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Method for cost and weight-efficient material diversity and partitioning of a carbon fibre composite body structure

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Abstract

A method for the early concept phase is proposed, aimed at limiting financial and performance-related risks when designing a carbon fibre composite automotive body structure. The method manages structural requirements imposed on the complete body structure and analyses the suitability of different carbon fibre material systems and processes. It also studies whether a high level of material diversity is desirable and how to identify the optimal partition of the body structure from a material system and manufacturing process selection point of view. Furthermore, since composite materials include both laminated and quasi-isotropic materials, an approach is presented that enables the comparison of these materials variants during conceptual material selection. A case study exemplifies the method and results show that, in spite of the cost sensitive nature of the automotive industry, utilisation of the maximum performance of these expensive composite materials is more important than efforts to achieve a rapid manufacturing process.

1 Introduction

Composite materials, especially carbon fibre composites, are finally gaining the amount of attention and interest from the automotive industry that was expected decades ago. Carbon fibre composites have been used in high-end applications such as racing cars, aerospace application etc. which are low volume industries. Expansion into high volume applications, such as the automotive industry, has been prevented by cost and manufacturing constraints. Cycle times, repeatability and high levels of material costs has meant the automotive industry has been reluctant to utilise these materials, even though they show superior weight benefits, design freedom and part integration potential. Within aerospace the transition from metallic materials to fibre composites was facilitated by low product volumes, with lower investments in process machines and tools as well as having a business case which clearly prefers lightweight solutions due to fuel cost and payload. While the aerospace industry can expect as much as 370 €/kg¹ in value of weight, the financial value of reducing the weight of a design, the automotive industry so far have had to relate to around 0.3-6 €/kg^{2,3}.

In the future, with tougher legislation on emissions, the automotive industry needs to drastically reduce the weight of vehicles. With the potential to reduce the steel body structure weight by 50-80%⁴ carbon fibre composites are, by many, regarded as the only option to achieve such a drastic decrease. In a car, the body structure is the single heaviest system and is therefore under considerable examination. Lack of experience regarding product development of composite parts is a great challenge to the potential success of such a major shift. Analysing the development chain of the body structure, the concept phase provides the first important choice regarding process and material systems. Furthermore, the concept phase also creates boundaries for future phases and limits the opportunities to change initial decisions. It is said that 80%^{5,6} of the cost of the final product is governed by decisions made in the early concept

phase and this could, logically, also be valid for the final structural weight. In the concept phase, the following questions exemplify the issues that must be addressed in order to design a cost and weight-optimised car body structure: Which manufacturing process should be used? Should the solution be based on one homogenous material system or a high level of material diversity? How is the optimum trade-off between an integral and differential design defined? Making such important choices in the critical concept phase based on limited experience of high volume composite manufacturing increases risks in regard to final weight and cost of body structure. Consequently, guidelines for selecting manufacturing process, material system and how to divide the body structure are required.

Several material selection methods are available ⁷, however not all are suitable for the concept phase since some are based on design solutions that are too detailed. Ashby ⁸ proposes a material selection philosophy suited to early phases of the design process based on material performance indices and the relationship to design objectives such as weight and cost. Aimed at a broad, general material selection the method demands rough material properties and cost estimates in order to compare material families. When concentrating on carbon fibre composites only, the demand for the accuracy of cost and performance data increases, even more when including laminar anisotropic as well as isotropic variants of the same material combination.

As described by Gutowski et al⁹ as early as 1991, many composite manufacturing processes of interest are under constant development or not yet in use and therefore the data necessary for cost estimates is unavailable. Unfortunately, this statement is still valid for high volume manufacturing of structural composites. Furthermore, if the aim is to study the production of seemingly similar constituent composite materials but for which the choice of manufacturing process governs different annual production

volumes and investment costs, a certain level of detail is required as concerns cost estimates. In order to solve this multi-objective problem, the identification of the optimum weight and cost of a composite component performance must also be valued in financial terms. Total cost counting approach has been used to select materials for car body panels where weight assumptions and their impact on fuel consumption costs have provided a value for performance which was included in the total cost for the part ¹⁰. Also, methods in which cost models are coupled with analysis of structural performance have been presented in order to solve multi-objective problems. Kaufmann et al ¹¹ used the value of weight as an evaluation tool and presented a method of optimising a generic, stiffened shell composite wing structure with regard to cost and weight for a pre-defined design and manufacturing method. Bader et al ¹² proposed a method to select optimum material and process in regard to cost base in a comprehensive cost model with weight assumptions for a generic shape with equal final properties ⁸.

In this paper a method for pre-selecting composite material system for an automotive body structure and dividing it based on the material and process choice is proposed, and a case study is conducted. The method is centred around the management of the requirements of the body structure and based on Ashby's material selection philosophy ⁸. The aim is to define optimum material and process diversity based on material and process pre-selection. The case study, performed to illustrate the method, addresses all stiffness and toughness requirements concerning the body structure of a combustion engine car. The manufacturing processes considered in the case study are Advanced Sheet Moulding Compound (A-SMC), Resin Transfer Moulding (RTM) and Thermoplastic Compression Moulding (CM). Furthermore, a cost model is developed for each of the processes and is designed with a series volume dependency. Within the cost model and case study, both continuous and discontinuous carbon fibre material systems are evaluated. As highlighted, it is necessary to be able to compare the performance of

anisotropic laminated materials with quasi-isotropic materials correctly, and such an approach is also proposed.

2 Method

The different steps of the method for pre-selecting carbon fibre composite material and initially dividing the body structure are illustrated in Fig. 1. The method requires that a cost model, as well as relevant material data, is available for the material systems and manufacturing processes of interest.

Fig. 1 The steps of the method

2.1 Requirements

The conceptual phase of developing an automotive body structure is initiated by a definition and summary of all requirements that influence the design work i.e. a list of prerequisites. The requirements are related to the final performance of the car and include safety, handling, comfort as well as quality and also requirements derived from sub-system prerequisites such as strength, flexural stiffness, temperature etc. There are also geometric requirements that define the design space for the body structure based on e.g. the outer and inner design, driver visual angles, legislation and subsystem space requirements. Some examples of requirements are given in Table 1 and shown in Figure 2.

2.2 Objectives

The objective of the material and process selection must be established in order to be able to evaluate and select the ideal carbon fibre composite material system and manufacturing process. In most cases these choices are not based on one but on a number of objectives. This creates a multi-objective problem where optimum trade-offs between, for example, cost and performance are the goal.

2.3 Material systems and processes

All material systems of potential interest must be specified, together with the manufacturing process considered. The method requires that all material systems and manufacturing processes included in the evaluation are equipped with defined material properties and that manufacturing cost models are available to address multiple objectives.

2.4 Requirement classification

Also, in order to evaluate the suitability of the material systems for the different areas of the body structure, requirements need to be classified to suite the material selection scheme.^{8,13} The requirements

are, consequently, categorised as local or global requirements of rigid or functional type, examples of such classification are presented in Table 1. Rigid type denotes a requirement which must be fulfilled by the material system's physical properties e.g. environmental and process requirements. Functional type consists of requirements which describe the demands related to mechanical properties for example stiffness, toughness and strength. These requirements are assigned to a certain area of the body structure i.e. a local requirement and are therefore affected by the geometrical constraints of that area.

Table 1 Examples of the classification of requirement for body structure

Requirement	Classification	Type
Temperature requirement paint shop	Global requirement	Rigid
Body structure design spaces	Local requirement	Rigid
Front structure, energy absorption	Local requirement	Functional
Roof structure, flex - less than 30 mm	Local requirement	Functional
A-pillar area, no intrusion more than 150mm	Local requirement	Functional
Engine proximity, increased service temperature +100°C	Local requirement	Rigid
Service temperature -40°C to + 60°C	Global requirement	Rigid

The geometrical requirements govern the design volume i.e. which space the body structure may occupy. This volume is defined by the design of the car body exemplified in Fig 2a which creates an outer space boundary. These include regulations such as driver's visual angles, safety requirements and legislation, as shown in Fig 2b, as well as passenger and subsystem space requirements. These requirements create a design space, a limited volume, for the body structure illustrated in Fig 2c. The design space will provide structural shapes for the different areas of the body structure, shapes such as panels, beams, rods etc. which are required to fulfil certain tasks i.e. the functional requirements.

a)

Fig. 2 Geometric requirements. **a)** A Design creates rigid geometric requirements for the outer surface, courtesy of Volvo Cars Group. **b)** Sub-components, passenger space requirements, wheels position etc. creates rigid geometric requirements for inner and outer boundaries, courtesy of Volvo Cars Group. **c)** The geometric requirements create a design space for the body structure.

Applying the methodology created by Ashby⁸, combining these two types of requirements, geometric and functional, a function is created e.g. panel stiffness. This function can be solved in different fashions as long as the geometrical requirements are maintained and the functional requirements are met. By visualising the functions in the design space for the body structure, as in Fig. 3a, a first partition is made creating a “function map” of the body structure. Furthermore, multiple functional requirements such as stiffness and toughness may be present in one geometrical area. All requirements must be treated in material selection, independent of area size i.e. attachment points with specific demands must also be addressed even though lacking a defined geometric shape. This is referred to further on as *local*.

Fig. 3 **a)** Example of a “function map” for the body structure. **b)** Graphical visualisation of largest part size for each process.

2.5 Screening – Globally and locally

Material system and manufacturing process evaluation can now be initiated by material screening. The material systems are required to fulfil the rigid requirements in order to be considered in the forthcoming steps e.g. service temperature, UV resistance etc. Hence, a material system which is unable to fulfil a local rigid requirement will be excluded from the selection for that specific area. An unfulfilled global rigid requirement will exclude the material system from the complete body structure.

2.6 Cost and weight ranking

A performance index^{8,13} is used to compare the material systems and processes and their suitability to execute the functions with regard to the objectives. Performance indices are used to describe the difference in impact between the mechanical property of the material system and the geometrical shape of the structure performing different functions (section Requirement classification) in regard to the objectives. Table 2 exemplifies some performance indices. The outcome can be perceived as a material system and process ranking for each of the chosen objectives, for example one for minimum weight and one for minimum cost for each function.

Table 2 Examples of material performance indices for minimising cost or weight;
C=material cost, €/kg, ρ =density, kg/m³, E=Young's modulus, GPa, G_{Ic} =Toughness, J/m²⁸

Function, functional requirements,	Objective	Material indices
Local, Stiffness,	Weight	ρ/E
Local, Stiffness,	Cost	$C*\rho/E$
Panel, stiffness,	Weight	$\rho/E^{1/3}$
Panel, stiffness,	Cost	$C*\rho/E^{1/3}$
Beam, stiffness,	Weight	$\rho/E^{1/2}$
Beam, stiffness,	Cost	$C*\rho/E^{1/2}$

Toughness,	Weight	ρ/G_{1c}
Toughness,	Cost	$C^*\rho/G_{1c}$

2.7 Analysis – objectives

In order to define a single optimum material system and process for each area, a trade-off between objectives must be made. This multi-objective problem is solved by defining a penalty function, P , based on the performance indices for the problem. By introducing a value for weight, α (€/kg), the performance index for weight, M_w , can be defined in the same unit as the performance index for cost, M_c (€/performance) and the problem can be solved ¹⁴ by minimising

$$P = M_c + \alpha * M_w \quad (1)$$

2.8 Partition

The previous step has divided the design volume into a large number of areas based on function and functional requirements. A preferred material system and process is defined for each of these areas. However, it should be noted that these areas do not represent the greatest potential part size or integration potential from a process point of view. The largest composite part size is not governed by a geometric shape or functional requirement, instead it is governed by the manufacturing process selected. Also, sometimes different composite material system can be processed together into one component in one single process step. Therefore, as shown in Fig. 3b, independent of the underlying function and functional requirement, the greatest interrelated area for the preferred process is sought defining the largest part sizes in the design space.

[insert Figure 3b]

3 Case study

Pre-selection of composite material systems and processes for an automotive body structure was performed according to the method presented in this paper. Due to the substantial number of requirements concerning automotive body structure, the number of functional requirements was limited to stiffness and toughness to make the methodology and case study comprehensible. Data and results are thus purely academic and should be treated in this fashion. Finally a minor trade off analysis was performed to further explore the feasibility of the method.

The proposed material selection philosophy⁸ in the method considers only the in-plane properties of the materials. In order to compare laminated with non-laminated material systems, anisotropic with isotropic materials, without neglecting the differences of in-plane and out-of-plane performance, the following methodology was used. The panel stiffness for the laminated material systems was calculated according to classical laminate theory¹⁵. Subsequently, when calculating the performance index, *panel stiffness*, the laminated material systems were given the in-plane tensile stiffness of an isotropic material providing the equivalent panel stiffness. However, when considering the *beam stiffness* index, the overall stiffness was assumed not to be effected by the stacking sequence due to the minor effect of ply position compared to the distance between the opposite flanges.

Three continuous and one discontinuous fibre material system were considered:

- Continuous high strength carbon fibre¹⁶ and resin transfer moulding epoxy resin¹⁷ manufactured by an extremely automated resin transfer moulding process, referred to as *RTM HA*

- Continuous high strength carbon fibre¹⁶ and resin transfer moulding epoxy resin¹⁷ manufactured by a less automated resin transfer moulding process, referred to as *RTM LA*
- Continuous high strength carbon fibre¹⁶ and polyamide thermoplastic prepreg manufactured by compression moulding, referred to as *CM*.
- Discontinuous high strength carbon fibres and epoxy resin prepreg manufactured by compression moulding, often called advanced SMC, referred to as *A-SMC*¹⁸.

The less automated RTM process, RTM LA, was included in order to visualise the effects of low levels of investment with fewer machines and robots and consequently higher cycle times and a more labour-intensive process. However, the same mechanical properties as for the RTM HA were here assumed for the final structure from the RTM LA process. Material data used in the case study are presented in Table 3.

Two different symmetrical laminate lay-ups were used for each continuous fibre material system in order to highlight the effect of structurally designed laminates. Fig. 4 shows the laminates considered, where one is quasi-isotropic symmetric, *QI*, and the other has 50% of its fibre volume in the main load direction, *UD*. The QI laminate was assumed to always be positioned so that the contribution to panel stiffness of the outer ply was maximised (Fig. 4a). The UD laminate was designed with the main load-bearing fibre volume in one of the mid-layers for reasons of fibre protection and therefore not in the optimal position for panel stiffness (Fig. 4b). Finally, A-SMC was considered quasi-isotropic. All material systems included high strength, HS, industry grade carbon fibres and standard resins. The material properties are presented in Table 3.

Fig. 4 **a)** Laminate layup considered for the QI laminate, thickness (t). **b)** Laminate layup considered for the UD laminate, thickness (t).

Table 3 Material properties^{16,17,19}, *same properties assumed for RTM HA and RTM LA

Material system	A-SMC	RTM HA UD*	RTM HA QI*	CM UD	CM QI
Material properties					
Density [kg/m ³]	1.5	1.5	1.5	1.5	1.5
In-plane stiffness [GPa]	38	70	45	70	45
In-plane stiffness, applied or panel stiffness index, [GPa]	38	47	77	47	77
Strength [MPa]	300	1617	1011	1617	1011
Toughness G _{1c} [J/m ²]	1500	65000	65000	93000	9300

Fig. 6, describes the operations of the manufacturing processes included in the cost model. The cost model provides the manufacturing cost of one kilo final structure, C_{FP} (in €/kg) assuming a part with a low geometric complexity, designed with a series volume dependency and with a detail level suitable for this pre-selection method.

Fig. 5 The manufacturing processes considered with the basic manufacturing operations.

4800 operating hours per year on three shifts were assumed. The annual production rate, M_{volume} , for one set of tools is governed by the cycle time, t_c , for the process. The cost for one kilo of final structure was defined as

$$C_{kg\ final\ part} = C_{part} + \frac{C_{invest}}{V} + INT \left[\frac{V}{M_{volume}} \right] * \frac{C_{reinv}}{V} = \frac{C_{total}}{V} \quad (2)$$

Where C_{invest} is the initial investment for the complete manufacturing line and $C_{reinvest}$ is the recurring investment needed to increase the annual volume. C_{part} is the part cost including material, $C_{feedstock}$, and scrap, m_{scrap} , labour cost, C_{labour} and overhead cost, C_{OH} .

$$C_{part} = C_{feedstock} * (1 + m_{scrap}) + C_{labour} * t_{cycle} + C_{OH} \quad (3)$$

All investments are assumed to be depreciated over 5 years. Process data are presented in Table 4.

Table 4 Process data for material systems and processes ²⁰

Material system and process	A-SMC	RTM HA	CM TP	RTM LA
Process data				
Cycle time [min]	3	5	1	30
Feedstock cost [€/kg]	36	17	39	17
Scrap level fibre [%]	2	20	20	20

The objectives of the material system and process selection in this case study were to minimise weight and cost. Since the cost model provided the cost for one kilo of final structure, the cost and weight-specific material indices could be compared. The requirements for the type of body structure considered in this case study were then categorised according to the method proposed. The temperature range constraint was set at -40/+60°C except for engine proximity where local screening was applied and the

service temperature was set to -40/100°C. Process-related constraints such as paint shop and assembly were assumed to be adapted to polymer materials. All material systems considered thereby fulfil all rigid requirements.

Performance indices (Table 2) addressing the functions and in regard to the weight and cost objectives were calculated for all material systems. Each material system then gained two material indices that expressed their ability to minimise cost respectively minimise weight for each area of the body structure. The value of weight, α , was set at 9 €/kg²⁰ in order to anticipate a future increase compared to today's value³. The penalty function was solved and the optimum material system and process was defined for each function. Finally, partition in regard to manufacturing processes and largest potential part and integration size was defined by using a colour code for each optimum process visualised on the design space of the body structure.

4 Results and discussion

The penalty equation (1) defines the preferred material system and process for each function, based on the value of weight. However, to improve understanding of results and differences between the material systems and processes under evaluation, their performance related to objectives cost and weight are visualised in graphs in Figs. 6.1-6.3. The graphs describe their ability to minimise weight on the y-axis and cost on the x-axis. The further to the left, the cheaper the solution with respect to performance and the further down the lighter the solution. The ideal trade-off between minimising weight and cost potential is sought and it can be observed that there are several solutions to the problem depending on priorities. The value of weight is introduced to define this balance between weight and cost. In Figs. 6.1-6.1 the value of weight is represented as the slope plotted in the graphs and characterises the gradient of

the value of weight used in the penalty equation along which the preferred solution is found i.e. the trade-off surface for the solution. Figs. 6.1-6.3 present the results for different series volume scenarios, 10 000, 50 000 and 100 000 parts/year, in order to emphasise the impact of cycle time and industrial investments.

Fig. 6.1 Cost/weight performance for panel stiffness presented with the trade of curve describing the value of weight 9€, presented for annual volumes of 10 000, 50 000and 100 000 parts/year.

Fig. 6.2 Cost/weight performance for beam, stiffness presented with the trade of curve describing the value of weight 9€, presented for annual volumes of 10 000, 50 000and 100 000 parts/year.

Fig. 6.3 Cost/weight performance for toughness presented with the trade of curve describing the value of weight 9€, presented for annual volumes of 10 000, 50 000 and 100 000 parts/year.

The trend observed is that RTM LA becomes the preferred choice for all functions and functional requirements at low volumes. The low investment and feedstock cost, together with high quality mechanical properties of the final structure governs the outcome. The low production rate per tool of the process is, however, penalised in larger series. With increasing annual volume, the automated processes RTM HA and CM become more competitive. As can be observed from Figs. 6.1-2, RTM HA is the preferred process for beam and panel stiffness functions. The combination of low feedstock cost together with high quality mechanical properties provides an advantage, although it is a slower process compared to CM. Finally, Fig. 6.3 shows that in spite of the cost-driven nature of the automotive industry, the more expensive but lighter solution CM becomes the preferred solution.

The lack of competitiveness of A-SMC, in spite of low cycle times and investment cost, emphasises the importance of utilising the high level mechanical properties and the potential of structurally- designed laminates of these expensive materials, instead of mimicking isotropic materials and cutting up the fibres. Combined with feedstock cost, this material system is not competitive. Hence, the results also highlight the importance of selection methodology taking into account the effects of laminated materials and structural design. If this had been neglected in the selection processes, RTM HA, RTM LA and CM would have been less competitive both in regard to cost for performance and weight of performance.

In Fig. 7, cost per kilo manufactured structure is shown in relation to annual volumes. When analysing the results, three phases can be observed: an initial phase, for series volumes below 10 000 units/year, which is investment-critical while cycle time, feedstock and running cost are of less importance. With increasing series volume a second phase, >10 000-50 000 units/year can be observed, during which a transition from investment cost dependency to feedstock and running cost dependency appears. This

phase is different in all manufacturing processes and dependent on the cycle time and the magnitude of investment. Stabilisation at running cost is reached after different annual volumes and at different cost levels for all processes studied. Above 50 000 units/year, a third phase occurs one of stabilisation towards cost governed by feedstock and operating cost. Furthermore, recurring investments are seen in Fig. 7 as local increases in the part cost; one for each time a new investment is needed due to shortage of production capacity. With increasing series volume, the impact of the recurring investment on the part becomes low compared to the final cost of a kilo of structure. Hence, the results show too that the feedstock cost becomes the competitive factor of a composite material system and process in regard to cost when approaching high series volumes. This is also why the RTM process, utilising less expensive materials lower down in the value chain, becomes much more competitive even though it requires higher levels of investments and longer cycle times.

Fig. 7 The cost of 1kg of final structure over the annual volume 1-100 000 parts/year based on the cost model, 4.1.2.

Moreover, RTM possesses another strategic advantage compared to the other manufacturing processes, it enables a strategy to begin at low investment levels for short series volumes (RTM LA) and with growing volumes increase automation without imposing major changes to structural or part design. This opportunity is less obvious with A-SMC or CM.

Fig. 8 Preferred process partition with structural design areas visualised (a) 10 000 parts/year, (b) 50 000 parts/year, (c) 100 000 parts/year.

The results shown in Fig. 8 visualise the partition of the body structure in relation the process choice i.e. the greatest part size for each preferred manufacturing process. As can be seen in Fig. 8a RTM LA is the preferred process for low annual volumes for the complete body structure. For higher series volume, Fig. 8b, the optimum cost/weight trade-off is to produce the structures with toughness demands such as

A and B pillar together with front structure in CM and all structures with stiffness related requirements in RTM HA. Finally as seen in Fig. 8c, the same solution is also identified for higher annual volumes. However, with the case study considering two functional requirements only, the partition of the body structure becomes low and not as diversified as if multiple functional requirements had been applied. However, since the complexity of the component does not influence the cost model in this study, further study is necessary as to whether producing the whole body structure in one or two highly complex parts really is the most cost efficient method.

4.1 Trade-off analysis

Different scenarios could affect the industry and the method results. The sensitivity of the method was examined when the following cases were addressed:

- Tougher legislation drives the value of weight towards aerospace industry levels.
- The development of low cost carbon fibre results in a new carbon fibre grade with 70% of the performance at 1/10 of cost compared to today's carbon fibres.

Increased value of weight. In the future, the automotive industry could experience a higher value of weight up to the level currently applied in the aerospace industry, e.g. up to 500 €/kg¹. As shown in Fig. 10, this would change the trade-off surface and make it minimising weight more favourable in comparison to cost. The difference is excessive but even at today's value of weight, structural designed parts with continuous fibre are favoured before discontinuous in this pre-selection case study due to lower performance cost. Hence, a higher weight value would not drastically change the results of material selection in this case study.

Fig. 9 Panel stiffness function for an annual volume of 100 000 parts/year. With the value of weight for the automotive respectively the aerospace industry as trade of surfaces.

Carbon fibre development. A carbon fibre based on a new precursor, lignin for example²¹, which would decrease the feedstock cost would have no effect on overall pre-selection between the different processes. Consequently, all material systems in the evaluation are carbon fibre-based and such a scenario would only lead to a general feedstock cost decrease and an overall lower performance. However, as shown in Fig. 10, comparing the low cost carbon fibre, denoted LIGNIN, with a standard carbon fibre both manufactured in the RTM process (Fig. 10a) a noticeable decrease in the cost per kilo structure using the RTM LIGNIN can be observed.

Fig. 10 (a) Cost model comparison between RTM HA process and RTM LIGNIN, and cost and weight analysis,(b) panel stiffness and (c) beam stiffness, of RTM HA QI and RTM LIGNIN with the equal structural lay-up, annual volume 100 000 parts/year.

Figs. 10b and c shows the evaluation of performance-related weight/cost towards the value of weight for the automotive industry. It can be observed that for both panel and beam stiffness, here exemplified at volume 100 000 units/year, RTM LIGNIN becomes the preferred material system in spite of lower potential to decrease weight.

5 Conclusions

A methodology to define cost and weight objective material diversity and to select suitable manufacturing processes for a composite automotive body structure was presented. An initial step concerning how to divide the body structure was made by defining the largest part size based on process selection. The method allows for an initial step in a design methodology and, used in the critical phase, it could limit risk in regard to cost and weight when designing a fibre composite body structure. In order to compare laminated with non-laminated materials, a method was successfully included in the

framework. The integration of such a tool was important as if these aspects were neglected, some of the advantages of working with structural design materials would have been missed and the outcome of the pre-selection would have been different.

A case study demonstrated the pre-selection method with its different steps and also showed how to define the largest integration/part size for each process. Unexpectedly, rapid cycle time was not rewarded in the material system and process selection. Instead, low feedstock cost in combination with utilising structurally designed and material properties to the fullest provided the best solutions. The relatively low investment cost for all composite processes in relation to expensive materials created this effect.

Finally, by utilising the value of weight as a trade-off between cost and weight, the method clearly indicates that the automotive industry is still a cost-driven industry. It was shown that the structurally designed continuous fibres system becomes the preferred choice for low as well as high volume series, despite a cost-driven selection. This is due to the fact that laminated continuous fibre systems utilise the potential of the expensive materials much better than, for example, A-SMC but at a similar or lower feedstock cost.

6 Future research

The method proposed describes where the structure should be divided in regard to preferred manufacturing process and describes the potential largest part size. However, even though the largest part size implies an integral design providing a limited number of joints, and by that a weight optimum, it might not be the most cost effective size. Consequently, a method to analyse if further partitioning of the largest part size should be advised is necessary. Such a methodology must consider how part size

and part complexity, as well as assembly techniques, influence the cost and weight of the final body structure.

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8 References

1. Wang K, Kelly D, Dutton S. Multi-objective optimisation of composite aerospace structures. *Compos Struct*. 2002 Jul;57(1-4):141–148.
2. Das S. The cost of automotive polymer composites: A review and assessment of DOE's lightweight materials composite research. 2001.
3. Adebisi AA, Maleque MA, Rahman MM. Metal matrix composite brake rotor: historical development and product life analysis. *Int J Automot Mech Eng*. 2011;4(December):471–480.
4. Mazumdar S. Composites Manufacturing: Materials, Product, and Process Engineering. 1st ed. CRC Press LLC; 2001.
5. Mileham, R. A., Currie, C. G., Miles AW, Bradford DT. A Parametric Approach to Cost Estimating at the Conceptual Stage of Design. *J Eng Des*. 1993;4(2):117–125.
6. Rodney D. Stewart RMW. Cost Estimator's Reference Manual. 2nd ed. Wiley Interscience; 1995.
7. Jahan A, Ismail MY, Sapuan SM, Mustapha F. Material screening and choosing methods – A review. *Mater Des*. 2010 Feb;31(2):696–705.
8. Ashby MF. Materials selection in mechanical Design. 4th ed. Butterworth-Heinemann; 2011.
9. Henderson R, Shipp C, Gutowski T. Manufacturing Costs for Advanced Composites Aerospace Parts. *SAMPE J*. 1991;27(3):37–43.
10. Carlsson BT. Selecting material for the exterior panel of a private car back door by adopting a total cost accounting approach. *Mater Des*. 2009 Mar;30(3):826–832.
11. Kaufmann M, Czumanski T, Zenkert D. Manufacturing process adaptation for integrated cost / weight optimisation of aircraft structures. *Plastics, Rubber Composites: Macromolecular Engng* 2009; 38(2–4): 162–166.
12. Bader MG. Selection of composite materials and manufacturing routes for cost-effective performance. *Compos Part A Appl Sci Manuf*. 2002 Jul;33(7):913–934.
13. Ashby MF, Bréchet YJM, Cebon D, Salvo L. Selection strategies for materials and processes. *Mater Des*. 2004 Feb;25(1):51–67.
14. Ashby MF. Multi-objective optimization in material. *Acta Mater*. 2000;48:359–369.

15. Jones RM. Mechanics of Composite Materials. New York: McGraw-Hill; 1975.
16. Sigmatex. Major PAN-Based Carbon Fibre Producers Product Comparison. 2013.
17. Hysol EA 9150. *Henkel Corp.* 2013;5–7.
18. Hexcel. HexMC ® Moulding Concept. 2000.
19. Corporation F. Fiberforge Carbon / Nylon Unidirectional Blank Matrix : *Mater data sheet*. 2012;1.
20. Volvocars. internal communication Volvo cars group. 2013.
21. Norberg I. Carbon fibres from kraft lignin. 2012;25–30.