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Integral versus differential design for high-volume manufacturing of composite structures

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Abstract

In order to decrease the weight of the automotive body structure and increase the energy efficiency of future cars, attention is now turning towards structural composites, mainly carbon fibre reinforced plastics. Composites have several advantages such as their excellent weight specific properties and the possibility to be manufactured in large integral designs for a reduced weight and potentially lower cost. However carbon fibre composites are expensive and for a cost sensitive industry, such as the automotive industry, the challenge lies in creating a favourable business case with a well-balanced trade-off between weight and cost. A method is proposed to visualise the cost and weight advantages of either pursuing an integral design

or a differential design i.e. dividing the structure into a greater number of parts which are later assembled. The method focuses on the impact on cost and weight and considers structures with different part sizes and geometrical complexities. It is shown that, depending on the manufacturing process and series volume, larger and more complex parts may become more cost effective when divided into several, later joined sub-parts. However, for smaller and/or less complex shapes an integral design solution is always the best choice.

Keywords: Composites, automotive, manufacturing, partition, design

Introduction

As the automotive industry strives towards more energy efficient cars, efforts to reduce the structural weight of the automotive body structure are increasing. This trend is further intensified by new customer demands, implementation of expensive batteries, and forthcoming legislation that will penalise fuel consumption. By implementing composite materials, particularly carbon fibre composites, the structural weight of an automotive body structure can be greatly reduced. The drawback, however, is the high part cost. In 1993, Gutowski et al ¹ and a few years later Rais-Rohani² described the high investments, material cost as well as the labour intensive nature of the composite manufacturing processes as barriers for the introduction of composite structures in the aerospace industry. Kang³ ruled out a carbon fibre composite body structure due to this high part cost.

When the attention now is turning towards high volume and highly automated manufacturing scenarios, it is claimed that the feedstock cost^{4,5} and not the investments is the most influential factor for the final part cost. Regardless of the cause of a high part cost, the main reason to why

carbon fibre composites are implemented in aerospace and not in the automotive sector is the different value of weight for these two sectors. The value of weight describes a sector's or a company's financial appreciation for decreasing the weight of their products. This dissimilarity between the two industries is most clearly described by comparing their respective value of weight which is suggested to be as low as 1,6-6,4 €/kg⁶ for the automotive sector and approximately 500 €/kg⁷ for the aerospace sector. To succeed with the implementation of carbon fibre composites into the automotive industry is consequently a more challenging task requiring knowledge on how to find balance between cost and performance.

Carbon fibre composites have several advantages over metals, where one is the potential to be manufactured in large complex integral designs. An integral design avoids expensive and heavy joints as well as reduces the number of tools and assembly steps. Carbon fibre composite structures have until recently mostly been used in low volume applications, where investments are critical for the final part cost. In the case of the cost driven automotive industry and high volume production, however, the choice between integral and differential design is not as obvious as for low volume production since different cost drivers are present.

While studying the manufacturing of an aircraft fuselage Apostolopoulos et al⁸ discussed the issue of dividing a structure with respect to cost. The authors focused on the size and the operational complexity in the manufacturing, but chose to exclude geometric complexity as well as the cost effects on the investment for a differential approach. The work was based on the theoretical cost model philosophy developed by Gutowski et al⁹ describing how complexity affects the ply lay-up, the labour time and consequently the final cost of the composite part. Many studies have been made on manufacturing driven design solutions in order to make composites more cost effective. But, since carbon fibre composites are mainly considered when

the aim is to decrease weight it is inadequate to consider only the cost aspect. Instead both cost and weight effectiveness of a design should be evaluated. A multi objective approach, considering both cost and weight, is therefore, more suitable to be able to establish the best trade-off for the application in mind.

Mårtensson et al⁵ proposed a conceptual framework for the pre-selection of composite material systems and processes as well as an initial partition of the automotive body structure based on the process choices. The method defined a largest part size for each process; however, it was argued that this part size might not be the most cost effective size even though it provided a weight minimum i.e. no joints adding weight. It was suggested that the problem of defining the most cost effective part size could be related to the size and complexity of the structure. By dividing a structure a more cost effective design with a better trade-off between cost and weight could be found. This paper proposes a method to define the most cost and weight effective solution in relation to the value of weight. The method analyses how the cost and weight of the initial structure changes when dividing it based on its size and complexity. The aim of this conceptual method is to identify basic features, trends and behaviours with regard to high volume composite manufacturing. In this paper three composite material systems and manufacturing processes are included; Resin transfer moulding (RTM) with carbon fibre and epoxy thermoset resin; thermoplastic compression moulding (CM) with carbon fibre polyamide prepreg; and advanced sheet moulding compound (ASMC) with a discontinuous carbon fibre vinyl ester prepreg compound. The geometries included are assumed to be feasible to manufacture and no geometric undercuts or special tools are considered.

Method

The method, visualised in Figure 1, includes a weight estimation module and a cost model which consists of a manufacturing cost module and an assembly cost module. The proposed method draws on the results from Mårtensson et al⁵ and is a part of a holistic method presented. It is, therefore, implicit that a preferred material system and process for the structure is already defined as well as the largest part size, in this paper referred to as the structure.

Figure 1. Description of the method

A multi objective function (MOF)^{10–12} is required to solve the problem of defining the ideal trade-off between cost and weight. The result is found by calculating this function, defined as

$$\text{MOF} = p * w_{\text{structure}} + C_{\text{total}}, \quad (1)$$

for different partitions and then chose the number of partitions that minimises MOF for a given value of p . C_{total} is the total cost of the structure, $w_{structure}$ the weight of the structure and p a weight factor. The weight factor used in this paper is the value of weight for the industry¹³. The total cost (C_{total}) is the sum of the manufacturing cost ($C_{manufacturing}$) and the assembly cost ($C_{assembly}$) of the complete structure

Cost model

The cost model developed in this paper can be described as a detailed design or expert judgement based model¹⁴. It can be argued that such methods are more sensitive to the estimator's knowledge and data used compared to cost estimation methods based on statistical relations and historical data. However, for a conceptual phase considering a new and still non-existing technology, such as high volume composite manufacturing, this type of approach is necessary.

Figure 2. The process flows for the three manufacturing lines RTM, CM and ASMC. The same surface treatment and assembly cost module is considered for all processes.

Figure 2 describes the three composite manufacturing processes addressed in the cost model and their main process steps. The total cost ($C_{manufacturing}$) is the sum of investment cost (C_{invest}), tool cost (C_{tool}), total material cost ($C_{tot_material}$), and running cost ($C_{running}$) for the manufacturing as well as the assembly cost according to

$$C_{\text{manufacturing}} = C_{\text{invest}} + C_{\text{tot_material}} + C_{\text{tool}} + C_{\text{running}} \quad (2)$$

The relation depends on the number of parts (n) the structure is comprised of, the size of the structure and the annual production volume (V). The cost model assumes parallel production lines for the part manufacturing while the assembly line is considered a serial assembly line similar to the automotive industry practice. The same assembly method is assumed for all material systems included in the model despite that more effective or suitable solutions are available. For simplicity, the cycle time for the processes is kept constant and independent of size and complexity of the part.

Investment and running costs. The investment cost (C_{invest}) is based on the total number of presses, machines and robots used in manufacturing and is volume dependent. The lead time, t_o , for each operation governs the total number of presses, robots and machines (m) required in each manufacturing step to realise the annual volume, V. The investment cost (C_{invest}) is described as:

$$C_{\text{invest}} = \sum C_{\text{machine}} * m; \quad m = \text{ceiling}[(t_o * u_o) / t_{\text{tot}}], \quad (3)$$

where t_{tot} is the effective operational time per year for one machine or robot and C_{machine} the cost for that machine or robot. u_o is the number of operations required for the annual volume to be reached. The running cost (C_{running}) is given by

$$C_{\text{running}} = \sum (g * d + C_{\text{elect}} + C_{\text{maint}}) (t_o * u_o) \quad (4)$$

and includes electricity (C_{elect}) and maintenance cost (C_{maint}) as well as labour cost based on the operator's salary (g) and the dedication (d) related to the specific operation.

Total Material cost. Both material and scrap costs are included in the total material cost ($C_{\text{tot_material}}$) and are directly related to the feedstock cost ($C_{\text{feedstock}}$) i.e. the purchase price for the material system used in the manufacturing process, according to

$$C_{\text{tot_material}} = C_{\text{feedstock}} * w_{\text{structure}} * (1 + s_{\text{scrap}}) \quad (5)$$

The sum of the material lost in pre-cutting and manufacturing (s_{scrap}) is said to be a certain percentage of the material used in the structure and $w_{\text{structure}}$ is the weight of the complete structure. A polymer composite material system consists of load carrying fibre reinforcement as well as polymer resin. The RTM process requires the fibre and resin to be purchased separately and the composite material is then created during the manufacturing process. This manufacturing technique has a lower feedstock cost since the materials are purchased at a lower level in the value chain with the drawbacks of a slower and more complex process. One alternative to this manufacturing technique is to use a prepreg material system as done with advanced sheet moulding (AMSC) and thermoplastic compression moulding (CM) processes. Prepreg material is delivered with the resin and fibre in a pre-made mix and is often more expensive but with the advantages of a better control of fibre/resin ratio as well as a more rapid manufacturing process.

Complexity factor. Geometric complexity can affect the manufacturing of composite structures in many ways e.g. effect the pre-cutting and pre-stacking of the fabrics or prepreg; the complexity of tools and resin injection process etc. The relations between these aspects of complexity and the final cost are challenging to define. The exact connection is affected by the structural design e.g. required fibre orientation and ply-layup, the geometry and size of the structure as well as the material system used. In order to investigate effects of the geometric complexity on the final cost, a theoretical complexity factor is proposed.

Figure 3. Examples of projected area ($A_{\text{projected}}$) and the height of the structure (h). Floor structure, roof structure, floor tunnel etc.

The complexity factor (k_{complex}) is here defined as the relation between the projected area of the structure (A_{project}) and the total area (A_{total}) of the part according to

$$k_{\text{complex}} = A_{\text{total}} / A_{\text{project}} . \quad (6)$$

The projected area is defined as the largest projected area of the structure. Examples of the area relation are shown in Figure 3.

The complexity factor equation (6) is designed so that for a flat structure the complexity factor is one. With increasing geometric complexity, increased depth of the structure and more features etc. the complexity factor increases.

Partitioning. In this work, it is implicit that each partition is made to reduce the complexity of the structure/parts. The complexity factor decreases for every partition and approaches gradually unity. Further, the model is designed so that the reduction in complexity is the greatest with the initial partition but gradually reducing with further partitions, according to

$$k_{\text{complex}(n+1)} = k_{\text{complex}(n)}^{(1/n)} \quad (7)$$

where n is the number of parts. A complexity factor of unity can only be achieved by an initially flat structure. The complexity factor (k_{complex}) will influence the total material cost by a direct relation to the scrap level as further described in the following sections. It is assumed that the partitioning splits the component into parts of similar size and the part count is increased with 1 unit for each partitioning. The perimeter (x) is used for determining the lead time for pre-cutting as well as the assembly process, described in the section *assembly model*:

$$t_{\text{o_cutting}} = t_{\text{cut_speed}} * x, \quad (8)$$

Scrap level. It is widely accepted that the scrap levels in composite manufacturing is connected to the geometric complexity of a structure/part so that the amount of scrap increases with increasing geometric complexity. A high complexity factor indicates a more complex ply lay-up, which for most geometries results in more complex pre-cutting pattern for the fibre fabric or prepreg to enable draping etc. The assumption is that this complexity increases the level of

scrap and when decreased the scrap cost also decreases. The impact of the proposed complexity factor on scrap cost is, also, related to the material system used. Continuous fibre systems, used in RTM and CM processes, requires a specific fibre orientation and therefore a certain pattern in the pre-cutting, which is highly dependent on the geometric complexity. For continuous fibre material systems the relation between scrap level and complexity factor is expressed by

$$S_{\text{scrap}}(n) = k_{\text{complex}}(n) * S_{\text{initial_scrap}} \quad (9)$$

implying that the scrap level decreases with decreasing geometric complexity. Discontinuous fibre system e.g. used with ASMC, without demands on fibre orientation and cutting pattern is considered not affected by the complexity. A linear relation between material use and scrap level is then assumed

$$W_{\text{scrap}} = W_{\text{structure}} * S_{\text{scrap}} \quad (10)$$

The complexity will in these cases only affect the operation time for the preforming.

Tool and press cost. By dividing the structure the number of parts (n) will increase and the part size reduces. The press costs is related to required press force and part size, where the cost is governed by the projected area ($A_{\text{projected}}$) of the part in the press direction as illustrated in Figure 3 and the required press force. The tool cost is affected part size, the projected area as well as the height (h) of the part i.e. the volume of the part, governing the amount of tool material needed. Figure 4 describes the tool cost per volume tool material as a function of part volume. A number of tenders for high-volume production tools were interpolated to establish the relation.

Figure 4. Tool cost per volume tool material as a function of the tool volume, a number of tenders for high volume steel tools were interpolated.

All manufacturing processes included in the cost model (RTM, CM, ASMC) are considered requiring single cavity tools and having the same tool cost (C_{tool}). The press cost was considered to be linear in relation to the required press force according to

$$C_{\text{press}} = 1.25 \times 10^3 \times A_{\text{projected}} \times p_{\text{press}} \times s \quad (11)$$

where s is a safety factor.

Assembly cost module. The assembly cost module considers the same main financial posts as included in the manufacturing cost module i.e. investment cost, running cost and material cost.

Tool cost is excluded since no tools are considered in the assembly line; instead an additional

robot is added for each adhesive applying robot in order to hold the structure in place during the time for curing. The same philosophy and equations (Eqn 4) as for the manufacturing module are used to calculate the number of robots required for the assembly. Where $t_{\text{adhesive_app}}$ is the speed at which the adhesive is applied and x the shortest possible perimeter for the given area (A_{total}), with the relation

$$t_{\text{o_adhesive}} = t_{\text{adhesive_app}} * X. \quad (12)$$

The assembly method used herein was a single overlap bonded joint, as shown in Figure 5. An overlap of 30 times the thickness of the laminate is considered a rule of thumb, as commonly used in the composite industry for monolithic laminates.

Figure 5. Single overlap joint, monolithic laminates bonded with structural adhesive.

Weight estimation module

Since this method focuses on one material system and process at a time only the final weight of the complete structure is compared as a metric for performance. The weight of the complete structure (w_{tot}) is given by the initial weight of the structure (w_{initial} at $n=1$), and the increased weight is due to the additional material used in the overlap joint (w_{bondarea}) as well as the weight of the adhesive (w_{adhesive}) applied in the assembly step

$$W_{\text{tot}} = W_{\text{initial}} + \sum W_{\text{bondarea}} + \sum W_{\text{adhesive}} \quad (13)$$

Cost objective function

Finally, the weight and manufacturing cost of the structure for different number of partitioning are used to solve the multi objective function, Eqn. 1. The weight factor (p) is used to value the change in weight of the structure in the unit of cost. The ideal solution based on both the cost and weight objective is found by minimising the MOF (Eqn 1). The weight factor (p) will have great influence on whether a partitioning should be advised or not. Therefore different industries will experience different results in this phase of the analysis.

Parametric study

A parametric study was conducted in order to investigate trends and effects on the final cost and weight of the complete structure when dividing it. Table 1 describes the values of the projected area and the total area ($A_{\text{projected}}$, A_{total} for $n=1$) as well as the height (h) relations included in the study.

Table 1 List of geometric combinations for the structures investigated in the parameter study

A_c [m^2]	A_p [m^2]	k_{complex}	h [m]
0.6	0.5	1.1	0.1
1.0	0.5	2.0	0.3
1.1	1.0	1.1	0.1
2.0	1.0	2.0	0.3
3.0	1.0	3.0	0.4
3.2	3.0	1.1	0.1
4.0	3.0	1.3	0.2
6.0	3.0	2.0	0.5

A weight factor (p) of 9 €/kg is considered for the automotive sector, accounting for future increases due to the use of expensive batteries and increased environmental legislations. Initial scrap levels in the range of 20-30%^{16,17} are normally used in cost estimations for composite

manufacturing of continuous fibre systems with demands on fibre orientation. In this study, the initial scrap level for the carbon fibre fabric and continuous fibre prepreg is assumed to be 20% for flat structures ($S_{\text{initial_crap}}=0.2$). Table 2 describes the material costs, initial scrap level and cycle time for the processes include.

Table 2. data for initial scrap levels and cycle times for the process included in the parameter study, all figures should be treated as rough or approximations ¹⁵

In-data	RTM	ASMC	CM
Cycle time [min]	5	3	1
Fibre volume fraction	0.55	0.50	0.55
Material cost			
Carbon fibre cost [€/kg]	20	NA	NA
Resin cost [€/kg]	5	NA	NA
Prepreg cost [€/kg]	NA	36.5	34
Scrap levels			
Initial scrap fibre level	0,2	NA	NA
Initial scrap resin level	0,02	NA	NA
Initial scrap prepreg level	NA	0.05	0.2
Density (resin fibre mix) [g/cm ³]	1.5	1.5	1.5
Asseblly module material cost			
Epoxy adhesive [€/m]	0.2	0.2	0.2

Table 3 and 4 present the data used for the parameter study and the cost model. All machines are requiring certain floor space and energy consumption and the cost model adds a 10% installation augmentation for each machine.

Table 3, general data for the model, all figures should be treated as rough or approximations ¹⁵

In-data		
Annual workdays	200	d/y
Shifts/day	3	
Work hours	24	H
Operator dedication	0.5	
Operator salary	30	€/h
Floor cost	160	€/m ²
Electricity variable cost	0.008	€/kWh

Table 4, Investment cost, ex installation fee, all figures should be treated as rough or approximations ¹⁵

Machine	Price	Operational speed
CNC cutter	150 000 €	0.25 m/s
Post treatment machine	300000 €	60 s/part
RTM equipment	300000 €	NA
Material handling robot	60000 €	10 s/ply
Conveyor oven	450000 €	NA
Hydraulic press	See press cost section	
Tool cost	see tool cost section	
Hydraulic draping press	See press cost section	
Pre-shape tool	See tool cost section	
Adhesive application robot	60000 €	0.1 m/s
Storage		
freezer	800 €/m ²	NA

Furthermore, the parameter study focuses on an annual volume of 100 000 parts per year, a depreciation of 5 years on investments.

Results and discussion

The results from the cost model are analysed and a cost breakdown is made, looking at investment, tool, running and assembly cost as well as material and scrap cost. The three automated manufacturing lines in the cost model show similar initial investment cost per process line, though with different annual production volume capacity due to different cycle times. A cost breakdown is visualised in Figure 6.1-3, and the general observation, regardless of size and complexity, is that the material cost is the single largest post for all manufacturing processes. However, material cost is a smaller portion of the total cost per part for resin transfer moulding (RTM) due to the longer cycle time requiring increased investments to reach the annual production volumes. The main reason for this long cycle time is that the process handles virgin materials (resin and fibre) which require that the resin impregnates the dry fibre before curing. This is, as said in Paragraph 4.1.2, one great cost advantage of RTM and the lower feedstock cost accentuate the difference in cost split between the prepreg processes and RTM, see Figure 6.

Figure 6. Part cost breakdown for an annual volume of 100 000 p/y, medium low complex part with an A_{complete} of 1 m²; a) RTM b) CM c) ASMC.

The compression moulding process (CM) using thermoplastic prepreg materials has the shortest cycle time providing a high annual manufacturing volume per line and therefore the lowest tool, running and investments cost per part of the three processes compared. The drawback of the CM-process is the high feedstock cost for thermoplastic prepreg, and consequently, the scrap cost becomes significant since it is a continuous fibre system. This leads to another important observation; the scrap cost for the continuous fibre systems is a major cost driver, obviously for CM, but also for RTM as seen in Figure 6. Advanced sheet moulding compound (ASMC) is, like the thermoplastic compression moulding process, dependent of an expensive material system making the material cost the single most important cost contributor. Scrap levels, however, are less important with ASMC, being a discontinuous fibre system, and together with a longer cycle time the importance of investment, running and tool cost increases for ASMC process compared to the CM process.

Figure 7. Cost breakdown of the part cost as a result of dividing the structure. a) Small low complex structure 0,5 m², b) small complex structure 0,5m².

All costs are affected when the structures in the study are divided to investigate if a more cost effective part size exists. Figure 7a shows the impact on the part cost when a 0,5 m² large structure with low geometric complexity is divided and it is seen that all processes exhibits an increased tool, running, investment and material cost, hence, an increased total cost of the part. Even though the part cost is increased it is clear that the assembly cost contribution is negligible, barely visible in Figure 7a. On the other hand, when the complexity is increased for a similar sized structure, see Figure 7b, both scrap and tool costs reduce for the continuous fibre systems, RTM and CM. CM actually shows a reduction in part cost when divided, since these positive effects become greater than the increases in material cost incurred by the increased material utilisation for the overlap joint (2 CM < 1 CM). For RTM the scrap cost is a less significant share of the part cost compared to CM and therefore, despite a decrease in scrap cost, the overall cost increases and the integral design remains more cost effective.

Figure 8. Cost breakdown of the part cost as a result of dividing the structure. a) Low complex structure of 1m^2 , b) High complex structure of 1m^2 .

When the size increases for structures with low geometric complexity the integral solution continues to provide the most cost effective design for all processes, as seen in Figure 8a and 9a. For more complex geometries and increased size, however, the trend seen for a smaller structure (Figure 7b) is enhanced. Figs 8b and 9b shows that both RTM and CM benefits from a differential design compared to an integral solution. With increasing size and for highly complex structures the scrap cost for an integral design becomes significant when using continuous fibre systems. Since the complexity of the structure is reduced by the partitioning so is the scrap cost even though the structural material used in the part increases. As long as the initial structure is sufficiently large and complex the positive cost effect of dividing the structure becomes greater than the increased cost due to the partition and the differential design becomes more cost effective than the integral. This effect is accentuated by a high feedstock cost; the effect is more distinctive for compression moulding (CM) compared to resin transfer moulding (RTM). With ASMC, however, where scrap cost is not in the same way related to size and complexity, this effect is not seen. Not being restricted to a certain cutting pattern in the pre-cutting step is, in fact, a great advantage when trying to maximise the material utilisation.

Figure 9. Cost breakdown of the part cost as a result of dividing the structure. a) Low complex structure of 3m^2 , b) High complex structure of 3m^2

The results reveal that also the total tool cost can be reduced by dividing a complex structure even though the effect of cheaper tooling has low impact on the overall part cost. The volume of the tool, the product of the height of the structure (h) and the project area is the key factor. When the complexity decreases as a result of a partition, so does the volume of the tools compared to the tool for the integral solution.

Despite several positive aspects of a differential design approach a structure with low geometric complexity will never benefit from being divided looking at the criteria used in this study, see Figure 7a, 8a and 9a. For such geometry, the scrap cost increases more or less linearly with the material utilisation and consequently the total part cost of the structure will increase for each partition. Also, the assembly cost increases even though that is marginal.

The results from the weight estimation module are shown in Figure 10, and the total weight continuously increases when the structure is divided. But, the weight increase is also size dependent and the larger the structure the smaller the impact of the weight increase becomes compared to the overall weight. These results indicate that also with the weight objective in mind a partition is more beneficial for larger structures.

Figure 10. Normalized weight increase for a complete structure depending on the number of including parts, presented for different structure area sizes.

Finally, both the weight and cost objectives are taken into consideration. The results from the objective function (Eqn. 1) for structures with a low complexity factor ($k_{\text{complex}} < 1,2$) shows that no benefits are seen when dividing the structures. As seen in Figure 11, all sizes of structures have an increase in weight as well as part cost when being divided, therefore, the initial integral design provides the best balanced solution.

Figure 11. Objective function results for structures with low complexity factor; sizes A_{complete} a) 0,5 m², b) 1 m², c) 3m²

However, as seen in Figure 12, when the complexity factor is increased the option to divide the structure is a more effective solution. Initially for the CM process but at larger sizes also for RTM.

Figure 12. Cost Objective Function (COF) results for structures with high complexity factor; sizes A_{complete} a) 0,5 m², b) 1 m², c) 3m²

For the smallest size only 1 partition (n=2) is required to get the best solution for CM, while for the largest size 2 partitions (n=3) provides the preferable solution. The results seen in Figs. 10b and 10c shows that the RTM process requires a larger overall size before a partition of the structure should be suggested. In smaller sizes, the effect becomes too small due to the lower feedstock cost compared to CM and therefore a partition is not advised.

The method has not specifically considered hollow structures which often come with a greater increase in complexity of the manufacturing process itself. Though, calculating the complexity factor in the way proposed in this paper would give a high complexity factor for hollow structures ($k_{\text{complex}} \gg 2$) and following partitioning the complexity would decrease in the same way as for most structures discussed herein.

In general, a decreased feedstock cost would change the recommendations to a more integral solution also for larger and more complex structures. But, the motive for dividing a structure will remain as long as the cost drivers continue to be material cost and by that scrap cost. As for discontinuous fibre systems, however, there is no reason for partition at any sizes or complexity. Instead cost effective manufacturing of highly complex parts are competitive strengths of these material systems. The weight incurred by the joints are, as seen in the results,

small compared to the cost benefits gained by reducing complexity and by that the scrap cost. Also, the cost increase incurred by the assembly has little impact on the overall part cost, which is also seen in other cost estimation studies ⁴. A structure without joints and with low scrap levels is of course ideal but the combination is challenging to find when the geometric complexity of a part increases. The results supports the claims ^{4,5} that the cost drivers for composite manufacturing shift from labour and investments costs to material cost when entering high volume, automated manufacturing and that for the cost driven automotive industry minimising of weight (only) normally becomes too expensive.

As for all modelling work, the sensitivity of the results depends on the data used and the assumptions when setting up the model. The cost breakdown in Figure 6 shows that the feedstock (material) cost dominates the total manufacturing cost. By decreasing this post the investment cost becomes more important for all processes. This implies that the material utilisation and cost progressively decreases at the same time as it grows for investment cost, i.e. an integral design solution becomes more competitive also for larger and more complex structures. However, the reduction of the feedstock cost must be drastic in order to change the cost driver from a material cost to investment cost governed process. Investigating the sensitivity on other parameters such as pre-stacking, pre-cutting or post milling operation times or purchase cost, little to no effect was seen on the investment cost. The reason is firstly that the purchase cost is low for machines and robots per part. Secondly, there is a large difference in the operation times of the pre and post processing compared to the main operation cycle time per part i.e. injection or compression moulding. This leaves the investment cost unaffected despite an increase of the pre and post operation times since no new machines robots are required to fulfil the annual production.

The automotive industry is a clearly cost driven sector general described with low a low value of weight (p). In this study a higher value ($p=9 \text{ €/kg}$) is used compared to figures⁶ mentioned for the automotive industry, still a very low value compared to performance driven industries such as the aerospace industry⁷. The results are therefore driven towards a partitioning of the structure, while within the future an increasing value for p , due to legislations and increasing customer demands, would result in a much more integral solution.

The potential effect of the joint on the overall performance of the structure is not considered in this work. Instead it is assumed that the structure is equally well performing after bonding. This is of course a simplification of the problem which will be further analysed in future work. A bonded area potentially decreases component strength but might also contribute to the overall stiffness if designed and positioned correctly. Further, manufacturing large structures out of several smaller sub-components simplifies replacement of damaged subparts. It might, also, decrease the risks during manufacturing by reducing the costs of scrapped sub-components or improve manufacturing cycle times. These are softer values and relations not available and can therefore not be integrated into the current version of the model.

Conclusions

Carbon fibre composites are today mainly used in low series volume and on markets with cost-insensitive customers or in industries where an ability to reduce the structural weight is highly valued e.g. the aerospace industry. Inexpensive tools and their possibility to be manufactured in large integral complex shapes, requiring a restricted amount of tools has made composites cost competitive despite their expensive nature. In high volume series, however, the cost breakdown looks different and an optimised material utilisation is critical. The method presented in this paper was based on a theoretical cost model and demonstrated a potential for a cost and weight effective differential design. It has been shown that larger and more complex

structures can become cost effective when manufactured in several parts if the partition is made in order to reduce the complexity and thus decrease the important scrap cost and in some cases also the tool cost. The additional cost due to joints was small and did not greatly influence the cost efficiency. The multi objective evaluation also demonstrated that an ideal cost and weight objective solution could be found when dividing the structure in spite of the added weight incurred by the partition. The increased weight had a small impact on the choice between integral and differential design since the objective of cost was dominant. However, the benefits are closely related to the manufacturing process and material system of choice. Continuous fibre composites are more sensitive to a complex geometry and therefore experience a greater advantage of a reduced complexity. The results showed that manufacturing cost can be improved for continuous fibre systems when divided but not for discontinuous ones. Complex and non-complex small structures and larger non-complex structures did not benefit from a partition since the reduction of the complexity and by that the scrap cost was not sufficiently large. To conclude, it was seen that to solely strive for a high integral design solution was not, as often recommended, beneficial despite the potential for composites to be manufactured in more or less any size and shape.

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