MANUFACTURING REQUIREMENTS IN DESIGN: THE RTM PROCESS IN AERONAUTICS

S. Mouton [1, 3], D. Teissandier [1], P. Sébastian [1], J. P. Nadeau [2]

[1] *Université Bordeaux 1; Cours de la Libération 33405 Talence cedex France*
denis.teissandier@u-bordeaux1.fr; Email: patrick.sebastian@bordeaux.ensam.fr
[2] *Arts et Métiers Paris Tech; Esplanade des Arts et Métiers 33405 Talence Cedex France;*
Email: jean-pierre.nadeau@bordeaux.ensam.fr
[3] *Corresponding author's Email: serge.mouton@u-bordeaux1.fr*

SUMMARY: A sub-unit of an aeronautical structure (fuselage, fin, wing, etc.) consists of a set of components fixed rigidly together. One of today's major industrial challenges is to produce these sub-units out of composite materials in order to increase the level of integration and reduce mass and cost. This article describes a procedure to assist in the industrialisation of aeronautical components produced from composite materials in a design for manufacturing context. In a multi-expertise approach, the problem of optimising integration is combined with the feasibility of injection for the Resin Transfer Molding process. This approach then takes into account admissible manufacturing deviations, defined from a classification of the structure parts. The limits set for admissible deviations guarantee the mechanical behaviour of the assembled component and the requirements of the assembly as a whole. Finally, an industrialisation solutions space is defined. A constraint satisfaction problem solver is used to carry out this research with a spar from a horizontal plane in an aircraft used to illustrate the procedure.

KEY WORDS: Resin Transfer Molding (RTM), assembly, residual stresses, industrialisation, strain, geometric specification for non-rigid parts, Constraint Satisfaction Problem (CSP) solver

INTRODUCTION

When taking industrialisation into account in the design cycle [1-3] two distinct and complementary aspects must be considered: technical feasibility and economic feasibility. The technical feasibility of the RTM process imposes specific shapes and dimensions. Moreover, the RTM process can cause strain as parts are removed from the moulds, caused by the architecture of the laminate and the great complexity of physical phenomena around the parameters governing the RTM process. These strains are characterised by manufacturing deviations from which the true geometry of the part can be defined in relation to its design geometry (CAD model). In order

to integrate a part into a sub-unit, it is often necessary to distort it. This is due to the highly over-constrained architecture of sub-units for aeronautical structures. If a part undergoes strain when it is integrated into a sub-unit this gives rise to mechanical stresses which could mean that the functional requirement of the sub-unit is not respected and could affect the mechanical behaviour of the part itself. With a classification of the structure components it is possible to identify those components for which significant strains are acceptable. These must then be quantified in order to define the induced stresses in the component and the stresses added to the sub-unit during the assembly phase. The aim of our study is to integrate these stresses generated in the part and the sub-unit by the assembly operation into the choices in the flow-process grid. The problems involved in integrating industrialisation into the design cycle are already taken into consideration in the expert rules provided by many aircraft manufacturers. These rules are the result of work by experts within the company. They have a limited area of validity and restrict the area available for design investigation. In this study our aim is to develop knowledge models in order to be more effective in finding the level of integration of the parts into a sub-unit, thus reducing mass and controlling costs.

CLASSIFICATION OF COMPOSITE STRUCTURAL COMPONENTS

A classification of the structural components identifies two types of component: type_1 and type_2. Each manufactured part is in contact with other parts in a sub-unit, which are called the adjacent parts. The adjacent parts will exert efforts via the contact surfaces, generating mechanical assembly stresses which are then distributed throughout the manufactured part and the sub-unit. These stresses can compensate for manufacturing deviations to a greater or lesser extent, in correlation with the strain caused by the shaping process. For type_1 components, mechanical assembly stresses have a great influence on the manufacturing deviations. Thus a fairly large defect can be specified in the general shape of the part in its free state. Stresses are characterised by geometric specifications associated with a stress condition [4], and the unit is shown on the definition of the part. However, mechanical assembly stresses should not exceed a certain maximum limit, determined by two criteria:
  - one criterion intrinsic to the manufactured part: mechanical behaviour,
  - one criterion intrinsic to the sub-unit: stress condition beyond which the sub-unit will be too distorted, thus jeopardising respect for certain functional requirements.

For type_2 components, assembly stresses have very little influence on strain generated by the process. As a result, manufacturing deviations cannot be compensated by contacts from adjacent parts. This results in a specification for a much more serious default in the general shape of the part in its free state than for the type_1 components. When the expert rules are applied to type_2 components, these components have symmetry from a geometrical point of view and also from the point of view of laminate architecture. This type of design limits the risk of strain but does not allow for the optimisation of mass and function integration. The use of specifications for each stress condition often proves to be unhelpful. In the design phase this distinction between groups of components will influence the laminate definition.

LAMINATE DESIGN AND RTM PROCESS

For parts with large dimensions, matter needs to be put in the places where stresses will occur hence the laminate is organised by zone. This is indispensable in order to reduce component mass. Each zone is a stack of fibers, with the juxtaposition of the zones ensuring variations in thickness. Each zone is defined by its shape, the number of fibers it contains and the orientation of each fiber in relation to a common frame of reference. Designing by zone in this way is linked with expert rules. In one of his papers, Gay describes an example of design by zone [5]. This organisation defines the optimised architecture for the laminate. To limit strain due to shaping, the unidirectional fibers are positioned using ply symmetry. Ply symmetry is the symmetrical arrangement of the stacks according to a design where the laminate is divided into two halves. In the RTM process, the stiffening pieces used are generally woven. This woven stiffener has a number of unidirectional continuous fibers or associated and oriented materials. In aeronautics, cost and delays in certifying composite material constituents can limit the types of stiffener that can be used. During the laminate design phase, an optimised architecture is defined for the laminate, however, using certified woven stiffeners may be the source of deviations between the optimised laminate architecture and the manufactured laminate architecture, and Fig. 1 illustrates this using an example showing the differences. To simplify the diagram, this example does not follow the rules of technological minimum [5]. This difference between the architectures impacts on the thickness of the laminate, and hence on the mass of the component and may give rise to strains. Organisation of the stacking is defined in a second phase in order to reach a compromise between reduction in mass and symmetry of stacking. We plan to use asymmetrical stacking for type_1 components. This asymmetry produces strains that are acceptable for type_1 components although not for type_2 components. Moreover, strains associated with using the RTM process are not caused solely by the architecture of the laminate. The different heat expansions of the constituent parts and the thermal cycles of polymerisation can also produce strain as parts are removed from the mould [6].
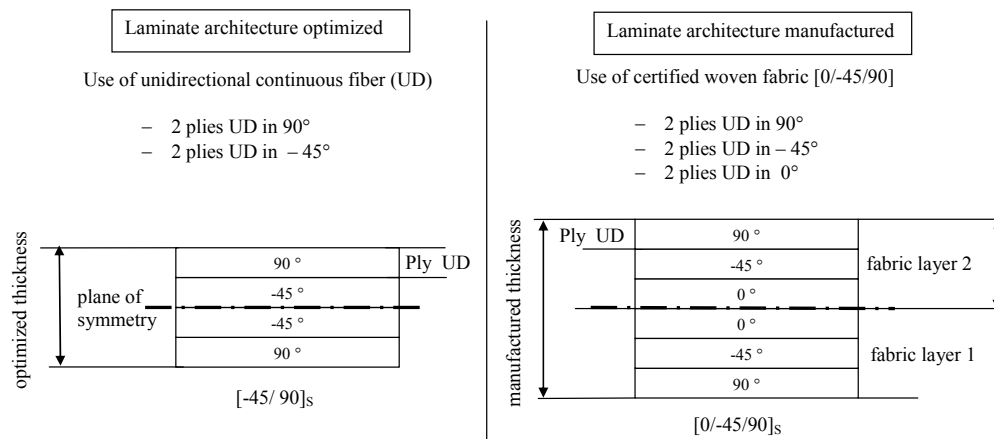
Fig. 1 Optimized and manufactured laminate architectures.

DIFFERENT GEOMETRIES FOR A TYPE_1 COMPONENT

During the industrialisation phase for a type_1 component, the aim is to estimate acceptable limits for manufacturing deviations in the RTM process according to the maximal limit of

mechanical assembly stresses. As well as specifying the acceptable limits for manufacturing deviations, industrial practices and ISO standards for geometric specifications also lay down a stress condition that derives either from the criterion defined for manufactured parts or the criterion for the sub-unit, as defined in the paragraph above, "Classification of structural composite components". To quantify the strains associated with the shaping process we will first define several component states. These definitions will be based on behaviours of the product in the design cycle. Each state is associated with specific stress conditions (Fig. 2). Free state [4]: the manufactured component is subjected only to the action of gravity and to the residual stresses of the shaping process. The Sub-unit state corresponds to the mechanical stresses of assembly: the manufactured part is integrated into the sub-unit to which it belongs. Lastly, we define an Airplane state where the aircraft is in normal operational conditions. The Primary stresses state corresponds to the inspection stage, where manufacturing deviations in the part must respect the two criteria: assembly requirements and mechanical behaviour.
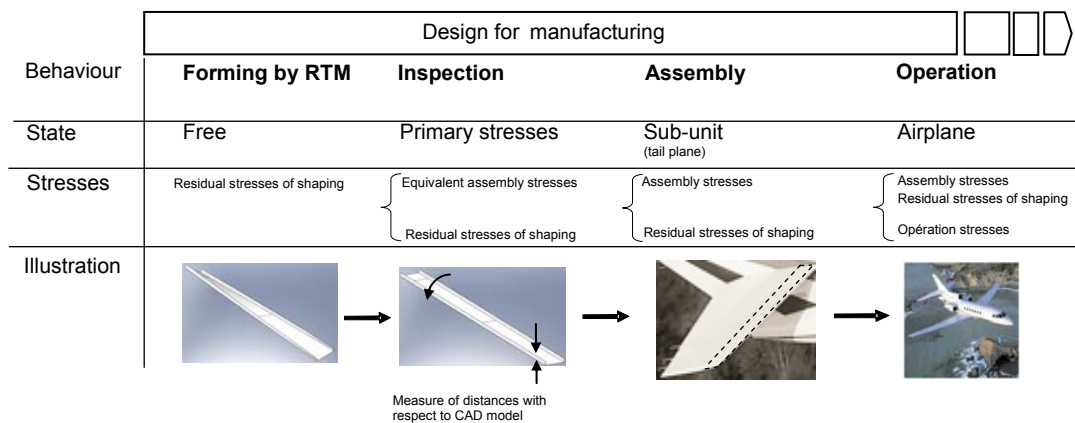

Behaviour	Design for manufacturing			
	Forming by RTM	**Inspection**	**Assembly**	**Operation**
State	Free	Primary stresses	Sub-unit (tail plane)	Airplane
Stresses	Residual stresses of shaping	Equivalent assembly stresses — Residual stresses of shaping	Assembly stresses — Residual stresses of shaping	Assembly stresses — Residual stresses of shaping — Opération stresses
Illustration		Measure of distances with respect to CAD model		

Fig. 2 Different states of a type_1 component.

INDUSTRIALISATION MODEL AND SOLUTIONS SPACE

The level of functional integration of an aeronautical sub-unit is determined by the ratio of the number of components assembled to the number of functions the sub-unit must carry out. This level is optimal if the sub-unit consists of a single component. The architecture of a component can give rise to several industrialisation solutions all of which would enable the component to be produced and to carry out the functions for which it has been designed. Our model must therefore be able to define a group of solutions which are compatible with the multi-expert stresses used. The stresses are formalised according to expert knowledge derived from the engineering and design department and the industrialisation departments and take the form of expert rules, arithmetic and logic relations. If expert software tools are used, then experimental designs can be set up from which response surfaces models can be generated. Each solution is defined by a free state. This set of solutions forms the industrialisation solutions space. The modelling variables (Fig. 3) are divided into four groups: **design variables**: engineering department and material (in the aeronautics industry this group is constrained by certification); **industrialisation variables**: process and laminate, in our study the sub-group process is limited to RTM [7];

performance variables: functional integration, feasibility injection and manufacturing deviations; **auxiliary variables**: set of variables needed to define constraints [8].

The resolution strategy based on exploring a solutions space produces value domains {D} associated with the variables {V}, these may be design variables, industrialisation variables and performance variables. Each solution thus defined will satisfy all the constraints of the problem {C} and will be formalised by the free geometric state of the component. This set of variables and constraints represents a constraint satisfaction problem. Values associated with the performance variables (performance indicators) will guide choice in the solutions space. Due to the heterogeneity of the variables being manipulated, the use of multi-expert constraints and the exploration of a solutions space, we considered using a constraint satisfaction problem solver [9].
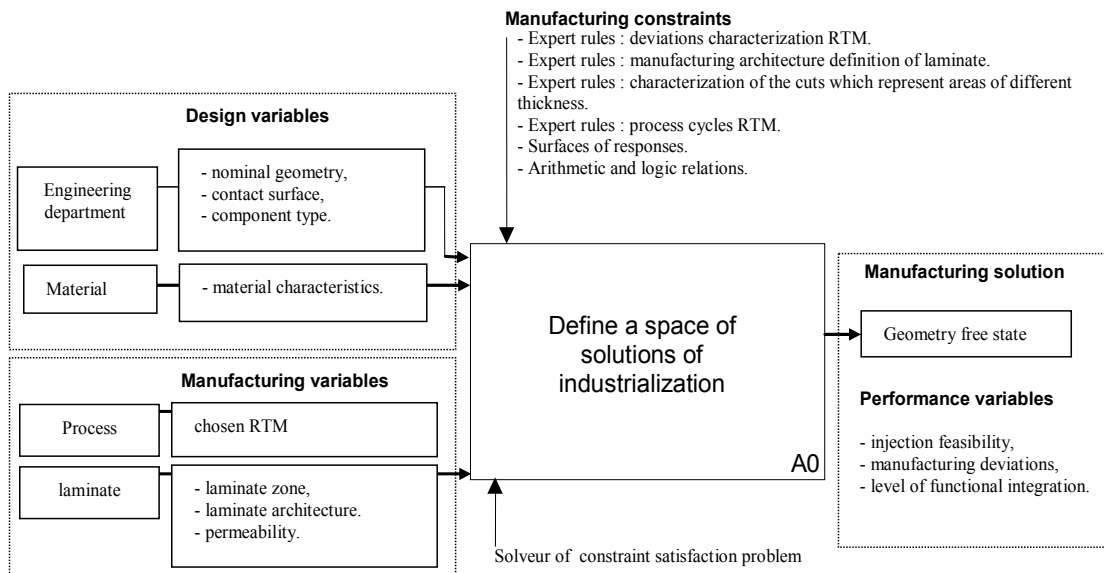

Fig. 3 Modelling to determine industrially feasible solutions (IDEF0 formalism).

Fig. 4 shows the processing of variables and their values, resulting in an industrialisation solution. The variables below are generally sets of elementary variables which define a parameter that is relevant to the design cycle for the component:
− nominal geometry: defined by a set of variables associated with the initial shapes and dimensions of the component. A second set of variables defines the shapes, dimensions and positions of additional geometries to the component's initial geometry,
− contact surface: defined by a set of variables describing the shapes, dimensions and positions of the contact surfaces, the number of variables may change with the level of functional integration,
− component type: this variable has two values (type_1 or type_2),
− material characteristics: defined by a set of variables describing the type of stiffener and the type of resin,
− laminate zone: defined by a set of variables describing the different shapes that are possible at the ends of the zones,
− laminate architecture: defined by a set of variables describing the stacking of the fibers, independently of the type of stiffener and the type of component,

- permeability: defined by a set of variables describing the types of resin flow through the preform in the tools,
- injection feasibility: defined for each solution by a variable whose value is a function of a porosity rate,
- manufacturing deviations: defined for each solution by a variable whose value is a function of the stress condition,
- functional integration: defined for each solution by a variable whose value is assessed based on the number of functions carried out by the component.
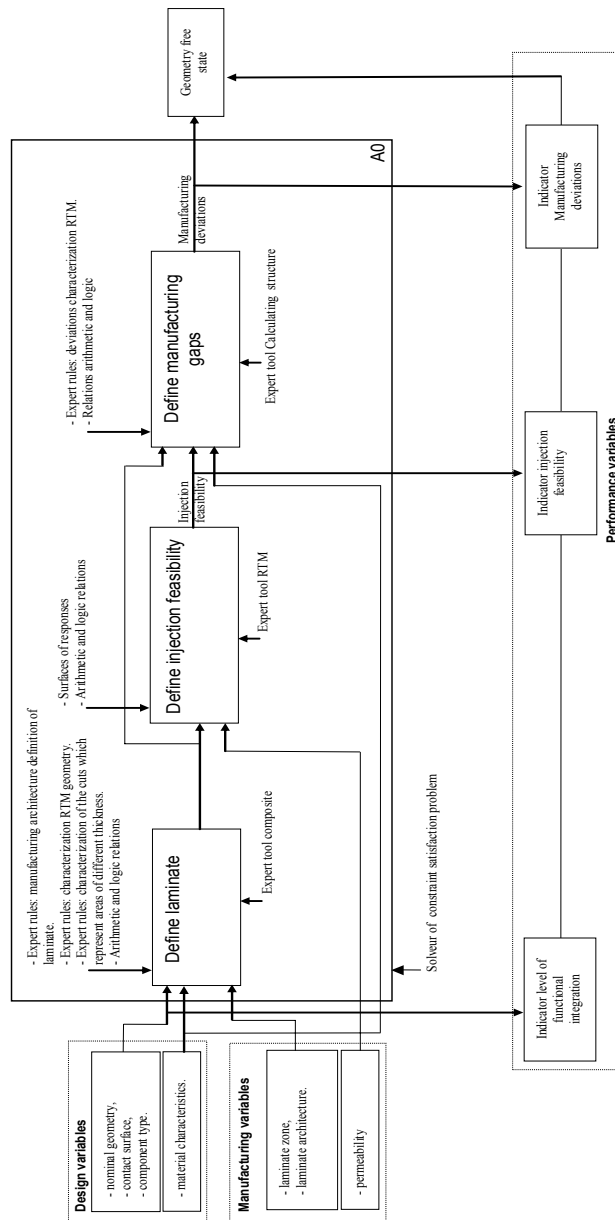

Fig. 4 Meta-model to determine industrialisation solutions (IDEF0 formalism).

A constraint satisfaction problem solver is an effective procedure to apply to an industrialisation model, taking into account causality when processing the variables and then prioritising these variables. In terms of digital processing, our work consisted of proposing a modelling framework

(meta-model). Using meta-models, the performance of constraint satisfaction problem solvers can be improved in terms of calculation time and solution quality [10]. In our study, three stages were necessary to finally define a solution:

- definition of two characteristics relating to the laminate and one relating to the geometry of the component: definition of the stacking of the laminate according to the nature of the stiffener and the component type and definition of the geometry of the end of the fibers that make up the zones, definition of the nominal geometry of the component adapted to the process (joint radius, maximum dimensions, etc.).
- estimation of solution injectability using a software tool. For this stage, permeability values must be defined, these values will be obtained experimentally or semi-analytically. Injectability can be estimated by measuring porosity rates from injection simulations.
- definition of admissible manufacturing deviations which depend on the condition imposed on the constraint when defined industrially. To obtain this value, solution injectability must be greater than a fixed percentage of porosity rates; if this is not the case the solution is abandoned. Results from the first stage combined with the characteristics of the material will produce a definition of manufacturing deviations. This definition guarantees the mechanical behaviour of the component and of the structure into which it will be inserted.

One of the major difficulties found with this type of constraint satisfaction problem is that the set of variables, the set of constraints and the set of domains may evolve during the solving process. This is traditionally identified as a dynamic constraint satisfaction problem. Moreover, the value domains associated with the variables may change across continuous and discrete spaces. Our problem falls into the category of dynamic mixed constraint satisfaction problem [11].

INDUSTRIAL APPLICATION

This study is part of a collaborative work with the Dassault-Aviation company. We chose to work on a component currently produced by RTM, i.e., the spars that make up the horizontal plane of the Falcon [12]. Assembly of the sub-unit that includes the spars is done using a rigid assembly tool, the spars are type_1 components. The spars are made of carbon fibre and epoxy resin. The solutions space defined by our industrialisation model will be compared with industrial solutions in order to estimate the validity of the modelling.

CONCLUSIONS AND FUTURE PERSPECTIVES

The aim of this aid to industrialisation is to explore a solutions space obtained using a constraint satisfaction problem solver. Constraints are a combination of design and industrialisation variables where each solution is associated with performance indicators. The final choice depends on industrial strategies. This aid to industrialisation can be used during several phases in the life cycle of a product:

- in detailed design, during exchanges between the design department and the industrialisation department. Using this tool it is possible to understand the effect of integrating new functions into the free state geometry of the component and hence estimate repercussions on the RTM shaping phase and the assembly phase,
- in industrialisation, by using specifications for non-rigid parts, to take into account strains due to the process of defining and implementing compliance criteria for manufactured parts,

- in manufacture, to reduce the requirements in terms of geometry for the RTM process.

This work could be associated with post-RTM strain predictions [13]. If strains could be predicted, then a tool could be produced to guarantee that the component's free state is respected.

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