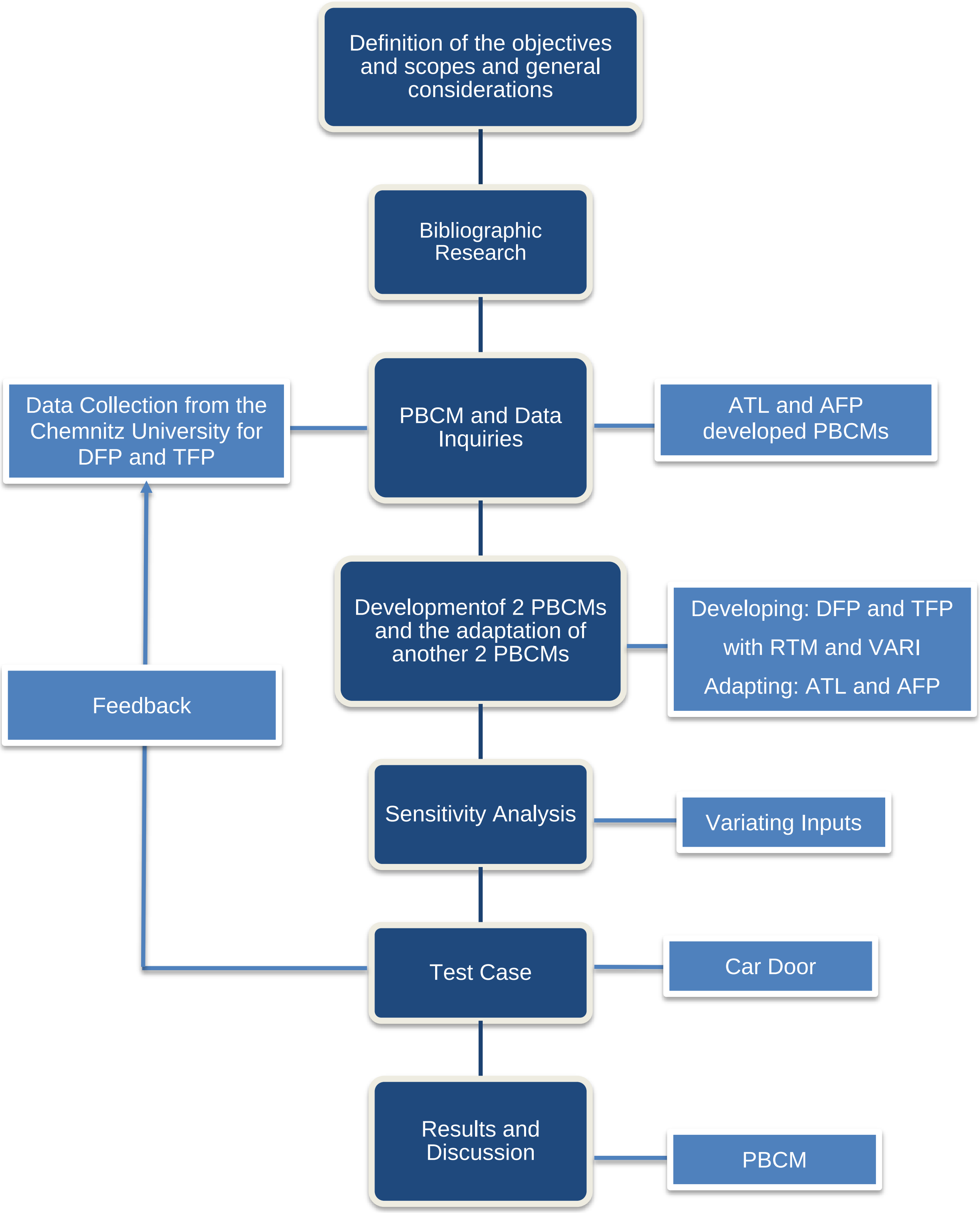


Figure 18 - Methodology

Chapter 5 – Application of the Cost Models

With this chapter, the Process-Based Cost Models (PBCM) will be explained in-depth, with the key goal of creating a greater insight on their applications and needs while explaining step-by-step all of the nuances and equations used during this work, with only the main information and important differences being pointed out throughout the explanation of the models' development.

5.1 Process-Based Cost Models

In most industries, cost modelling is one of the first steps done in product development. It is a theoretical model done in order to prevent the misuse of valuable resources and money that would otherwise happen due to a policy of trial and error needed to understand how certain aspects would interfere with the final price of the piece. With the creation of estimates, it allows engineers to identify the basic variables that affect the cost the most, being an essential tool to compare costs of materials, labour or tooling, or to examine the effect of changes in the production scenario, making informed decisions concerning technology alternatives before operations are in place [72] [73].

There are two types of costs, the Fixed costs, which are the ones that will be independent of the production rate, and they include the machine, the tooling needed, the overheads and the building, and there are also the Variable costs, this includes the material, consumables, scrap, labour and energy costs, the costs that are directly affected according to the production amount.

With these metrics, a company can identify the main cost drivers associated with the production of the part and, taking the correct decisions, reduce costs and therefore generate a higher profit or just understand if a part is profitable when produced using a certain process.

5.2 PBCM Development Technique

While there are many ways to develop a Process-Based Cost Model, Kirchain [74] shows that a very efficient way to construct a cost model is to decompose it into three categories: the Process Model, the Operations Model and the Financial Model, as it can be seen on the figure 19, This simplifies to a great extent by dividing the problem into three interdependent sections, which with its own set of questions that need to be answered to analyse the problem correctly while also providing support on defining the scope and boundaries of the task in hand [72] [73].

In the Process Model, fundamental engineering principles are employed, with every engineering principle that is connected to the manufacturing process being asked for. This includes, for example, the materials, cycle times, number of workers or energy used.

In the Operations Model, contemplating what has been answered beforehand on the process model, it is asked how everything will be implemented and how the plant will be optimized during the entire process, with how many machines, workers and amounts of the material described in detail.

Finally on the Financial Model, by defining the costs of all the resources needed during the manufacturing and with a simple accounting of the factors required to produce the part it is possible to define the final cost of the part, thus completing the PBCM. [75]

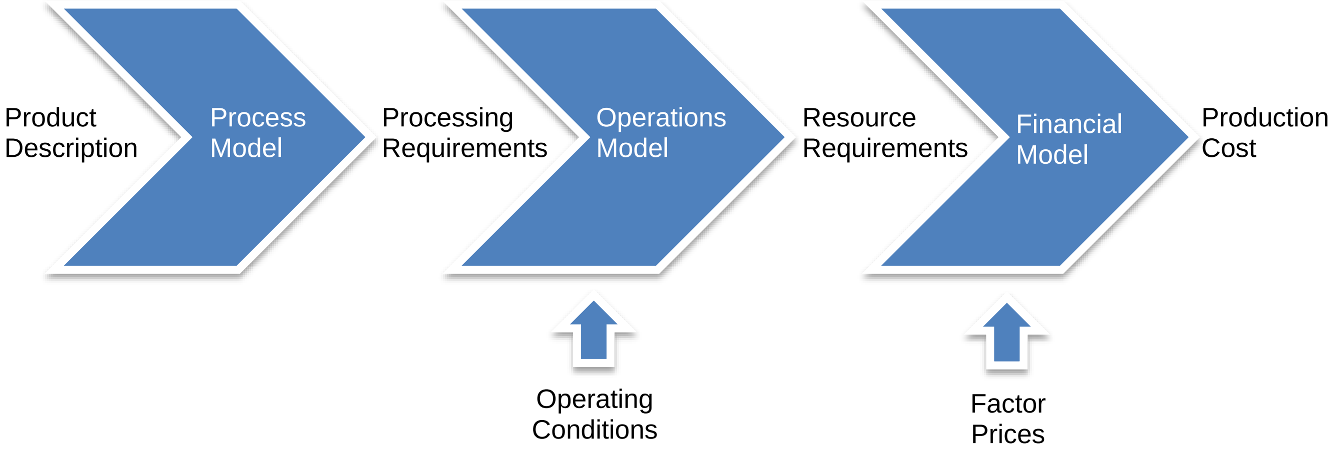


Figure 19 - Process-Based Cost Model decomposition [75]

As it can be observed on the figure above, the cost model starts by the description of the problem, which defines the process model, then the requirements for the process are established considering the operating conditions, generating the Operations Model. With the resource requirements estimated, there remains to convert them into the economic costs of the project, originating the Financial Model.

5.3 Models Development

In order to begin the construction of the PBCMs, first, it is important to identify the pertinent cost elements, then a Diagram of Process Operations needs to be drawn out, along with the Material Flows, then after identifying what are factors that impact the costs it is possible to find the desired inputs of the cost model.

5.3.1 Main Costs

The main costs that were identified for DFP and TFP are the ones shown on table 2:

Table 2 - Main Costs

Variable Costs	Fixed Costs
Material Cost	*Main Machine Cost*
Consumable Cost	*Tooling Cost*
Scrap cost	*Fixed Overhead Cost*
Labour Cost	*Building Cost*
Energy Cost	*Maintenance*
Building Cost (Curing Step)	

5.3.1.1 Variable Costs

- Material Costs are the costs related to direct materials used in both production methods. For DFP the materials used are the carbon fibre rovings, the binder, the sandwich core, and the epoxy resin and for the TFP the materials are also the carbon fibre rovings, the sandwich core and the epoxy resin, but the carrier as well.
- Regarding Consumables, both processes need different items, which include vacuum film, tacky tape, peel ply, vacuum pipes, etc.
- In terms of Scrap both the processes have it, but TFP is more likely not to have anything since most times there is no need for trimming.
- Direct Labour Costs are associated with manufacturing, machining, and inspection, which include for example preparing the machines, vacuum bagging, putting into the autoclave and operating it, etc.
- The Energy costs concern the energy consumption expenditure of all machines used during the processes.
- In reference to the Building costs associated with the curing step, they occur due to the need for the moulds to cure, taking approximately 48 hours for VARI and 30 minutes for RTM.

5.3.1.2 Fixed Costs

- The Main Machine cost is connected to the price paid by the manufacturer for the fibre placement, RTM and trimming machines.
- In terms of Tooling, this concerns the cost of the moulds involved with the production of the specified part.

- About the fixed overheads, these costs are not directly related to the manufacturing but include engineering, technical and non-technical services (secretary, security, etc.) and office supplies.
- Finally, the Non-Dedicated Building cost is related to the machine and workplace floor needed to produce parts.

5.3.2 Production Time

Regarding the production time, the Uptime was introduced to measure the factory's efficiency and availability. With the aim of calculating the uptime the equation used below is used, where there are two factors needed: the sum of the time where the machine is running and the total amount of time available for the machine to run.

$$Plant\ Uptime\ (\%) = \frac{Actual\ production\ run\ time}{Total\ available\ time\ for\ production} \tag{1}$$

Where the actual production run time is simply:

$$Actual\ production\ run\ time = \ Total\ available\ time\ for\ production - Downtime \tag{2}$$

Downtime is calculated through the sum of the average times of Line shutdown, Worker unpaid and paid breaks, on shift maintenance, idle time, and unplanned downtime.

The time required for a single step can be calculated by multiplying the cycle time of the stage, by the number being produced annually:

$$Time\ required = \ Cycle\ time \times Number\ of\ parts \tag{3}$$

5.3.3 Processes Steps

In this chapter, both DFP and TFP are divided into steps which allow for an individual close examination of each of their costs.

5.3.3.1 Dry Fibre Placement

As it can see been below on figure 20, the DFP process operation is divided into sections:

Figure 20 - DFP Process Operation

The first step of DFP is the reception and storage of materials. In this step, the binder, sandwich cores, epoxy resin and carbon fibre rovings are stored in the warehouse and the rovings are placed on creels.

On the next step (and as displayed on figure 21), the rovings are pulled by a conveying unit through a spreader that proceeds to spread the roving into a thinner wide tape, which goes across a binder application module. With the binder in place, it proceeds to the fibre placement machine (which has 4 actuators) where there is a pneumatic clamp called gripper which is stationary and designed to hold the roving in place, then there is a blade that cuts the tapes in the desired length, which are then placed by another 2 grippers that do the placement of the carbon fibre tapes, moving with 2 degrees of freedom while powered by individual motors.

Figure 21 - DFP Machine (Provided by TU Chemnitz)

After the preform is completed, it is placed on a hot press aiming to activate the binder so that the single layers are connected to the desired thickness. While the preform is still hot, it is positioned on the mould and then the core is applied.

With every step completed, the resin infusion, heat and curing of the preform on the mould is completed by RTM or VARI, depending on what is chosen.

Afterwards, de-moulding occurs, trimming and finishing are done, cutting the windows and the edges present on the piece.

Not included on the scope of this thesis, would be the non-destructive testing done later, so that the part complies with the requirements put in place beforehand and with the NDTs finished, the assembly would be required. This involves the hinges for the doors to be placed onto the car.

5.3.3.2 Tailored Fibre Placement

TFP and DFP are quite similar in terms of process flow, but there are still a few key differences as they can be observed on the figure below and described in detail afterwards.

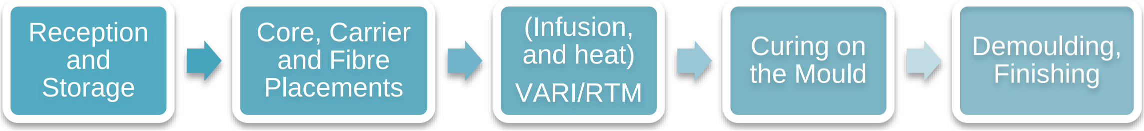


Figure 22 - TFP Process Operation

Regarding storage of all materials, this is alike the DFP process.

On the second step, completely different techniques are used, as it is represented in the figure 23. Since TFP uses embroidery technology, where a machine table does the movement on the XY plane (that manoeuvres the carrier material and later the preform) and where a robot-guided sewing machine head executes the Z-rotation and stitching-relevant motions, allowing for a flexible orientation of any fibre roving. It stitches a polyester yarn by a zig-zag pattern on the sides of a continuous carbon fibre roving (preferably keeping the penetration of the roving to a minimum), which gets attached to a nonwoven base material and a sandwich core. The roving is placed following a pre-defined course by the rotation of the roving pipe and by moving the base material in two perpendicular paths.

Figure 23 - TFP machine (Provided by TU Chemnitz)

Then just like DFP, the TFP process continues by performing the resin infusion either by RTM or VARI, followed by curing, demoulding, and finishing. Trimming is usually not performed since the TFP process already considers the shape of the part, with no extra carbon-fibre generally being added.

5.3.4 Inputs

With all the process operations laid out, the breakdown process begins. The PBCM’s inputs were split into two key groups: the main inputs, that reflect the exogenous variables, which are dependent on the company and/or factory where the part is produced and that are common to every block present throughout the cost model, and the specific process inputs, which are the inputs required for a single block, being present in few operations, but being essential, nonetheless.

All inputs present on the PBCM's are listed in the table 3, split into the two main groups aforementioned.

Table 3 - Exogenous Variables

Days per Year	days/year
Wage (including benefits)	€/hr
Unit Energy Cost	€/kWhr
Opportunity cost of capital	%
Equipment Life	year
Building Unit Cost	€/sqm
Building Life	years
Production Life	years
Idle Space	%

Regarding the variables on table 3:

- Days per year refer to the number of working days in a year when the factory is up and running.
- Wage concerns the average amount of pay that each worker receives per hour.
- Unit energy cost is the cost in euros per kilowatt-hour.
- The opportunity cost of capital corresponds to the annualized rate at which the company must pay the lender the money needed to finance its endeavours.
- Equipment life is the average life that the machinery used in the factory will last.
- Building unit cost is the price per square meter where the factory is situated.
- Building life relates to the time in years which the factory will remain solid without major renovations needed.
- Production life represents the number of years which the part will be built in the factory.
- Idle space is the available space inside the factory, but that is not being used.

As for the specific process variables of the project, they are comprised in table 4:

Table 4 - Specific Process Variables

Part Complexity	1,2,3
VARI or RTM	0,1
Production Volume	units/year
Material cost	€/kg or €/m^2
Scrap Percentage	%
Scrap Price	€/kg

Workers	number
Number of machines	units
Acquisition Cost	€/unit
Floor Space	m^2
Energy Consumption	kW
Machine Time	h
Setup Time	h
Maintenance	%
Overheads	%
Curing Time	h
Mould Size	m^2

The specific variables include several types of information regarding each step of the process, which include part information, production volume, materials, scrap, machines, consumables, and overheads.

Below there is a simple explanation for these variables present in table 4:

- Part Complexity is the geometric complexity of the part introduced ranging from 1 to 3, being 1 not very complex and 3 very complex.
- VARI or RTM is the input given by the user which picks the type of resin infusion used on the part required.
- Production Volume corresponds to the number of parts produced per year.
- Material Cost is the cost in euros of each kilogram of material chosen.
- Scrap Percentage represents the percentage of scrap for each type of material.
- Scrap Price is the price at which each kilogram of scrap is sold for.
- Workers are the number of workers needed for each task.
- Acquisition Cost is the price at which each machine was bought for.
- Floor Space indicates the space occupied by each machine/workstation.
- Energy Consumption is the energy spent by the systems of the block.
- Machine Time is the working time of each machine per part.
- Setup Time signifies the time needed for workers to arrange the machine/workplace/tool for it to be in running condition.
- Maintenance is the price of the yearly maintenance based on the percentage of the price of the machine.
- Overheads correspond to the price paid for costs are not directly related to the manufacturing in terms of percentage base on the price paid for the workers.
- Curing Time is the time taken by the preform to cure before it can be de-moulded.
- Mould Size is the size in square meters of each mould.

5.3.5 Costs Breakdown

With the flow of materials and process flows defined, combined with the chosen inputs gathered from decomposing the costs into smaller process blocks, it is finally possible to calculate all the costs related to the manufacturing.

5.3.5.1 Variable Costs

Material Cost

The way how all the material costs were calculated is shown below, with epoxy being the one with the most calculations to provide with the final result. The figure 24 represents the calculation flowchart of epoxy for TFP or DFP, with numbers for each calculation performed, so to explain later with ease.

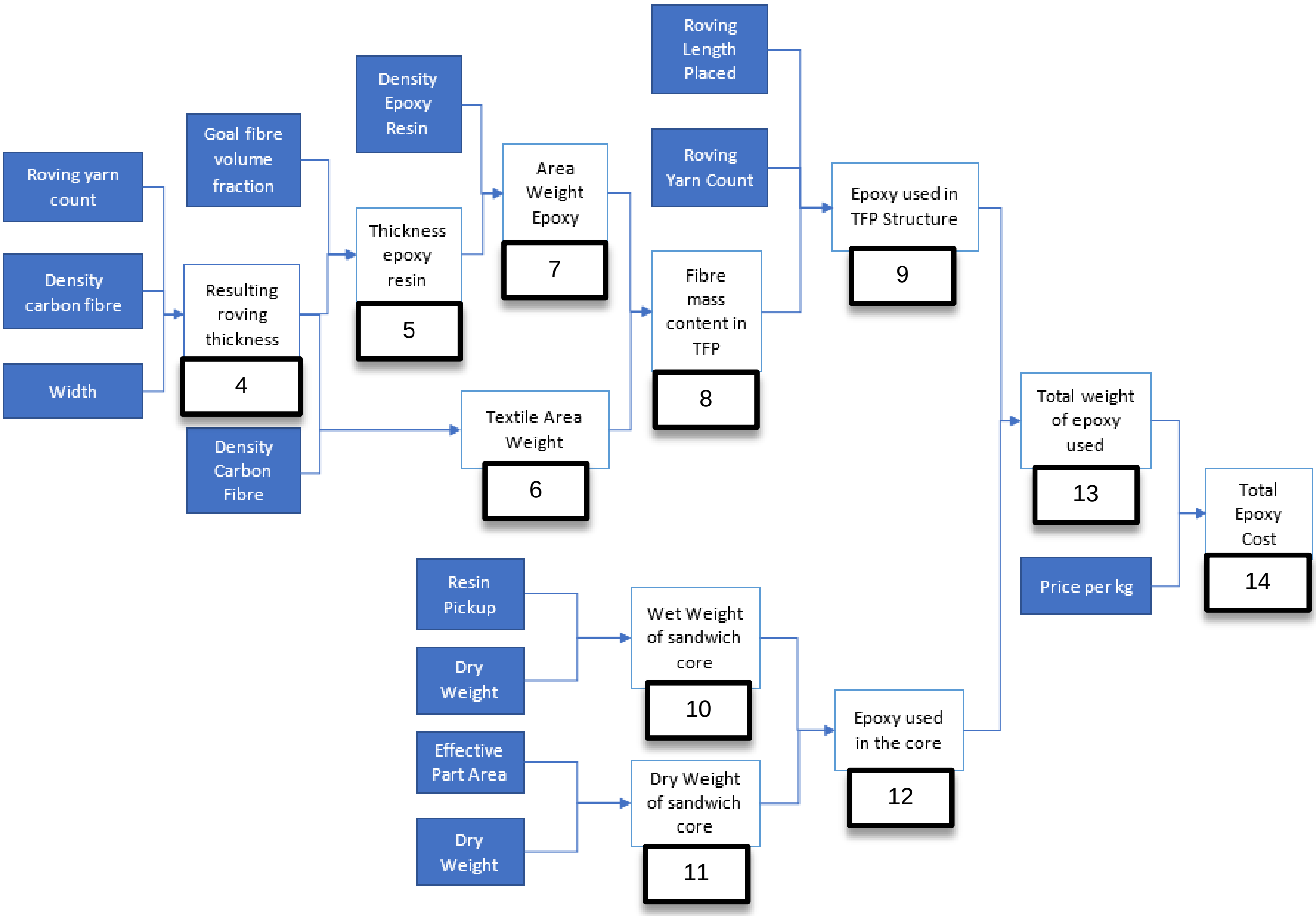


Figure 24 - Total epoxy cost schematics

The resulting roving thickness is determined by dividing the roving yarn count (the weight of yarn in a meter of tow), by the density of the carbon fibre multiplied by the width of the fibre used.

$$\boxed{4} \qquad Resulting\ roving\ thickness\ [m] = \frac{Roving\ yarn\ count\ \left[\frac{kg}{m}\right]}{Density\ of\ the\ carbon\ fibre\ \left[\frac{kg}{m^3}\right] \times Fibre\ width\ [m]} \tag{4}$$

The thickness of the epoxy resin in the structure is calculated using the resulting thickness of the roving (1) and the goal fibre volume fraction (which is the percentage of fibres in the whole structure, related with the amount of epoxy found on the composite. A ratio that if higher, typically results in better mechanical properties of the composite).

5

$$Thickness\ of\ the\ epoxy\ resin\ in\ the\ structure\ [m] = Resulting\ Roving\ thickness\ [m] \times \left(\frac{1}{Goal\ Fibre\ Volume\ Fraction\ [\%]} - 1\right) \qquad (5)$$

The textile area weight is computed by the multiplication of the resulting roving thickness calculated on (5) by the density of the carbon fibre.

6

$$Textile\ Area\ Weight\ \left[\frac{kg}{m^2}\right] = Resulting\ roving\ thickness\ [m] \times Density\ of\ the\ carbon\ fibre\ \left[\frac{kg}{m^3}\right] \qquad (6)$$

The Area weight of epoxy is the multiplication of the density of the epoxy resin, by the thickness of the resin in the structure (6).

7

$$Area\ Weight\ Epoxy\ \left[\frac{kg}{m^2}\right] = Density\ epoxy\ resin\ \left[\frac{kg}{m^3}\right] \times Thickness\ of\ the\ epoxy\ resin\ in\ the\ structure[m] \qquad (7)$$

The Fibre mass content is the division of the textile area weight (6), by the area weight of epoxy (7).

8

$$Fibre\ mass\ content\ in\ TFP = \frac{Textile\ area\ weight\ \left[\frac{kg}{m^2}\right]}{Area\ weight\ epoxy\ \left[\frac{kg}{m^2}\right]} \qquad (8)$$

The Epoxy used is calculated by multiplying the roving length placed by the roving yarn count and dividing this by the fibre mass content (8).

9

$$Epoxy\ used\ in\ TFP\ structure\ [kg] = \frac{\left(Roving\ lenght\ placed\ [m] \times Roving\ yarn\ count\ \left[\frac{kg}{m}\right]\right)}{Fibre\ mass\ content\ in\ TFP} \qquad (9)$$

The Wet core weight is computed by multiplying the effective area of the part by the sum of the dry weight (weight of the part per square meter) plus the resin pickup (the weight of resin existent in a square meter of the part).

10

$$Wet\ core\ weight\ [kg] = Effective\ part\ area\ \ [m^2] \times \left(Dry\ weight\ \left[\frac{kg}{m^2}\right] + Resin\ pickup\ \left[\frac{g}{m^2}\right]\right) \qquad (10)$$

The dry core weight is simply the multiplication of the dry weight by the effective area of the part.

11

$$Dry\ core\ weight\ [kg] = Dry\ weight\ \left[\frac{kg}{m^2}\right] \times Effective\ part\ area\ [m^2] \tag{11}$$

With (10) and (11) calculated, its subtraction results in the weight of epoxy used in the part.

12

$$Epoxy\ used\ in\ core\ [kg] = Wet\ core\ weight\ [kg] - Dry\ core\ weight\ [kg] \tag{12}$$

By adding the epoxy used in the structure (6) and the epoxy used in the core (9), the total weight of epoxy used is assessed.

13

$$Total\ weight\ of\ epoxy\ used\ [kg] = Epoxy\ used\ in\ TFP\ structure\ [kg] + Epoxy\ used\ in\ core\ [kg] \tag{13}$$

To finally get the total cost of the epoxy, a simple calculation of the cost per kilogram multiplied by the total weight of epoxy used (13) is performed.

14

$$Total\ epoxy\ cost\ \ [€] = Cost\ per\ kg\ \left[\frac{€}{kg}\right] \times Total\ weight\ of\ epoxy\ used\ [kg] \tag{14}$$

To calculate the price of the carbon fibre roving:

$$Weight\ of\ roving\ used\ [kg] = Roving\ lenght\ placed\ [m] \times Roving\ yarn\ count\ \left[\frac{kg}{m}\right] \tag{15}$$

$$Roving\ cost\ [€] = Weight\ of\ roving\ used\ [kg] \times Cost\ per\ kg\ \left[\frac{€}{kg}\right] \tag{16}$$

Analysing the cost of the sandwich core and the carrier material:

$$Cost\ of\ material\ [€] = Cost\ per\ m^2\ \left[\frac{€}{m^2}\right] \times Total\ area\ used[m^2] \tag{17}$$

To calculate the price of the binder:

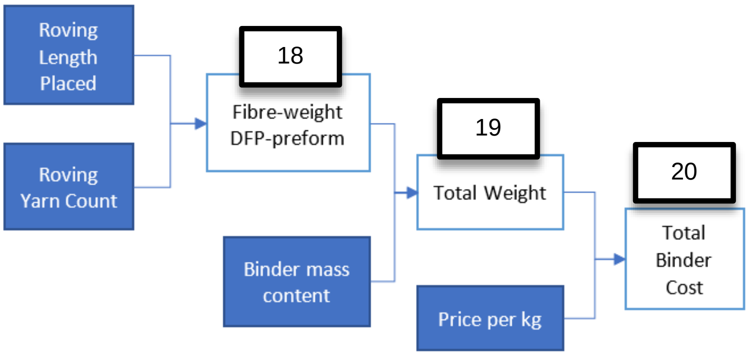


Figure 25 - Binder Cost Flowchart

To calculate the cost of the binder shown in figure 25, first, the fibre-weight of the preform is computed by multiplying the roving yarn count by the roving length placed:

18

$$\mathit{Preform\ Fibre\ Weight}\ \ [kg] = \mathit{Roving\ lenght\ placed}\ [m] \times \mathit{Roving\ yarn\ count}\ \left[\frac{kg}{m}\right] \qquad (18)$$

Now, the fibre-weight (18) is multiplied by the binder mass content (5%), to result in the total weight of binder used.

19

$$\mathit{Binder\ total\ weight}\ \ [kg] = \mathit{Preform\ Fibre\ weight}\ [kg] \times \mathit{Binder\ mass\ content}\ [\%] \qquad (19)$$

Finally, with the weight calculated (19), the result is multiplied by the price of binder per kilogram, providing the final binder cost of the part.

20

$$\mathit{Total\ Binder\ Cost}\ \ [€] = \mathit{Weight}\ [kg] \times \mathit{Binder\ Price\ per\ kg}\ \left[\frac{€}{kg}\right] \qquad (20)$$

Consumables Cost

The consumables costs are calculated by the following equation:

$$\mathit{Consumables\ Cost}\ [€] = \mathit{Consumables\ cost\ per\ unit}\ \left[\frac{€}{unit}\right] \times N^{\underline{o}}\ \mathit{of\ parts}_i[\mathit{units}] \qquad (21)$$

Scrap cost

The scrap costs are calculated by the following equation:

$$\mathit{Scrap\ cost}\ [€] = \mathit{Scrap\ price}\ \left[\frac{€}{kg}\right] \times \mathit{Scrap\ percentage}\ [\%] \times \mathit{Material\ Weight}_i\ [kg] \qquad (22)$$

Labour Cost

The labour costs are calculated by the following equation:

$$\begin{aligned}\mathit{Labour\ Cost}[€] = {} & N^{\underline{o}}\ \mathit{of\ Workers}_i[\mathit{units}] \times \mathit{Cycle\ Time}_i[h] \times \mathit{Wage}\left[\frac{€}{hour}\right] \times \mathit{Dedication}_i[\%] \\ & \times N^{\underline{o}}\ \mathit{of\ Parts}_i[\mathit{units}]\end{aligned} \qquad (23)$$

Energy Cost

Energy costs are calculated by this equation:

$$Energy\ Cost\ [€] = Cycle\ Time_i[h] \times nº\ of\ Parts_i[units] \times Power[kW] \times Unit\ Energy\ Cost\ \left[\frac{€}{kWh}\right] \tag{24}$$

5.3.5.2 Fixed Costs

Main Machine, Tooling and Building Costs

The equivalent annual cost (referenced in excel as the function PMT):

$$Equivalent\ annual\ cost_i = \frac{Investment[€] \times Interest\ Rate[\%]}{1 - (1 + Interest\ Rate[\%])^{-Production\ Life_i}} \tag{25}$$

Machine costs are calculated by these equations:

$$Machine\ investment[€] = Machine\ Cost[€] \tag{26}$$

$$Machine\ cost_i[€] = \frac{(Equivalent\ annual\ machine\ investment[€] + Maintenance\ annual\ cost[€]) \times Allocation[\%]}{Nº\ of\ Parts_i[units]} \tag{27}$$

Dedicated Tooling costs are calculated by this equation:

$$Tooling\ cost_i[€] = \frac{Equivalent\ annual\ tooling\ cost[€]}{Nº\ of\ Parts_i[units]} \tag{28}$$

The building costs are calculated by these equations:

$$Building\ investment = (1 + Idle\ space[\%]) \times Building\ unit\ cost\ \left[\frac{€}{m^2}\right] \times Floor\ Space[m^2] \tag{29}$$

$$Building\ cost_i[€] = \frac{Equivalent\ annual\ building\ cost[€] \times Allocation[\%]}{Nº\ of\ Parts_i[units]} \tag{30}$$

Fixed Overhead Cost

Overheads can be calculated by this equation:

$$Overheads = Labour\ cost[€] \times\ Overhead\ Percentage[\%] \tag{31}$$

5.3.5.3 OoA Methods Model

Table 6 - VARI Model Variables

VARI Model		
Floor Space	15	m^2
Workers	2	units
Mould cost	5 000	€
Machine Cost	1 500	€
Consumables Cost	20	€/unit
Energy consumption	21	kWh
Setup Time	30	min
Machine Time	150	min
Overheads	160%	%
Maintenance	10%	%
Curing Time	48	hours

Table 5 - RTM Model Variables

RTM Model		
Floor space	15	m^2
Workers	2	units
Machine Cost	30 000	€
Mould cost	20 000	€
Consumables Cost	10	€/unit
Energy consumption	50	kWh
Setup Time	30	min
Machine Time	15	min
Time outside the mould	150	min
Overheads	160%	%
Maintenance	10	%
Curing Time	30	min

These variables above on tables 5 and 6 provide with building, labour, machine, consumables, energy, and overhead costs for both VARI and RTM. With this data, the number of moulds required, and the total space needed for curing in a certain production volume can also be obtained as explained in figure 26.

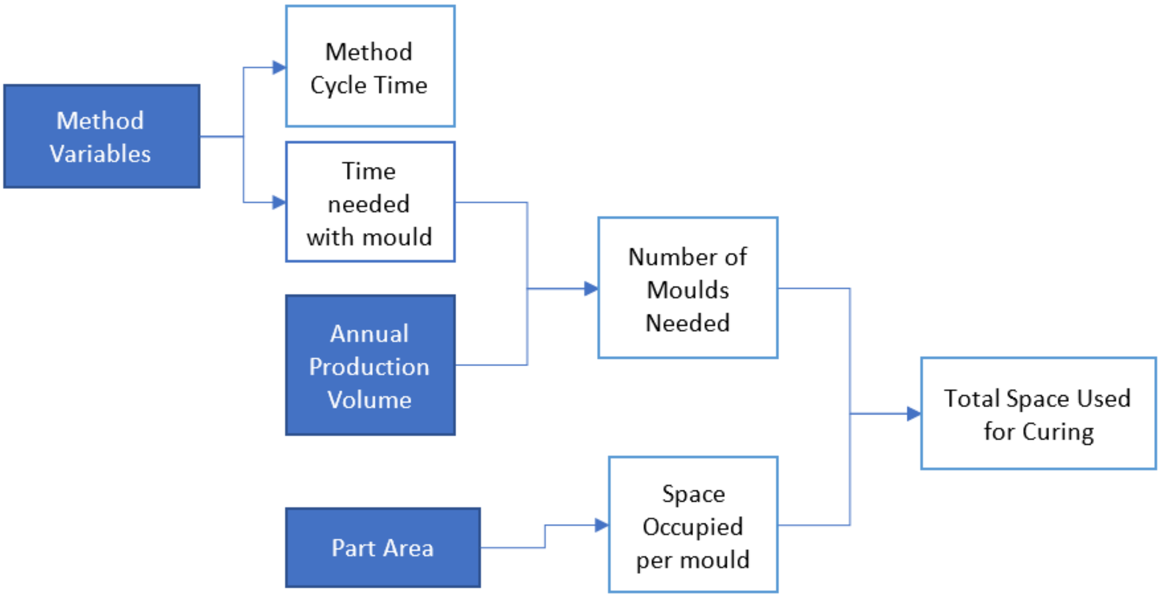


Figure 26 - VARI and RTM schematics

Chapter 6 – Results and Discussion

In this chapter, with information from the test case, the PBCM's created for DFP and TFP are studied in detail, with various testing done, as a mean to validate them, which includes understanding the main cost drivers and sensitivity analyses.

With this validated PBCM's, a comparison is then established with two other cost models for AFP and ATL, that have been created for another master thesis [4] and that were adapted for this test part.

6.1 Test Case

The test case used is the 0,86m^2 door belonging to the new hydrogen concept car from the TU Chemnitz team known as *Fortis Saxonia*. In figure 27 is shown the 2017's model called *UrbanSAX*, which only weighs about 154kg, due to its CFRP monocoque and parts. The inputs gathered for this test case can be seen on the Annex.

Figure 27 - *UrbanSAX* urban concept car [3]

6.1.1 Exogenous Variables

The exogenous variables used in the PBCM's are presented below in table 7. They represent estimates created considering real industries that could be producing this part, but also an estimate on a similar part's production life.

Table 7 - Exogenous Variables used

Days per Year	240	days/year
Wage (including benefits)	10,00 €	€/hr
Unit Energy Cost	0,08 €	€/kWhr
Opportunity cost of capital	15%	%

Equipment Life	15	year
Building Unit Cost	1 500,00 €	€/sqm
Building Life	30	years
Production Life	15	years
Idle Space	20%	%

6.1.2 Materials Information

As stated in previous chapters, the materials used in DFP and TFP are different, even though both are dry fibre processes. And so, on the following tables, the materials used by TU Chemnitz are displayed.

6.1.2.1 DFP

The information related to the material used in the production of this part with DFP is presented below:

Table 8 - Carbon Fibre Roving used in DFP

Material	SGL Sigrafil C T50-4.0/240-E100	
Cost per kg	20	€/kg
Density	1,80	g/cm^3
Roving yarn count	6840,00	g/km
Width	50,00	mm
Area DFP Placement single layer	1,18	m^2
Area DFP Preform single layer (trimmed)	0,86	m^2

Table 9 - Binder Material used in DFP

Cost per kg of Binder	20	€/kg

Table 10 - Sandwich Core used in DFP

Material	Coremat XM 3mm (Polyester)	
Resin pickup	1150,00	g/m^2
Dry weight	110,00	g/m^2
Total area used	1,25	m^2
The effective area in the door	0,86	m^2
Cost per m^2	14,15	€/m^2

Table 11 - Epoxy used in DFP

Material	L-Resin + GL-2 Hardener	
Cost per kg	20,00 €	€/kg

6.1.2.1 TFP

In TFP the sandwich core and the epoxy are the same as in DFP, but the carbon fibre roving is quite different on both the roving yarn count and the width. Besides these materials, TFP also makes use of a carrier material, which is presented below.

Table 12 - Carbon Fibre Roving used in TFP

Material	SGL Sigrafil C T50-4.0/240-E100	
Cost per kg	20	€/kg
Density	1,80	g/cm^3
Roving yarn count	3420	g/km
Width	4,50	mm

Table 13 - Carrier used in TFP

Material	HP-Textiles HP-P200C, Plain Weave	
Cost per kg	26,95	€/kg
Area weight	200	g/m^2
Total area used	1,25	m^2
The effective area in the door	0,86	m^2

6.1.3 Placement Information

Alongside the materials and type of production, both CFRP production methods have different types of roving placements as stated on tables 14 and 15.

6.1.3.1 DFP

Table 14 - Carbon fibre placement in DFP

Seconds/Tape	8	s/tape
Tapes per layer	27	units
Number of layers per preform	4	units
Tapes per local reinforcement	10	units
Number of local reinforcement tapes	8	units
Number of local reinforcement layers	2	units
Time for repositioning placement table between layers	15	s

6.1.3.2 TFP

Table 15 - Carbon fibre placement in TFP

Stitches per minute	650	stitches/min
Stitches needed (2xTFP-Pattern)	25678	stiches
The average distance between stitches	6,4	mm

6.2. Model validation and analysis to major cost drivers

Following the structure of the PBCMs created, each one of the sections was analysed in detail contemplating each of its segmented costs, with the intent of confirming their accuracy. A 50 parts/year production was used since the goal for TU Chemnitz is to study and compare low production volumes across different types of production methods.

Table 16 - Costs for a 50 parts/year production with DFP with VARI or RTM and TFP with VARI or RTM

		DFP	TFP	DFP	TFP	DFP	TFP	DFP	TFP	DFP	TFP	DFP	TFP	DFP	TFP	DFP	DFP	TFP	TFP
		Reception and Storage	Reception and Storage	Binder and Fiber Placements	Core, Carrier and Fiber Placements	Core Placement + VARI - Infusion	VARI - Infusion	Core Placement + RTM - Infusion	RTM - Infusion	VARI - Curing Step	VARI - Curing Step	RTM - Curing Step	RTM - Curing Step	Demolding, Trimming and Finishing	Demolding, Trimming and Finishing	**VARI - Total Costs**	**RTM - Total Costs**	**VARI - Total Costs**	**RTM - Total Costs**
Variable Costs	*Material C.*	-	-	17,34 €	63,07 €	48,02 €	27,25 €	48,02 €	27,25 €	-	-	-	-	-	-	**65,36 €**	**65,36 €**	**90,32 €**	**90,32 €**
	Consumable C.	-	-	-	-	20,00 €	20,00 €	10,00 €	10,00 €	-	-	-	-	-	-	**20,00 €**	**10,00 €**	**20,00 €**	**10,00 €**
	Scrap C.	-	-	-	-	-	-	-	-	-	-	-	-	4,48 €	-	**4,48 €**	**4,48 €**	-	-
	Labour C.	0,14 €	0,32 €	6,84 €	8,25 €	60,00 €	60,00 €	60,00 €	60,00 €	-	-	-	-	6,03 €	5,00 €	**73,01 €**	**73,01 €**	**73,57 €**	**73,57 €**
	Energy C.	-	-	8,00 €	11,00 €	4,20 €	4,20 €	1,00 €	1,00 €	-	-	-	-	0,08 €	-	**12,59 €**	**9,39 €**	**15,20 €**	**12,00 €**
	Total Var. C.	0,14 €	0,32 €	32,18 €	82,32 €	132,22 €	111,45 €	119,02 €	98,25 €	0,00 €	0,00 €	0,00 €	0,00 €	10,59 €	5,00 €	**175,44 €**	**162,24 €**	**199,09 €**	**185,89 €**
Fixed Costs	*Main Machine C.*	-	-	7,47 €	5,91 €	0,22 €	0,22 €	0,36 €	0,36 €	-	-	-	-	0,02 €	-	**7,71 €**	**7,85 €**	**6,13 €**	**6,27 €**
	Tooling C.	-	-	-	-	17,10 €	17,10 €	68,41 €	68,41 €	-	-	-	-	-	-	**17,10 €**	**68,41 €**	**17,10 €**	**68,41 €**
	Fixed Overhead C.	0,22 €	0,51 €	10,95 €	13,20 €	96,00 €	96,00 €	96,00 €	96,00 €	-	-	-	-	9,65 €	8,00 €	**116,82 €**	**116,86 €**	**117,71 €**	**117,71 €**
	Building C.	0,01 €	0,01 €	5,87 €	1,93 €	3,90 €	3,90 €	3,90 €	3,90 €	11,54 €	11,54 €	11,54 €	11,54 €	0,52 €	0,43 €	**10,31 €**	**21,94 €**	**6,27 €**	**6,27 €**
	Total Fixed C.	0,23 €	0,52 €	24,29 €	21,04 €	117,22 €	117,22 €	168,67 €	168,67 €	11,54 €	11,54 €	11,54 €	11,54 €	10,19 €	8,43 €	**151,93 €**	**215,05 €**	**147,21 €**	**198,66 €**
TOTAL COST		0,37 €	0,84 €	56,47 €	103,36 €	249,44 €	228,67 €	287,69 €	266,92 €	11,54 €	11,54 €	11,54 €	11,54 €	20,78 €	13,43 €	**327,37 €**	**377,42 €**	**346,31 €**	**395,85 €**

On table 16, the costs are presented by step and by type with each step to be studied in detail on the following section.

6.2.1 Analysis per step

Considering that DFP and TFP are quite similar in terms of sections, both are displayed and studied at the same time so that comparison is done simultaneously.

As stated in chapter 5, DFP and TFP split into 5 different sections:

Figure 28 - DFP Process Operation

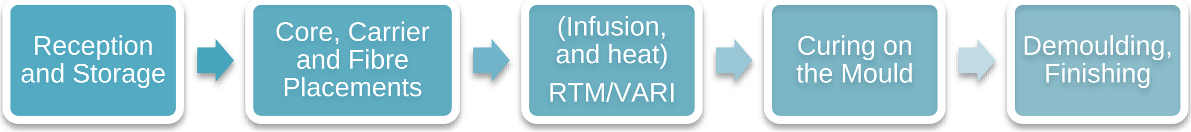


Figure 29 - TFP Process Operation

Starting with Reception and Storage, graphs for both DFP and TFP were made with the final costs for the production of 50 parts/year of the test case.

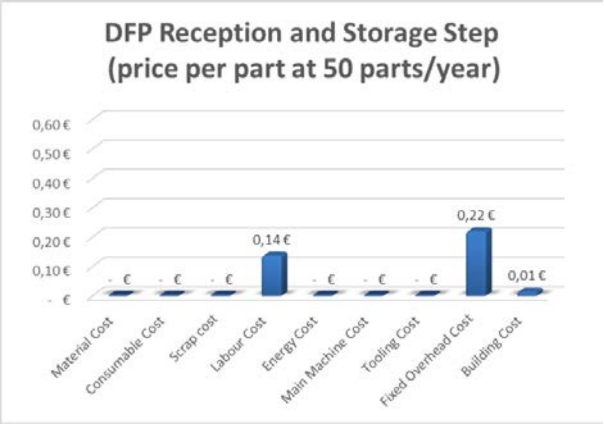


Figure 30 - DFP Reception and Storage Step (price per part at 50 parts/year)

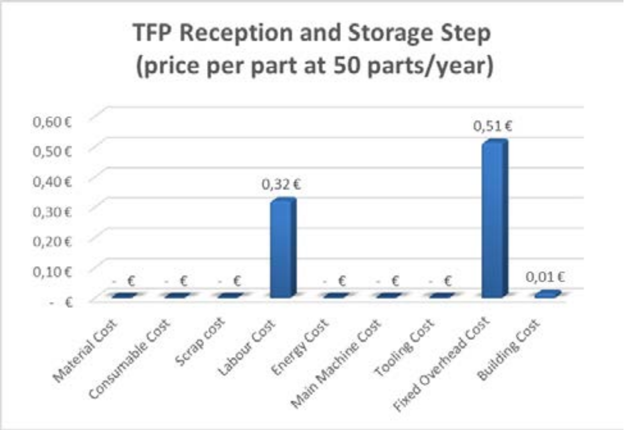


Figure 31 - TFP Reception and Storage Step (price per part at 50 parts/year)

As observed on graphs 30 and 31, both processes only have Labour Fixed Overheads and Building costs connected to them. Labour is related to the time spent by the worker to receive, store, and place the materials on their respective spots, including the carbon fibre rovings which are placed on creels, and since the overheads are directly connected to the labour cost, when labour increases, the overheads increase as well. Since TFP uses more rovings per part (due to the different widths and other placement factors), it is more labour intensive and needs more building space, correlated by prices shown on the graphs.

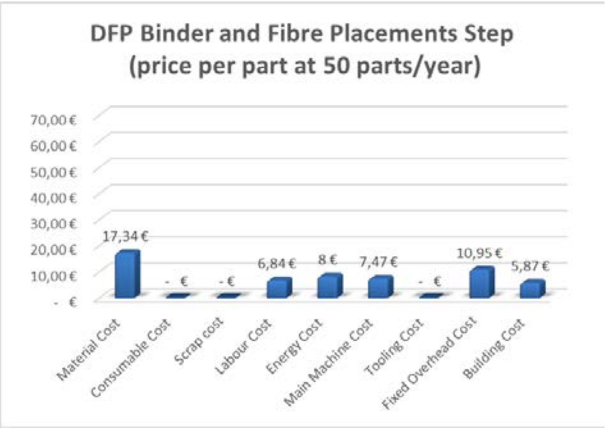


Figure 32 - DFP Binder and Fibre Placements Step (price per part at 50 parts/year)

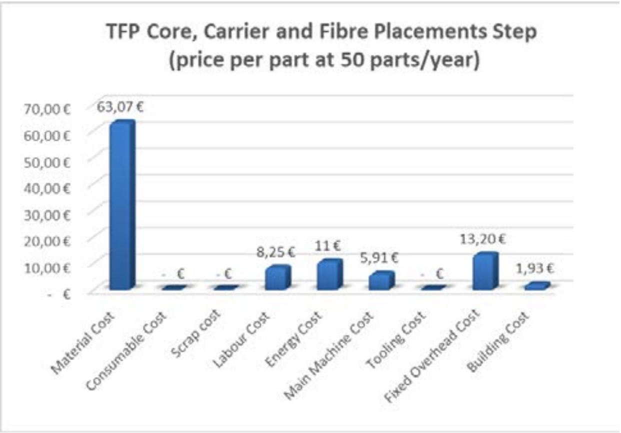


Figure 33 - TFP Core, Carrier, and Fibre Placements Step (price per part at 50 parts/year)

On figures 32 and 33, while with DFP only binder and the carbon fibre are placed, in TFP the core, carrier and fibre are placed, accounting for the difference on the material costs shown on the figures above. This is correlated with a slight increase in labour, energy, and overhead costs. In TFP the machine and building costs are lower since the embroidery machine is cheaper and occupies less building space.

Both processes include material, consumables, labour, energy, machine, tooling, overheads and building costs. The only key difference is shown on the material cost, which is clarified by the placement of the core in this step for DFP (which was already placed in an early stage for TFP)

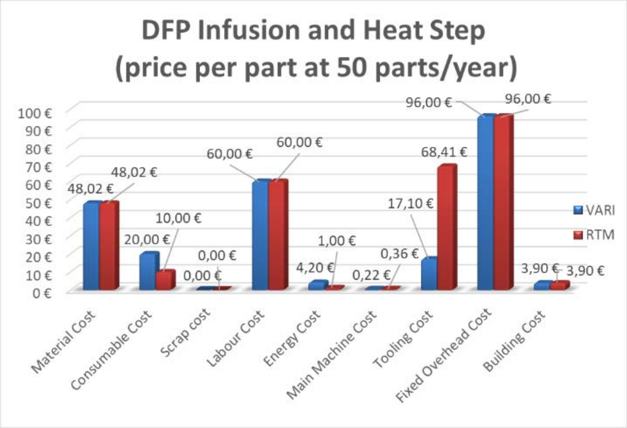


Figure 34 - DFP Infusion and Heat Step (price per part at 50 parts/year)

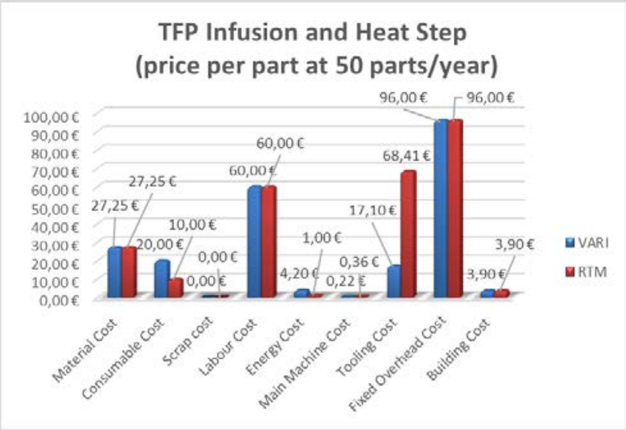


Figure 35 - TFP Infusion and Heat Step (price per part at 50 parts/year)

The two types of curing methods studied were VARI and RTM as show side by side on both figures 34 and 35, so to create an easy comparison. First, the difference between these two processes was studied and then the contrast between both DFP and TFP was analysed.

On both graphs, the differences with the use of the OoA methods were found on the consumables cost and the tooling cost. The difference in consumables highly depends on which types of vacuum film, tacky tape, peel ply or vacuum pipes used in the process and the price of different bulk orders, so this difference is neglectable. As for the tooling divergence, this can be supported by the difference in price for each type of mould, something that will be explained in the next chapter with larger production volumes.

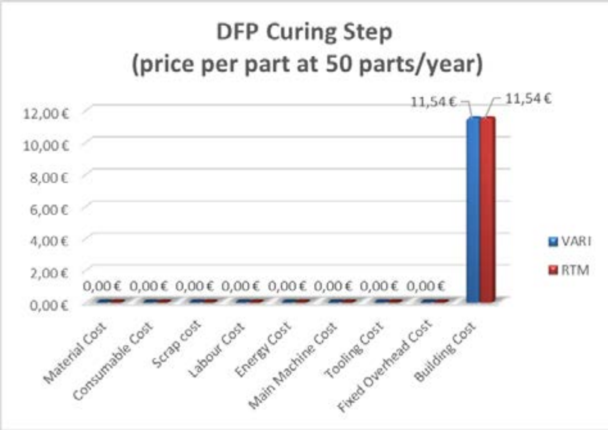


Figure 37 - TFP Curing Step (price per part at 50 parts/year)

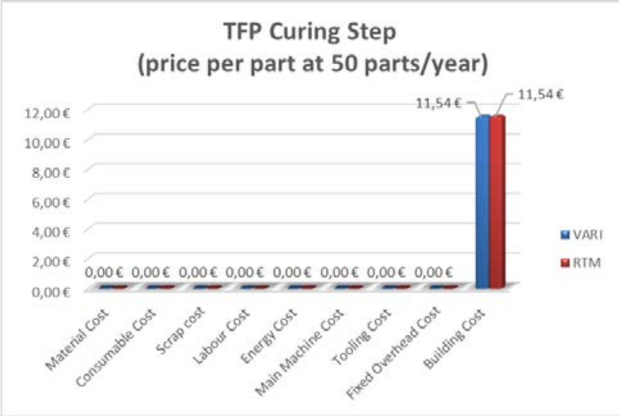


Figure 37 - DFP Curing Step (price per part at 50 parts/year)

.This curing step is characterized by the curing of the preforms and so the building space is required, as the building cost being the only cost given on both graphs. The tooling cost (related to the price of the mould) and other factors are shown as null, as it is already calculated in the previous stage.

More analysis will be performed on the quantity of moulds used for different production volumes, but as it can be seen on figures 36 and 37, the difference is negligible considering a low volume production status.

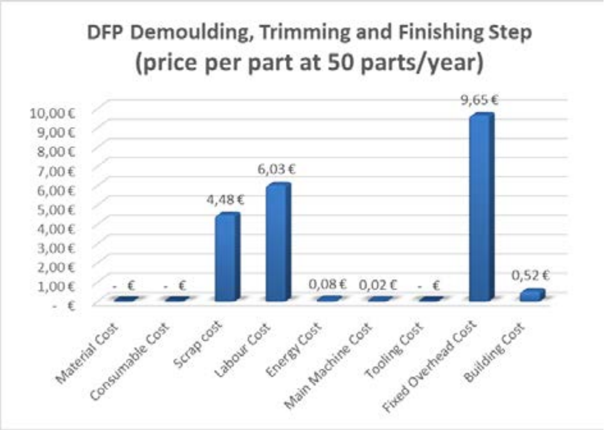


Figure 38 - DFP Demoulding, Trimming and Finishing Step (price per part at 50 parts/year)

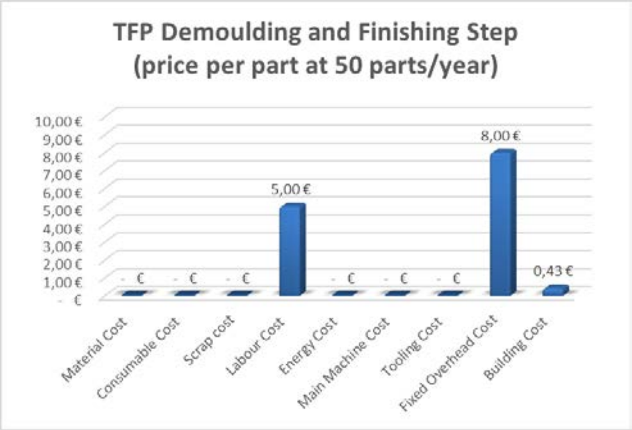


Figure 39 - TFP Demoulding and Finishing Step (price per part at 50 parts/year)

In this step, the preform is taken out of the mould, trimmed, and finished. In TFP, there occurs no trimming for this part, as this is a method that allows for the deposit of the fibres precisely where they are required, with no excess supplied.

Given that there is no need for trimming in TFP this results in less labour, energy, main machine, overhead and building costs as it can be seen when comparing both figures 38 and 39 above.

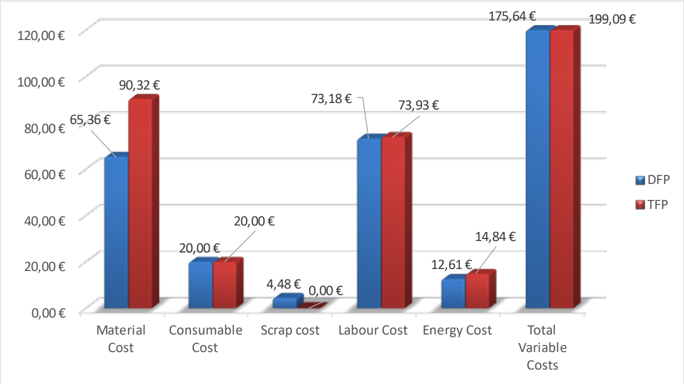


Figure 40 - TFP vs DFP w/ VARI Variable Costs (costs per part at 50 parts/year)

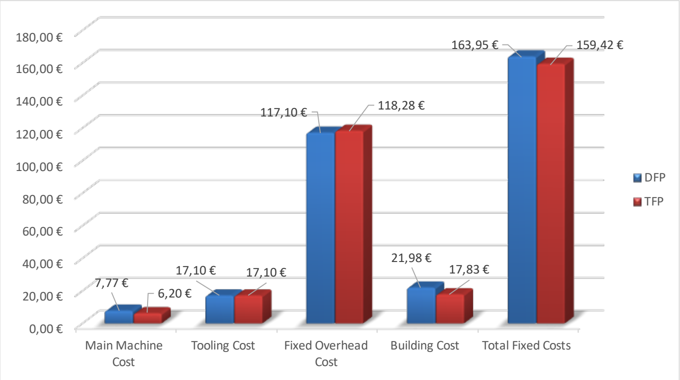


Figure 41 - TFP vs DFP w/ VARI Fixed Costs (costs per part at 50 parts/year)

As perceived on the figures 40 and 41, which show the variable and fixed costs for both DFP and TFP, it is easy to study that the differences are in the material, scrap, energy, machining and building costs, with material costs being the prominent key difference.

As observed on the figure 42 below, it is the material costs that provide the advantage of using DFP instead of TFP for a production of 50 parts per year when choosing the type of production according to the cheapest option. Making DFP the better-suited candidate for a low production status of this part of 50 parts per year. It can also be concluded that, for this low production status, the OoA method that delivers the cheapest production value is VARI (even though the difference is small, in other circumstances and with different inputs which might have distinctive and unique margins of error, the difference might also be neglectable).

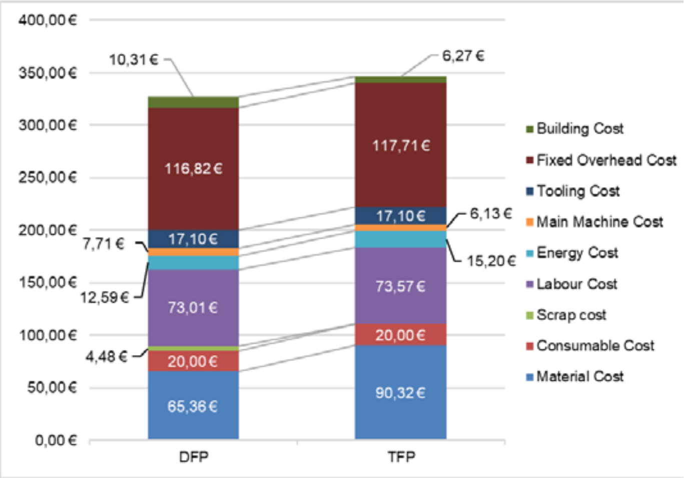


Figure 42 - TFP vs DFP w/ VARI (costs per part at 50 parts/year)

6.2.2 Production volume analysis for DFP and TFP

Since TU Chemnitz will only employ these two methods at low production volumes, more research and analysis were completed on this type of production. However, significant data is yet to be analysed, when dealing with higher production volumes. So, in the following section, a general examination is performed on the evolution of the costs for 1 to 50 parts per year, followed by detailed analyses for a larger status of 50 to 250 parts and finally for an even bigger production of from 250 to 5000 parts.

6.2.2.1 Low production volumes

Starting with low production volumes, a comparison between both processes is presented below on figures 43 and 44. As expected, even lower production volumes incur in even higher costs, mainly due to the tooling required to produce the parts. As the moulds can only be used for this part and therefore, they are dedicated in this production.

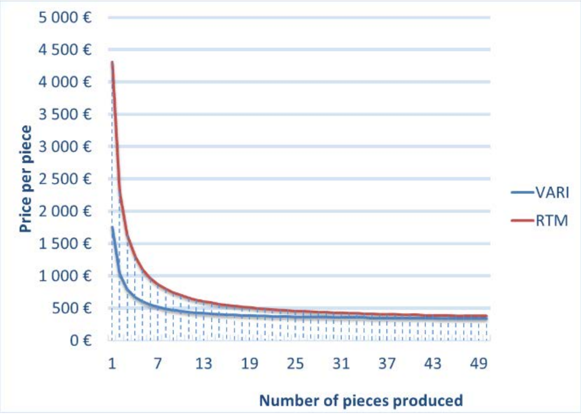


Figure 44 - DFP with VARI and RTM for low production volumes (1 to 50 parts/year)

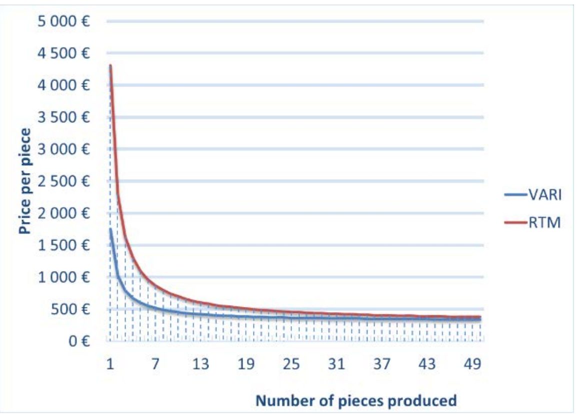


Figure 43 - TFP with VARI and RTM for low production volumes (1 to 50 parts/year)

For DFP and TFP, VARI seems to be always cheaper than RTM for low production volumes, starting at highly lower costs, due to the lower investment costs. Both figures are quite similar since there are no major differences between these two dry fibre production methods, but it is expected that with larger production volumes, one of them will eventually be cheaper.

6.2.2.2 Other production volumes

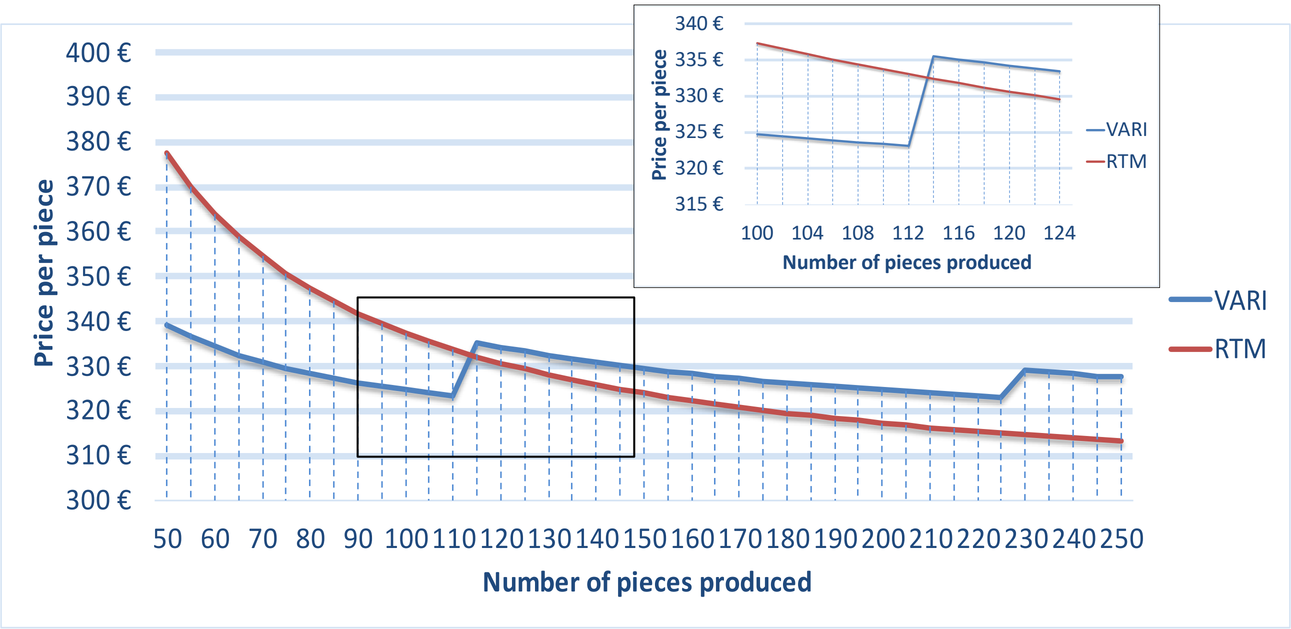


Figure 45 - DFP with VARI and RTM for larger production volumes (50 to 250 parts/year)

Eventually and as expected, it is visible on figure 45 that RTM becomes cheaper per part than VARI and this is due to the number of moulds needed. The change occurs at a production volume of 114 parts per year, with another jump occurring at 226 part/year, as will be studied in detail afterwards.

For TFP, a similar behaviour as seen underneath can be found.

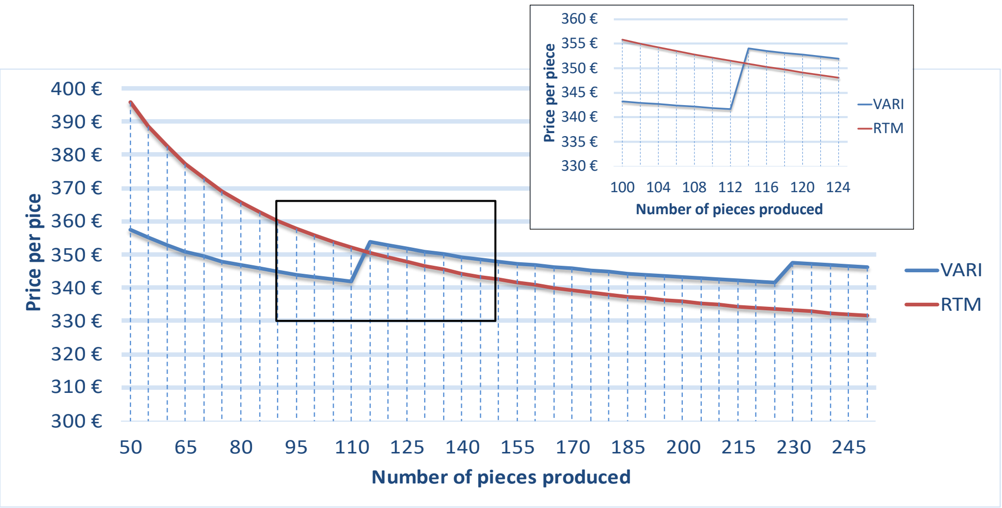


Figure 46 - TFP with VARI and RTM for larger production volumes (50 to 250 parts/year)

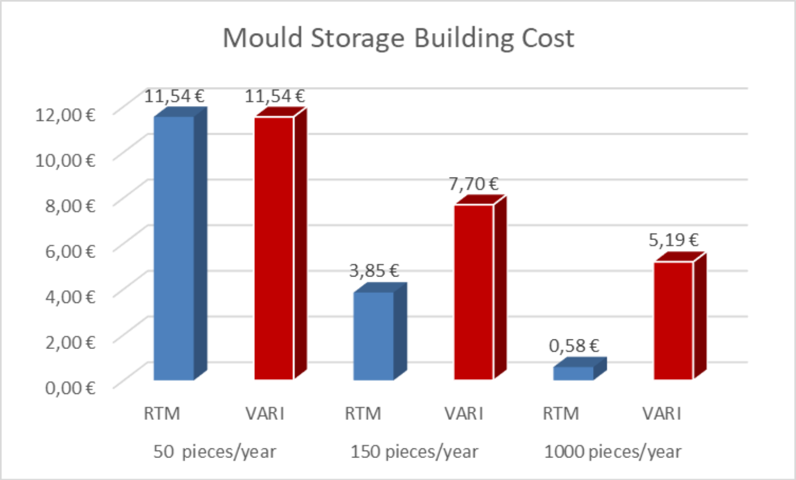


Figure 47 - Mould storage analysis for the TFP Curing Step

In this figure 47 and linked with the tooling costs of the infusion step (figure 36), a downward trend of the mould storage building cost is presented, as the number of moulds needed and stored is reduced, less space and therefore fewer costs are incurred on the production of the parts.

Table 17 - Numbers of Moulds needed by production volume for TFP

Production Volume	**50**	**150**	**1000**
Numbers of Moulds needed for RTM	1	1	1
Numbers of Moulds needed for VARI	1	2	9

Table 18 - Production volume per numbers of moulds for TFP

Number of Moulds needed	**2**	**3**	**4**	**9**
Production Value at Change RTM	1	1	1	1
Production Value at Change VARI	114	226	339	903

Comparing both the figure 47 and the tables 17 and 18, a conclusion can be crafted that the tooling costs decrease with the growth of production numbers and that the VARI's tooling decreases at a slower rate than the RTM's. An RTM mould has a much larger price tag than a VARI mould (20.000€ vs 5.000€) and this difference can be explained by the high discrepancy between the prices of the moulds due to the distinct complexities and materials used on their production. But even though its price is much greater, since less moulds are required with bigger production volumes, this provides an opportunity for RTM to be a lot cheaper than VARI on these bigger production values, something that will be examined later.

To confirm the behaviour of the production methods for even bigger production volumes, the figures 48 and 49 further down were created to analyse if, as expected, RTM remains cheaper than VARI after the intersection at 114 parts/year.

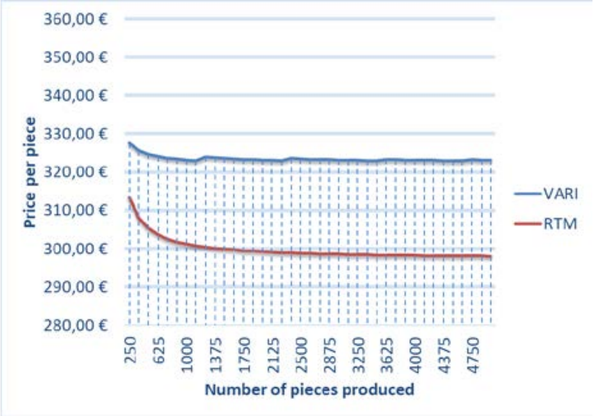


Figure 48 - DFP Production evolution
250-5000 pieces/year

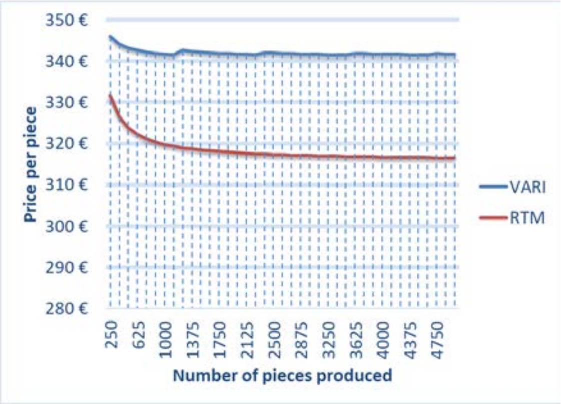


Figure 49 - TFP Production evolution
250-5000 pieces/year

With DFP and TFP studied individually for larger production values, a comparison between them was created for both OoA methods, in order to determine which would be cheaper over time. Concluding upon the assessment of figures 48 and 49, RTM continues to be cheaper than VARI for both processes.

With the data found on the figures 50 and 51 below, it can be concluded that, for this type of part, DFP is overall cheaper to use than TFP, with the overall quantity of material used being the determinant factor.

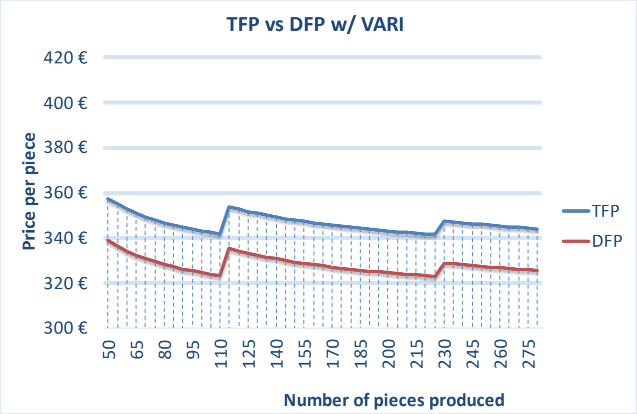


Figure 50 - TFP vs DFP with VARI

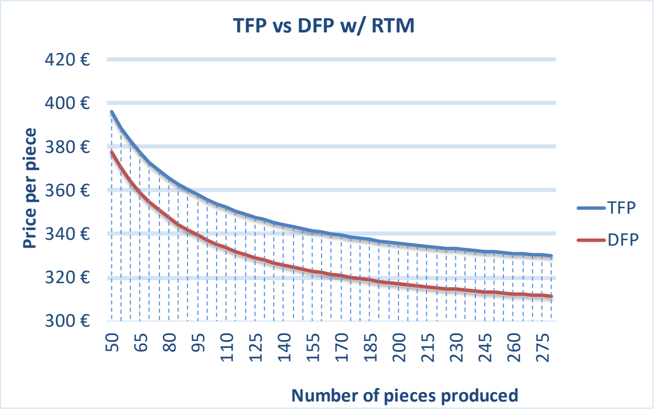


Figure 51 - TFP vs DFP with RTM

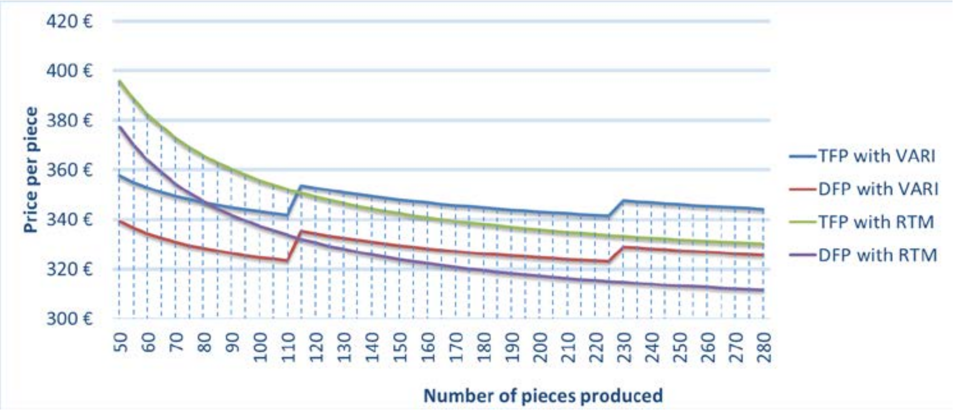


Figure 52 - TFP vs DFP with VARI or RTM

Concluding by analysing all the previous figures, the option that delivers the cheapest production method for this type of part for a low production status of 1-113 parts/year is DFP using VARI and after a production volume of 114 parts per year it is DFP using RTM.

6.2.3 Production volume analysis for AFP and ATL

Now studying the behaviour of the changes on production volumes of the traditional autoclave methods, which will then be compared to the dry fibre methods. Starting with low production volume analysis and evolving to larger volumes.

In the figure 53 below, first AFP presents “bumps” due to the quantity of material in the tow, which is dedicated. The bigger the tow of carbon fibre, the more expensive it is and the more influence it possesses when considering small production numbers.

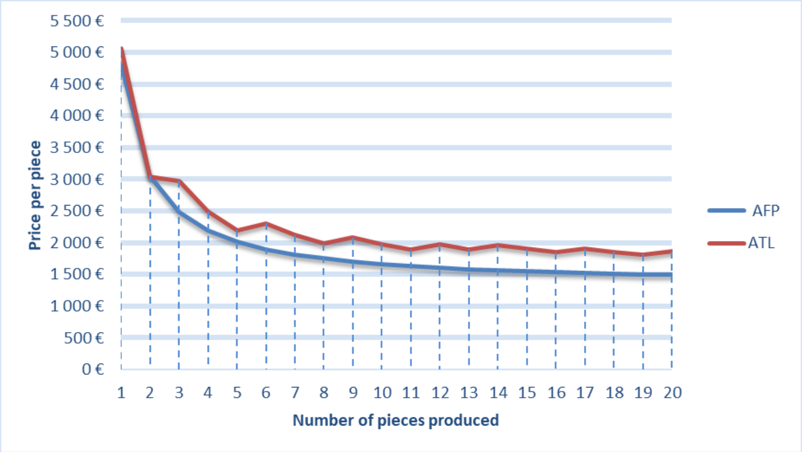


Figure 53 - Low production volume analysis for both AFP and ATL (1-20 parts/year)

AFP uses tows with 30m^2 of carbon fibre and on the other hand, AFP uses tows of 90m^2, which provides a smoother figure for AFP, but one with apparent soars for ATL. When more tows are bought, its cost is split into the number of pieces produced, but for ATL it is more expensive, and it is not used completely. So, a surplus carbon fibre which was not used was already paid for, representing the increase of cost per part.

.

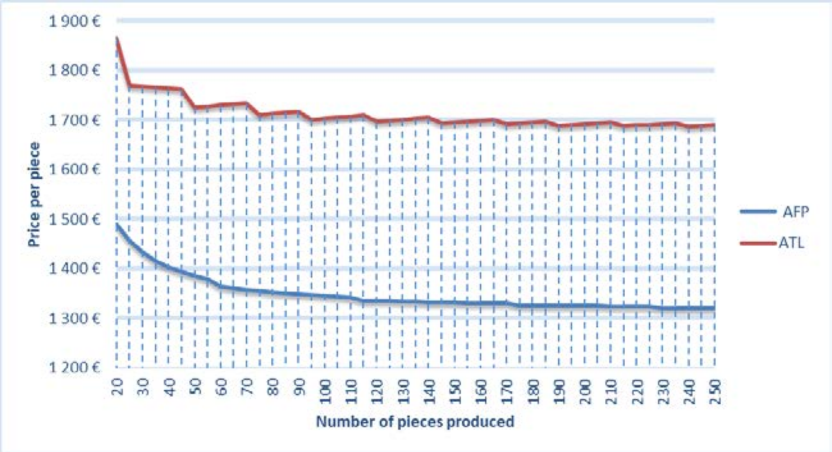


Figure 54 - Larger production volume analysis for both AFP and ATL (20-250 parts/year)

Now, with a larger production volume, the trend continues for ATL, but with soars being apparent for AFP as well. After analysing the table below, which represents the number of tows needed in an ATL production, it can be concluded that these soars are due to the quantity of material per tow of carbon fibre, but now they occur because there is no need for 2 new tows per 5 parts produced and instead only 1 is bought, reducing the final price per part.

The difference in the behaviour of the ATL figure occurs on intervals of 25 as shown below,

Table 19 - Number of tows needed for ATL production.

Nº Parts	**35**	**40**	**45**	**50**		**60**	**65**	**70**	**75**
Total Cost	23 400 €	27 020 €	39 600 €	32 420 €		39 600 €	43 200 €	46 800 €	48 600 €
Cost/Part	668,57 €	675,50 €	880 €	648,40 €		660 €	664,62 €	668,57 €	648 €
Nº Tows	13	15	17	18		22	24	26	27
Difference		+2	+2	+1			+2	+2	+1

For AFP, the same behaviour occurs, but it is only felt slightly on with intervals of around 55 parts due to the smaller size and price of each tow, as it can be studied on figure 54.

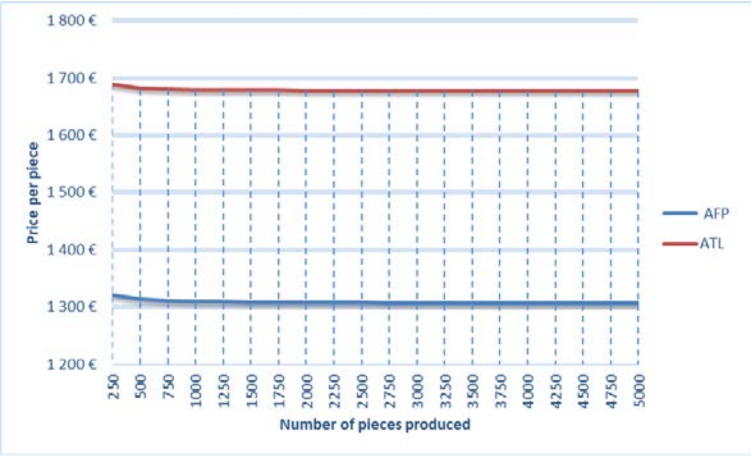


Figure 55 - Significant production volume analysis for both AFP and ATL (250-5000 parts/year)

Until now AFP has been the cheapest option between both production types and this statement is also confirmed for even bigger production values as observed below. This happens since the part that is being produced is relatively small, which for ATL represents a larger time-consuming process and has significantly more scrap than AFP, something that has already been addressed in another paper as that is shown below on figure 56 (by B. A. R. Soares, E. Henriques, I. Ribeiro & M. Freitas (2019) [40]).

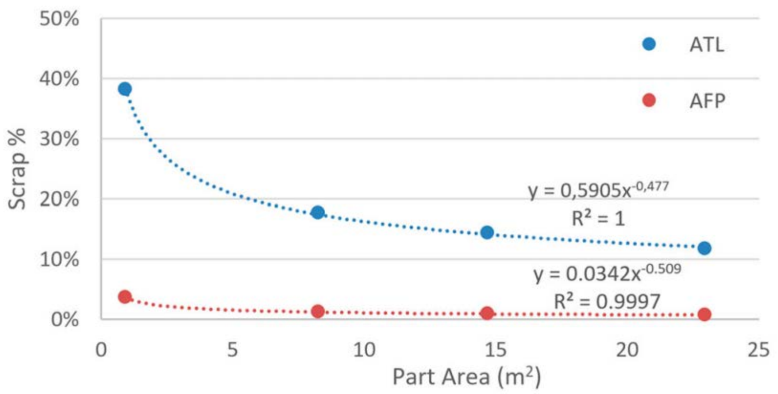


Figure 56 - Percentage of material-technical scrap as a function of the part area [40]

6.2.4 Comparing DFP, TFP; AFP and ATL

Now taking special consideration for a low production volume of 50 parts per year, which is the rate at which TU Chemnitz will produce the test part, an analysis of DFP and TFP versus AFP and ATL is produced. This provides with a chance for a comparison between the dry fibre methods studied in this thesis and others well known and evolved autoclave processes, a contrast between the new and innovative ways to produce CFRP and the old ways of producing parts made of carbon fibre.

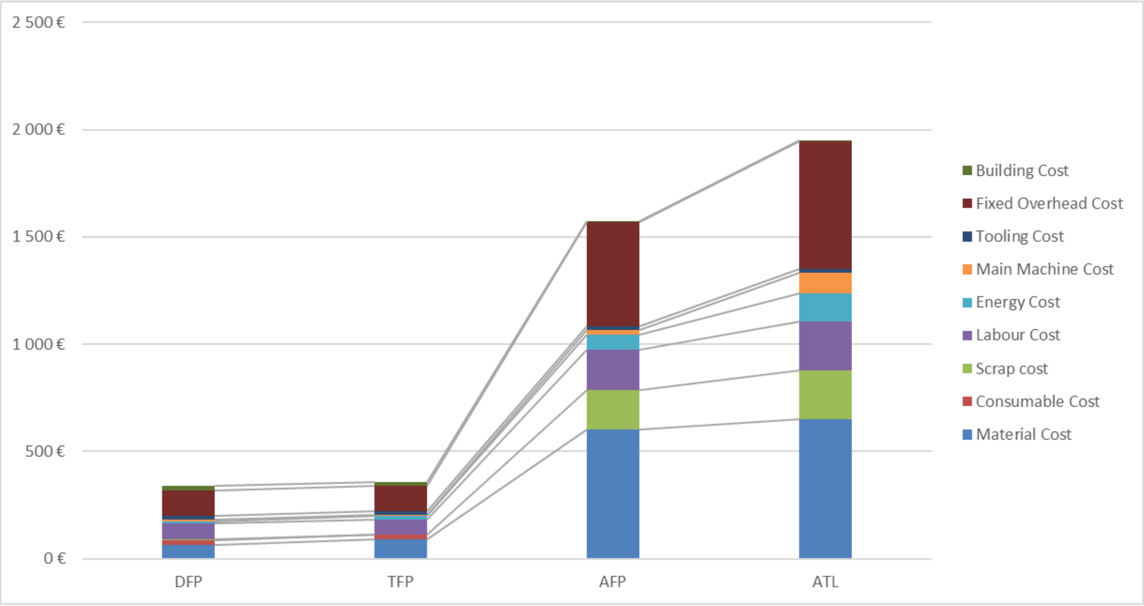


Figure 57 - DFP vs TFP vs AFP vs ATL

Detailed costs were not included, since AFP and ATL embody a few simplifications made so that the test part can be built using the already built PBCMs, which provide approximated results.

As shown on the figure 57 above, AFP and ATL are much more expensive than DFP or TFP when producing this test part. This disparity is due to the fact that everything is more expensive when using these autoclave methods.

The material costs represent a big percentage of the final cost of AFP and ATL, since traditional prepregs are a lot more expensive than dry fibre tows, with a lot more material being wasted as well since dry fibres allow for more precise placement.

The need for refrigeration (for prepregs) and an autoclave, increase dramatically the cost of machines and energy necessary for these methods to work, and also the increase of labour for moving, storing, and checking how the process is running since there are more costly mistakes that can be made. Since labour is related to the overhead costs, this also increases with the extra need for more worker time per part.

Building costs are quite analogous for both, as AFP and ATL modern machines are not necessarily bigger than DFP or TFP machines and the autoclave and refrigeration space costs are nearly equalled by the need for building space for curing the moulds.

This analysis assumes isoperformance, but ATL and AFP might create parts with better performance/weight ratio and preferred repeatability and precision, however with a more expensive price and such, this would need to be contemplated.

With this test part, the increased price tag would most likely need to be considered to make sure that the fuel consumption savings over time would outweigh the increased cost.

Finally, if other parts were assumed, its size and geometries would be an important factor as well, since bigger parts would be easier to produce using an autoclave instead of using VARI or RTM.

6.3 Sensitivity Analysis on the inputs

With all the particularities and major calculations explained, the models need to be analysed in order to be validated. Consequently, sensitivity analyses were produced by varying all the inputs and later checking if they are resulting in a final part cost which makes sense according to the calculations made in the cost models. This provides an opportunity to understand the magnitude and significance of the effect that certain variables have on the final cost.

As shown below, by varying each of the models’ inputs by -30% to 30%, the results allow for the analysis of the magnitude of each input. Most of the inputs influence the cost directly with first degree equations, which translate into a linear trend.

3.1 DFP inputs Sensitivity Analysis

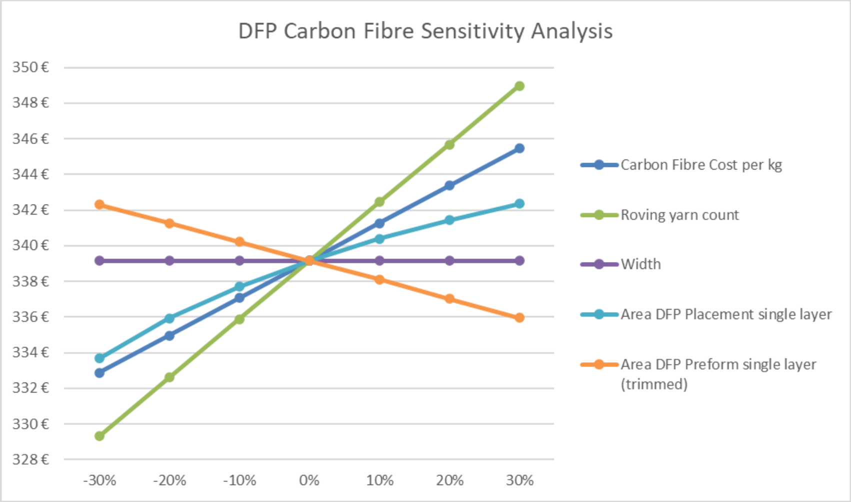


Figure 58 - DFP Carbon Fibre Sensitivity Analysis

Here in the figure 58 the carbon fibre used in the DFP preform is analysed. When increased, the area trimmed decreases the final cost of the part and the other factors increase the final price with their growth when the input is increased by 30%. The roving yarn count is the factor which influences the final price the most, with a very steep ~10€ difference. Width does not affect the final price in this PBCM as there was no data available on different types of placement for different widths of tape.

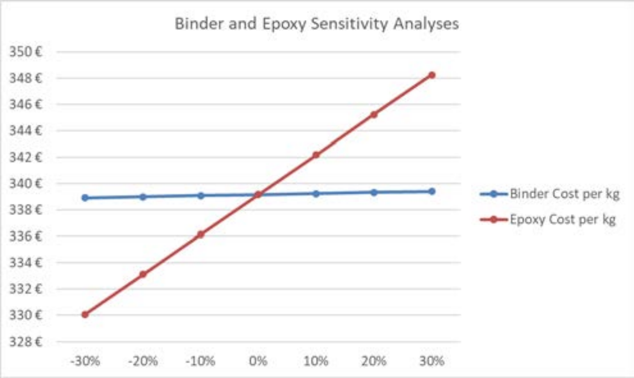


Figure 59 - DFP Binder and Epoxy Sensitivity

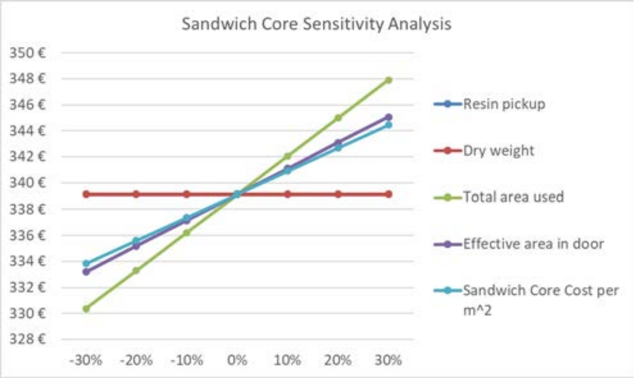


Figure 60 - DFP Sandwich Core Sensitivity Analysis

On Figure 59, the price per kg for binder and epoxy is studied. As there is not a large quantity of binder used per part (the binder mass content is 5%, which accounts for around 40g), this factor does not influence the final cost as epoxy does, since the part has as a goal fibre volume fraction of 50%, resulting in extensive use of epoxy throughout the preform.

On Figure 60, the sandwich core placed on both DFP and TFP is studied, the resin pickup and the effective area in door have the same values as they are both connected to the weight of the core when wet, which ultimately result in the same epoxy price change in the final price. The Total area used and the cost per square meter have the same difference as well since each is multiplied by the other, creating the same result. Finally, the dry weight does not influence the final price, only on the final weight of the part, which is a crucial factor in the production of the part, not in terms of price of the part, but in terms of fuel efficiency, something that is not on the scope of this work.

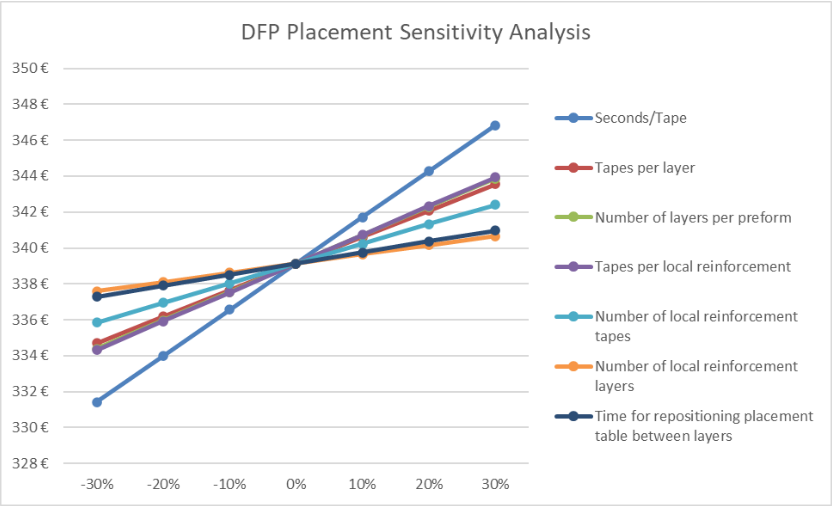


Figure 61 - DFP Placement Sensitivity Analysis

Contemplating the figure 61, seven factors are analysed. The seconds that it takes to place a tape is the element which represents the most magnitude when changed and the number of local reinforcement layers being the factor which has the least magnitude on the final price.

6.3.2 TFP inputs Sensitivity Analysis

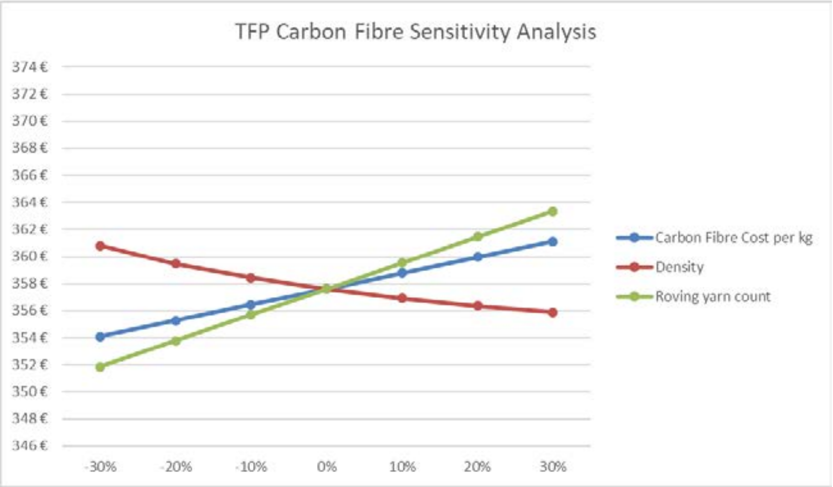


Figure 62 - TFP Carbon Fibre Sensitivity Analysis

As shown on figure 62 which displays the sensitivity analysis of the carbon fibre applied for DFP, the major cost impact is the roving yarn count. Just as in DFP, there is not enough information regarding the influence of the width with different values and so, it remains constant throughout the variation.

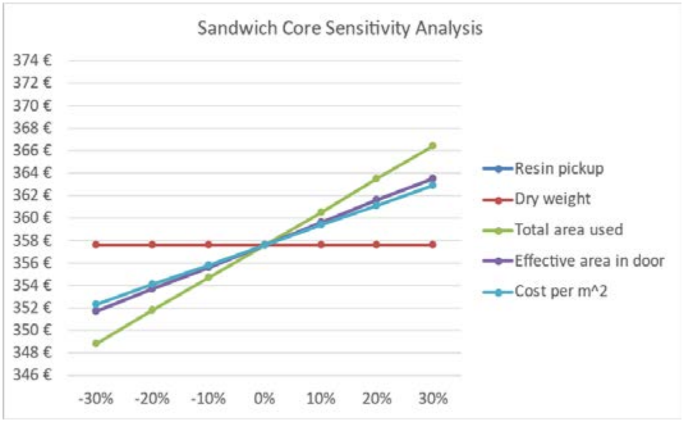


Figure 63 - TFP Sandwich Core Sensitivity Analysis

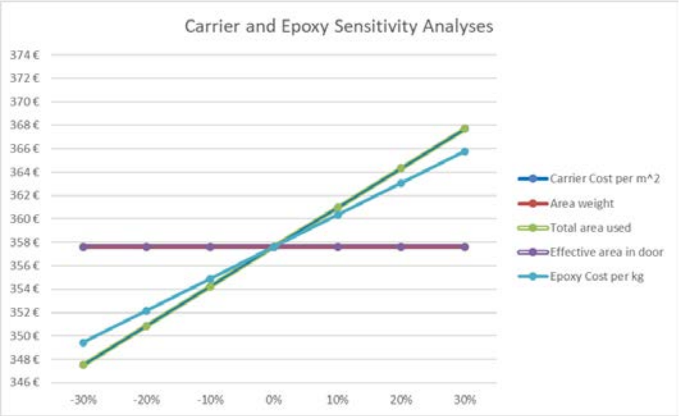


Figure 64 - TFP Carrier and Epoxy Sensitivity Analyses

The total area used of sandwich core is the input which presents the biggest influence over the final cost of a part, as shown in figure 63. It bigger than the cost per square meter since the percentage increase represents a bigger change in terms of magnitude. Like for TFP, the dry weight also does not influence the final price, since it only influences the weight of the final part, being a number that would have an impact on the efficiency and fuel economy of a vehicle.

Depicted in figure 64, the carrier cost per square meter and the total area of the carrier used have the same impact since they are multiplied by each other to produce the price of the carrier used. The effective area in door has a null influence because the carrier scrap in this PBCM is not reused or sold. The area weight also does not affect the final price change since it is only used to calculate the part weight.

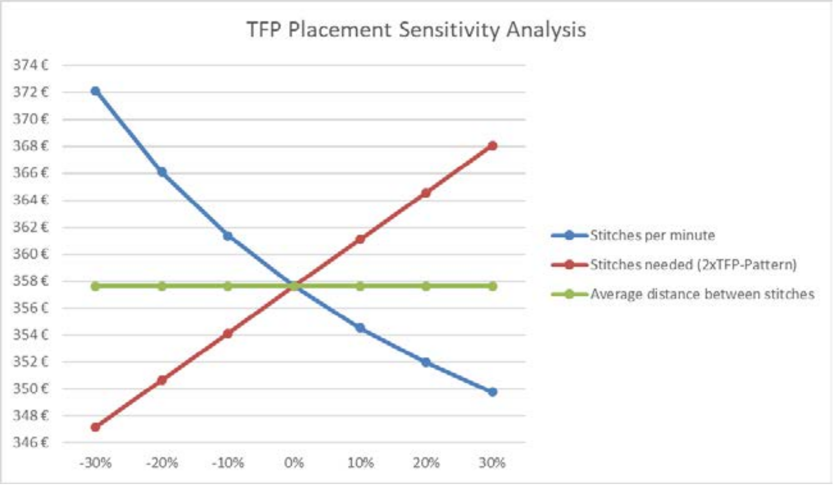


Figure 65 - TFP Placement Sensitivity Analysis

As seen on figure 65, with the increase of the number of stitches placed in one minute, the final cost of the part declines as expected by decreasing the amount of time needed to produce the part, which decreases the quantity of labour, energy, overheads and building expenditures. As expected, with the number of stitches needed, the more material is used and so the price rises steadily. There is no information on how to calculate the number of stitches needed and its influence with the average distance between them, and such the average distance is only used to assess the area of fibre placed per minute.

In conclusion, for TFP the input that has the most influence on the final cost of the test part is the number of stitches needed, shown on figure 65. Meaning that this is the input which, when altered by a certain percentage, changes the value of the final part the most, increasing the price by 14€, when decreased by 30%. As for DFP, the roving yarn count is the input with the greatest impact (10€ when modified by 30%), but the epoxy cost per kilogram and the area of sandwich core used also having a substantial effect on the cost.

This study illustrates the inputs which need to be taken into consideration the most when designing a part which is cost restricted, indicating the inputs that, when altered, create the biggest cost difference, determining that these should be the first to be studied when costs need to decrease.

Chapter 7 – Conclusions and Future Work

Amid the COVID-19 crisis in 2020, the global market for Carbon Fibres is estimated at 3.8 Billion and is projected to reach a size of 7.2 Billion dollars by 2027, an increase of around 9,5% per year [76]. With the decrease of costs of processing composites by increasing automation and by the use of new and improved CFRP (Carbon Fibre Reinforced Polymers) production techniques, carbon fibre will become more versatile and cost-effective, providing with an opportunity to fabricate just about everything [77].

The primary focus of this thesis was to develop two process-based cost models for two promising methods of CFRP production: DFP (Dry Fibre Placement) and TFP (Tailored Fibre Placement) and compare them with two older and already proven processes AFP (Automatic Fibre Placement) and ATL (Automatic Tape Laying). These models are quite versatile as they provide with estimates of the production costs of all kinds of sizes and geometries of parts, with the possibility to adapt to the desired annual production volume.

The PBCMs (Process-Based Cost Models) were built to show the decomposition of costs throughout the process and to comprehend how the cost of the part is affected by several parameters. Using the cost prediction tools built on this thesis, numerous materials, processes, and part designs can be tested, consequently estimating the impact of proposed improvements or developments.

From the test case analysed in this thesis, it is concluded that DFP is the overall cheapest production method. For low volume productions, the cheapest option is DFP using VARI technology and for bigger production volumes (above 114 parts per year) the cheapest option becomes DFP using RTM technology. These dry fibre methods have lower costs for the production of this part, but this does not imply that they should automatically be chosen over AFP or ATL, since analysis assumes isoperformance, but these methods that use an autoclave are capable of producing parts with better performance/weight ratio and preferred repeatability and precision, but that involve bigger investments.

When other parts were to be analysed, its size and geometries would furthermore be an important factor, since bigger parts would be easier to produce using an autoclave instead of using VARI or RTM.

Several sensitivity analyses were developed to understand the behaviour of the different parameters on the final cost. The inputs that have the most influence are the number of stitches needed for TFP and the roving yarn count for DFP, with these being the ones that have the most influence on the final part cost. Meaning that if reduced they create the biggest cost difference, concluding that these should be the first to be studied when costs need to decrease.

The greatest limitation of the present thesis is related to the layup rated present on both dry fibre PBCMs and the number of stitches needed for TFP, as further study would have to be completed to ensure how layup rate correlates with the surface area and how many stitches are needed, with real data or estimations having to be used until now.

It is also suggested that in the future, the number of machines and workers is further analysed and optimized, with more sensitivity analyses to be performed by varying different inputs to verify how the models respond, evaluating the impact on the final cost.

Another analysis of the limitations of the size of parts when using DFP and TFP or RTM and VARI should also be executed, as to understand until which point are these processes feasible.

Another recommendation is the creation of more user-friendly and less time-consuming cost models, by creating databases with multiples types of materials, or machines, which would then be chosen according to the part, instead of inserting every single input manually.

The scope of the cost models could also be broadened, by including the non-destructive testing and assembly phases, which would be required phases for the production of new parts and that would create a more comprehensible analysis on the overall costs.

It is not yet clear whether future composite parts will be manufactured using prepreg or dry fibre technology since both technologies have their advantages and disadvantages. Compared to dry fibre material the layup of prepreg is easier, the fibre volume content can be easier stipulated and controlled, alongside the part’s mechanical properties [78]. On the other hand, the resin ages and the prepreg expires very quickly, if not stored in huge deep-freezing storages. Moreover, expensive autoclaves need to be used for resin curing and are seen as the major bottleneck for the manufacturing process. Instead, when dry fibre is applied there is no need for the carbon fibre to be deep-frozen and no autoclave is needed for the curing.

Concluding, the decreased price tag of using dry fibres instead of prepregs needs to be considered, making sure that several variables occur as intended, such as repeatability, precision, physical properties, or fuel consumption savings.

Bibliography

[1] D. D. L. Chung, *Carbon composites: Composites with carbon fibers, nanofibers, and nanotubes: Second edition*. 2016.

[2] H. A. Toutanji, T. El-Korchi, and R. N. Katz, “Strength and reliability of carbon-fiber-reinforced cement composites,” *Cem. Concr. Compos.*, vol. 16, no. 1, pp. 15–21, Jan. 1994, doi: 10.1016/0958-9465(94)90026-4.

[3] TU Chemnitz, “Fortis Saxonia,” 2019. http://www.fortis-saxonia.de/fahrzeuge (accessed Apr. 13, 2020).

[4] J. P. C. Pinto, “Economic comparison between materials in the aerospace industry,” 2017.

[5] A. D. Evans, “Development of Automated Dry Fibre Placement for High Rate Deposition,” vol. M, no. January, 2020.

[6] Ö. E. İşmal and R. Paul, “Composite textiles in high-performance apparel,” in *High-Performance Apparel: Materials, Development, and Applications*, Elsevier, 2017, pp. 377–420.

[7] M. A. Masuelli, “Introduction of Fibre-Reinforced Polymers − Polymers and Composites : Concepts , Properties and Processes Introduction of Fibre-Reinforced Polymers − Polymers and Composites : Concepts , Properties and Processes,” no. December, 2013, doi: 10.5772/54629.

[8] E. G. Koricho, A. Khomenko, T. Fristedt, and M. Haq, “Innovative tailored fiber placement technique for enhanced damage resistance in notched composite laminate,” *Compos. Struct.*, vol. 120, pp. 378–385, Feb. 2015, doi: 10.1016/j.compstruct.2014.10.016.

[9] O. Rimmel, D. Becker, and P. Mitschang, “Maximizing the out-of-plane-permeability of preforms manufactured by dry fiber placement,” *Adv. Manuf. Polym. Compos. Sci.*, vol. 2, no. 3–4, pp. 93–102, Oct. 2016, doi: 10.1080/20550340.2016.1260900.

[10] H. M. El-Dessouky, M. N. Saleh, M. Gautam, G. Han, R. J. Scaife, and P. Potluri, “Tailored fibre placement of commingled carbon-thermoplastic fibres for notch-insensitive composites,” *Compos. Struct.*, vol. 214, pp. 348–358, Apr. 2019, doi: 10.1016/j.compstruct.2019.02.043.

[11] W. B. Goldsworthy, “Geodesic path length compensator for composite-tape placement head,” Apr. 1974.

[12] University of Salford. Department of Pure and Applied Physics. and Royal Aircraft Establishment (Great Britain). Materials Department., *Fabrication techniques for advanced reinforced plastics : symposium [held on] 22-23 April 1980 [at the] University of Salford, UK.* IPC Science and Technology Press, 1980.

[13] B. Howard, “BMW i3 : Cheap , mass-produced carbon fiber cars finally come of age,” *Extremetech*, pp. 1–6, 2013.

[14] Composites lab, “Composites VS. Aluminum - Composites Compared,” 2016. http://compositeslab.com/composites-compared/composites-vs-aluminum/ (accessed Oct. 08, 2020).

[15] A. M. Sabido, “Development of an Automated Fiber Placement Process for the Development of an Automated Fiber Placement Process for the Fabrication of Thermoplastic Composite Laminates.” Accessed: Oct. 07, 2020. [Online]. Available: https://scholarcommons.sc.edu/etd.

[16] C. Beaumont, Peter W R; Soutis, *The Structural Integrity of Carbon Fiber Composites - Fifty Years of Progress and Achievement of the Science, Development, and Applications-Springer Inte*, 1st ed. Springer, 2016.

[17] M. Assadi and T. Field, “AFP Processing of Dry Fiber Carbon Materials (DFP) for Improved Rates and Reliability,” *SAE Tech. Pap.*, vol. 2020-March, no. March, pp. 1–6, 2020, doi: 10.4271/2020-01-0030.

[18] D. H. J. A. Lukaszewicz, C. Ward, and K. D. Potter, “The engineering aspects of automated prepreg layup: History, present and future,” *Compos. Part B Eng.*, vol. 43, no. 3, pp. 997–1009, Apr. 2012, doi: 10.1016/j.compositesb.2011.12.003.

[19] CompositesWorld, “AFP/ATL evolution: Dual-process workcells,” 2015. https://www.compositesworld.com/columns/afpatl-evolution-dual-process-workcells (accessed Oct. 08, 2020).

[20] “Smarter, integrated data for ATL/AFP,” 2019. https://www.compositesworld.com/articles/smarter-integrated-data-for-atlafp (accessed Oct. 08, 2020).

[21] F. Raspall, R. Velu, and N. M. Vaheed, “Fabrication of complex 3D composites by fusing automated fiber placement (AFP) and additive manufacturing (AM) technologies,” *Adv. Manuf. Polym. Compos. Sci.*, vol. 5, no. 1, pp. 6–16, Jan. 2019, doi: 10.1080/20550340.2018.1557397.

[22] Composites One, “Prepregs.” https://www.compositesone.com/product/prepreg/ (accessed Oct. 08, 2020).

[23] United States Government Accountability Office, “Aviation and the Environment.”

[24] Airbus, “Growing horizons 2017/2036,” 2017.

[25] A. Clements, “Automated dry-fibre placement drives aerospace efficiency | IOM3,” 2019. https://www.iom3.org/materials-world-magazine/feature/2019/may/30/automated-dryfibre-placement-drives-aerospace (accessed Oct. 08, 2020).

[26] Composites Insider, “New TFP capability for Carbon ThreeSixty,” 2020. https://www.insidecomposites.com/new-tfp-capability-for-carbon-threesixty/.

[27] “Voith unveils fully digital production line for Audi A8 carbon fiber rear wall panel | JEC Group,” Mar. 13, 2018. http://voith.com/corp-en/news-room/press-releases_100233.html (accessed Oct. 13, 2020).

[28] G. Gardiner, “Rear wall reboot: One-stop, tow to tape to CFRP part,” *Compos. World*, 2018, Accessed: Oct. 13, 2020. [Online]. Available: https://www.compositesworld.com/articles/rear-wall-reboot-one-stop-tow-to-tape-to-cfrp-part.

[29] Amanda Jacob, “Audi A8 to feature carbon fibre rear wall,” *www.insidecomposites.com*, 2017. https://www.insidecomposites.com/audi-a8-to-feature-carbon-fibre-rear-wall/ (accessed Oct. 20, 2020).

[30] E. Saunders, “Irkut MC-21 Deliveries To Begin in 2021,” Sep. 25, 2020. https://airlinergs.com/irkut-mc-21-deliveries-to-begin-in-2021/ (accessed Oct. 22, 2020).

[31] J. Sloan, “Infused wing sheds light on aerocomposites future.” https://www.compositesworld.com/articles/infused-wing-sheds-light-on-aerocomposites-future (accessed Oct. 22, 2020).

[32] ZSK, “Tailored Fibre Placement – Enhancing the Use of Carbon,” 2018. https://www.zsk.de/en/branchenloesungen/technische-stickerei/tailored-fibre-placement.php (accessed Oct. 13, 2020).

[33] Net Composites, “ZSK Enhances Tailored Fibre Placement Technology,” 2018. https://netcomposites.com/news/zsk-enhances-tailored-fibre-placement-technology/ (accessed Oct. 13, 2020).

[34] JEC Composites, “Composites poised for wider automotive use as ZSK enhances TFP technology.” http://www.jeccomposites.com/knowledge/international-composites-news/composites-poised-wider-automotive-use-zsk-enhances-tfp (accessed Oct. 13, 2020).

[35] Wenjun Li, “Effect of Cure Pressure on Woven Carbon Fibre/Epoxy Composite Laminate Properties,” 2003.

[36] “Transportation Composites Market by Resin, Manufacturing Process, Fiber, Application, Transportation Type, and Region - Global Forecast to 2025.” https://www.globenewswire.com/news-release/2020/07/01/2056218/0/en/Transportation-Composites-Market-by-Resin-Manufacturing-Process-Fiber-Application-Transportation-Type-and-Region-Global-Forecast-to-2025.html (accessed Nov. 13, 2020).

[37] A. Eriksson, “Developing a product costing model using Process-Based Cost Modeling,” KTH.

[38] R. E. Kirchain, “Cost Modeling of Materials and Manufacturing Processes,” in *Encyclopedia of Materials: Science and Technology*, Elsevier, 2001, pp. 1718–1727.

[39] C. Bloch and R. Ranganathan, “Process based cost modeling,” in *IEEE/CHMT European International Electronic Manufacturing Technology Symposium*, Jan. 1991, pp. 406–412, doi: 10.1080/10157891.2007.10462279.

[40] B. A. R. Soares, E. Henriques, I. Ribeiro, and M. Freitas, “Cost analysis of alternative automated technologies for composite parts production,” *Int. J. Prod. Res.*, vol. 57, no. 6, pp. 1797–1810, Mar. 2019, doi: 10.1080/00207543.2018.1508903.

[41] M. K. Hagnell and M. Åkermo, “A composite cost model for the aeronautical industry: Methodology and case study,” *Compos. Part B*, vol. 79, pp. 254–261, 2015, doi: 10.1016/j.compositesb.2015.04.043.

[42] L. Veldenz, C. Ward, and Y. Bauswein, “Developing a cost comparison technique for hand layup versus automated fibre placement, and infusion versus out-of-autoclave,” 2018. [Online]. Available: https://www.researchgate.net/publication/326059802.

[43] L. Veldenz, M. Di Francesco, P. Giddings, B. C. Kim, and K. Potter, “Material selection for automated dry fiber placement using the analytical hierarchy process,” *Adv. Manuf. Polym. Compos. Sci.*, vol. 4, no. 4, pp. 83–96, Oct. 2018, doi: 10.1080/20550340.2018.1545377.

[44] M. H. Nguyen, A. A. Vijayachandran, P. Davidson, D. Call, D. Lee, and A. M. Waas, “Effect of automated fiber placement (AFP) manufacturing signature on mechanical performance,” in *AIAA Scitech 2019 Forum*, 2019, doi: 10.2514/6.2019-0516.

[45] SAMPE, “Society for the Advancement of Material and Process Engineering Automated Tape Laying and Fiber Placement Technologies.” Accessed: Oct. 16, 2020. [Online]. Available: www.sampe.org.

[46] P. Boisse, *Advances in composites manufacturing and process design*. Elsevier Inc., 2015.

[47] Torreslayup, “Automated Tape Layer machine.” www.mtorres.es/en/aeronautics/products/carbon-fiber/torreslayup (accessed Oct. 17, 2020).

[48] B. T. Åström, *Manufacturing of polymer composites*, 1st ed. London : Chapman & Hall, 1997.

[49] D. H.-J. A. Lukaszewicz, “Optimisation of high-speed automated layup of thermoset carbon-fibre preimpregnates,” *Univ. Bristol*, 2011.

[50] M. Szcesny, F. Heieck, S. Carosella, P. Middendorf, H. Sehrschön, and M. Schneiderbauer, “The advanced ply placement process-an innovative direct 3D placement technology for plies and tapes,” 2017, doi: 10.1080/20550340.2017.1291398.

[51] M. N. Grimshaw, C. Machine, C. G. Grant, J. Manuel, and L. Diaz, “Advanced technology tape

laying for affordable manufacturing of large composite structures.”

[52] A. Crosky, C. Grant, D. Kelly, X. Legrand, and G. Pearce, “Fibre placement processes for composites manufacture,” in *Advances in Composites Manufacturing and Process Design*, Elsevier Inc., 2015, pp. 79–92.

[53] E. DO., *Fiber placement. Cincinnati: Cininnati Machine*. 1997.

[54] K. K. Chawla, “Composite Materials,” Cham: Springer International Publishing, 2019.

[55] Electroimpact, “Composites Manufacturing.” https://www.electroimpact.com/Products/Composites/Overview.aspx (accessed Oct. 17, 2020).

[56] L. Nicolais, A. Crosky, C. Grant, and D. Kelly, “Fiber Placements,” in *Wiley Encyclopedia of Composites*, Hoboken, NJ, USA: John Wiley & Sons, Inc., 2012.

[57] M. Belhaj *et al.*, “Dry fiber automated placement of carbon fibrous preforms,” *Compos. Part B Eng.*, vol. 50, pp. 107–111, 2013, doi: 10.1016/j.compositesb.2013.01.014.

[58] H. Temmen and R. Degenhardt, “Tailored Fibre Placement optimization tool,” Aug. 2006.

[59] A. Pye, “Tailored Fibre Placement - complex composite designs delivered at speed with reduced waste,” Mar. 12, 2020. https://knowledge.ulprospector.com/10345/pe-tailored-fibre-placement/ (accessed Oct. 15, 2020).

[60] Association of the Nonwoven Fabrics Industry, “What is a Nonwoven Fabric?” https://www.inda.org/about-nonwovens/ (accessed Oct. 15, 2020).

[61] K. Uhlig *et al.*, “Meso-scaled finite element analysis of fiber reinforced plastics made by Tailored Fiber Placement,” *Compos. Struct.*, vol. 143, pp. 53–62, May 2016, doi: 10.1016/j.compstruct.2016.01.049.

[62] H. Almeida, L. Bittrich, A. Spickenheuer, J. Humberto, and S. Almeida, “Fiber path optimization of a composite break booster manufactured via tailored fiber placement,” 2017. [Online]. Available: https://www.researchgate.net/publication/327745561.

[63] P. Schiebel, T. Block, and A. S. Herrmann, “Prospects and risks of tailored preforms for advanced composite applications,” in *Proceedings of the 9th International Conference on Textile Composites - TEXCOMP9: Recent Advances in Textile Composites*, 2008, pp. 215–220, [Online]. Available: https://www.researchgate.net/publication/272292140.

[64] K. Gliesche, T. Hübner, and H. Orawetz, “Application of the tailored fibre placement (TFP) process for a local reinforcement on an ‘open-hole’ tension plate from carbon/epoxy laminates,” *Compos. Sci. Technol.*, vol. 63, pp. 81–88, Jan. 2003, doi: 10.1016/S0266-3538(02)00178-1.

[65] K. Gliesche, T. H. Hu¨bner, and H. Orawetz, “Application of the tailored fibre placement (TFP)

process for a local reinforcement on an "'open-hole"' tension plate from carbon/epoxy laminates." [Online]. Available: www.elsevier.com/locate/compscitech.

[66] U. K. Singh and M. Dwivedi, *Manufacturing Processes*, 2nd ed. New Age, 2018.

[67] "Processes and Materials – Sherwood Advanced Composite Technologies." https://www.sherwoodcorp.com/processes-and-materials/ (accessed Nov. 13, 2020).

[68] "Manufacturing of fibre–polymer composite materials," in *Introduction to Aerospace Materials*, Elsevier, 2012, pp. 303–337.

[69] "Nanotechnology and Resin Transfer Molding (RTM) | ESA Space Solutions." https://spacesolutions.esa.int/technology-transfer/esa-broker-italy/technology/nanotechnology-and-resin-transfer-molding-rtm (accessed Nov. 13, 2020).

[70] A. McIlhagger, E. Archer, and R. McIlhagger, "Manufacturing processes for composite materials and components for aerospace applications," in *Polymer Composites in the Aerospace Industry*, Elsevier Inc., 2015, pp. 53–75.

[71] J. Schuster, Q. Govignon, and S. Bickerton, "Processability of Biobased Thermoset Resins and Flax Fibres Reinforcements Using Vacuum Assisted Resin Transfer Moulding," *Open J. Compos. Mater.*, vol. 04, no. 01, pp. 1–11, 2014, doi: 10.4236/ojcm.2014.41001.

[72] R. Kirchain, "3.080 Econ & Enviro Issues In Materials Selection," 2005. https://ocw.mit.edu/courses/materials-science-and-engineering/3-080-economic-environmental-issues-in-materials-selection-fall-2005/lecture-notes/ (accessed Sep. 10, 2020).

[73] S. Mazumdar, *Composites Composites - Materials, Product, and Process Engineering*. 2002.

[74] E. R. H. Fuchs, E. J. Bruce, R. J. Ram, and R. E. Kirchain, "Process-Based Cost Modeling of Photonics Manufacture: The Cost Competitiveness of Monolithic Integration of a 1550-nm DFB Laser and an Electroabsorptive Modulator on an InP Platform," *J. Light. Technol.*, vol. 24, no. 8, 2006, doi: 10.1109/JLT.2006.875961.

[75] F. Field, R. Kirchain, and R. Roth, "Process cost modeling: Strategic engineering and economic evaluation of Materials technologies," *JOM*, vol. 59, no. 10, pp. 21–32, Oct. 2007, doi: 10.1007/s11837-007-0126-0.

[76] Global Industry Analysts, "Global Carbon Fibers Industry," Jul. 2020. Accessed: Nov. 22, 2020. [Online]. Available: https://www.reportlinker.com/p05010577/Global-Carbon-Fibers-Industry.html.

[77] R. West, "3 Predictions About the Future of Carbon Fiber Composites," 2017. https://www.rockwestcomposites.com/blog/3-predictions-about-the-future-of-carbon-fiber-composites/ (accessed Nov. 22, 2020).

[78] N. Stoffers and C. Krombholz, “Wingcover: Efficient production of wing shells in dry fiber placement technology,” *Proceeding 17th Eur. Conf. Compos. Mater.*, pp. 26–30, 2016.

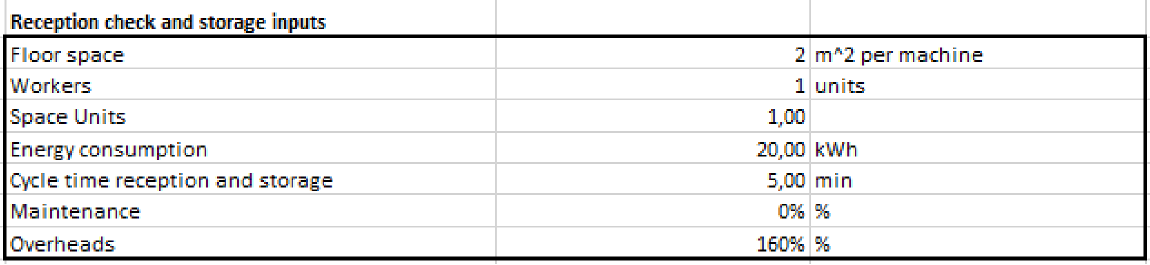
[79] D. Masand and A. Schiavo, “The Future of Carbon Fiber Composites,” 2020.

[80] G. Nica, “BMW i3 Might Be Cheaper to Live with Due to Carbon Fiber Construction - autoevolution.” https://www.autoevolution.com/news/bmw-i3-might-be-cheaper-to-live-with-due-to-carbon-fiber-construction-73054.html (accessed Oct. 07, 2020).

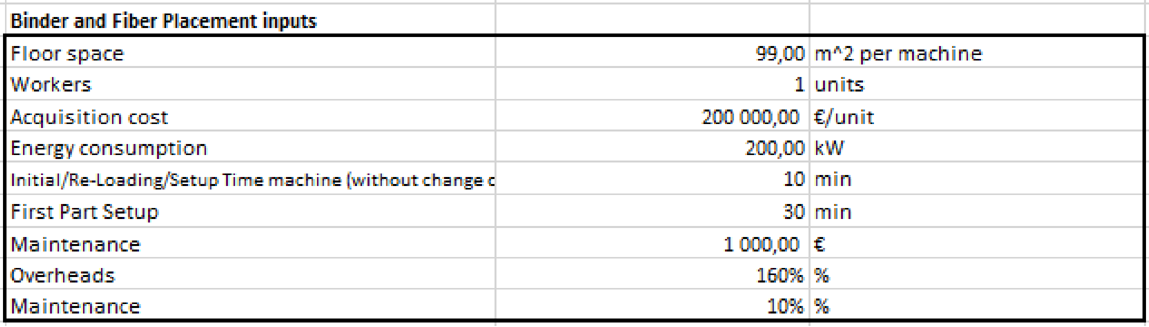
Annex A

Inputs

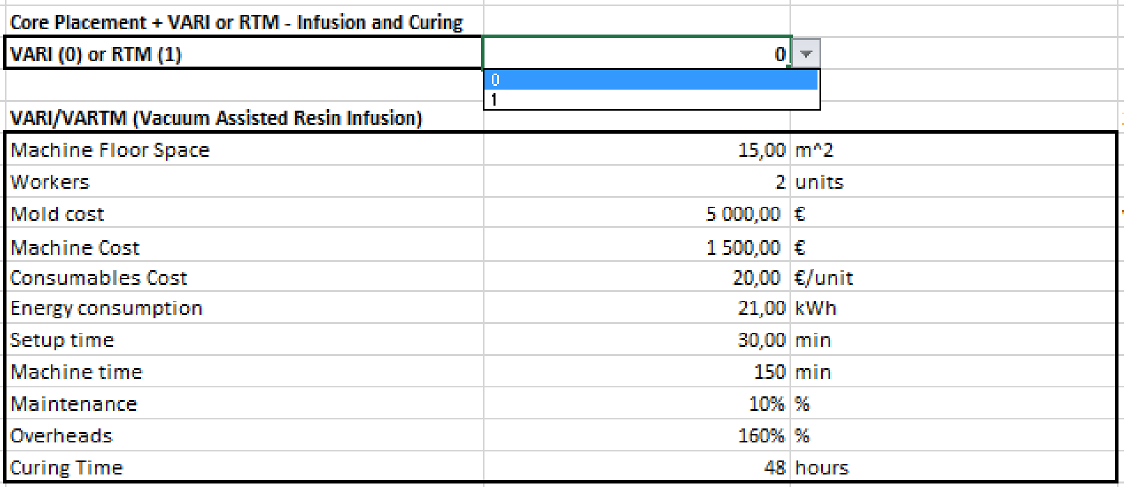
DFP



Reception check and storage inputs		
Floor space	2	m^2 per machine
Workers	1	units
Space Units	1,00	
Energy consumption	20,00	kWh
Cycle time reception and storage	5,00	min
Maintenance	0%	%
Overheads	160%	%

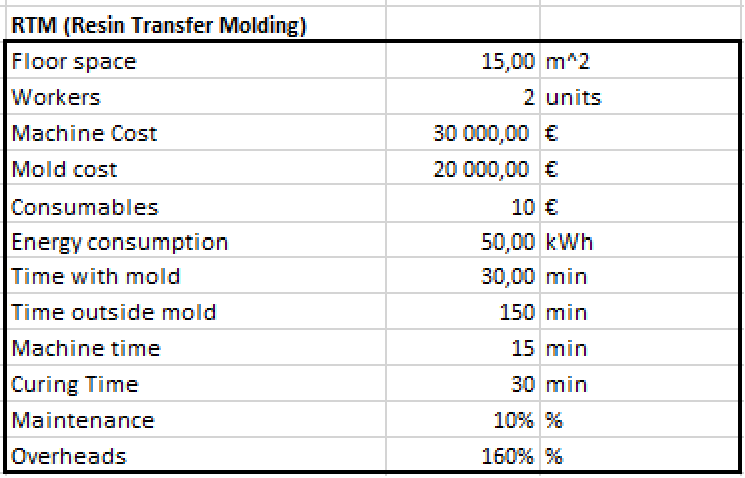


Binder and Fiber Placement inputs		
Floor space	99,00	m^2 per machine
Workers	1	units
Acquisition cost	200 000,00	€/unit
Energy consumption	200,00	kW
Initial/Re-Loading/Setup Time machine (without change c	10	min
First Part Setup	30	min
Maintenance	1 000,00	€
Overheads	160%	%
Maintenance	10%	%

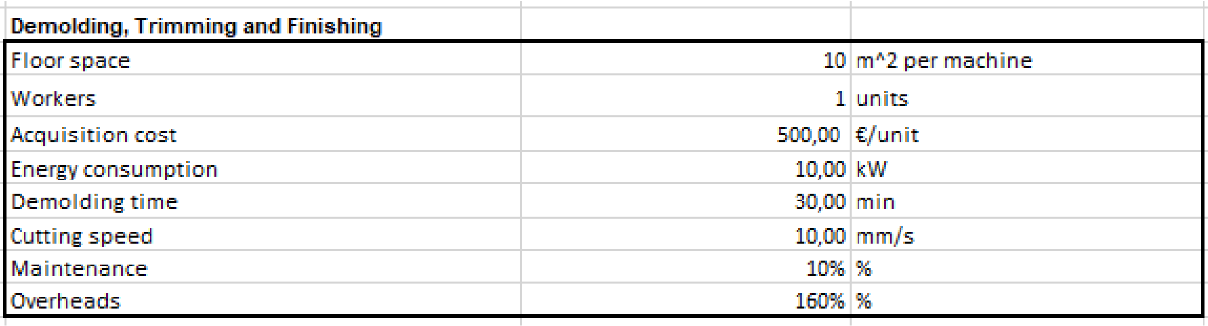


Core Placement + VARI or RTM - Infusion and Curing		
VARI (0) or RTM (1)	0	

VARI/VARTM (Vacuum Assisted Resin Infusion)		
Machine Floor Space	15,00	m^2
Workers	2	units
Mold cost	5 000,00	€
Machine Cost	1 500,00	€
Consumables Cost	20,00	€/unit
Energy consumption	21,00	kWh
Setup time	30,00	min
Machine time	150	min
Maintenance	10%	%
Overheads	160%	%
Curing Time	48	hours

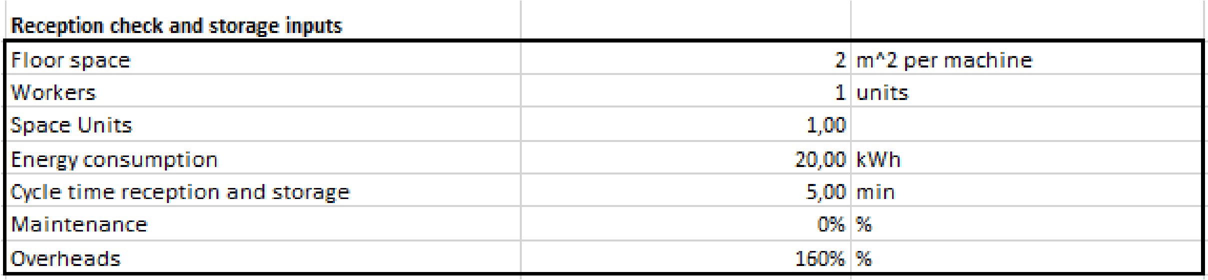


RTM (Resin Transfer Molding)		
Floor space	15,00	m^2
Workers	2	units
Machine Cost	30 000,00	€
Mold cost	20 000,00	€
Consumables	10	€
Energy consumption	50,00	kWh
Time with mold	30,00	min
Time outside mold	150	min
Machine time	15	min
Curing Time	30	min
Maintenance	10%	%
Overheads	160%	%

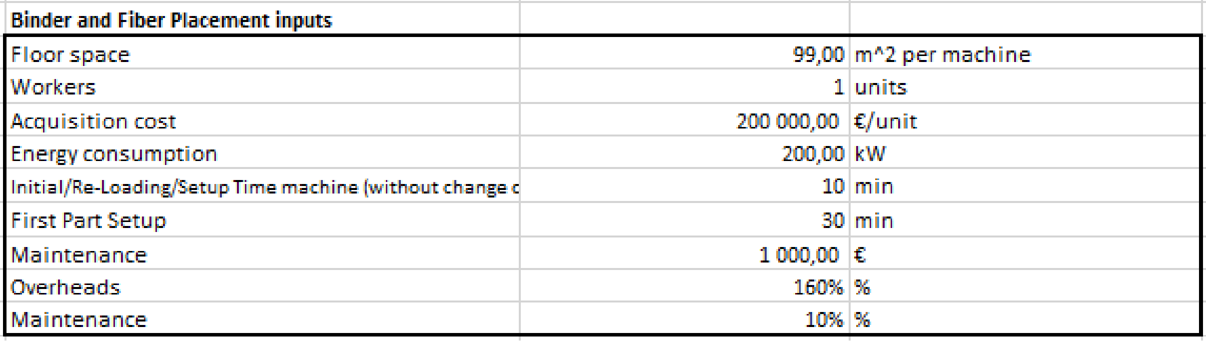


Demolding, Trimming and Finishing		
Floor space	10	m^2 per machine
Workers	1	units
Acquisition cost	500,00	€/unit
Energy consumption	10,00	kW
Demolding time	30,00	min
Cutting speed	10,00	mm/s
Maintenance	10%	%
Overheads	160%	%

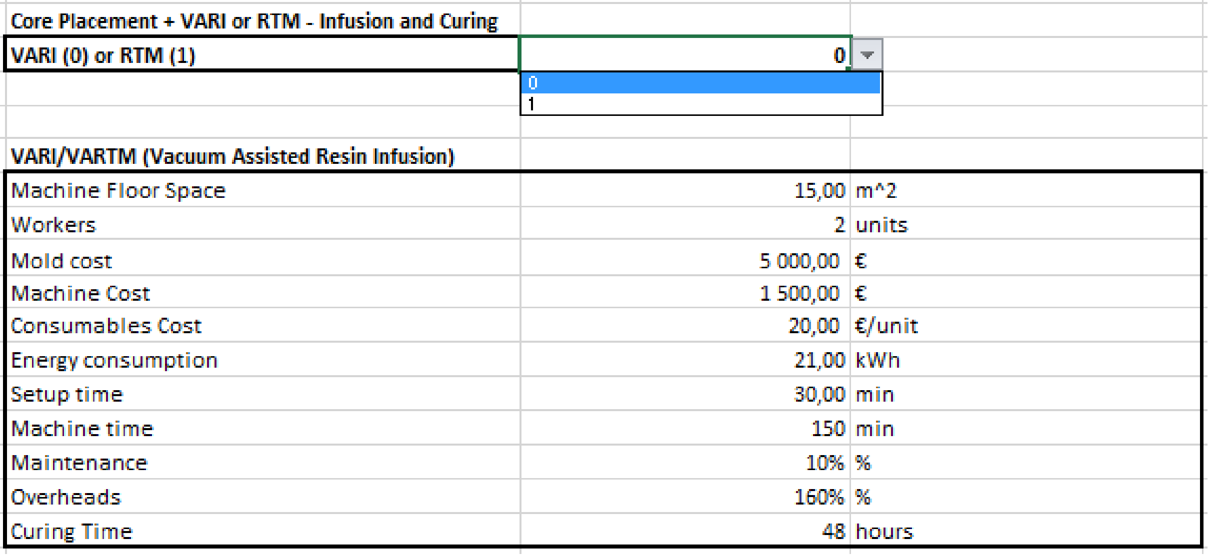
TFP



Reception check and storage inputs		
Floor space	2	m^2 per machine
Workers	1	units
Space Units	1,00	
Energy consumption	20,00	kWh
Cycle time reception and storage	5,00	min
Maintenance	0%	%
Overheads	160%	%

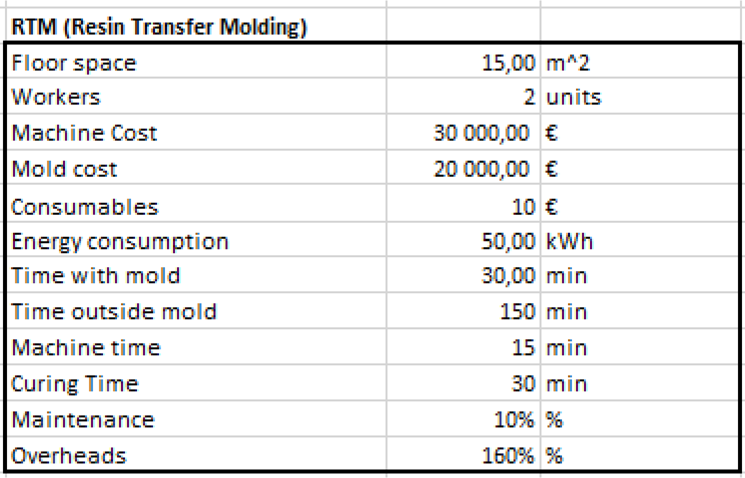


Binder and Fiber Placement inputs		
Floor space	99,00	m^2 per machine
Workers	1	units
Acquisition cost	200 000,00	€/unit
Energy consumption	200,00	kW
Initial/Re-Loading/Setup Time machine (without change c	10	min
First Part Setup	30	min
Maintenance	1 000,00	€
Overheads	160%	%
Maintenance	10%	%

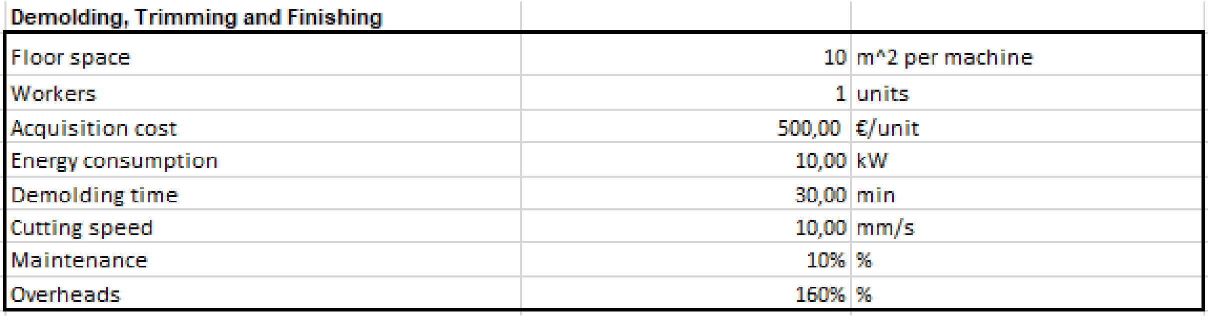


Core Placement + VARI or RTM - Infusion and Curing		
VARI (0) or RTM (1)	**0**	

VARI/VARTM (Vacuum Assisted Resin Infusion)		
Machine Floor Space	15,00	m^2
Workers	2	units
Mold cost	5 000,00	€
Machine Cost	1 500,00	€
Consumables Cost	20,00	€/unit
Energy consumption	21,00	kWh
Setup time	30,00	min
Machine time	150	min
Maintenance	10%	%
Overheads	160%	%
Curing Time	48	hours



RTM (Resin Transfer Molding)		
Floor space	15,00	m^2
Workers	2	units
Machine Cost	30 000,00	€
Mold cost	20 000,00	€
Consumables	10	€
Energy consumption	50,00	kWh
Time with mold	30,00	min
Time outside mold	150	min
Machine time	15	min
Curing Time	30	min
Maintenance	10%	%
Overheads	160%	%



Demolding, Trimming and Finishing		
Floor space	10	m^2 per machine
Workers	1	units
Acquisition cost	500,00	€/unit
Energy consumption	10,00	kW
Demolding time	30,00	min
Cutting speed	10,00	mm/s
Maintenance	10%	%
Overheads	160%	%