Assessing Material Costs and Deposition Rates of Automated Lay-up Composite Technologies

Gonçalo da Veiga França da Rocha e Castro
goncalo.castro@tecnico.ulisboa.pt

Instituto Superior Técnico, Universidade de Lisboa, Portugal

January 2021

Abstract

The demand for carbon fiber composite materials has grown considerably over the last decade, particularly in the aerospace sector, as they present high strength while yielding low weight. This makes them ideal for structural weight and fuel consumption savings compared to metals, which have been the primary aviation materials for almost a century. Carbon fiber composite aeronautical parts are mainly produced through two advanced composite manufacturing technologies: Automated Tape Laying (ATL) and Automated Fiber Placement (AFP). Studies on the productivity of composite manufacturing machines and the influence of their configuration parameters in the production of aerospace parts are scarce, moreover composite lay-up models in the literature are relatively simple, not allowing the study of more complex shapes. This thesis assesses material costs, deposition rates and scrap levels of ATL and AFP technologies for aerospace flat composite parts with arbitrary planar complexity. For that, a detailed parametric model of the manufacturing machines' automated lay-up process was developed. The model helps decision-making regarding technology selection and machine's parameters configuration by allowing fast and accurate part manufacturing simulation in early development stages. The model is validated with literature results and data from an aeronautical specimen test part. Several studies are conducted to obtain lay-up and scrap rates for aeronautical representative parts and a first tape lay-up offset study is performed to survey technical scrap reduction. ATL two-phase systems provide the best lay-up rates while yielding the highest scrap rates. First tape offset lay-up revealed promising for plies with multiple gaps and complex shapes.
Keywords: Aerospace Industry, Automated Lay-up Technologies, Material Costs, Lay-up Rates, Scrap Rates

1. Introduction

The use of composite materials in the manufacturing industry has had a notorious growth over the last decade, in major part due to its excellent properties [1]. The aerospace sector in particular is one where this kind of materials shows great upside due to their high strength to weight ratio. Composites offer a great alternative to metals due to lower part count and structural weight savings enabling aircraft to consume less fossil fuels as consequence. Composite aeronautical parts are mainly produced through two automated composite manufacturing technologies: Automated Tape Laying (ATL) and Automated Fiber Placement (AFP). Both are considered additive manufacturing and consist of heating and compacting synthetic prepreg resin with non-metallic fibers onto a mold. Both technologies require high initial investment in machines and prepreg material is also expensive. Finding ways to reduce cost associated with the latter is critical to the development of these technologies. A study regarding first tape lay-up offset for technical scrap reduction is then performed in this scope.

There is currently a lack of literature information on part lay-up rates and a shortage in models that can reproduce the lay-up process for flat parts with complex shapes. The main goal of this thesis is then to develop an algorithm capable of simulate the lay-up process of flat laminates for both technologies and provide lay-up and scrap rates, as well as improve the latter by reducing the material wasted through improved lay-up configurations. Influence of machine constraints and part geometry on lay-up productivity can also be studied. Finally, the model would also serve as an estimating tool for the lay-up material costs, as well as helping decision making regarding technology selection and machine's parameters configuration and with it, improve the efficiency of its design phase. With this in mind, machine lay-up process description will be presented along with current State-of-the-Art for both processes.

2. Automated Lay-up Composite Technologies

2.1. Automated Tape Laying - ATL

2.1.1 Process description

ATL uses single fiber tape with 3, 6, or 12 inches (76.2, 152.4 or 304.8 mm) width. This value is normally selected taken into account the curvature of the part to be produced. ATL machines are usually mounted on horizontal gantries, typically on an open bay gantry configuration, or vertical column system due to the mass of the material and machine head. They can have up to 11 axis of movement, 6 for the machine head and 5 for the gantry movement. These machines can either be a flat or contour tape laminating machine, being the latter capable of laying material in contours up to 40º and is the most used in the aerospace industry [2].

There are two main different material delivery technologies used in ATL systems: single-phase (most common) and two-phase. For the first, the process starts by loading the spool of material into the delivery head. After, the prepreg has its backing paper removed and the lay-up can begin with the tape being laid onto the tool through a silicone roller with compaction pressure and heat application. In these systems, the machine must slow down or stop to make the materials cuts. Scrap is then generated and it can be removed together with the carried paper resulting in a lower productivity as the cutting speed is reduced or, if it would interfere with subsequent process steps, deposited outside the part on the work area after each course lay-up.

In contrast, in the two-phase system, which is a more advanced technology, the excess material for complex course paths is pre-cut on an offline cutting machine. In this case, the machine does not need to decelerate for the cutting operation reducing lay-up time and prompting productivity. Also, the after process of removing scrap is eliminated, thereby heightening the savings. ATL two-phase systems also possess the capability of bi-directional lay-up, which also increases productivity. One unique feature of ATL systems is its ability to provide net shape contours which enables the lay-up of any contour on the component without the scrap being placed on the part, contrary to AFP systems. An example of a typical ATL machine configuration is displayed in Figure 1 [3, 4].

ATL machines can reach speeds up to 1 ms^{-1} and accelerations of 1 ms^{-2}. The minimal course length for this technology is around 100 mm for most systems [5]. Lay-up rates can vary between 10 and 150 kg/h for flat or mildly contour parts [6], depending strongly on material width and fiber areal weight. It also presents scrap rates in the order of 2 to 4% in larger parts up to 30% for small parts. Scrap rates are dependent on part

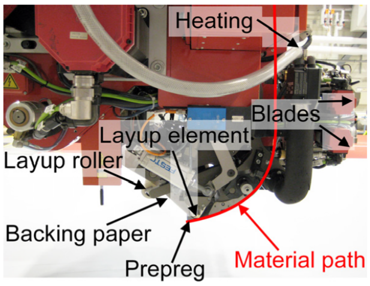

Figure 1: Typical ATL lay-up head configuration [5].

size as the lay-up has a significant decrease in efficiency as the part gets smaller. According to Grimshaw et al. [2], scrap rates tend to be higher for smaller parts but decrease with the part size increase, reaching a plateau. Inversely, lay-up rates increase with part size. This technology is commonly use to produce composite parts like wing and stabilizer skins.

2.2. Automated Fiber Placement - AFP

2.2.1 Process description

AFP is a similar but more advanced process than ATL because it is capable of laying small fiber tows, enabling steering and thus producing composite parts with higher degree of curvature. Material used for this technology can be impregnated tows or slit prepreg tape as well as binder powder fiber for dry fiber placement. These are usually fed into bobbins from an external creel rack or included in the placement head. An image of a typical configuration of an AFP machine head is shown in Figure 2. The tow width can range from 1/8, 1/4 and 1/2 of an inch (3,175, 6,35 to 12,7 mm) in single width. It also can vary in the number of tows delivered, ranging from 1, 2, 4, 8, 16, 24 to 32.

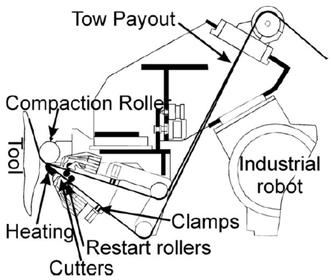

Figure 2: Typical AFP lay-up head configuration [7].

The tows align in parallel with low and adjustable tension and compaction pressure to form a band of fiber deposited material. Compaction is applied during lay-up in order to avoid defects by eliminating entrapped air and inner band gaps present in the plies also ensuring accurate position and sufficient adhesion between tows and component. Each tow can be controlled individually allowing independent cut, positioning and restart [8]. Furthermore, it allows almost no excess length at component edges reducing scrap rates.

For AFP systems, the performed cuts can only be done transversely thus the shape placed is not net shape. The maximum cutting speed is very important to these machine's productivity as it should accompany a rise in lay-up velocity for optimum lay-up. The latter is fundamental for the cut "on the fly" concept and it only exists on AFP machines, along with the initiation speed. AFP tends to have lower minimal course length than ATL, normally around 50 mm [5] for smaller robotic arms and 90 - 124 mm for larger machines [9]. AFP lay-up rate can range from 2 to 150 kg/h [6] and scrap rates range from 2 - 5% as per [10]. AFP lay-up speeds can reach to 1.2 m/s and accelerations of 3 m/s^2 [9]. These machines are responsible for the manufacture of components like fuselage panels.

2.2.2 Lay-up productivity

It is industry norm that when lay-up rates are revealed, as examples presented in this document, it usually comes without revealing the exact shape of the part, the lay-up speed or the tape width used. Even though the value of the lay-up is revealed, it is of no use to assess that machine's productivity for that part. In addition, for comparison purposes, either within the same automated technology or with other, it becomes useless. The tool to be developed in this thesis should diminish this problem as both technologies can be compared and the influence of machine constraints and part geometry on lay-up productivity can be studied.

Some academic literature such as Lukaszewicz [4] provided some insight on composite lay-up productivity by automated technology regarding lay-up speed and part size variation. However, the study is somewhat limited due to the simplicity of the part geometry used and the simple equations on what it was based on. Nonetheless, this benchmark work was given high relevance by industry experts and researches, as it is cited multiple times in articles and papers, which reveals the impact and importance of this data on the composite industry and just how imperative it is to provide a more accurate and broader tool to perform this kind of research.

2.2.3 Programming and optimization

The main goal of offline programming is to make sure surfaces and contours defined in the ply book are completely covered with prepreg material with its corresponding fiber orientation. However, simulating the manufacturing process also provides essential information such as material lay-up rates and scrap factors [2]. Furthermore, scrap can be minimized [3], herein one of this thesis goals is inserted. In addition to a tool capable of the lay-up simulation, the proposed work comprises a focus on reducing material scrap by searching an optimized lay-up strategy of the initial tape lay down in each continuous part of each ply. Usually, the left boundary of each first tape laid coincides with the left boundary of the part geometry because, in that manner, scrap is being diminished. However, with the first tape being set that way, the rest of the lay-up may not be optimized for scrap reduction, as an offset in the outer direction of the ply might have a trickle down effect on setting the consequent adjacent tapes for a better material usage, therefore diminishing scrap. Results on this study are presented in subsection 4.3.

3. Methodology

3.1. Process Mathematical Formulations

These equations constitute the first step in transforming the mechanical process which is the composite material deposition in an array of mathematical formulas that can represent it and contribute towards developing a realistic simulation tool. They can be divided into five different global prisms: material and technical scrap, distances, times, lay-up productivity and material costs. All equations are based on the 2D coordinate system shown in Figure 3. This referential coordinate has its ordinates axis aligned with the left boundary of each course.

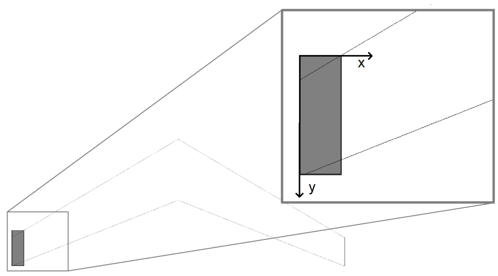

Figure 3: Model 2D coordinate reference system.

3.1.1 Material and Technical Scrap

The formula for the total material deposited in the lay-up of any flat part is described in Equation 1. Knowing the area of the part to be laminated, the technical scrap can be obtained the formula expressed in Equation 2, and its percentage in Equation 3. The areas are expressed in m^2.

$$Mat_{dep} = T_{width} \sum_{Ply_i=1}^{n_{Plies}} \sum_{r=1}^{n_{Tape/Tows}} (T_{length_r})_{Ply_i} \quad (1)$$

$$Tech_{Scrap} = Mat_{dep} - Area \times n_{Plies} \quad (2)$$

$$\%Tech_{Scrap} = \frac{Tech_{Scrap}}{Mat_{dep}} \times 100 \quad (3)$$

3.1.2 Lay-up Process Distances

In order to obtain the time spent by the machine in the lay-up process, the distance travelled by its head needs to be calculated. Tow ordinates are represented by set A and B. Set B depicts the ordinates of each tow starting location and A the ordinates of each tow finishing location. After all tow courses of a said set B finish depositing the minimal course length, the machine can accelerate to its configured lay-up speed.

Two methods exist to calculate initiation and cutting distances which are dependent on machine configuration: method 1 has the machine starting the acceleration from idle before reaching the part in order to attain initiation speed on the exact location of the part's edge; method 2 has the machine starting the acceleration from an idle position on the exact location of the part's edge. The distance travelled at initiation speed for method 1 is displayed in Equation 4. ($D_{reach_{is}}$) is the length the machine requires to reach initiation speed from idle and Min_{length} is the minimal course length.

The distance travelled at cutting speed, analogously, for method 1 is provided by Equation 5. (D_{reach_0}) is the required length for the machine to stop when moving at cutting speed. For method 2, both ($D_{reach_{is}}$) and (D_{reach_0}) are not required. Finally, the distance travelled at lay-up speed is depicted in Equation 6.

$$Dist_{ispeed\_AFP} = \sum_{Ply_i=1}^{n_{Plies}} \sum_{j=1}^{N_{Courses}} [max(B_j) - min(B_j) + Min_{length} + D_{reach_{is}}]_{Ply_i} \quad (4)$$

$$Dist_{cspeed\_AFP} = \sum_{Ply_i=1}^{n_{Plies}} \sum_{j=1}^{N_{Courses}} [max(A_j) - min(A_j) + D_{reach0}]_{Ply_i} \quad (5)$$

$$Dist_{lspeed\_AFP} = \sum_{Ply_i=1}^{n_{Plies}} \sum_{j=1}^{N_{Courses}} [|min(A_j) - max(B_j)| - Min_{length}]_{Ply_i} \quad (6)$$

For ATL technologies more variety in the deposition process was found. The distance travelled while at or getting at initiation speed for ATL single-phase systems is shown in Equation 7 and was assumed to be two times the minimal course length as standard, although some machines have different values. A constant time value then needs to be added for the time on part calculation of these parameters. The distance run at lay-up speed for single-phase systems is shown in Equation 8. For two-phase systems, the machine does not need to stop nor it has initiation or cutting speed, only a lay-up speed. Its lay-up speed distance is easily computed as shown in Equation 9.

$$Dist_{ispeed\_ATL\_singleph} = \sum_{Ply_i=1}^{n_{Plies}} \sum_{j=1}^{N_{Courses}} (2 \times Min_{length})_{Ply_i} \quad (7)$$

$$Dist_{lspeed\_ATL\_singleph} = \sum_{Ply_i=1}^{n_{Plies}} \sum_{j=1}^{N_{Courses}} [(y_{max_j} - 2 \times Min_{length}) - (y_{min_j} + 2 \times Min_{length})]_{Ply_i} \quad (8)$$

$$Dist_{lspeed\_ATL\_twoph} = \sum_{Ply_i=1}^{n_{Plies}} \sum_{j=1}^{N_{Courses}} (y_{max_j} - y_{min_j})_{Ply_i} \quad (9)$$

Transitional course distances formulas were also developed following the same logic as previously explained equations.

3.1.3 Manufacturing Process Times

All time parameters related to the deposition process are based on an uniformly accelerated movement. The two main time parameters of automated tape deposition are the cycle time and the lay-up time. The first constitutes the time the whole process takes from the moment the machine is being prepared and configured for a part lamination (setup time), through the lamination process itself (lay-up time), to finally the time needed to change tape/tow rolls in the machine creels. Its formula can be seen in Equation 10. All time parameters have as its base unit the second. The lay-up time consists of the time on part and the time off part. The first is the time the machine spends on actual lamination. The second is the time spent in processes such as tape/tow course transitions, horizontal and vertical gaps, ply transitions and in head approach/retract procedures. The time on part parameter can then be split into the time the machine spends at initiation speed, cutting speed and lay-up speed. As for the approach and retract time, as the name indicates, it is the time the machine spends to descend from neutral position to start a course and the time the machine takes to return to that same neutral position after completing it.

$$Cycle_{time} = Setup_{time} + Layup_{time} + Rolls_{ch_{time}} \quad (10)$$

$$Layup_{time} = T_{on\_part} + T_{off\_part} \quad (11)$$

$$T_{on\_part} = \sum_{Ply_i=1}^{n_{Plies}} (T_{lspeed} + T_{ispeed} + T_{cspeed})_{Ply_i} \quad (12)$$

$$T_{off\_part} = T_{transitional} + T_{appr\_retr} \quad (13)$$

$$T_{transitional} = \sum_{Ply_i=1}^{n_{Plies}} (T_{tow/tape\_tr} + T_{gap\_tr} + T_{ply\_tr})_{Ply_i} \quad (14)$$

$$T_{appr\_retr} = \sum_{Ply_i=1}^{n_{Plies}} \sum_{j=1}^{N_{Courses}} [(T_{approach} + T_{retract})_j]_{Ply_i} \quad (15)$$

The time needed to change material rolls and the number of rolls required for a certain composite deposition were also formulated.

3.1.4 Lay-up Productivity

The total mass deposited in the process is obtained by Equation 16. Other mass parameters are the scrap mass, Equation 17, and the lay-up rate, Equation 18. $M_{aweight}$ is the material areal weigth.

$$Total_{mass} = M_{aweight} \times Mat_{dep} \quad (16)$$

$$Scrap_{mass} = M_{aweight} \times Tech_{scrap} \quad (17)$$

$$Layup_{rate} = \frac{Total_{mass}}{Layup_{time}} \quad (18)$$

3.1.5 Material Costs

The material cost is computed by Equation 19. Equation 20 describes the cost that manufacturers pay to dispose of technical scrap.

$$Mat_{cost} = Mat\_unit_{cost} \times Mat_{Dep} \quad (19)$$

$$Scrap_{cost} = Scrap\_unit_{cost} \times Scrap_{mass} \quad (20)$$

3.2. Algorithm Development

The input parameters for this tool can be divided into machine constraints, part specifications and model setup variables. In addition, the outputs are divided into time, material and cost related results. The main concept of the algorithm is depicted in a high-level flowchart in Figure 4, which is divided into part drawing input, image processing, part manufacturing simulation, results processing, and relevant outputs.

3.2.1 Model Inputs and Outputs

The tool allows for some user customization as it provides several options. Firstly, and in order to save computational time, an option to display the lay-up was added. A second option to see the lay-up simulation be performed ply by ply is available. If the latter is not selected, the tool will show a better approximation to reality as the deposition will be shown as a ply being added on top of the previous plies. These options also enable a clearer understanding of how the tapes/tows are being placed. Figure 5 and Figure 6 show an example of ply by ply lay-up for ATL and AFP, correspondingly.

A third option enables the user to see the machine toolpaths which is industry norm. This enables the visualization of where the machine head

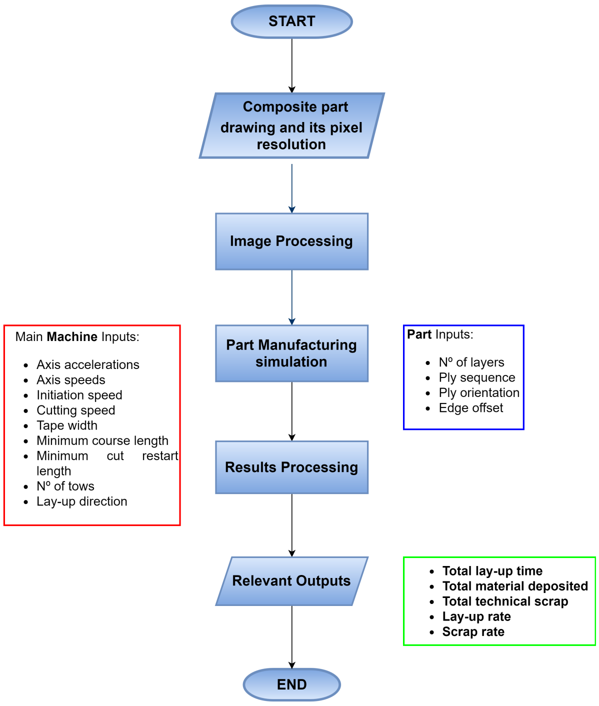

Figure 4: High-level algorithm description.

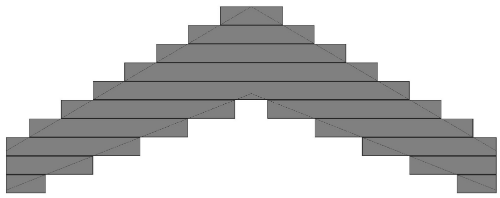

Figure 5: Example of ply Lay-up 0º - ATL (top to bottom).

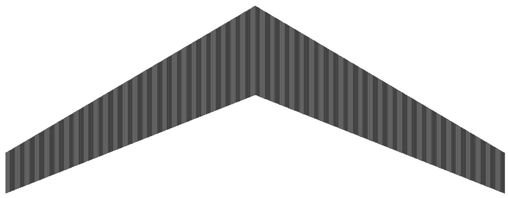

Figure 6: Example of ply Lay-up 90º - AFP (left to rigth).

will effectively pass in each course deposition. After a simulation is performed, the results are processed and the outputs presented. Most relevant outputs are the cycle time, the total material deposited and finally the lay-up and scrap rates. Finally, costs for technical scrap disposal and material deposited are calculated.

4. Results & discussion

4.1. Validation

4.1.1 Embraer's specimen test

In order to validate this model and evaluate its performance, comparison with experimental and published data was conducted. The first comparison consists of an Embraer's specimen test which is a machine check-up test to assess if everything is working properly to perform the lay-up of the company's composite parts. The data was collected *in situ* through the machine's software during my internship at Embraer's facilities in Évora. Machine data input is seen Table 1. The number of plies utilized were 24 with a [45, 0, -45, 90]º x 3, symmetric stacking. Material areal weight was 0.296 kg/m^2.

Table 1: Embraer's machine data.

Parameter	Value	Unit
a_{lam}	315	mm/s^2
v_{lam}	416.67	mm/s
v_{init}	300	mm/s
v_{cutt}	283.33	mm/s
v_{app}	83.33	mm/s
v_{ret}	166.67	mm/s
T_{width}	6.35	mm
Min_{len}	101.6	mm
$Min_{cut.rest}$	101.6	mm
N_T	16	-
$Layup_d$	Uni directional	-
M_{Offset}	20	mm
$Course_{start/finish}$	At part's edge	-

This part had a particular geometry for the lay-up of plies at 45 and -45º angles depicted on Figure 7. A type of "ears" were added at the top left and bottom right corners with 25x75 mm dimensions. Its lay-up was needed in order to use it as a pick up zone to remove the part from the mold without touching the effective laminated area. For plies at 0º and 90º, the ears were not included. Here, the tool's capability of being able to lay-up different part geometries in different plies achieved its purpose.

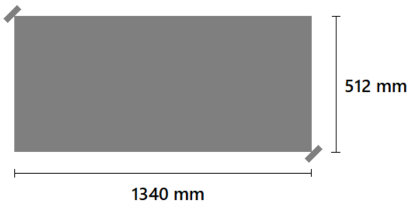

Figure 7: Embraer's specimen geometry for lay-up at 45º and -45º plies.

The tool is assessing geometries correctly since the difference between the part area and $A_{original}$ calculated by the model is the same as seen in Table 2. Areas with offset are also very similar, with the difference of 0.39% only for the 45/-45º plies. This demonstrates that the tool's ability of resizing an image to the right amount to deliver an offset was accomplished. Then, the difference between actual material deposited and Mat_{dep} is practically null, 0.21% to be precise. The time on part necessary to complete one full lay-up is almost exactly the same as the calculated $T_{on_{part}}$, with 0.41% difference. Other outputs like, $Mass_{dep}$, $Tech_{scrap}$ and $\%_{scrap}$ are a consequence of the previous discussed outputs. The small percentage differences for all outputs, with the highest being 0.71% for the the lay-up rate, indicates a successful tool development for the parameters tested.

Possible algorithm faults were being covered due to the simplicity of the part being studied. Because of this, a more complex geometry was studied and presented next.

Table 2: Embraer's specimen validation data.

Parameter	Embraer's Data	Model Res.	Diff.
$A_{original_{0.90}}$ - m^2	0.686	0.686	-
$A_{original_{45.-45}}$ - m^2	0.690	0.690	-
$A_{offset_{0.90}}$ - m^2	0.762	0.762	-
$A_{offset_{45.-45}}$ - m^2	0.766	0.769	0.4%
Mat_{dep} - m^2	18.547	18.586	0.2%
$Mass_{dep}$ - kg	5.491	5.502	0.2%
$Tech_{scrap}$ - m^2	2.082	2.077	0.2%
$\%_{scrap}$ - %	11.226	11.175	-
$T_{on_{part}}$ - h	0.244	0.243	0.4%
$Layup_{rate}$ - kg/h	22.504	22.664	0.7%

4.1.2 Soares et al horizontal stabilizer

The horizontal stabilizer present in Soares et al. [11] and shown below was used to validate the model with more complex geometries.

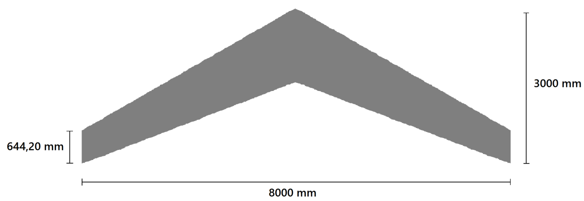

Figure 8: Horizontal Stabilizer part geometry [11].

The part was simulated with 40 plies with a [0, 90, 45, -45]º x 5, symmetric stacking and material areal weight of 0.3 kg/m^2. Tape width utilized was 304.8 mm for ATL and 12.7 mm with 24 creels for AFP. Time related outputs will not be compared here because there is no reference to the speeds and accelerations used as inputs in the referred paper.

Once more, and now with a more complex geometry, the correct reading of the part boundaries and consequent lay-up is being done properly since the difference between material deposited is less than 1.76% in all four ply orientations for both technologies, as seen in Table 3 and Table 4. The technical scrap in AFP technology presents a larger difference being that value around 35%. This happens because the values are very small and a difference between small values results in a high difference percentage. Nonetheless, it represents no major error in the tool's algorithm and therefore it has minor relevance. All other parameters had a very good agreement revealing another successful comparison.

Table 3: Horizontal stabilizer validation - ATL.

Parameter	[11] - ATL	Model - ATL	Dif.
$A_{original}$ - m^2	8.26	8.266	0.07%
Mat. at 0º - m^2	10.6	10.63	0.28%
Mat. at 90º - m^2	9.43	9.596	1.76%
Mat. at 45º/-45 - m^2	10.06	10.056	0.04%
Mat_{dep} - m^2	401.39	404	0.65%
$Mass_{dep}$ - kg	120.42	120.59	0.14%
$Tech_{scrap}$ - m^2	71.04	71.34	0.42%
$\%_{scrap}$ - %	17.7	17.746	-

Table 4: Horizontal stabilizer validation - AFP.

Parameter	[11] - AFP	Model - AFP	Dif.
$A_{original}$ - m^2	8.26	8.266	0.07%
Mat. at 0º - m^2	8.37	8.349	0.25%
Mat. at 90º - m^2	8.31	8.304	0.07%
Mat. at 45/-45º - m^2	8.37	8.332	0.45%
Mat_{dep} - m^2	334.19	333.18	0.30%
$Mass_{dep}$ - kg	100.25	99.95	0.3%
$Tech_{scrap}$ - m^2	3.84	2.52	35.38%
$\%_{scrap}$	1.15	0.757	-

4.1.3 Lukaszewicz's model

Lukaszewicz's test part was crucial to the validation of this model since it provides scientific background to this thesis once the comparison is validated. In his work [4], a model was also developed through some simple equations. The geometry consisted of a 16x8 m rectangle and the number of plies utilized were 8 with [0, 45, 90, -45], sym. and 0.412 kg/m^2 of material areal weight. Technical data for the machine system is shown in Table 5 as per [4].

Table 5: Lukaszewicz's machine data [4].

Parameter	Description		Unit
	AFP	ATL	
a_{lam}	2000	500	mm/s^2
v_{lam}	1000	1000	mm/s
T_{width}	6.35	302.4	mm
Min_{len}	50	100	mm
N_T	32	1	-
Cutting ply time	0	6	s
Start laying shoe time	5	5	s
$Roll_{ch.time}$	300	300	s
$Creel_{ch.time}$	15	-	s

After a tape course has been laid, the machine used in Lukaszewicz's study advances to a position outside the part and deposits a sequence with minimal course length. Also, the time for starting and stopping the ply using a laying shoe and the time for cutting the tape, seen in Table 5, were added to the results presented in the document. For AFP lay-up, only the time for starting a course was added. All the aforementioned parameters and the time for removing scrap obtained from [4] had to be subtracted from Lukaszewicz's results for ATL and AFP in order to make a viable comparison as they were not accounted in the model developed in this thesis.

4.1.4 ATL lay-up validation

Comparison between the model results and Lukaszewicz's extrapolated values is shown in Table 6. Most data had a good agreement with differences up to 4-5% with the exception of the time on part at 45º and -45º plies and the technical scrap.

The first difference can be attributed to the simplicity of the numerical model developed by Lukaszewicz. For 0º and 90º plies there is almost identical lay-up time for both models but for 45º and -45º angles there is not. This can be due to the higher complexity on calculating course distances at those angles, especially for corner distances. The 9.47% difference in time on part for these plies and the consequent 5% difference in the time on part parameter is thus a result of that.

Table 6: Lukaszewicz's ATL validation.

Parameter	L. Data [4]	Model r.	Diff.
$Time_{on.part}$ - h	1.241	1.179	5%
$A_{original}$ - m^2	128	127.98	0.02%
$Time_{on.part}$ - 0º - s	972	972.36	0.04%
$Time_{on.part}$ - 90º - s	1059.05	1060.32	0.12%
$Time_{on.part}$ - 45º/-45º - s	1218.66	1103.28	9.47%
Mat_{dep} - m^2	1058.67	1049.88	0.83%
$Mass_{dep}$ - kg	436.17	432.55	0.83%
$Tech_{scrap}$ - m^2	36.438	26.077	28.43%
$\%_{scrap}$ - %	3.44	2.48	-
$T_{c_{rolls}}$ - h	1.227	1.167	4.89%
N_{rreq}	15	15	-
$Layup_{rate}$ - kg/h	176.71	184.38	4.34%

The second and biggest difference between these two models is in the technical scrap value, with 28.43%. This could be related to the use of an offset on the part geometry that was not referenced in the document. To verify this hypothesis a simulation was done adding 20 mm offset to the part in question. The results revealed that adding 20 mm of part offset translates into a better comparison between models as the technical scrap difference reduces from 28.43% to less than 1.6%. Moreover, material and mass deposited difference both reduce from 0.83% to 0.2% which indicates the strong possibility of the inclusion of this part offset reflected on Lukaszewicz's lay-up results. ATL technology simulation performed by the tool developed in this thesis can then be safely validated.

4.1.5 AFP lay-up validation

For AFP technology the same validation methodology was applied. The comparison results are presented in the Table 7. It can be seen that, overall, the difference between parameters is not higher than 4% except for the same values already discussed for ATL technology comparison, the time on part for 45º and -45º angles plies and the technical scrap. The values for these differences are 7.05% for both plies and 90.34% for the latter. The difference in the time on part parameter for these plies has, most likely, the same explanation given for ATL lay-up.

Table 7: Lukaszewicz's AFP validation.

Parameter	L. Data [4]	Model r.	Diff.
$Time_{on.part}$ - h	1.455	1.506	3.51%
$A_{original}$ - m^2	128	128.01	0.01%
$Time_{on.part}$ - 0º - s	1320	1319.64	0.03%
$Time_{on.part}$ - 90º - s	1343	1342.56	0.03%
$Time_{on.part}$ - 45º/-45º - s	1288.56	1379.4	7.05%
Mat_{dep} - m^2	1037.62	1025.36	1.18%
$Mass_{dep}$ - kg	427.5	422.45	1.18%
$Tech_{scrap}$ - m^2	13.49	1.303	90.34%
$\%_{scrap}$ - %	1.3	0.127	-
$T_{c_{rolls}}$ - h	4.54	4.55	0.22%
N_{rreq}	681	684	0.44%
$Layup_{rate}$ - kg/h	71.31	69.78	2.15%

Another simulation was therefore performed with the inclusion of a 20 mm offset for AFP technology. After the 20 mm part offset simulation was performed, it was understood that a simulation with 30 mm was required as the 20 mm part offset values did not have a good agreement with the values obtained by Lukaszewicz's AFP lay-up. For 30 mm, the technical scrap difference between studies reduced from 90.34% to 16.5% which indicates a better value agreement. A higher offset required for AFP comparing to ATL might be due to higher tow tolerances and the smaller tow width. Nevertheless, the model can therefore be safely validated for AFP technology as well.

4.2. Lay-up and Scrap rates for aeronautical representative composite parts

The full potential of the model developed is shown as four different aeronautical representative composite parts were studied, a wing flap, a horizontal and vertical stabilizer and a wing skin. The full output information will only be presented for the first example due to synthesis purposes. All parts were simulated with 40 plies with the same [45, 0, -45, 90]º x 5, symmetrical angle orientation stacking. Material areal weight of 0.6 kg/m^2 and material and scrap unit cost of 71 and 3 €/kg were utilized.

The parts were tested for both technologies with ATL being tested for single and two-phase systems and AFP tested for course starting and finish before and at ply start location options. AFP and ATL two-phase were also simulated for uni and bi-directional lay-up. For AFP technology, the simulations were performed with tow width of 12.7 mm and 32 tows. All axis acceleration were set at 2000 mm/s^2 and layup speed at 1000 mm/s.

For ATL technology, tape width width was chosen as 304.8 mm. 1000 mm/s^2 and 1000 mm/s were selected for all axis acceleration and lay-up speed, respectively. The values used for initiation and cutting speed were chosen on a 2/3 rule of the lay-up speed as the parts to be simulated are flat computing 600 mm/s and 700 mm/s, correspondingly. Minimum course and minimum cut restart length were chosen as the standard value of 101.6 mm. For the ATL single-phase system an average value of 4 seconds was used for its starting and cutting course time. Finally, the roll and creel changing time were selected as 300 and 15 s, respectively. The roll length and setup time were defined as 240 m and 2 h.

4.2.1 Wing flap

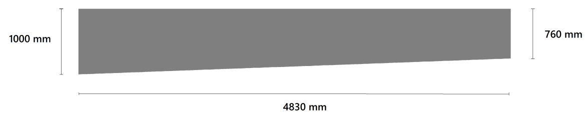

Figure 9: Wing flap part geometry.

Table 8: Model results ATL vs AFP - Wing flap.

Symbol	Mat_{dep}	$Tech_{scrap}$	$\%_{scrap}$	$Mass_{dep}$
ATL	215.92	45.04	20.86	129.55
AFP	181.66	10.78	5.94	109
Unit	m^2	m^2	%	kg

For this case, most relevant output information is shown in Table 8, Table 9 and Table 10. Cycle times are higher for ATL technology versus AFP technology, although the ATL two-phase system with bi-directional lay-up has similar values to those of AFP systems. This is due to the higher axis accelerations used in AFP and the higher bandwidth of 406.4 mm (32 * 12.7 mm) versus 304.8 mm in ATL. The time to change rolls is higher for AFP (64 rolls for 32 tows) when comparing to ATL (3 rolls for a single tape) because of the time required to adjust each AFP machine creel, although AFP only changes the 32 tows rolls simultaneously once comparing to twice for ATL. Nonetheless, this time parameter has less impact on the cycle time when comparing to the faster acceleration and larger bandwidth of AFP spending less time on part. The material deposited is, as predicted, higher in ATL (215.92 m^2) than for AFP (181.66

m^2), due to AFP being able to cut and lay independent tows. Even though having a higher maximum bandwidth, AFP technology is able to adjust it as suited, laying down less scrap in consequence, 45.04 m^2 (20.86%) vs 10.78 m^2 (5.94%). The technical scrap percentages are then in accordance to the reference made in subsubsection 2.1.1. Consequently, the material costs are higher for ATL than for AFP. Finally, the lay-up rates are higher in ATL two-phase systems despite the higher cycle times. This happens because, while having greater cycles times, this technology also deposits more material and, as a consequence, more technical scrap as well and thus boosting higher lay-up rates. In addition, the time off part for systems which are uni-directional (0.585 h for ATL and 0.334 h for AFP) is significantly higher than that of the same system but with bi-directional lay-up (0.380 h for ATL and 0.246 h for AFP). This is due to a reduction in the transitional tape/tow time from uni to bi-directional lay-up, 0.322 h to 0.118 h, in ATL, and 0.175 h to 0.087 h, in AFP. Finally, regarding the location of course start and finish, with option 1 being to start a course lay-up before the part's boundaries and finishing after and option 2 starting and finishing at the part's boundaries, its selection affects the time on part parameter, as by selecting option 2, that parameter is reduced and consequently the cycle time is also reduced because there is a shorter course to run by the machine.

Table 9: Model detailed results - Wing flap - ATL.

Symbol	ATL single	ATL two	ATL two bi-dir.
$Cycle_{time}$ - h	4.095	3.079	2.875
$Layup_{time}$ - h	1.928	0.912	0.708
T_{onpart} - h	1.343	0.328	0.328
$T_{offpart}$ - h	0.585	0.585	0.380
T_{trans} - h	0.338	0.338	0.133
$T_{trans.t}$ - h	0.322	0.322	0.118
$T_{app/ret}$ - h	0.247	0.247	0.247
$T_{c_{rolls}}$ - h	0.167	0.167	0.167
N_{rreq}	3	3	3
Mat_{cost} - €	9198	9198	9198
$Layup_{rate}$ - kg/h	31.641	42.075	45.064

Table 10: Model detailed results - Wing flap - AFP.

Symbol	AFP		AFP bi-dir.	
$Course_{s/f}$	1	2	1	2
$Cycle_{time}$ - h	2.821	2.782	2.733	2.703
$Layup_{time}$ - h	0.604	0.566	0.516	0.478
T_{onpart} - h	0.270	0.232	0.270	0.232
$T_{offpart}$ - h	0.334	0.334	0.246	0.246
T_{trans} - h	0.182	0.182	0.094	0.094
$T_{trans.t}$ - h	0.175	0.175	0.087	0.087
$T_{app/ret}$ - h	0.152	0.152	0.152	0.152
$T_{c_{rolls}}$ - h	0.217	0.217	0.217	0.217
N_{rreq}	64	64	64	64
Mat_{cost} - €	7739	7739	7739	7739
$Layup_{rate}$ - kg/h	38.641	39.177	39.884	40.326

4.2.2 Results comparison

By analyzing both Figure 10 and Figure 11, some observations can be made. The first, and the most evident, is that the lay-up rate increase, as discussed in theory, with part size for the same machine systems. Although most cycle times are lower for AFP, as discussed in previous paragraphs, ATL machines lay down more material because they do not possess the ability to cut and restart individual tows and therefore produce more technical scrap. By laying down more material in more, although almost similar time, the difference in material deposited has a bigger impact than the difference in cycle times for ATL two-phase systems. They then possess the highest lay-up rates for all part sizes being the ATL two-phase bi-directional system the most efficient one. The systems can be generally ranked in order of productivity from ATL dual-phase bi-directional system, followed by ATL two-phase uni directional (smaller parts), AFP bi directional 2 and 1 (larger parts), AFP uni-directional 2 and 1 and finally ATL single-phase.

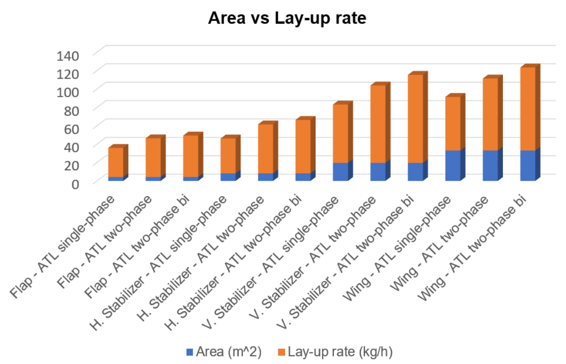

Figure 10: Area vs lay-up rate for all ATL machine systems.

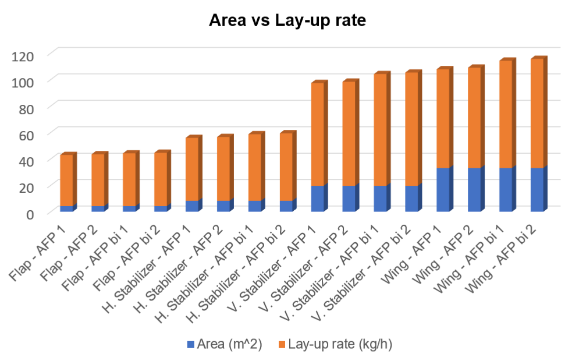

Figure 11: Area vs lay-up rate for all AFP machine systems.

4.3. First tape offset study results

The first scenario to be studied was the horizontal stabilizer seen in Figure 8. Ply sequence used was [0, 90, 45, -45]º x 5, totalling 40 plies. Material and scrap unit cost were set at the same 71 and 3

€/kg values. The results utilizing the model were 89.02 m^2 of technical scrap when laying the first tape aligned with the part's boundary and 88.89 m^2, a negligible saving of 0.13 m^2 or 0.15%, when using an offset on the first tape laid in each ply. In a second scenario, the same figure was modified as to include gaps in the direction of lay-up of the machine. This approach tries to describe a situation where this study could have a greater potential. The total technical scrap saved was 1.8 m^2, or 2.36%. Most relevant plies in which the offset was indeed required were plies 2, 6, 10, 14, 18, 27, 31, 35 and 39 (Figure 12) which got and offset of 7 and 52 pixels (22.225, 165.1 mm).

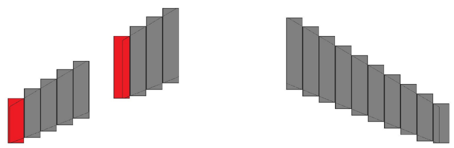

Figure 12: Offset study - ATL Ply Lay-up 90º (left to right).

5. Conclusions

The tool developed was successfully validated, for both technologies, with differences of less than 1% for the Embraer case study and differences not higher than 1.76% except for the case of [11]. Furthermore, the tool was validated trough a comparison with Lukaszewicz [4] benchmark studies. The time off part parameter was not able to be validated as there was no data available for comparison. However, by validating all other time parameters there is a strong premise to accept the values obtained for this parameter since the methodology applied was the same.

Several representative aircraft parts were simulated in order to assess its material costs and deposition rates. It was concluded that, as a general rule, and as stated in Grimshaw et al. [2], the material costs, material deposited and the lay-up rate increase with part area increase. They were found to be higher for ATL two phase bi-directional systems as they deposit more material, despite the slightly higher cycle times. The results from the first tape offset lay-up proved to be negligible for simple geometries as it was attained a material cost reduction of 0.15%. For more complex geometries, with the same area, the cost reduction was a more promising 2.36%. This value increases as material areal weight, part size and the material cost per kg increases. With the validations and analysis performed, the developed model presents itself as a tool capable of estimating material costs and deposition rates using current machine technology for real world parts with complex planar shapes.

References

[1] D. K. Rajak, D. D. Pagar, R. Kumar, and C. I. Pruncu. Recent progress of reinforcement materials: a comprehensive overview of composite materials. *Journal of Materials Research and Technology*, 2019.

[2] M. N. Grimshaw, C. G. Grant, and J. M. L. Diaz. Advanced technology tape laying for affordable manufacturing of large composite structures. In *2001: a materials and processes odyssey*, volume 2, pages 2484–2494. SAMPE, 2001.

[3] H. Lengsfeld and J. Lacalle. *Composite Technology: Prepregs and Monolithic Part Fabrication Technologies*, chapter Prepregs: Processing Technology, pages 47–113. Hanser, 2015.

[4] D. H.-J. A. Lukaszewicz. *Optimisation of high-speed automated layup of thermoset carbon-fibre preimpregnates*. PhD thesis, University of Bristol, 2011.

[5] D. H.-J. A. Lukaszewicz, C. Ward, and K. D. Potter. The engineering aspects of automated prepreg layup: History, present and future. *Composites*, Part B(43):997–1009, 2011.

[6] M. K. Hagnell and M. Åkermo. A composite cost model for the aeronautical industry: Methodology and case study. *Composites Part B: Engineering*, 2015.

[7] Salman Khan. Thermal control system design for automated fiber placement process. Master's thesis, Concordia University, 2011.

[8] Russell DeVlieg, Kyle Jeffries, and Peter Vogeli. High-speed fiber placement on large complex structures. In *SAE Technical Paper Series*. Eletroimpact, Inc, 2007.

[9] Coriolis Composites. Coriolis c1 - the reference in automated fiber placement. Online, 2020. https://www.coriolis-composites.com/fiber-placement-machines/coriolis-c1/ last accessed 8 August 2020.

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

[11] B. A. R. Soares, E. Henriques, I. Ribeiro, and M. Freitas. Cost analysis of alternative automated technologies for composite parts production. *International Journal of Production Research*, 2018.