DEVELOPING A COST COMPARISON TECHNIQUE FOR HAND LAYUP VERSUS AUTOMATED FIBRE PLACEMENT, AND INFUSION VERSUS OUT-OF-AUTOCLAVE

Yves Bauswein[1], Laura Veldenz[2], Carwyn Ward[3]

[1] Université de Lorraine,
34 cours Léopold, CS 25233,
F-54052 Nancy cedex - France
[2] National Composites Centre,
Feynman Way Central,
Emersons Green, Bristol, BS16 7FS, UK
[3] ACCIS (Advanced Composites Collaboration for Science and Innovation),
University of Bristol,
University Walk,
Bristol, BS8 1TR, UK

ABSTRACT

Almost in direct competition with the traditional technique of hand layup, modern automated methods have been developed in order to produce the same structural composite material part. These machines are particularly employed in the aerospace industry, and designed to attempt to reduce manufacturing costs, as well as increasing the reliability and quality of the produced part. Despite increasing deployment numbers and uses, such machines are yet to fully replace hand layup as the main method of manufacture within the industry; and perhaps for new builds, further complicates the process of selecting the best manufacturing process for a given component. For example, a production engineer must now today not only choose between hand layup and Automated Fibre Placement (AFP), but also between AFP prepreg or dry fibre infusion; as well as the curing system to use (including autoclave, oven, and out-of-autoclave options). How such choices are made are critical to a component's success or failure, although little published work is available to assist in this arena. The most common approach appears to be based on cost estimates; although it is often the case that detailed understanding is not available (even between materials using the same process), which leads to significant risk of capability and performance limitations. This paper seeks to address this, presenting the initial work towards a cost estimation technique that includes activity models & cost drivers.

1. INTRODUCTION

In the modern manufacturing environment there is an ever expanding variety of processes available for the production of composite parts. Increased variability within a single process is also possible, with for example Automated Fibre Placement (AFP) now offering different options of prepreg or dry fibre techniques for fibre collation; as well as subsequent resin processing such as autoclave or Out-of-Autoclave techniques. Although quality and right first time manufacture remains paramount, process choice decisions based on productivity and cost efficiency are increasing as demand and supply continues to pressurise the composites industry from several market sectors (aero, auto, amongst others). To achieve this, not only is a cost comparison between techniques required; but the costs structure, the determination of cost drivers, and the influence of production parameters such as the production volume. This work offers one example of a methodology towards that goal, based on developing a new cost estimation technique that includes feature based activity models and cost drivers.

2. METHODOLOGY AND PROCEDURE

The principles for the cost model, and subsequently its method and procedure, are:

a) To provide a better level of precision than current qualitative techniques may offer

In the review by Niazi *et al.* [1], existing cost modelling techniques were classified into four categories, each of them with features, advantages, and limitations - see Figure 1. According to Niazi *et al.*, analytical techniques are able to provide the best level of precision among the four categories of cost modelling techniques, and as such it was chosen as the backbone for the construction of the cost model.

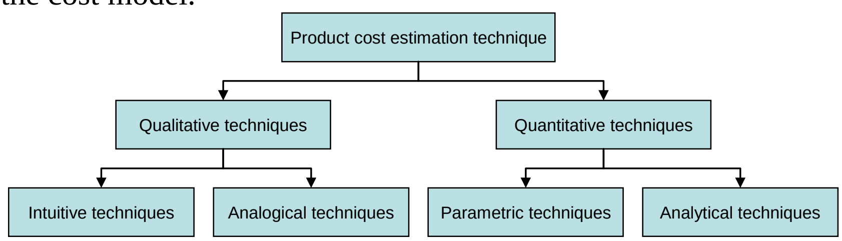

Figure 1. *The classification of cost estimation techniques, reproduced from [1].*

b) To be able to provide an accurate cost estimation for flat laminate parts up to 20 square meters, with a reasonable length/width ratio

Parametric costing techniques use knowledge and data of similar products and processes to derive the cost of a new product, assuming the fact that the new product differs from the others in a controlled set of parameters. As a result, the cost of a part may be defined as a function of some sizing parameter. The authors' developed cost model uses part area, part length, and part perimeter as general cost drivers; as well as part's dimensions respectively along and transverse to the ply orientation for the AFP cost estimation. As a present limitation, a maximum length/width ratio of 10 has been set for the cost simulations. The cost estimation relationships integrated into the cost model were mainly sourced from [2], in relation to the Process Cost Analysis Database (PCAD). Where cost estimation relationship functions were unknown, production times for the manufacturing steps were gathered from either production trials or detailed observations of staff at work.

c) To incorporate parameters the production engineer is interested in

Real-world production parameters were to be introduced into the developed cost model. Taking AFP as an example, 40 parameters describing the machine, the deposition head, the process, the mould, the workforce, and the overall equipment efficiency were necessary to characterise the process times and costs. The influence of the overall equipment efficiency on costs - defining times & rates for layup, inspection, rework, head cleaning, material problems, downtime maintenance, and creel loading - were all derived from Chen *et al.* [3].

d) To allow sensitivity studies using a range of cost drivers

As noted, the models analytical technique is based on detailed process mapping for each of the processes. As shown in Figure 2, for each step of a process selected, an associated cost is generated which is itself a function of a set of cost drivers. As a consequence, the sum of these costs is also a function of these cost drivers, and it becomes possible to envisage sensitivity curves which represent the process costs, as a function of a specific cost driver.

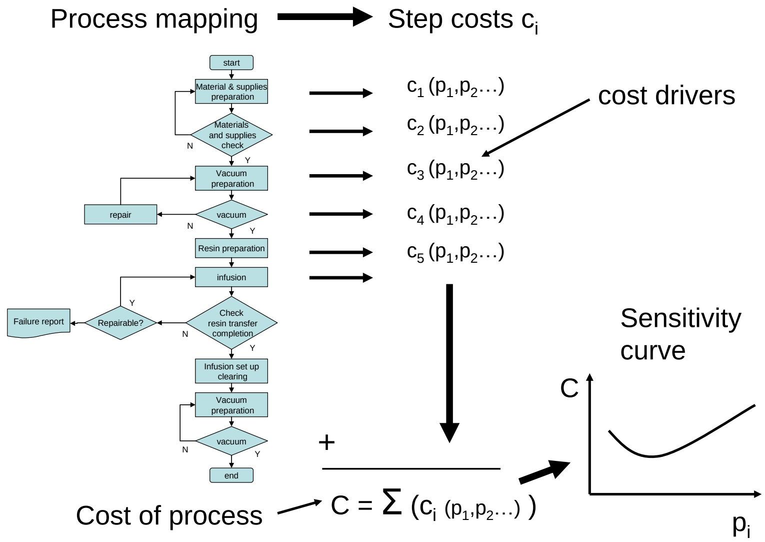

Figure 2. *Schematical represenatation of the cost drivers and available sensitivity curves*

e) To deliver global cost estimations as well as cost breakdowns

As a consequence of the calculation process depicted in Figure 2, it is possible to derive the global cost estimation, c, of any process. The cost breakdowns however are derived by using another consolidation technique, see Figure 3. All process step costs ci are split into categories before summation, which gives the sought after data for the cost breakdown. The work of Deo [4] (based on operations cost structures), was used to inform on these categories, see Figure 4.

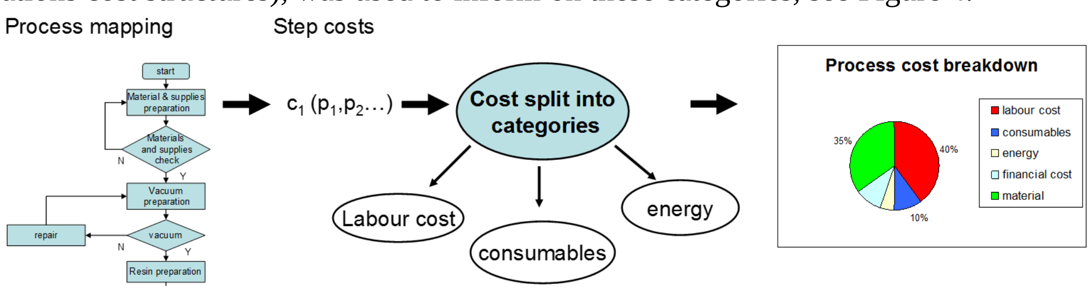

Figure 3. *The consolidation technique used for cost breakdowns and summation.*

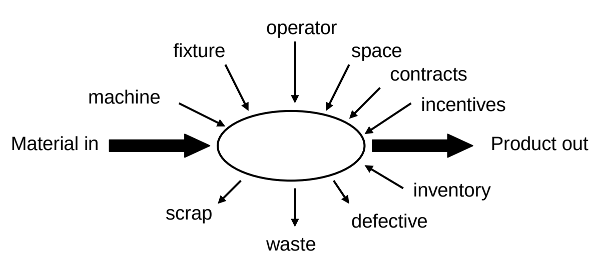

Figure 4. *A typical operation and its cost structure, based on [4].*

f) To assign the overhead costs to a level which is actually demanding the related resources

Cooper & Kaplan [5] wrote that assigning operating expenses to the wrong hierarchy level of the factory (whether it is facility, product, batch, or part) may be misleading. As a result a tree structure (product, batch, part) has been introduced into the model to allow each type of overhead cost to be assigned at the level where the corresponding resource is being used.

g) To have a modular configuration for the customer, to be able to expand the model according to need - such as part complexity, other processes etc.

Modular configuration is essential for the cost model being able to be expanded in the future. As the use of a spreadsheet software was imposed on the authors, the currently developed cost model includes input sheets that have similar features to data base formulas, calculation sheets which have the same structure as queries, and output sheets which includes figures and diagrams. This structure also allows the user's interface to be intuitive as required in h).

h) To offer an intuitive interface in order to reduce the model induction time

See g) above.

3. RESULTS

In order to validate the model's development, two quasi-isotropic flat panels which only differ from each other in terms of thickness, were chosen as a point of reference. Table 1 shows a small example of some of the 150 parameters used in the model. Most values were obtained through experience and detailed observation of processes at the National Composites Centre (Bristol, UK), some from generally accepted industrial practices (such as debulking), and the remainder from personal experience. The model was developed and populated, and three key outputs developed to investigate its performance - production costs between processes and part thickness, time dependant effects, and the influence of production volume.

Table 1. An example of some of the process parameters and part characteristics used.

property	value	property	value
part properties		equipment costs	
part area	0,22 m²	yearly maintenance cost	6 % of replacement value
part length	0,5 m	equipment lifetime	10 years
part perimeter	1,9 m	2,25 m3 oven acquisition cost	25000 £
number of 0° plies	8 (thick), 3 (thin)	2 x 3 m autoclave acquisition cost	350000 £
number of - 45° plies	8 (thick), 3 (thin)	cutting machine acquisition cost	50000 £
number of + 45° plies	8 (thick), 3 (thin)	AFP machine acquisition cost	1100000 £
number of 90° plies	8 (thick), 3 (thin)	tooling durability	250 parts
volume fraction of fibres	60%	labour costs	
production schedule		laminator	45 £/hour
production run	10 years	AFP technician	55 £/hour
number of parts a year	25	AFP process details	
size of batch	10	configuration	robotic X axis
facilities availability	two shifts full time	number of workplaces	1
material prices		deposition speed	0.8 m/s
dry AFP tows spool	28 £/m²	number of tapes	8
prepreg tows spool	41 £/m²	tows width	6.3 mm
epoxy resin	60 £/Kg	other	
hand lay up prepreg	22 £/m²	debulking	10 minutes every 4 plies

3.1 Comparison of the production costs between processes and part thicknesses

Figure 5 demonstrates results as an overview of the costs of different processes, and their contributions as process steps in the manufacture of the 32 ply thick part. For the purpose of simplicity in the figure, the following should be noted:

- In the hand layup process, debulking has been integrated into the hand layup bar as this task arguable happens during the process of manufacture.
- This integration is similarly done for the prepreg AFP process, with the exception of the last debulking cycle which could be done outside the AFP workstation.
- For the dry fibre AFP plus infusion process, the fibre cost has been integrated into the dry fibre AFP bar, and the resin cost has been integrated into the infusion bar.

From Figure 5 it appears that prepreg AFP, with costs ranging from 522 GBP to 658 GBP per part, is still more expensive than a hand layup option of between 476 GBP and 482 GBP per part. For the dry fibre AFP plus infusion process, there is a negligible difference of 9% compared to hand layup. It is therefore somewhat arguable that in the case of a thick part, the choice between hand layup and dry fibre AFP processes is not driven by production cost reasoning. When directly comparing the difference between an oven & autoclave it is found that the autoclave is slightly more than 15% more expensive to operate than an oven (mostly driven by amortization costs); but that these costs only represent some 10% of the total (36 GBP per part for the use of an oven and 42 GBP per part for the use of autoclave).

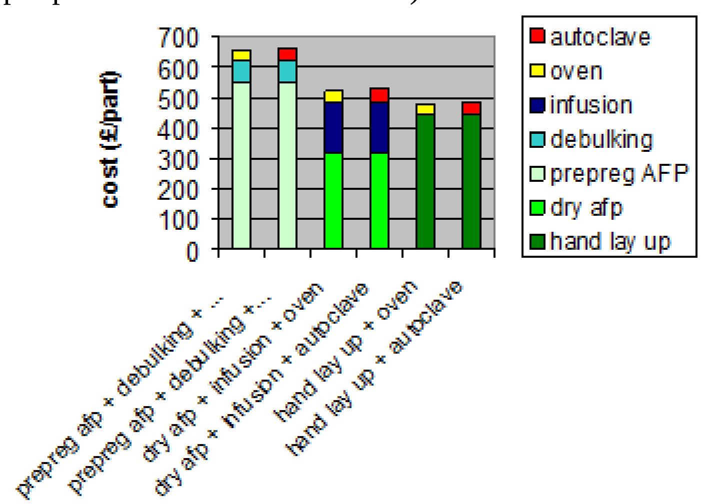

Figure 5. *Estimated production costs of different manufacturing options for a 32 ply thick part.*

However, the distribution of production costs presented in Figure 5 should not be taken as a general result for all components and sizes - for example Figure 6 presents a cost overview of the different processes, and their breakdown, for a 12 ply thin part. In contrast to the previous results, the hand layup process now appears to be the most expensive option, ranging from 357 GBP per part to 363 GBP per part, whereas the AFP processes ranges from 305 GBP per part and 326 GBP per part. This is partly due to the last debulking task in the hand layup process, which is considerably time consuming. For the dry fibre AFP plus resin infusion process, it appears that for thin parts the proportional share in cost of the infusion step has increased, relative to the thick part. When now directly comparing the difference between an oven & autoclave it is found that the autoclave is still slightly more expensive than the oven option, and for the same reasons.

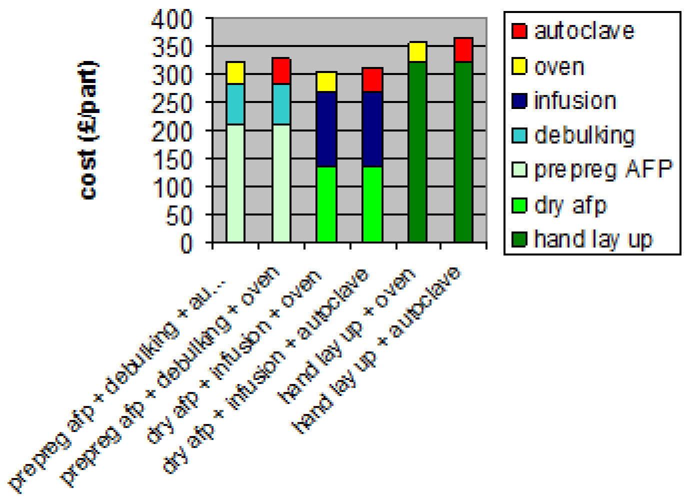

Figure 6. *Estimated production costs of different manufacturing options for a 12 ply thick part.*

Note that having run the cost model for different values of part thickness, results suggested that a part 16 ply thick was required to obtain similar costs for the hand layup and dry fibre AFP plus resin infusion processes. In both thickness cases it is perhaps noteworthy that hand layup remains relatively insensitive in terms of the range of costs possible, whilst AFP varies considerably and is clearly sensitive to the inputted parameters.

3.2 Assessment of time dependant effects on the production costs

The previous results (Figure 5 and Figure 6) only featured the production costs of various processes during the first year of production. It is therefore of interest to investigate how the cost differentiates between the options of hand layup and AFP over time. Figure 7 showcases the evolution of relative costs of production as a function of time, using the thick part (32 plies) as a reference. These results were calculated using a newly identified learning curve ratio of 0.93 for prepreg AFP [6], and mostly affects the costs of the options which are labour intensive. As a result, and evident in Figure 7, the difference in cost between the hand layup process, the prepreg AFP process, and the dry fibre AFP plus resin infusion process (which is labour intensive) continually widens with time.

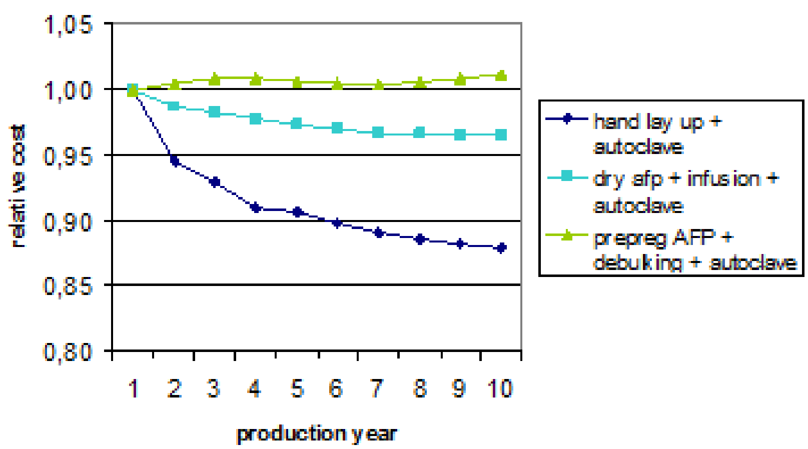

Figure 7. *Time dependent effects on production costs for hand layup and AFP processing.*

In combination, both phenomena (initial production costs range and costs evolution by time) can be seen to reinforce each other in the case of the thick part so that hand layup is the most favourable process. Comparing hand layup and dry fibre AFP plus resin infusion, it was found that there was a 9% difference in costs at the beginning of the commercial cycle (year 1) and a 19 % difference after ten years of production. But, these results must be viewed with prejudice - not only by the fact that the aforementioned combination is not relevant for the case of the thin part; but also by the fact that some parallel effects should not be overlooked. In particular, the influence of maintenance costs, which significantly increase over time, and in Figure 7 only appear on the prepreg AFP curve (the addition of maintenance to dry fibre AFP plus resin infusion was omitted due to it being a currently unknown quantity and further work to add this value in is required).

3.3 The influence of production volume on costs

As the profitability of a project depends on its production volume (amongst several other factors), a brief sensitivity analysis has been done for production volumes of 25, 50, 100, 200, 400, and 800 parts per annum; and taking the 32 ply thick part with a ten parts batch size as a reference. Two different processes were assessed: hand layup plus autoclave curing, and dry fibre AFP plus resin infusion in an autoclave. It was assumed that none of the production capacities was over the limits of factory capability. The production costs of each of these processes, as functions of production volume, are shown in Figure 8.

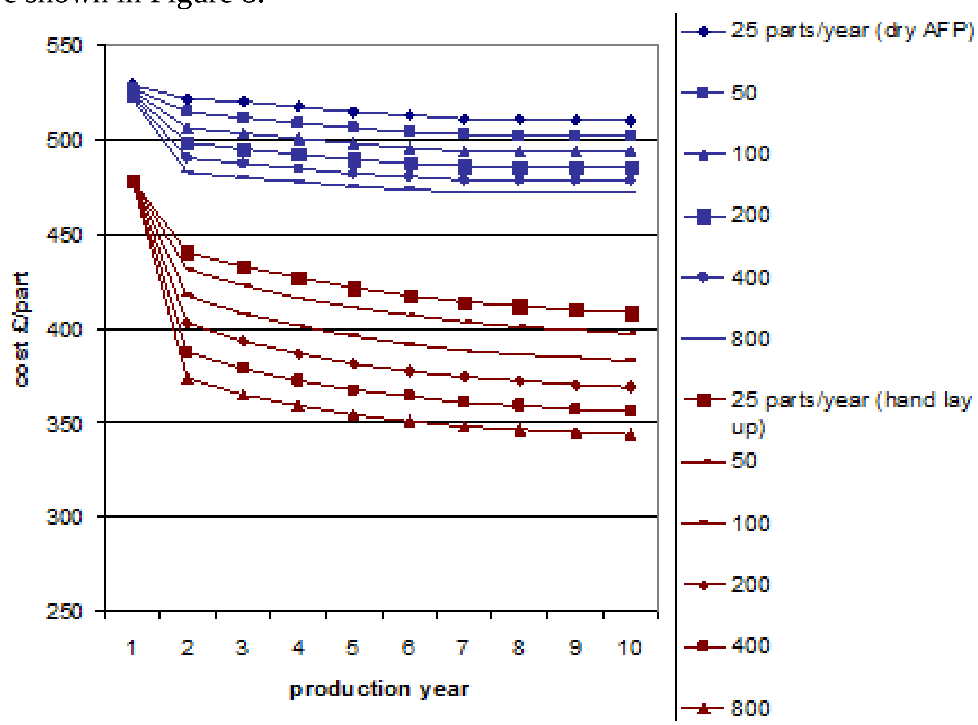

Figure 8. *The influence of production volume on production costs, comparing hand layup with dry fibre AFP.*

It is found that both the duration of the production programme and the production volume have an influence on cost. The biggest gains in costs are expected to be made during the first year irrespective of programme length, and as a result, there should be no expectation for a big gain from a 20 year programme versus a 10 year programme and vice versa. In addition, using an exponential scale for production volumes, the gain in cost in this case appears to be quite arithmetical, suggesting that the variation of production cost as a function of volume is able to be described as logarithmic. However, these results are only valid as long as the capacity of the facilities have not been reached. If the production volume requires additional capital investment, the cost of production will move upwards and the related curve will begin to saw-tooth.

3.4 Model performance and assessment

To date the model has been evaluated on one geometry type, and although a range of general variations within that one type have been attempted, the model predictions have yet to be evaluated against a live production part. Thus whilst the model is efficient in calculation, its accuracy and performance is undefined until such a detailed analysis is attempted/reported.

4. CONCLUSIONS

The aim of this paper was to present some initial works undertaken by the authors towards a new cost estimation technique, that includes feature based activity models and cost drivers, to better understand and identify the risks in manufacturing and material choice. It was achieved by investigating the possible costs of production of a relatively simple flat component over a variety of processes, including hand layup and AFP, and prepreg versus dry fibre infusion processes. To achieve this a simple yet deceptively detailed cost model was developed using a spreadsheet, that once appropriate inputs in areas such as the component geometry and material are provided, allows the user to output cost estimations as well as investigative comparisons between the candidate processes and (at this stage limited) sensitivity analysis. The particular study undertaken showed evidence of an ability to make logical choices for one process over another using the cost model. But, a large number of cost drivers involved in the calculations towards the production costs were based on generally narrow assumptions, and so the interpretation of the results provided requires a high level of understanding; and could risk returning subjective answers. Thus further works should also be conducted in terms of developing the knowledge capture and exploitation processes. In the future, this work will aim to be able to distinguish between processes, and identify the cost implications of taking certain decisions, so that technique selection based on a components build and allowances can be made.

5. REFERENCES

1. A. Niazi et al. (2005) Product cost estimation: technique classification and methodology review. J. Manuf. Sci. Eng 128 (2) 563-575
2. T. G. Gutowski et al. (1994) Development of a theoretical cost model for advanced composite fabrication. Composites Manufacturing 5 (4) 231-239
3. J. H. Chen et al. (2017) Trends and innovations of Automated Fiber Placement. In: 3rd Intl Symp Automated Composites Manufacturing, 20-21 April 2017 Montreal, Quebec, CA. Concordia University: Montreal, CA
4. B. S. Deo (2001) Operation based costing model for measuring productivity in production systems. Thesis (PhD) University of Manitoba
5. R. Cooper, R. S. Kaplan (1991) Profit priorities from activity-based costing. Harvard Business Review May-June 1991. Harvard Business Publishing: Harvard University
6. D. Winter et al. (2017) Using real-time data for increasing the efficiency of the Automated Fibre Placement process. Intl J Vehicle Structures and Systems 9 (1) 11-16