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Composite Manufacturing: How Improvement Work Might Lead to Renewed Product Validation

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ABSTRACT

High-performance polymer composites are mainly used in applications where the benefits of high strength and low weight justify the high material and manufacturing costs. Many of these applications are found today in the aerospace, space and defense industries. Most of today's commonly used manufacturing methods within this area are highly labor intensive. Furthermore, the quality requirements from the customers require a high level of process control. The purpose of this paper is to explore how changes that are introduced in order to improve productivity in a manufacturing system are managed, particularly with regard to who takes the decision to implement a change and how a change is validated. The study is based on qualitative interviews performed at several companies that manufacture composite components for the aerospace, space and defense sectors. The findings show that the responsibility for deciding to implement a change and the need for validating it are based on many diverse and interconnected factors. Therefore, it is difficult to construct guidelines for early assessment of the scope and cost of a proposed change. Hence each individual change request must be evaluated on its own. The study also shows that the validation process can be adapted to a level that is based on the type of change. In addition, it highlights that control over process parameters in manufacturing is essential.

Keywords: composite manufacturing, validation, change request management

1. INTRODUCTION

High-performance polymer composites offer a combination of high strength and low weight that is often desirable in complex applications. Many of the production methods used for manufacturing this type of product are labor intensive, with a high degree of manual operations and handling. Manufacturing of complex products for advanced applications also requires a high level of process control [1]. These factors result in high manufacturing costs that, combined with high costs for raw material, result in high product costs. Therefore, complex products manufactured from high-performance composites are mainly used in areas where the low weight can justify a high cost, such as in space, aerospace and defense applications. The high manufacturing costs encourage improvement work within the manufacturing system aimed at lowering the final product cost. The changes introduced to lower manufacturing costs must be verified in order to comply with the strict quality standards in the space, aerospace and defense industries.

The purpose of this paper is to increase the awareness of the connection between productivity-improving changes in the production system, and the need for product and process validation when manufacturing

composite parts in the aerospace, space and defense industries. It also shows examples of management systems that are used in industry to handle change requests. The paper aims to explore examples of different types of changes in the composite manufacturing system that can be introduced in order to increase productivity, and how the changes can result in the need for renewed validation of processes and products due to quality standards.

2. METHODOLOGY

A literature review has been performed to identify the research front in the area of change management and process validation in composite manufacturing, as well as in other lines of business. The manufacturing techniques that are employed by the companies in the study have been examined by means of both theoretical and empirical studies.

Three different companies engaged in composite manufacturing were studied, mainly by means of qualitative studies [2]. The research was performed in cooperation with the companies in three separate stages. The first stage was an introduction to the company and some of the manufacturing processes during factory visits. The second stage consisted of a semi-structured interview [3] with five prepared thematic questions. The questions related to the interviewed

person's background and experiences in composite manufacturing, the company's product development model and the certification/validation of newly developed products. In the third stage, a semi-structured interview based on a number of hypothetical cases was conducted. The cases present changes that can be relevant in order to improve the production system. The aim is to explore how the changes will be handled and what type of validations will be required to implement the changes. All of the interviews were conducted with the same representative from each company. In addition, all of the interviewees had extensive experience in the manufacturing of polymer fiber composites, and work as managers for either product development or manufacturing engineering departments at their company.

3. PRESENTATION OF COMPANIES ENGAGED IN THE STUDY

Three companies using polymer composite material in their production have been included in this study. All three companies are active in and represent either the aerospace, space and/or defense industries in Sweden. The companies have different manufacturing commitments, depending on their products and customers. However, all of the studied companies have products that are considered to be Contracted Design and Manufacturing, or CDM, commitments, and all employ the rigorous quality standards that are used in the space and aerospace industries.

3.1 Company A

Company A is a subsidiary company within a group of companies, with a size similar to a traditional SME (Small and Medium-sized Enterprise). The company's major markets are the aerospace, defense and transport industries, and it offers a wide range of products. The products can be divided into three separate segments. One segment of products has been developed internally within the company, and these products are sold as final products. The second segment is made up of products that have been developed in collaboration with the final customer as a traditional CDM commitment. The last segment consists of products that have been developed by the customer and produced at the company according to the customers' specifications. The manufacturing techniques that are employed within the company are filament winding, Resin Transfer Molding (RTM) and manual pre-preg placement. The company also has capacity for machining and assembly.

3.2 Company B

Company B is an Original Equipment Manufacturer, or OEM, which also produces components for other manufacturers. Its main external customers are found in the aerospace and space industries. The composite products that are manufactured within the company can be divided into three segments. The first segment consists of OEM products, where the company owns the product specification. The second segment is made

up of CDM products that are manufactured for external customers, and where the company is responsible for design and production. The third segment is also comprised of products that are manufactured for external customers, but are strictly built to the customer's specifications. The manufacturing techniques that are used within the company are manual pre-preg layup and Automatic Tape Laying (ATL), where both layup techniques can be combined with different types of forming operations. The company also has capacity for machining, surface treatment and assembly.

3.3 Company C

Company C is an SME-sized part of a large international aerospace and defense group. Its major market is international space components, and the company manufactures subsystems for space applications. The products are usually developed within the company in very close cooperation with its customers and according to their specifications. The company has a very limited production of composite products, instead purchasing most composite structures from suppliers. In a few cases, composite parts have been manufactured internally by means of manual pre-preg layup. The main focus for the production department is machining and assembly. The production organization is responsible for manufacturing by the suppliers, as well as for providing the suppliers' manufacturing unit with the correct information.

4. COMPOSITE MANUFACTURING PROCESSES

Several different manufacturing processes are used in the composite manufacturing industry. In this section, four common manufacturing processes are described.

- Manual pre-preg layup
- Automated pre-preg layup with Automated Tape Laying (ATL) or Automated Fiber Placement (AFP)
- Resin Transfer Molding (RTM)
- Filament winding

The four processes above are all employed by the companies in this study. The theoretical descriptions of the techniques are complemented by flowchart descriptions showing examples of processes that have been identified within the companies during the study.

4.1 Manual pre-preg layup

Pre-preg consists of fiber reinforcement that is pre-impregnated with uncured resin. The material hardens in room temperature and must be stored in refrigerated facilities prior to use. To manufacture a product from pre-preg, the single layer pre-preg is cut manually or with automated cutting machines into plies ready for layup, as diagramed in Figure 1.

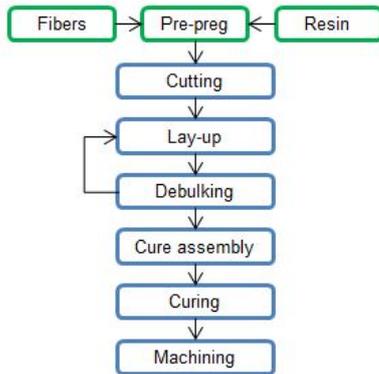


Fig. 1: Manual pre-preg layup

These plies are manually placed in an open mold in the desired fiber orientation. Several layers are stacked in the mold with intermediate debulking. When the lay-up is completed, the stack is vacuum bagged (cure assembly) and cured in an autoclave. The curing cycle with variations in pressure and temperature is computer controlled. [4]

4.2 Automated pre-preg layup with Automated Tape Laying or Automated Fiber Placement

The two main technologies for automated manufacturing of advanced composite laminates from unidirectional pre-preg today are Automated Tape Laying (ATL) and Automated Fiber Placement (AFP). In ATL, unidirectional pre-preg tape with widths ranging from 75-300 mm are automatically placed in a mold, as shown in Figure 2.

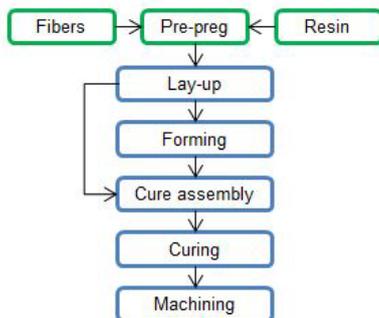


Fig. 2: ATL layup and forming process

AFP systems basically employ the same type of tape but in much narrower widths, ranging from 3.2-12.7 mm, and the system can place up to 32 tapes at the same time. The narrower tape makes it possible to use

AFP for more complex shapes than is feasible with ATL. Generally, the ATL machines are larger and heavier than the AFP systems, but result in higher productivity [5]. After the automated placement of pre-preg in the mold, the next step can be either a forming operation or cure assembly. The automated layup can be utilized to manufacture laminates with simple shapes that are formed to the desired shape in a separate forming operation before the cure assembly. The operations made after forming are the same as for manual pre-preg layup.

4.3 Resin Transfer Molding

Resin Transfer Molding (RTM) is a commonly used manufacturing process for producing near net shape products in rigid double-sided molds. [4] For short series, the reinforcing fibers can be cut and placed in the mold directly, layer by layer, as seen in Figure 3.

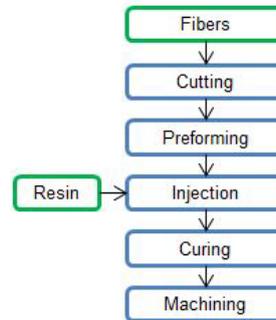


Fig. 3: RTM manufacturing process

For large volume production, preforms are manufactured so that all fibers are placed in the mold at the same time.[1] When the fibers are placed in the mold it is closed and resin is injected into the cavity. When the filling is completed the resin supply is shut off. The part cures and solidifies in the mold and is not removed until the curing is completed.

4.4 Filament winding

Filament winding is only applicable for certain product shapes. The technique is easily automated which gives low labor cost, high reproducibility and reduced levels of scrap [6]. Fiber strands are unspooled, impregnated with resin in a resin bath and wound onto a mandrill, as Figure 4 illustrates.

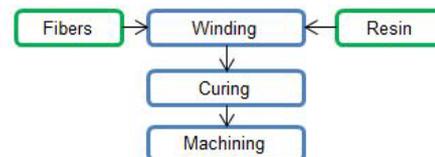


Fig. 4: Filament winding process

The mandrills can either be reusable or a template that becomes an integrated part of the final product, where it can serve as an internal liner. In the winding machine the fiber angle, rotation speed and other parameters are

computer-controlled. When the winding is completed the mandrill is moved to an oven to allow for curing. After a complete curing cycle the mandrill can, in the case of a reusable mandrill, be removed in a special removal station [4].

5. Engineering change and validation

Huang and Mak [7] establish that changes or modifications made to form, fit, material, dimensions or function of a product or component are usually referred to as engineering changes, or EC. Such a change can range from a simple change in production documentation to an entire redesign of a product. Usually, changes in business organization and operational changes that do not affect the product design are not considered to be engineering changes. [7]

B.G. Dale [8] present five main reasons for changes that are made to existing products and to new products that just have been introduced in production.

- To make it possible to manufacture the product or to assure that it will comply with product specifications when introducing a new product in manufacturing design.
- To take advantage of manufacturing technology enhancements during the product lifecycle.
- To improve the products' reliability, maintainability, safety and other properties.
- To cut production costs, facilitate a change of supplier, increase flexibility in sourcing etc.
- To avoid a permanent loss of supply of a component or material.

In a case study Vianello and Kristensen [9] examine when ECs are generated and what the main reasons for the changes are. For one of the products in the study, an aircraft engine, the great majority of all engineering change reports are generated during the production phase. The major reason for the changes proposed in the manufacturing phase is manufacturing/assembly. It is interesting to notice that a closely related area, buildability, is the fourth most common reason.

Huang and Mak [7] argue that a company can gain significant competitiveness in the marketplace if engineering changes are carried out properly. On the other hand, poor execution can lead to a loss of time, money, and profitability, as well as the loss of control over the configuration of the product. Therefore, an effective and efficient engineering change management system is required. [7]

Many versions of engineering change management systems exist, with some minor differences. One example of an engineering change management system is presented by Reddi and Moon [10]. In the model, which is described in Figure 5, an EC Committee is in charge of managing the entire lifecycle of a change request. The committee is comprised of members from many different departments within the

company such as product design, accounting, manufacturing, marketing etc. The committee is led by an EC coordinator.

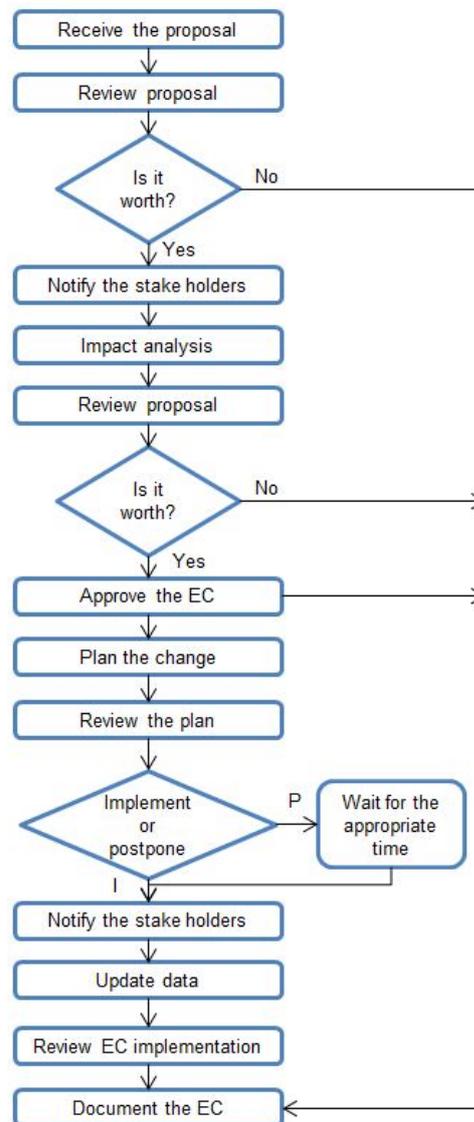


Fig. 5: Model for engineering change management redrawn from Reddi and Moon [10]

The engineering change requests can originate from all parts of an organization [7]. Dale [8] concludes that many people from various departments are engaged in handling engineering changes. Therefore, it is essential that the EC management system is designed with clear responsibilities. Working with EC also requires large amounts of information from many stakeholders in order to plan and control the work. The quality of this data is a key factor in the successful handling of engineering changes. [8]

Barzizza et al. [11] highlight that effective EC management should be supported by extensive reporting that can support a traceback and rapid analysis of previous ECs. Changes that are handled must be traceable.

Huang and Mak [7] notice that some companies seek to obtain effectiveness by including numerous checkpoints to make sure that no changes are lost track of, as this can lead to negative consequences. This approach seems to suffer from delays at the checkpoints. A balance is needed between the management system's effectiveness and efficiency. [7] Dale [8] argues that minor changes that can make a substantial improvement in product cost, quality etc. can be costly. It can take a long time to run through a system that is designed for handling major functional changes. An engineering management system should be flexible enough to handle simple changes in an effective way. [8]

Several authors focus on the timing to implement the change in order to generate as small a cost for the implementation as possible. The only article found during the literature review that discusses the validation aspect was by Diprima [12], who concluded that before an engineering change is created, the engineering department spends a preliminary period to determine how well the change will function. Dale [8] also mentions that a broad investigation should take place in the engineering and design departments before an EC is proposed. This should be done in order to minimize the risk for unnecessary work in other departments.

5.1 Verification and validation

Dostaler [13] calls attention to the fact that aircraft manufacturing companies' efficiency is somewhat hampered, since they rely on a number of safety nets and non-value adding activities in order to achieve high product quality. Within the sector, a risk-sharing approach with regard to which development and assembly is divided among several different companies is common. The responsibility for detailed design and manufacture of major subassemblies can be attributed to first-tier suppliers. Having many companies involved increases the complexity of the product development process. [13]

Maropoulos and Ceglarek [14] point out that complex engineering products, such as aircraft, require a set of verification and validation stages that satisfy legislative requirements as well as the demanding nature of the customers. This must be done in a cost-competitive way. The products themselves are highly complex and commonly designed by international design teams spread out over many countries and organizations. These factors, in combination with challenging requirements, call for a formal and robust design and development methodology in terms of verification [14].

According to Maropoulos and Ceglarek [14], the level of inspections that are required are decided by the risk of non-conformance. In the aerospace industry the

inspection levels are high, and high-risk features are subjected to a 100% inspection rate [14]. Furthermore, Maropoulos and Ceglarek [14] argue that features that can be effectively controlled by validating the manufacturing process can be subjected to a reduced inspection rate, typically yielding a 50-75% reduction in the final inspection load [14].

6. FINDINGS

Each of the three companies in this study use standardized processes for the development of new products. Even though the processes differ between the companies, all of the processes include formal steps to validate product design, production methods and technologies. The validation process is time-consuming and constitutes a significant part of the total development time for new products. After a completed validation process the drawings and production specifications are released in a final version. Following the release a formal change request routine must be used in order to change drawings and product specifications. The basic demand for a formal change request after the specifications are released is valid for all three companies. However, the interpretation of the requirement for formal change requests and routines for handling them differs, and the way that changes are validated is not consistent.

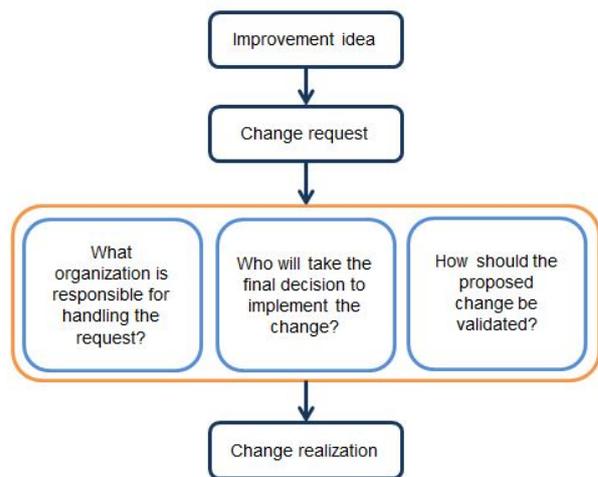


Fig. 6: Decisions to make when an engineering change is introduced

Figure 6 describes a general process, based on findings from the case study, for decision making and management of engineering changes. It has been concluded that when an improvement idea is formally introduced as a change request, many questions are raised. They must be answered before the improvement idea can be realized and implemented. Some of the questions that have to be dealt with early on in the change process are highlighted in Figure 6.

6.1 Management of Change Request

A change request can come from all departments within a company and from its customers. Within all of the

companies in the study change requests originating from the production and supply chain organizations or from designers are the most common. Examples of requests originating from customers have also been documented.

All the studied companies have routines for formal change request handling. This means, for example, that a formal change request form must be filled in for all proposed changes. The proposer uses the form to explain the scope of the change, and the form is filed for traceability. Depending on the type of a proposed change and other factors, many of them the same that determine the requirements for validations, the request is sent to an organization for handling and decision. The organization can for instance be a local change board for a department, a general change board for the whole company, an expert group or a project team. In some cases, the final customer must be involved in the decision.

In some cases, changes can be implemented without the use of a formal change request. This can be the case if the change is considered to be minor and without any real affect on product quality.

6.2 Guidelines for validation

Proposed changes must in most cases be validated before they are implemented in order to assure product quality. Instead of going through an extensive test program, as is necessary for new products, there is a possibility to adapt the validation program to the type of change that is proposed. The validations can range from theoretically proving that the quality is not affected to minute inspections and extensive tests. The following factors are a summary of examples that the companies mention as factors affecting what type of validation process will be used for a proposed change.

- Customer requirements, standards and traditions.
- Type of change and expected consequences.
- Owner of product design and production specifications.
- Previous experiences in related areas.
- Ownership of tools, molds and mandrills.
- Products' safety class/function.
- Level of detail in existing specifications.
- Is the change affecting the product's form, fit or function?
- Is the change affecting an interface to other components?
- Is the change temporary or permanent?
- Is the change affecting final article drawings or production specifications?
- Is the change affecting the production process of composites before the material has cured?

6.3 Process parameters

The production specifications can include method descriptions for manual processes, process parameters, settings and programs for automated processes. A predominant observation for the manufacturing of composite materials before curing is that the process parameters have a great effect on the product quality and performance. Therefore, it is important that process parameters are clearly described as a part of the production specifications and are not altered without validation. Examples from all three companies confirm the importance of process control. In one of the companies, the process of composite production from raw material to cured part is classified as a "special process", to enface the special attention that has to be paid to the manufacturing process.

6.4 Hypothetical change request cases

Tables 1 through 5 are a summary of the answers collected during the third round of interviews at the companies. Hypothetical cases were presented during the interviews. The focus was to understand how the company would handle each scenario. The tables summarize each company's answer, in order A, B and C, to the questions below.

- WHO is responsible for the final decision to implement a proposed change?
- HOW is that change validated?

The following guidelines were used for all of the hypothetical cases that were explored during the interviews.

- The proposed change concerns a previously verified part that is in a production-ready state and that is manufactured in high-performance composite material.
- The change is initiated internally and caused by an improvement to increase the productivity in the production system.
- A proposed change is seen as an isolated event, and no consideration is taken for effects that it can have on other products or processes.

The caption for each table describes what hypothetical case is summarized in the table.

Table 1: A change that will affect the geometric shape of the final product

Company A	
WHO	If the change affects the interface to other products the decision is made by the customer. In other cases it depends on what type of change it is, but the customer is usually involved in the decision.
HOW	The type of validation depends on what type of product it affects, if it is safety-critical and it also depends on the customer's requirements and traditions.
Company B	
WHO	After acceptance from the final customer the Change Board organization within the company takes the final decision.
HOW	If no process changes are made the change is validated by a renewed first article inspection.
Company C	
WHO	The final customer.
HOW	The type of validation depends on what the change affects. The specifications for the delta qualification are prepared in cooperation with the customer.

Table 2: A change of material in the final product

Company A	
WHO	If the product is already qualified and safety-critical the final customer makes the decision.
HOW	For a well-known material it can be satisfactory to show similarities between the two materials. New materials require extensive testing.
Company B	
WHO	Change Board within the company.
HOW	Change Board decides on validation specifications. Can range from simple to extensive depending on the assumed effects of the change.
Company C	
WHO	The final customer.
HOW	For a well-known material it can be satisfactory to show similarities between the two materials. New materials require extensive testing.

Table 3: A change of a shaping or curing mold that does not affect the final shape of the product

Company A	
WHO	If the customer owns the tool the decision is made by the customer, otherwise the decision is made by the supply chain organization within the company.
HOW	Increased inspections that are adapted to find deficiencies that can be expected from the change are used.
Company B	
WHO	Local Change Board within the composite manufacturing department.
HOW	Experts within the material and process group specify validation criteria based on the customer requirements and the nature of the change.
Company C	
WHO	Internal project manager for the affected projects.
HOW	No additional tests; the ordinary acceptance tests are considered sufficient. In some cases, the project manager can ask for extra validation of the tool made by the internal quality department.

Table 4: A change in manual production methods

Company A	
WHO	Internal decision if only the production method and not the product is affected.
HOW	Ordinary production inspections; if it is a major change, the inspections of the first produced articles can be extended.
Company B	
WHO	Local Change Board within the composite manufacturing department if the change does not affect the product design.
HOW	The validation is dependent on the type of change and can range from simple first article inspection to extensive first part qualification
Company C	
WHO	Decision is made by department manager for production department or project manager.
HOW	The new method can be verified by the quality department but no extra validation is made for the final product; the ordinary acceptance tests are considered sufficient

Table 5: A change of process parameters for a certain production process

Company A	
WHO	If the company owns the design and production process the decision is made internally within the company. If not, the customer must take the decision.
HOW	Increased inspections that are adapted to find deficiencies that can be expected from the change are used.
Company B	
WHO	Local Change Board within the composite manufacturing department.
HOW	Experts within the material and process group specify validation criteria based on the customer requirements and the nature of the change. For process changes the validations are extensive.
Company C	
WHO	Depends on how process parameters are specified for the production made by suppliers. If they are specified in detail by the company the supplier must inform the company that will inform the customer of changes.
HOW	In most cases, the composite parts are manufactured by suppliers and the company relies on suppliers' standards and validation routines for their respective production processes.

7. DISCUSSION

Because many different factors affect how a change request will be handled, e.g. who is responsible for the decision to implement and how the change should be validated, it is important to examine each request in detail. Two change requests that on a general level appear to be equivalent, since they concern the same type of change to the same type of product and have the same final customer, are not necessarily dealt with in the same manner. Minute differences can mean that they are managed completely differently. For instance, changes in process parameters can generate a need for a very thorough verification plan if the type of change never has been made before. If the type of change has been made before, and the predicted results are well known and previously proven, the scope of the validation process can be limited.

If a proposed change generates a need for extensive validation, the cost and time for this can be considerable. The cost for a validation must be factored in when deciding if a proposed change should be implemented. This is especially important if the change is aimed to cut cost or improve productivity. The fact

that many factors influence the decision process can make it hard to determine costs for implementing a change early on in the change process. A standardized assessment model for early estimates of implementation costs would be desirable in order to quickly assess the profitability of a change request. Such a model, however, is very difficult to design because minute details in a proposed change can determine the entire scope of the validation. Each change request still needs to be assessed in great detail.

Manufacturing companies that have several customers and a great variety of products are exposed to many different quality requirements, standards and traditions at the same time. This requires a comprehensive knowledge of all the customers' requirements. There is a risk of confound requirements from different customers or product groups. Therefore, a risk of making incorrect decisions regarding proposed changes is apparent. This could lead to the implementation of quality-affecting changes without the correct level of validation.

Even with systems and routines for formal change request handling there is a risk for the introduction of changes without the use of the formal routine and proper validation. This risk could be increased by the fact that some minor changes are allowed to be introduced without formal change request handling.

In manual work it is difficult to document every single operation in great detail in production specifications. Therefore, a small window for variation exists. Greater detail in descriptions for manual work does not automatically generate higher process control. This is due to the fact that it is difficult to ensure that all operators always perform the operations exactly the same way, on a very detailed level. For instance, individual interpretations of the descriptions and previous experiences will generate differences. Therefore, there is a risk that detailed production descriptions of manual operations can cause a false sense of process control. Very detailed descriptions can also increase the number of change requests that need to be managed. The relationship between production documentation and process control for manual operations is an interesting field to explore in future research, since manual operations are common in the manufacture of high performance composite products with high quality demands.

8. CONCLUSION

Based on the cases it is evident that for all three companies, the general routine is that the customer must be involved in the decision to implement a proposed change if the change can affect a validated product's form, fit or function. The demand for extensive validation is not necessarily the highest if form, fit and function are affected. Instead, the demand for validation is high for process changes where it can be hard to detect undesired results. Based on the cases, it is not possible to suggest general guidelines for the

responsibility to decide if a change should be implemented and how it should be verified. All change request cases must be assessed individually. The validations made to assure that the product and process quality are not affected by a change can, in most cases, be adapted to suit the scope of the change. These validations, however, are less extensive than the validations that are made when developing new products.

Systems and routines for handling engineering change requests within composite manufacturing must be flexible to handle various customers' requirements, product groups, manufacturing processes etc. The basis of each engineering change management system in this industrial segment must as of today, be an individual and detailed assessment of each change request.

9. FURTHER RESEARCH

Based on the literature review, there appears to be a lack of published research focusing on the need for validation created by an engineering change request. This field is interesting to further explore in order to create a greater understanding about the intricate connections and interactions between customers, products and manufacturing processes within companies dealing with composite materials. One aim for the research can be to find key factors that will always lead to costly and extensive validations.

The relationship between detailed production specifications in manual operations and level of process control is also interesting to explore in greater detail in further research. An interesting topic is to investigate what level of detail is correct with respect to making sure that the process is performed exactly the same every time. The level of detail, however, must not be so detailed that it conceals process variations. It is also interesting to examine how greater levels of detail in production specifications influence the need for engineering change requests.

10. ACKNOWLEDGEMENTS

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