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A METHODOLOGY FOR THE SELECTION OF MANUFACTURING PROCESSES FOR FIBRE REINFORCED COMPOSITES

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ABSTRACT

Liquid moulding technologies are well established processes for the manufacturing of fibre reinforced composites for nautical and automotive applications. Their implementation is difficult because of unformalized product and process specifications. This paper proposes a methodology for helping the manufacturing department select robust and cost-effective manufacturing processes for aeronautical fibre reinforced composites. The information models required for the formalisation of manufacturing rules as well as cost models used in the evaluation of possible industrialisation scenarios have been developed.

KEYWORDS: Industrialisation, concurrent engineering, fibre reinforced composites

1. INTRODUCTION

Composite materials are being increasingly used for aerospace applications due to their high performance. It is stated that around 60% of the structural weight of the A350 commercial airplane is represented by advanced composite materials, more than half of this quantity being reserved to advanced composite parts [1]. High specific stiffness, strength and weight reduction are the main characteristics that account for the successful employment of fibre reinforced composites in such fields.

Numerous manufacturing processing routes may be employed for the fabrication of advanced fibre reinforced composites [10,12]. The most common process consists in the lay-up of prepregs followed by autoclave curing. This processing method allows for the fabrication of high performance composite parts with high fibre volume fractions. Nowadays, more cost performant processes tend to replace the prepreg lay-up/autoclave curing process. Such processes are represented by Liquid Moulding Technologies which overcome the high costs induced by the part's curing in an autoclave. They consist in the impregnation of a dry perform by liquid resin followed by curing in a less expensive equipment. The result is a cheaper part which, in some cases, may equal autoclave cured parts in terms of fibre volume fraction.

Selecting suitable manufacturing routes for the fabrication of cost-effective fibre composite parts is a complex task. Relevant parameters related to the product, to the process and to the necessary resources have to be defined (the PPR couple). The relationship between these parameters is translated into manufacturing constraints which are used afterwards for the screening of the possible industrialisation solutions which allow the manufacturing of the specified part. Different objective functions are expressed in order to evaluate the performance of concurrent industrialisation solutions. The highest amount of research has been carried out on the subject of the optimisation of the part cost and part weight couple [2,8]. Part mechanical performance has been introduced to further analyse the suitability of manufacturing routes [3,11].

The process of defining the list of industrialisation solutions for a specific product resumes to the specification of the possible processing routes. These routes contain information related to raw materials, operation sequencing and available resources necessary for the realisation of the product specifications. The definition process is based on the experience of the design department, the manufacturing department and the production management department [7]. Thus, the selection of a cost-effective manufacturing route for new products is directly related to the relevance of these actors' decision.

In order to overcome the risks related to manual process planning, concurrent solutions have been developed for the automatic definition of manufacturing process plans. Computer Aided Process Planning (CAPP) is a solution for the integration of the specifications issued from different departments. Two approaches for process planning are in use [5, 13].

When creating a new part's process plan, engineers try to find similarities between the new part and previously analysed parts in order to define a process plan that is based on models created for specific cases. This kind of reasoning corresponds to a first method of process planning: variant process planning. It consists in the identification of relevant product parameters which help to classify the new parts in specific product families. This approach is based on the Group Technology method or Cased Based Reasoning. A process plan corresponds to each family and the next task for the engineer is to operate minor modifications on the generic process plan in order to adapt it to the new product. It can be easily stated that the drawbacks of such an approach consist in the high amount and the relevance of data that needs to be gathered for the definition of product families.

A different approach of process planning consists in generating a new process plan for each new part. Generative CAPP systems are based on algorithms which employ manufacturing rules for the creation of these plans. Previously analysed cases are no longer stored but only the methods used for operation sequencing are capitalized. Different solutions exist for generative process planning, neural networks, decision tree methods or constraint programming are some of them.

Generative CAPP solutions have been mostly used for machining applications in which the use of machining features facilitates the products decompositions in elementary entities. Thus, manufacturing rules related to part accessibility and operation sequencing can be rather quickly implemented. However, this is not the case of fibre reinforced composite parts for aeronautical applications. The design of such parts is carried out in a global manner and the required manufacturing data is not sufficiently formalized.

Data related to the product and to the manufacturing environment (process and resources) must be formalized in order to automatically exploit it in order to obtain reliable process plans. Generic models have been proposed to cover the different views that characterize a products manufacturing process. One such model is the FBS-PPRE model (Function Behaviour and Structure – Process Products Resources and External Effects) [9]. It is based on the application of the FBS concepts to the four distinct views with the main objective of integrating the relevant manufacturing knowledge. Little research has been carried out to formalize manufacturing data related to composites manufacturing. Estimation models which take into account the effects of material, labour, tooling and equipment effects for autoclave curing have been realized [15]. Models for Liquid Moulding manufacturing processes have been also developed. Resin transfer moulding and vacuum assisted infusion processes have been considered for the development of manufacturing models taking into account labour and process flow estimations [4].

This study aims to propose a methodology for the selection of manufacturing routes for fibre reinforced composites based on a hybrid approach of variant and generative process planning. Relevant knowledge related to the manufacturing of composite parts by autoclave curing and liquid moulding technologies have been identified. The selection of the appropriate manufacturing routes is based on a cost estimating model. The method's implementation will be assisted by a software application.

2. METHODOLOGY OUTLINES

This section is dedicated to the presentation of the main steps required for the implementation of the proposed methodology and the related concepts. Figure 1 presents the UML use cases diagram which captures the interaction between the different design actors that were identified during the selection of manufacturing routes by the means of the proposed methodology's conceptual model.

This paper is focused on the "select capable manufacturing routes" use case and on the actions required to its implementation through a decision support tool. This use case is further detailed through an IDEF0 diagram which presents the main activities and resources employed by this methodology (Fig. 2).

The main activities required for the methodology's implementation are developed in the following sections. Section 3 deals with the manufacturing experts' knowledge formalisation through PPR information models which support the second activity (A2). The cost models which have been developed as support for the third activity (A3) are presented in section 3.4.

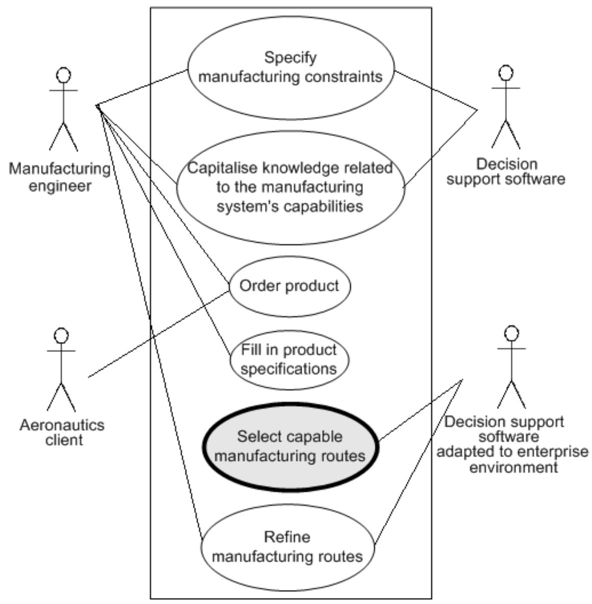

Fig. 1. UML use cases diagram for the methodology's implementation

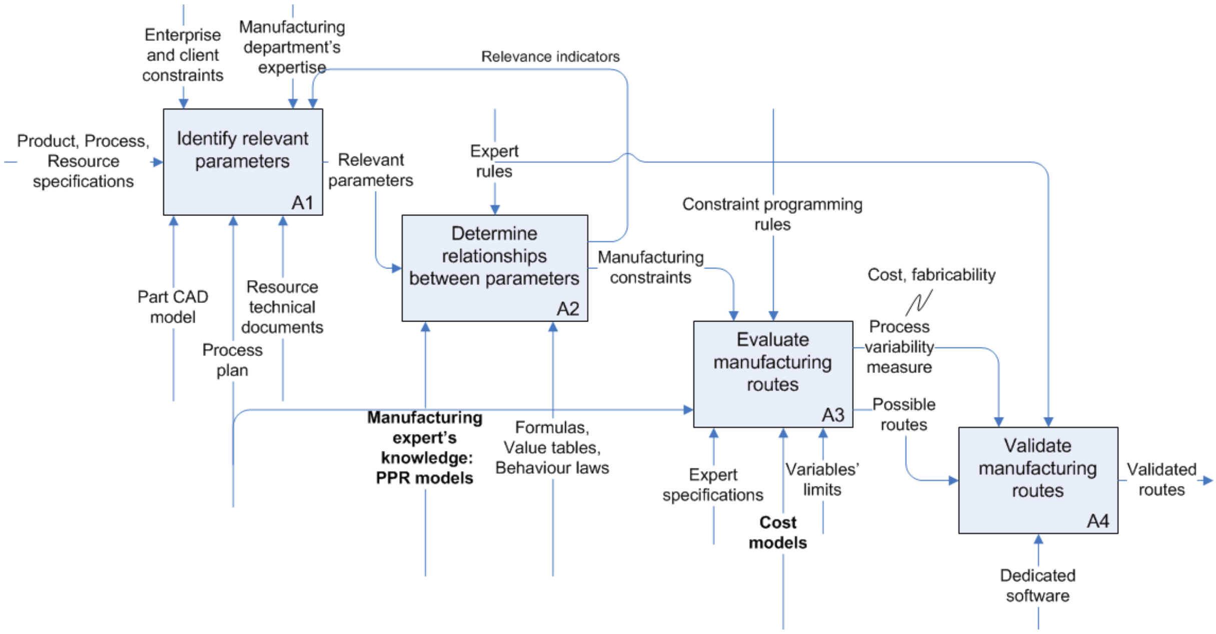

Fig. 2. IDEF0 diagram which captures the methodology's outlines

2.1. Basic steps

During the first stage, relevant design parameters related to the PPR couple need to be identified in accordance to enterprise and client constraints. Product related parameters are of two kinds: generic and material related. Generic parameters capture the part's geometry as well as the description of the elementary components that it contains. Raw materials are presented through parameter tables specific to the fibre architecture and the matrix, as well as to core and auxiliary materials. Process and resource capabilities need to be introduced along with production parameters (labour, energy, maintenance, investment, *etc*.). It is essential that the number of the identified parameters is sufficient for a high-performance evaluation methodology. This characterizes the method's completeness and robustness. The method's relevance is given by the parameter's field of validity. These considerations make parameter identification one of the most important stages because it represents a consistent basis for comparison and evaluation for the steps that follow in the decision process.

Quantitative and qualitative relations can be expressed between the parameters identified at the level of the PPR couple. These manufacturing relationships are issued from the designer's experience. Expert rules take the form of manufacturing constraints and they serve to initialise a data processing tool, the purpose being the treatment of the available manufacturing routes on a hierarchical basis. This second step may be used together with appropriate indicators as a refining tool for eliminating irrelevant parameters.

Algorithms based on constraint programming are implemented for the evaluation of the available processing routes. Figure 3 presents the UML class diagram which outlines the classification and evaluation model. Each process is characterised by a discrete number of performance indicators. The role of the algorithm is to evaluate whether the performance values of the listed process are situated within the limits of the performance to be obtained by using manufacturing constraints as a selection method.

A list of manufacturing routes responding to the specified characteristics is generated in this way. Another output of the evaluation stage is a measure of the processes' variability which is used for the control of the validation stage. This last step is carried out by simulating different scenarios (simulation of the generation of processing routes for representative parts).

2.2. Knowledge capitalisation

The software which supports the proposed method's implementation uses different types of data: initial, filled in and calculated data. Initial data represent the tool's knowledge base and requires an instrument which allows the user to capitalise manufacturing knowledge.

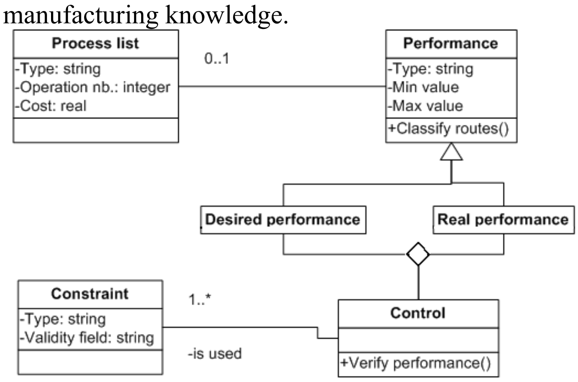

Fig. 3. UML class diagram of the process performance view

In our case, manufacturing knowledge is captured by the means of capitalisation charts. They are based on the concept of ID charts which was first introduced by Villeneuve [14]. These tools serve for the initialisation of the knowledge base with data related to the process (manufacturing route types and sequenced operations) and to the resources (resource type, capabilities and economical data). Capitalisation charts are responsible for the software's evolution by capitalising knowledge related to new processes and resources.

3. MANUFACTURING PROCESS SELECTION

The methodology proposed for manufacturing process selection is based on the formalisation of manufacturing rules and on an evaluation algorithm which represent the basis of a decision support tool. The different models that were created to support the process of formalisation and capitalisation of manufacturing data related to the PPR couple are presented in the sections that follow.

3.1. Product model

The product view is expressed through an UML class diagram (Fig. 4) and it represents the main variables required for the capitalisation of design data. The manufacturing route being a sequence of operations, intermediary part states have been identified and associated to each operation. They represent the successive states a part has after each shaping process until the fabrication of the finished product.

Raw material is usually imposed by the client for the fabrication of aeronautical composite parts. Thus, their selection is simplified and it is up to the user to select the necessary material from the material data base. Different materials are proposed to the user: prepreg, dry reinforcement and liquid thermoset resins, as well as core materials and consumables.

Elementary part components need to be obtained in order to validate a part state. A list of shaping processes is available for the realisation of each state. It is at this level that manufacturing rules are formalised by using product-process capitalisation charts (Fig. 5).

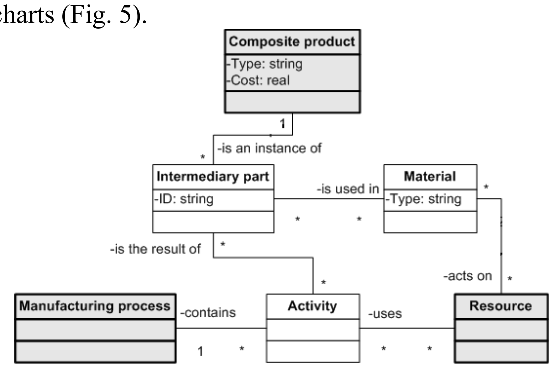

Fig. 4. UML class diagram for the PPR view

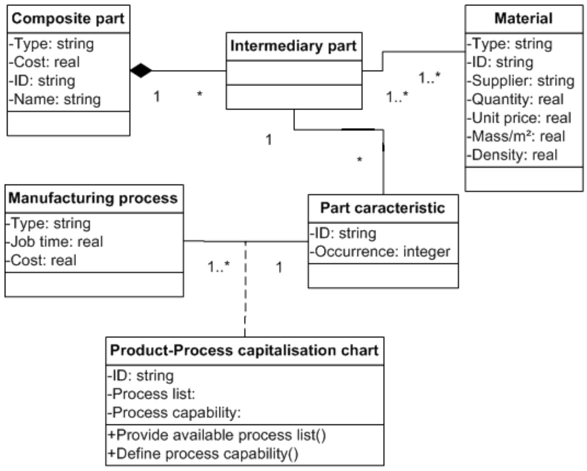

Fig. 5. UML class diagram for the product view

3.2. Process model

Two manufacturing routes have been selected for the desired comparison: conventional prepreg technique and the liquid infusion process. These manufacturing routes are fixed but different primary processes may be used at the level of each activity for the completion of a part state. To better capture this aspect, the concepts of direct and indirect activities have been introduced. Direct activities are mainly made up of shaping processes which are used at the level of the following activities: cutting, performing, lay-up, consolidation, curing, demoulding, machining and non-destructive testing (NDT). Indirect activities constitute supporting operations for the shaping processes. The main indirect activities are handling, set-up and idle activities. The UML class diagram shown in Fig. 6 captures the aspects stated above and the interactions between the process and resource models. For each activity a list of capable resources is available. The process-resource capitalisation charts represent the tool which materialise the relationship between resource capabilities and the activities which make up the manufacturing routes.

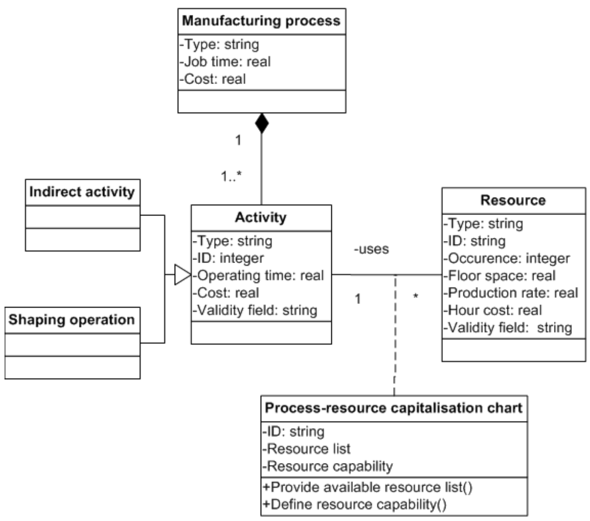

Fig. 6. UML class diagram for the process view

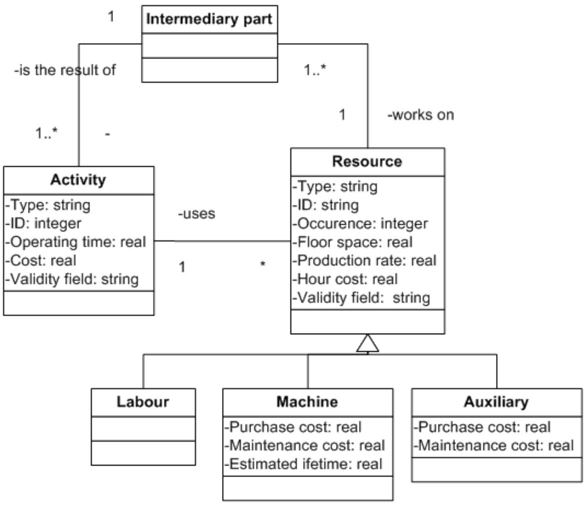

Fig. 7. UML class diagram of the resource view

3.3. Resource model

Figure 7 presents the UML class diagram for the resource model. Intermediary parts are the result of shaping activities which use different types of resources to this purpose. The most important resource parameter is their capability to realise a certain part feature and the quantification of this capability which serves for selecting the appropriate process. The aim of the selection methodology is to compare different activities which are labour intensive such as prepreg lay-up to with activities that detain a certain degree of automation which may increase productivity with the disadvantage of using more expensive resources.

3.4. Cost estimating models

As stated in the previous sections, in order to meet client needs, the industrial actors are beginning to gradually replace conventional prepreg fabrication techniques with liquid moulding technologies which are more cost effective. In some cases, these technologies may allow for the fabrication of products having mechanical performances as elevated as those obtained by the prepreg technique. In the case of aeronautical parts, mechanical performance levels are usually imposed by the client. Thus, the manufacturing engineer needs to compare different manufacturing routes according to their cost for equivalent performance.

Our methodology aims to formalise the manufacturing engineer's decision process that is carried out during the selection of a cost effective manufacturing process for a composite part. For a given part, two process families have been taken into consideration. These manufacturing routes correspond to the conventional process consisting in the lay-up of prepregs followed by autoclave curing (Fig. 8a) and to the resin infusion process consisting in the impregnation of a dry perform by a liquid thermoset resin assisted by vacuum (Fig. 8 b).

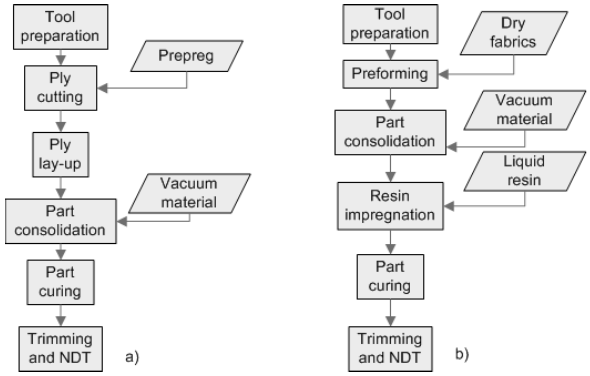

Fig. 8. Process flow diagrams for: a) prepreg lay-up and autoclave curing; b) liquid resin infusion

The initial manufacturing routes are composed of direct and indirect activities. Each activity may be accomplished by a finite number of processes and to each activity different resources capable of providing the desired product characteristic can be allocated. In this way, a multitude of manufacturing routes may be generated, each one of them being characterised by a specific fabrication cost.

The final manufacturing process cost incorporates expenses related to material, resources and operation (eq. 1):

$$C = \sum_{i=1}^{n} C_{mi} + \sum_{i=1}^{n} C_{ri} + C_o \tag{1}$$

where C is the total cost of a specific manufacturing route, C_m is the materials cost, C_r is the resource cost and C_o is the operations cost.

The calculated cost C is an approximate one but it allows for a first hierarchical evaluation of the possible manufacturing routes. It represents a relative cost model issued from a method called resource-based modelling. The main characteristic of this modelling methodology resides in the fact that it enables the assessment of different manufacturing processes since they use equivalent resources for the fabrication of the same finished product [6].

Material cost is given by eq. 2:

$$C_m = q \cdot P_u \tag{2}$$

where q represents the quantity of raw material used for the part's fabrication and P_u is the unit price of the specific material. The quantity q depends on product geometrical specifications and it also incorporates the scrapped material since this material can not be recycled. This is the case of scrapped reinforcement after cutting operations or scrapped resin entrapped in the vacuum and infusion hoses.

Resource cost is given by eq. 3:

$$C_r = \left(\frac{P_a}{U} + M \right) \cdot \frac{t_p}{t_{lot}} \cdot c\% \tag{3}$$

where P_a is the resource's purchase price, U is the estimated time of the resource's utilisation (in years), M is the annual maintenance cost, t_p an t_{lot} represent the duration while the resource is immobilized for the manufacturing of a part and of the entire lot of parts, respectively. Usually, the same resource is used for the fabrication of different parts. This fact is captured by the means of the c% coefficient which represents an estimation of the resources utilisation for the considered part lot compared to the entire production.

Equation 3 captures the cost of investment for unanimated resources (tooling and equipment). A second type of resources is used by the enterprise during manufacturing operations: labour. Equation 4 gives the operating cost which represents resource operating cost: labour cost as well as unanimated resource cost (energy consumption).

$$C_o = \sum_{i=1}^{n} c_{hi} \cdot t_{oi} \qquad (4)$$

where c_{hi} represents the hour cost of the *i*th resource and t_{oi} the duration of operation i.

4. Evaluation methodology

Manufacturing process selection is carried out by the means of decision support software based on the proposed methodology. Manufacturing rules and process and resource capabilities are capitalised in the software's knowledge base in the form of manufacturing constraints. Cost constraints together with fabricability constraints are introduced. These constraints bare the form stated by eq. 5:

$$c_{\min} < c_i < c_{\max}, i = 1..n$$

where c_i is the cost of the *i*th activity and c_{min} and c_{max} represent the limits the cost constraint must satisfy. Constraints may be expressed in a quantitative way in the form of a value interval or behaviour laws but in a qualitative form too (capable/not capable).

Different manufacturing routes are generated from the two initial process families once product specifications related to geometry, elementary components, material and production measures have been introduced. These routes are based on prepreg or infusion techniques and represent a combination of the available primary processes. A list of efficient manufacturing routes is proposed to the user after the execution of the constraint satisfaction algorithm.

5. CONCLUSIONS

In this paper a methodology for the formalisation and capitalisation of manufacturing knowledge related to aeronautical composite parts has been proposed. The implementation of this methodology in an industrial environment is supported by a decision support tool with the aim to provide a selection procedure for manufacturing process selection.

A brief description of the methodology's basic steps has been provided together with the main information models related to the formalisation of the PPR couple knowledge. A resource-based cost model has been presented for the evaluation of possible manufacturing routes for two competitive techniques: prepreg and liquid resin infusion.

The proposed methodology represents a first approach to incorporating manufacturing rules and cost estimating models for the selection of manufacturing processes for fibre reinforced products. Future work will be concentrated on the introduction of performance and robustness indicators as well as on the validation of the selection algorithms.

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