

## INTEGRAL OR DIFFERENTIAL DESIGN FOR A COST EFFECTIVE COMPOSITE AUTOMOTIVE BODY STRUCTURE

P. Mårtensson<sup>1,2\*</sup>, D. Zenkert<sup>2</sup>, M. Åkermo<sup>2</sup>

<sup>1</sup> Volvo Car Corporation, SE-40531 Gothenburg, Sweden

<sup>2</sup> Department of Aeronautical and Vehicle Engineering, Lightweight Structures  
KTH Royal Institute of Technology, SE-10044 Stockholm, Sweden

\* Corresponding author ([per.martensson@volvocars.com](mailto:per.martensson@volvocars.com))

**Keywords:** Conceptual design, composites manufacturing, cost effectiveness

### Abstract

*The business case needs to be improved in order to make carbon fibre composites useful for the automotive industry. It is often claimed that one of composite greatest advantages over metals is the ability to be manufactured in large complex integral geometries. By reducing the number of tools and avoiding or minimising the assembly processes, an integral solution is commonly seen as more cost effective. In high volume manufacturing these claimed advantages might be questioned. This paper presents an investigation of how complexity and size of a structure affect the manufacturing design choice between integral and differential design. The study is based on a conceptual cost model with a part cost and assembly module for carbon fibre composite manufacturing. The result shows that an integral design solution is not necessary the most cost effective option. Instead, dependent of the size and complexity of the part a divided structure may both minimise total material cost and tool cost.*

### 1. Introduction

Reducing the fuel consumption has become a major aim for the automotive industry due to coming legislations and an increased customer demand for more energy efficient cars. In order to succeed with this quest the structural weight of the car needs to decrease. Since the weight reduction potential of the today used metal based materials are limited, carbon fibre composite materials are commonly seen as the only promising option for weight reduction. Though, there are many obstacles for implementing structural composite materials in the automotive industry such as high material cost, long process cycle time, lack of computer aided engineering tools and simulation accuracy; obstacles that are all related to cost and high annual volumes. In order to find the business case for new processes and material systems all these aspects needs to be considered.

The weight specific mechanical properties of carbon fibre composites are unsurpassed but the part cost becomes expensive compared to traditional solutions. Therefore, the focus turns to the manufacturing and the financial posts that can be influenced to improve this disadvantage. For low volume applications Gutowski et al[1] and Rais-Rohani et al[2] described the manufacturing of composites as labour intensive and complicated and therefore slowing down the implementation of carbon fibre composite materials into the aerospace industry. In the

automotive industry, with focus on high volume applications, there are other financial challenges and cost drivers such as cycle time and material cost [3], [4].

It has been suggested that one of composites greatest advantage over metals is that it may be manufactured in large integral structures [5] and that this should be utilised as a cost advantage. This might be a general advice for low volume or custom made products where investments and tool cost are critical for the cost competitiveness of composites. When focusing on high-volume applications these guideline could be questioned where the cost driver is the material cost. Mårtensson et al [4] suggested that the choice between an integral or differential design solution was related to the size and complexity of the structure. Apostolopoulos, et al [6], investigated the option of dividing an aeroplane fuselage in relation to manufacturing cost. The authors based the paper on theoretical complexity indices for the manufacturing operations proposed by Gutowski et al [7] though choosing not to include effects of geometric complexity or investment cost.

This paper presents a method for financial comparison between integral and differential design solutions based on a cost model with a series volume dependency. The model is develop to show basic trends and relations between size and complexity of the structures and their effects on the final part cost The cost model considers an automated resin transfer moulding (RTM) process and the materials included are high strength carbon fibre non crimp fabric and epoxy resin.

## **2. Method**

The methodology proposed includes two cost estimation modules; one for the manufacturing of the composite parts and one for the assembly of the parts creating the larger structure. Overall size and basic geometric relations are considered and a geometric complexity factor is proposed to enhance the cost model including it into a more general method for integral and differential cost analysis. 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.

### *2.1 Manufacturing processes*

Figure 1 describes the major steps in the RTM process including the assembly step. The RTM process uses dry carbon fibre and thermoset resin and the two components are mixed in the same step as the manufacturing of the part. This characteristic of the method makes it slower compared to other composite manufacturing processes where an already mixed material system is used in the moulding step. Though, the utilisation of materials from a lower level of the value chain is also an advantage providing a lower feedstock cost compared to semi-finished material systems.

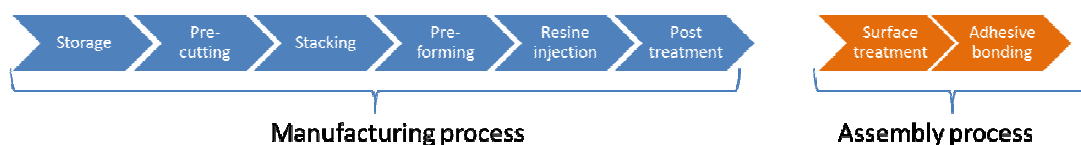


Figure 1. Manufacturing and assembly process flow for resin transfer moulding (RTM).

The cost model considers the investment cost ( $C_{invest}$ ), total material cost ( $C_{tot\_material}$ ), tool cost ( $C_{tool}$ ) and running cost ( $C_{running}$ ) for the manufacturing and, if required, assembly of the structure;

$$C_{Tot} = \sum_V C_{invest} + C_{tot\_material} + C_{tool} + C_{running} \in \text{assembly, manufacturing} \quad (1)$$

The number of machines, robots, tools and presses needed,  $x$ , is calculated based on the time for one operation ( $t_0$ ) and the required number of operations needed for the annual volume ( $n_0$ ). The equation

$$x = t_{Tot} / (t_0 * n_0), \quad (2)$$

describes this relation. An increased number of parts influence all financial posts in the cost model.

### 2.2. Tool cost

The tool cost is estimated based on the material costs for the tool producing the selected three-dimensional part geometry. High volume steel tools are considered.

### 2.3. Press cost

A linear relation for the press cost [8] against the projected area was used, described by following equation;

$$C_{press} = 1,25 \times 10^3 \times T, \quad (3)$$

where  $T$  is the press-force in *ton-force* (1 ton  $\approx$  10kN) required for the part.

### 2.4. Total material cost

Simplified the material costs consists of two parts: the material used in the structure and the material ending up as scrap. The material utilisation is affected by the pre- and post-scrap accumulation, where post-scrap includes trimming, sanding, drilling etc. of the part creating a limited amount of scrap difficult to reduce any further. In the pre-scrap shares the pre-cutting of the prepreg or dry fibres accumulates a more significant amount of scrap. The total material cost included in this model consists of material cost and scrap cost from the pre-cutting. The material cost is intimately related to the feedstock cost ( $C_{feedstock}$ ) of the material system (resin and fibre) and the structural weight of the part. A partitioning increase the weight of the structure due to additional overlapping structural material and the adhesive required for the joint. A partition thereby also increases the material cost. As shown in Figure 2, single overlap joints with an overlap length of 30 times the laminate thickness are considered in this cost model.

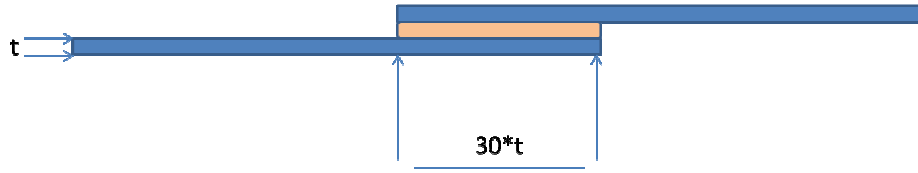


Figure 2. Single overlap joint, monolithic laminates bonded with structural adhesive

The scrap cost comprises fibre waste created during pre-cutting of the NCF and the small amount of resin waste created in the manufacturing process (assumed to be 2%). The scrap levels are often described to be in the range of 20-30% for composite manufacturing based on continuous fibre systems and with demands on fibre orientation [9][10]. In this study, the initial scrap level for the carbon fibre NCF mat is assumed to 20% (initial scrap level,  $S_{initial}=0,2$ ) for flat structures.

### 2.5. Complexity

It is widely accepted that the scrap cost is related to the complexity of the part and increases with the same. Though, the exact relation between scrap and part complexity is much dependent of the geometry and size of the part as well as requirements on fibre orientation and structural integrity. To show basic trends on the influence of part complexity on material and assembly costs, it is suggested that the complexity can be described by the relation between the projected area of the part (press area) and the total part area. This theoretical complexity factor can be described according to:

$$k_{complex} = A_{total} / A_{project} \quad (4)$$

It is implicit that a partition of a structure is made to reduce the part complexity and that a more rapid reduction of the complexity is seen with the first partitions. Further, a complexity factor equal to one is only feasible with an initially flat piece. Therefore, the following conceptual relation between the partitioning and the complexity factor is assumed:

$$k_{complex\_new} = k_{complex}^{(1/n)} \quad (5)$$

The total material cost is calculate by the equation,

$$C_{Tot\_material} = W_{structure} * C_{feedstock} * (1 + k_{complex} * S_{initial}) \quad (6)$$

where  $W_{structure}$  is the weight of the complete structure (bonding adhesive excluded),  $S_{initial}$  is the scrap level for a geometry with a complexity factor of unity and  $C_{feedstock}$  is the purchase cost for the material system.

### 3. Parameter study

A parameter study is conducted on structures with increasing size and complexity. The projected area is kept constant

Generic structure	Total area	Projected area
Flat	1	1
Increased complexity	2	1
High complexity	3	1

Table 1. Generic geometric structures included in the parameter study

#### 4. Results and discussion

The presentation of the results is made through a cost breakdown of the part cost, divided in investment, tool, running and assembly cost as well as material and scrap cost. Figure 4 shows that for a flat structure with low complexity all financial posts increases when dividing the initial structure. The additional material required for the overlap in the joints adds cost together with the scrap cost that follows with increased material use. Assembly cost also increases since additional adhesive are required when the total length of the joints increases. However, the cost related to assembly is nearly negligible for the part cost independent of partition for this size.

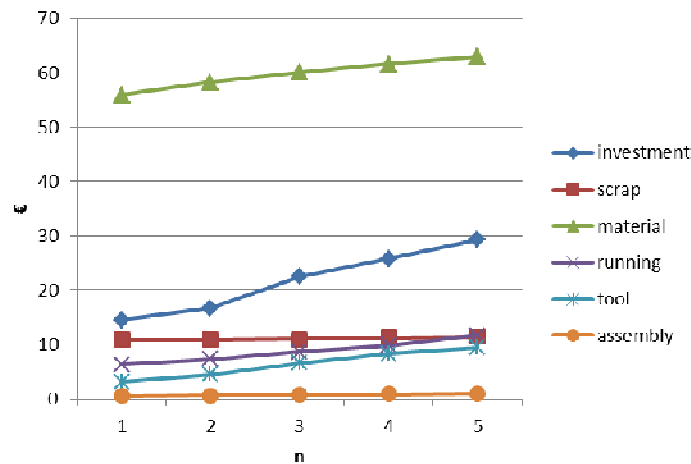


Figure 4. Part cost breakdown for a structure with total area of 1m<sup>2</sup>, after dividing the main structure into a number of parts (n).

In Figure 5, however, it is seen that for a larger size and slightly higher complexity level the initial pattern of the scrap cost changes. Instead of a steady increase, the scrap cost decreases as a larger structure is divided into smaller less complex parts.

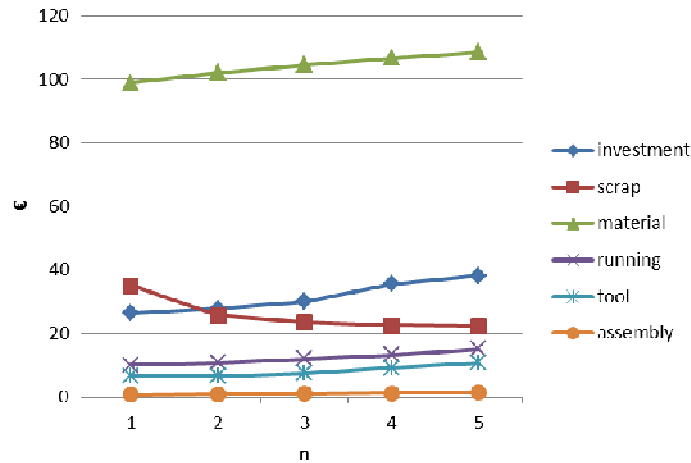


Figure 5. Part cost breakdown for a structure with total area of 2m<sup>2</sup>, after dividing the main structure into a number of parts (n) which are assembled.

The reason for this is that the complexity of the initial part causes a high degree of scrap and by decreasing the complexity a more effective material utilisation is found. In Figure 6 it is seen that this effect grows stronger with size and complexity, but also a new effect of the partitioning is seen, the tool cost decreases. The tool cost is directly linked to the volume of the part in space and when divided the complexity as well as the overall volume of the new parts decreases compared to the initial structure. If the difference is sufficiently great the total tool cost decreases, even though the number of tools increases. Also, the investment cost is affected and not as rapidly increasing since the handling and preforming of the numerous but smaller parts are becoming more cost effective.

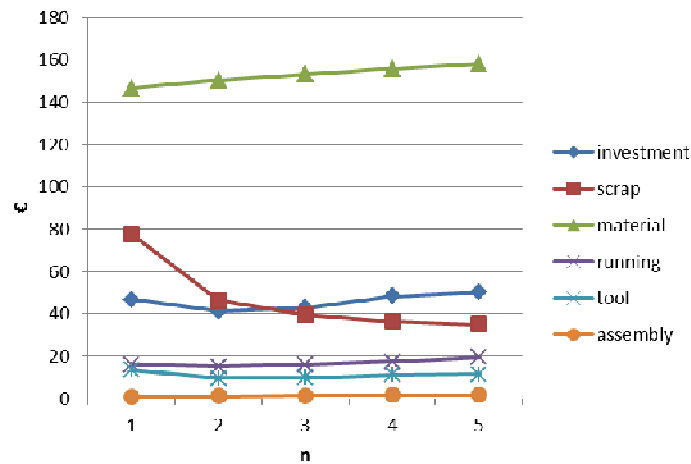


Figure 6. Part cost breakdown for a structure with total area of 3m<sup>2</sup>, after dividing the main structure into a number of parts (n) which are assembled.

The part cost for the complete structure is shown in Fig. 7 and only the structure with low complexity ( $A_{total} \approx A_{project}$ ) shows an increasing part cost for an differential solution. For the larger structures with higher complexity ( $A_{total} \gg A_{project}$ ) the part cost decreases when dividing the initial structure.

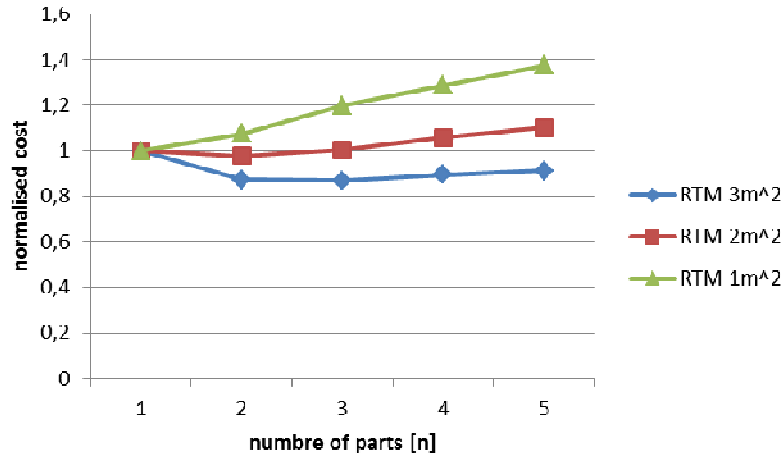


Figure 7. Normalised cost development for the three different structures with complete total of 1, 2 and 3m<sup>2</sup> and when dividing the main structure into a number [n] of parts which are assembled.

Finally, the results indicate that reduced material utilisation is a key factor for improving the overall business case for high volume manufacturing of carbon fibre structures. To be able to lower the scrap cost is essential for the cost sensitive automotive industry. As long as scrap level benefits exceed the cost of the additional material required for the joints there is a case for a differential design. Tool and assembly costs becomes less important in high volume manufacturing. Though, to improve also that financial post one solution could be to make the partition in the pre-cutting phase while the manufacturing of the part is made as an integral design with the joint overlaps in the main tool.

## 5. Conclusion

The aim of this paper was to compare the financial effects of an integral design with a more differential design. It was shown, which supports earlier research, that the material utilisation is the most important share of the part cost in high volume composite manufacturing. And more important, that reducing scrap can be more central than to focus on keeping an integral design with a superior weight solution. The partition of a larger composite structure may be beneficial if a reduced complexity and by that a lower scrap level could be achieved. Low complex structures should, however, be manufactured in an integral design. The conceptual method presented shows that when the relation between scrap and complexity is strong, a partition of the structure would improve the business case.

## 6. References

- [1] R. Henderson, C. Shipp, and T. Gutowski, "Manufacturing Costs for Advanced Composites Aerospace Parts," *SAMPE J.*, vol. 27, no. 3, 1991.
- [2] M. Rais-Rohani, "Manufacturing and cost considerations in multidisciplinary aircraft design," *NASA Grant NAG-1-1716 Grant Rep.*, 1996.

- [3] E. Fuchs, F. Field, R. Roth, and R. Kirchain, "Strategic materials selection in the automobile body: Economic opportunities for polymer composite design," *Compos. Sci. Technol.*, vol. 68, no. 9, pp. 1989–2002, Jul. 2008.
- [4] P. Mårtensson, D. Zenkert, and M. Åkermo, "Method defining optimum material diversity and partitioning for an automotive CFRP body structure," *Mater. Des.*, no. Submitted, 2014.
- [5] P. J. Kang, "A technical and economic analysis of structural composite use in automotive body-in-white applications," Massachusettsinstitute of technology, 1996.
- [6] P. Apostolopoulos and C. Kassapoglou, "Recurring Cost Minimization of Composite," *J. Compos. Mater.*, vol. 36, no. 04, 2002.
- [7] T. Gutowski, D. Hoult, G. Dillon, and E. Neoh, "Development of a theoretical cost model for advanced composite fabrication," vol. 5, no. 4, pp. 231–239, 1994.
- [8] K. Wikenfors, "Communication." DIN MASKIN AB.
- [9] R. a. Witik, F. Gaille, R. Teuscher, H. Ringwald, V. Michaud, and J.-A. E. Månson, "Economic and environmental assessment of alternative production methods for composite aircraft components," *J. Clean. Prod.*, vol. 29–30, pp. 91–102, Jul. 2012.
- [10] E. Kleineberg, M., Schradick, M., Sperlich, "CEAS European Air and Space Conference, pp. 727e734," in *ALCAS centre wing Box-Lower cover low cost resin infusion stringer manufacturing.*, 2007, p. 727,734.