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Linköping University Post Print

N.B.: When citing this work, cite the original article.

Original Publication:
Frida Andersson, Astrid Hagqvist, Erik Sundin and Mats Björkman, Design for Manufacturing of Composite Structures for Commercial Aircraft: The Development of a DFM strategy at SAAB Aerostructures, 2014, Procedia CIRP, (17), 362-367.
http://dx.doi.org/10.1016/j.procir.2014.02.053
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Postprint available at: Linköping University Electronic Press
http://urn.kb.se/resolve?urn=urn:nbn:se:liu:diva-113084
Variety Management in Manufacturing
Proceedings of the 47th CIRP Conference on Manufacturing Systems

Design for Manufacturing of Composite Structures for Commercial Aircraft - the Development of a DFM strategy at SAAB Aerostructures

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Abstract
Within the aircraft industry, the use of composite materials such as carbon fiber reinforced plastics (CFRPs) is steadily increasing, especially in structural parts. Manufacturability needs to be considered in aircraft design to ensure a cost-effective manufacturing process. The aim of this paper is to describe the development of a new strategy for how SAAB Aerostructures addressing manufacturability issues during the development of airframe composite structures. Through literature review, benchmarking and company interviews, a design for manufacturing (DFM) strategy was developed. The strategy ensures that the important factors for successful DFM management are implemented on strategic, tactical and operational levels that contribute to a more cost-efficient product development process and aircraft design.

1. Introduction
Historically, aircraft manufacturing, and especially assembly operations, has mainly been performed manually. This was due to long development times with continuous changes in aircraft design, making serial manufacturing not applicable. [1] It was not economically feasible to invest in expensive equipment, even when it was technically feasible. Previous commercial aircraft manufacturing and design was to a large extent conducted in-house, while today the design and manufacturing of parts and subsystems are often outsourced to several different sub-suppliers. This network of suppliers puts strong requirements on cost and time of delivery, since it is normally easier to change a supplier than shut down an in-house division [2]. The amount of air travel is expected to increase in the coming 20 years, by around 5% per year according to Airbus [3] and Boeing [4]. This means a higher demand for aircrafts among the world’s aircraft manufacturers [2]. Besides the change from single-unit manufacturing to series manufacturing, this also requires a shorter time for product development and manufacturing in order to achieve low costs [5].

One way to meet these demands is to work more with design for manufacturing (DFM) strategies and methods, since DFM directly address the costs for manufacturing, which are a large part of the entire product cost [6]. DFM is a way to lower manufacturing costs while not lowering product quality [6]. DFM is not a new design method; as early as in the 1920s, Henry Ford was conducting a kind of DFM [7]. Although Ford performed DFM back in the 1920s, the traditional “over-the-wall” design approach was not common practice until the 1950s to at least the 1970s in Western companies [8]. In the 1980s, concurrent engineering spread rapidly in research and industry. Foremost, it was the American automotive industry that led the way in adopting new product development organizations and processes in order to compete with Japanese competitors. In addition, since concurrent engineering spread so fast among the manufacturing
companies of the Western world, it is likely that there must have been a tremendous need to improve the product development process in many countries [8].

Initially, many DFM efforts placed it at a general level. This changed, however, with the growing attention towards automation. According to Riley [9], the pace of automation in the USA accelerated during the 1950s due to high production volumes, increasing labour costs and the introduction of the vibratory bowl feeder.

Interestingly, after redesigning for automatic assembly, many firms discovered that the redesigned product became so simple to assemble manually that automatic assembly was no longer economically feasible [10]. This means that DFM can significantly improve design both for manual and automatic assembly, e.g. reduction of components and easier part insertion.

The consequence of not designing products for manufacturing can be prolonged product development and manufacturing, and at the same time, high costs for development and manufacturing. This is due to the high risk of creating products that are unnecessarily complex to manufacture, or that needs to be redesigned in order to manage problems not discovered until manufacturing ramp-up [8].

In aircraft manufacturing, there is also a high demand for lowering fuel consumption and environmental impact. One way that aircraft manufacturers are dealing with these demands is to reduce the weight of the aircraft by using new types of materials, especially composites of carbon fiber reinforced plastics (CFRP). Historically, these materials have not been used to a large extent in aircraft production, and it is important to incorporate and regard the specific material properties of these materials in the DFM methods that are going to be used in the aircraft industry.

There has been limited implementation of DFM in the aircraft industry, since the main focus in aircraft design has traditionally been on functionality, weight reduction, material usage and durability. However, the increased importance of cost reduction, in combination with increased production volumes and usage of CFRP, makes it vital to implement DFM. It is important when working with DFM to regard the manufacturing process early in the product development process. An issue when working with DFM is that problems with assembly are usually not discovered until the manufacturing phase, when the costs for design changes are very high [11].

A majority of the problems in manufacturing are derived from an inadequate design [5], which depends much on weaknesses in both knowledge and communication between designers and manufacturing engineers [5, 11]. Therefore, there is an industrial need to develop and work with DFM.

1.1. Aim

The aim of this paper is to describe the development of a new strategy for how SAAB Aerostructures which should address manufacturability issues during the development of airframe structures with composite materials such as carbon fiber reinforced plastics.

1.2. Methodology

In order to reach the aim of this research, a combination of research methodologies was used. First, a literature study was performed within the areas of design for manufacturing, aircraft manufacturing and composite materials. The literature study was performed at the Linköping University library as well as using the Scopus and LIBRIS databases. In parallel to the literature study, an interview series was conducted with staff at SAAB Aerostructures working in different disciplines. The interviewees came from the departments of product development, composite engineering, manufacturing, final assembly and lean production coordination. The interviews were semi-structured and lasted between 30 minutes and one hour. In addition, a benchmarking study was conducted at other manufacturers in Sweden working with design for manufacturing. These companies are developing and manufacturing other kinds of products, e.g. heavy trucks, agricultural machinery, separators and forklifts. The data from the benchmarking was collected by industrial visits, with interviews on site and/or via telephone. In all, seven companies were benchmarked. Observation studies were performed at the departments of composite manufacturing and final assembly within SAAB Aerostructures in order to get a better picture of the current situation.

After these initial steps, workshops about DFM were held with stakeholders and future users of DFM methodology. At these workshops, DFM issues that had not been identified in the interviews and observations were brought up.

As a second step, DFM success factors were identified, along with a mapping of current manufacturing and development processes. Based on these results, a DFM strategy for SAAB Aerostructures was established.

1.3. SAAB Aerostructures

At SAAB Aerostructures in Linköping, structural parts such as doors and ailerons for commercial aircrafts are being developed and manufactured. The major customers are Airbus and Boeing. One of the products produced at SAAB in Linköping is the large cargo door for the Boeing 787 program, as depicted in Fig. 1. The product development process at SAAB is divided into two major phases, preliminary development and detail development. The focus in the development projects has traditionally been functionality, weight reduction, material usage and durability. Manufacturability, however, has not had the same strong focus. The execution of the development projects is adjusted to comply with the different requirements of the development processes of Airbus and Boeing.
1.4. Aircraft manufacturing

The most common materials in aircraft manufacture are aluminum, stainless steel, titanium and CFRP. CFRP is considered to have good weight and material features, in primary structural parts it is now used as well in all wing and stabilizer components such as skin panels, ribs and spars, control surfaces as in fuselage skin, stringers and frames. Historically it has been used extensively in secondary structures such as fairings, floor panels and interior. The manufacturing process for CFRP parts is very expensive, due to the high price of raw materials and the special tools needed for manufacture [2]. The process also has a high number of manual operations, which makes it expensive to perform in a high-wage country like Sweden.

Composite parts are becoming more common in structures for civilian aircrafts [12]. At the same time as the use of composites is increasing, the competition between manufacturers has become more intense [13]. The areas of application for CFRP are increasing fast, which means that the development efforts within composites are also increasing [14]. The implementation of new materials and technologies requires new procedures for how to design and build aircrafts [15].

Some of the main reasons for increasing the use of composites in aircraft structures are the expectations of decreased life-cycle cost, weight and number of parts [15]. A suitable composite construction can contribute to good design flexibility, lighter components, simplified manufacturing and installation methods, higher resistance to corrosion and high fatigue strength, as compared to general metal structures [16].

2. Success Factors for Design for Manufacturing (DFM)

Within the context of the literature study, different commercial DFM methods were charted. Many similarities between the different methods were found, the most important being that the majority of the methods were developed for high-volume products of metallic or plastic materials. The methods are also all designed for automatic assembly. There are many different ways a DFM method can be configured, but one general guideline is that the method should contain some kind of analytical evaluation of the design solutions [17]. The benchmarking showed that none of the investigated companies used a commercial DFM method. Instead, the companies had developed their own DFM methodology and processes. But when comparing the structure of the different commercial DFM methods with the way the benchmarked companies work with DFM, some generic success factors were found. The identified success factors can be categorised into three groups: general, organizational and process-related.

2.1. General success factors

Aim - One of the most important factors is to set measurable aims for the DFM work to be able to ensure that the desired goal is obtained [18].

Adapted to the conditions at the company - Herbertsson [8] and Norström & Rimskog [19] state that the DFM methodology needs to be adapted to the manufacturing process and company, since what is efficient in one manufacturing system not necessarily efficient in another. Moreover, a DFM method does not automatically create collaboration between different departments in a company; rather, the right organizational prerequisites need to be in place. This corresponds well with the findings from the benchmarked companies that work with DFM.

Designers educated in the manufacturing system - All of the benchmarked companies offered education in their manufacturing process to their designers to ensure that they understand the possibilities and limitations of the process.

DFM method implemented within the whole company - The DFM method needs to be accepted throughout the whole organization and to be an integrated part of the product development process [20]. This also corresponds well with the findings from the benchmarked companies.

Understanding of which parameters in the product design affect the manufacturability – Herbertsson [8, 17] states that in order to develop a DFM method, the parameters in the product that have the most effect on the manufacturability need to be identified. This is needed to be able to either create design guidelines on how to design the product according to DFM, or to be able to simulate how changes in the design impact the manufacturability. The benchmarked companies had a good understanding of which parameters in the product design affect the manufacturability. In fact, this was a condition for being able to develop their DFM methodologies.

2.2. Organizational success factors

Cross-functional and collocated product development teams – Herbertsson's [8] studies clearly show the need for cross-functional teams to be successful in DFM work. The companies in the benchmarking all used these kinds of teams; the larger companies also co-located the different competence areas when executing big product development projects.

Clear division of responsibilities - The benchmarking showed that the companies had a clear division of
responsibilities within DFM. This is supported by theory within the area. Eskilander [21] stresses the need for division of responsibilities to be able to ensure that the aim of the DFM work is reached, as well as the continuous improvement of the DFM methodology.

**Link between design and production departments** - One common challenge in product development is risk of conflicts between different departments due to differences in priorities and aim [6]. Many of the benchmarked companies have a group that is used as a link between the design and production departments in order to handle and prioritise the different demands on the product.

**Forum for communication of design changes** - Many of the investigated companies stress the need to handle proposals for design changes in a structured way. Meetings between the design and production departments, where problem areas in the design are presented visually and suggestions for design changes are discussed, is common. In practice, simulations or physical prototypes are used for this purpose.

### 2.3. Process-related success factors

**DFM is used early in the product development process** - Kuo et al. [20] state the need for the DFM method to be used early in the product development process, since the cost for making design changes increases as the development progresses. Almost all the investigated companies agree with this, and think that this is essential in order to succeed with DFM.

**Use of checklists when reviewing product designs** - All the investigated companies used some form of checklist when reviewing the design, as this is an easy and efficient method to ensure that no essential aspect is overlooked and that all demands are met.

**DFM should be a help for the designer in the development process** - The designer needs to understand why DFM is important and how the designs are being evaluated [17].

**DFM should inspire and contribute to creative solutions** [20].

**Time to redesign problem areas in the design** - The companies that were investigated have all seen the need to have sufficient time between design reviews and the start of production in order to be able to correct design flaws and improve problematic designs. The review and evaluation of designs need to be continuous during the development process, and not just occur at the end of the development project.

### 3. The new Design for Manufacturing strategy at SAAB Aerostructures

Based on the interviews, workshop and observation studies held at SAAB, several areas for improvement were identified at the company. By comparing the success factors identified from the literature study and benchmarking against how SAAB’s product development work is organized, some potential areas for improvement were found. Another important area that was identified was the trade-off between complexity in the manufacturing of CFRP parts and complexity in final assembly. A high integration of functions at the CFRP part level may reduce complexity and costs in final assembly. However, an unsuitable integration may create fewer but more complicated assembly operations, and thus increase assembly costs. Furthermore, high integration often induces costs and quality issues in the manufacturing of CFRP parts. This aspect is important to consider when developing a tool to be used in the product and production development process.

From the identified success factors needed at SAAB to succeed with DFM, a strategy adjusted for SAAB and its development areas was designed. The DFM strategy developed for SAAB will create the potential to make the product development process more effective regarding the work with manufacturability. The DFM strategy is divided into three organizational levels (see also Fig. 2):

- **Strategic**
- **Tactical**
- **Operational**

The strategy describes how the work with DFM should be performed on the different organizational levels. It also includes a DFM tool/method, specially adapted for the conditions at SAAB, for the designers to use in the concept development phase.
The strategic level consists of several guidelines on how the aims for the DFM work should be stated and implemented. It is important that the aim with DFM complies with the overall aims at SAAB. The DFM work should be implemented in the whole organization, and contribute to good coordination and communication between disciplines within the company. It is important that the designers know what in the design contributes to lower/higher costs and less/more complex manufacturing, including the trade-off between costs in the manufacturing of CFRP parts and the final assembly.

The tactical level describes how the work with DFM should be organized. It is preferable that the development core team is cross-functional. Another major change in the organization is the implementation of a design and production coordination (DPC) team. This team will function as a link between different disciplines within the organization and development team. The members of the DPC team have the overall responsibility for the DFM work. They will facilitate the communication between different product development projects, and prioritize between requirements from different departments regarding design matters. In the long run, the company should set up a system for knowledge sharing to be able to spread good solutions to DFM problems.

On an operational level, a DFM method is implemented for the designers to use during the concept and design development. In addition, the routine for the design review is extended with a set of aspects to consider when evaluating the design. Both the DFM method and the review procedure aim to ensure that no important aspect of DFM is neglected during the development process. Finally, a decision matrix was developed. The matrix is to be used when making decisions about the design, and should function as a guide for the project team to make informed decisions, and be an easy way of weighting different requirements put on the design.

4. Implementation of the DFM method

The DFM method developed is focusing on efforts in the first phase in the product development process called preliminary product development, see Fig. 3. There are six stages in the implementation of the DFM method marked with circles in Fig. 3. To support these six stages four documents were developed. The next paragraphs describe the stages in the DFM method:

1. Map the product - the first step is to divide the product parts into components. Components refer to the elements that create the structure of the product. Thereafter, the base component is defined. The base component is the component that the remaining components and sub-assemblies should be mounted on. Usually, it is the component that will be attached to the jig/fixture. Depending on the size of the product, it may be divided into several sub-assemblies, which can be assigned to different designers for further work. This stage is performed in-between "Prerequisites review" and "Establish functional baseline" in the process for preliminary product development at SAAB Aerostructures (see Circle 1 in Fig. 3).

2. Investigate integration possibilities - the designer must answer questions regarding the components. These questions, along with instructions on how to apply and use them, are presented in Document 1: Possibilities of Integration.

   The purpose is to identify the components that are possible to eliminate or integrate. The result of this is the basis for concept generation in the next step. However, integration must be weighed against the costs and difficulties that may arise in the composite workshop due to a more complex component. Furthermore, the number of assembly operations is reduced in final assembly with high integration, but the remaining assembly operations can become more complicated (see Circle 2 in Fig. 3).

3. Generate concepts - the designers generate different concepts that integrate the components identified in Stage 2. A DFM knowledge database should serve to support this process. The images from the DFM knowledge database should show good examples of design solutions that are verified and work well in the existing production (see Circle 3 in Fig. 3).

4. Analyze concepts - the generated concepts should at this stage be evaluated using the checklist in Document 2: DFM analysis. It is then possible to repeat Stages 3 and 4 in an iterative process to further develop the concepts. One or more concepts are then transferred to Stage 5.

5. Select concept - based on the decision matrix in Document 3: Decision matrix, the selected concepts are evaluated against each other. The evaluation will be done by a discussion between the team members in the preliminary design. The team members represent all different categories of engineering. The aim is to create a discussion about the manufacturability to highlight problem areas and develop the concepts further, in order to avoid the production of technically difficult structures and designs.

Fig. 3. Process for preliminary product development at SAAB Aerostructures.
6. Evaluate product - the concept selected in Step 5 will be further developed to a maturity level similar to that at the Preliminary Design Review (PDR). Before the PDR takes place, the product shall be evaluated and approved by the DPC Group. The survey is based on the DPC checklist in Document 4: DPC checklist. The evaluation should be done in advance of the PDR so that there is time for the designer to address any objections. The review will then be repeated later in the product development process, during the Critical Design Review. The four documents;

- Document 1: Possibilities of Integration,
- Document 2: DFM analysis,
- Document 3: Decision matrix, and
- Document 4: DPC checklist

that support the DFM method are not presented in this paper due to lack of space. However, they will be presented at the 47th CIRP Conference on Manufacturing Systems, 28-30 April 2014 in Windsor, Canada.

5. Discussion and conclusions

In DFM theory, several success factors were identified and categorized into three groups: general, organizational and process-related. These success factors were then used to develop a DFM strategy customized for SAAB Aerostructures’ aircraft manufacturing containing composites such as carbon fiber reinforced plastics. The newly developed DFM strategy contains a DFM method operating at three organizational levels: strategic, tactical and operational. The developed DFM method is designed to be implemented at the six stages: 1. Map the product, 2. Investigate integration possibilities, 3. Generate concepts, 4. Analyze concepts, 5. Select concept and 6. Evaluate product. The new DFM method gives SAAB a structured approach to achieve better products adapted for manufacturing in a shorter time than the previous product development process did. The method is adapted for SAAB’s aircraft manufacturing with extensive use of carbon fiber reinforced plastics.

Acknowledgements

The authors would like to thank the Swedish Governmental Agency for Innovation Systems (VINNOVA) for financing this research project called “Next Generation Composites Structures for Commercial Aircraft” through their program called “Grön flygteknisk demonstration”. The authors would also like to thank everyone who supported them during the empirical study, and especially those involved from SAAB Aerostructures.

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