A NEW PRE-DESIGN METHODOLOGY FOR INNOVATIVE COMPOSITE STRUCTURES

Florian Neveu[1], Bruno Castanié[1] and Philippe Olivier[1]

[1] Institut Clément Ader, Université Fédérale Toulouse Midi-Pyrénées, UMR CNRS 5312
3 rue Caroline Aigle, 31400 Toulouse, France
Email: florian.neveu@univ-tlse3.fr, web page: http://www.institut-clement-ader.org/

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ABSTRACT

The use of composite materials keeps growing in the transport industries as well as in the recreational industries. Their integration in brand new products or products previously designed raises the question of designing or re-designing composite parts and sub-assemblies. Due to the very nature of composite materials, complex geometries can be achieved and there is a wide variety of reinforcement/matrix couples as well as many manufacturing processes. The outcome is a hyper-choice of materials and processes for anyone designing a composite part replacing one or several metallic parts, giving the task more complex to converge towards a proper final solution. To this day no clear process for designing composite parts exists and this article aims to present an original methodology to quickly identify the most relevant concepts.

1 INTRODUCTION

Designing a part or a mechanical product is a long process starting from the definition of needs, functions and constraints until the manufacturing step, the maintenance of the product and its possible recycling phase. In many cases, the experience acquired in a specific field helps to tackle the conception phase efficiently, minimizing the risks due to uncertainties about the mechanical properties of the parts or the manufacturing processes for example. Nevertheless, the methodologies which can be applied on homogenous and isotropic materials (metallic alloys, plastics…) do not necessary work for designing new composite parts. The geometric shapes imposed by the manufacturing processes, new constraints specific to the very nature of composite materials, many different architectures available. All these specific aspects inherent to the composite structures suggest the need to revise the design methodologies and to adapt them to these new constraints.

The work presented in this paper aims to propose a pre-design methodology dedicated to composite parts emphasizing the generation of concepts with a quick analysis of their main attributes: the shape, the architecture of the composite structure and the manufacturing process. An evaluation of all the concepts with their own attributes should be done and should provide enough information to pick the most pertinent solutions in order to iterate to the next design loops. This paper will present at first an overview about the generation of concepts, showing the importance of having many pre-design solutions, and then will define the specificities of the composite structures and their impact in the design process. In a second time, the design methodology will be explained and will be applied on a generic example.

2 THE GENERATION OF CONCEPTS IN MECHANICAL ENGINEERING

2.1 Definition of concept and its role in the development of a part

A concept is an idea which is enough developed to be able to evaluate the physical principles governing its behavior. In other terms, considering a mechanical part, we will consider that a concept should respect the following conditions in order to be part of the first design loop:

- The main functions of the product should be fulfilled
- The constraints should also be respected, especially the volume of conception

A concept can take many different forms to represent its idea: it could just be verbal or written descriptions, diagrams, sketches or any other mean describing how the functions can be fulfilled. In this paper, the example of concepts will be shown using 3D CAD (Computer-Aided Design) models because these are the simplest way to illustrate ideas of conception and they are widely used nowadays.

The importance of the concepts should not be underestimated in any case because they are the starting point of the future final part. It is therefore essential to have as many concepts as possible in the pre-design phase of the project because it will increase the chances of success. Having only one or too few concepts and then develop them until the final stages of the project can increase the risks to have a poor solution in the end as explained in Ullman's book [1]. The methodology presented here will focus on this idea to get a large amount of concepts that are suitable for composite parts starting from the geometry.

2.2 Some methods to help generating concepts

Many methods exist to stimulate the creativity and to help generating ideas and solutions to a given problem. The most known and used technique today is the brainstorming which consists in a group of people working on a subject and enumerate a large amount of ideas to create links between them. No judgement should be done on the ideas and it is crucial to let the members propose unrealistic ideas which could be source of inspiration. One alternative to this method is the brainwriting, or 6-3-5 method [2], which is based on the same principle as the brainstorming but it also gives equal participation for all the members. Working with analogies can also be a good source of inspiration, it implies finding solutions based on already known solutions for similar functions. These analogies are particularly used in bio-inspired solutions which are premised on the observation of nature [3]. On the contrary, one can think by contradictions and generate solutions to answer the problem given. A method called Evaporating Cloud [4] takes advantage of these contradictions, its name comes from the fact that the contradictions will disappear at the end of methodology. TRIZ method (theory of inventive problem solving) [5] is also well-known for its ability to solve technical problems by generating innovative solutions based on existing technical solutions.

These methods briefly presented can be applied in various projects where the main goal is to innovate. They are also interesting for our purpose since they can help generating ideas of concepts for composite structures. However, the search of technical solutions with the help of these methods will not tell if the concepts are consistent regarding the domain of composite structures. In order to have an efficient methodology, one should have some knowledge in composite materials to be able to evaluate correctly the concepts generated and determine if they are coherent between their shape, architecture and manufacturing process.

3 THE SPECIFICITIES OF COMPOSITE DESIGN

3.1 A different structural approach

Unlike homogeneous and isotropic metallic materials, composite materials have structural characteristics that lead to anisotropic and non-homogeneous properties of the material. When we design a mechanical product, we can think in the following way: the product must meet the defined functions while satisfying the external constraints applied to the system. In other words, the geometry of the part - and therefore its shape - must fit in the design volume defining the space dimensions and must respect the functional surfaces, but it must also withstand the mechanical stresses imposed by the external solicitations. For a metallic part, an approach commonly used is, for example, topological optimization [6] which makes it possible to determine the optimum shape – by minimizing the volume / resistance ratio for example - of a part from a monolithic block. The optimal geometries obtained are then post-processed so that the part can be machined correctly. If this method can be useful for knowing the stress paths and thus orienting the design of the composite part, the topological result cannot be used as such for a composite part. This is mainly due to the fact that composite structures rely heavily on manufacturing processes and therefore their geometry cannot adapt to what a topological result could offer by default. In addition, the notion of composite architecture, which occupies a central place in the methodology presented in this paper, needs to be addressed in more detail. The term architecture refers to the complex and precisely designed structure of an object or something. Applied to composite structures, this definition can be interpreted at different scales and a representation is given in Fig. 1.

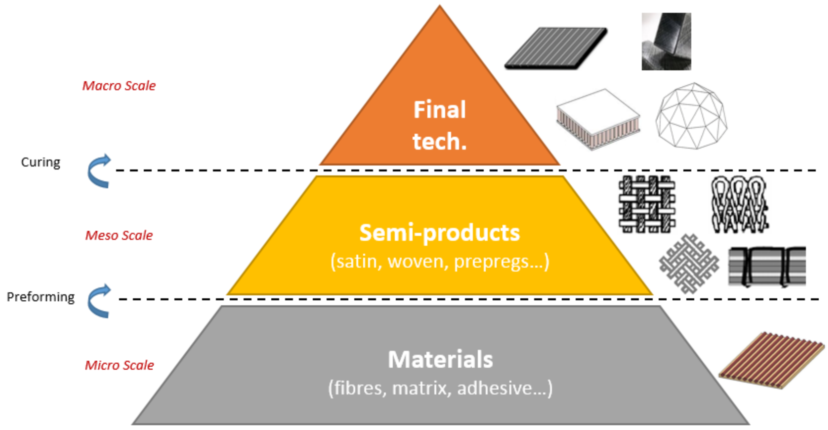
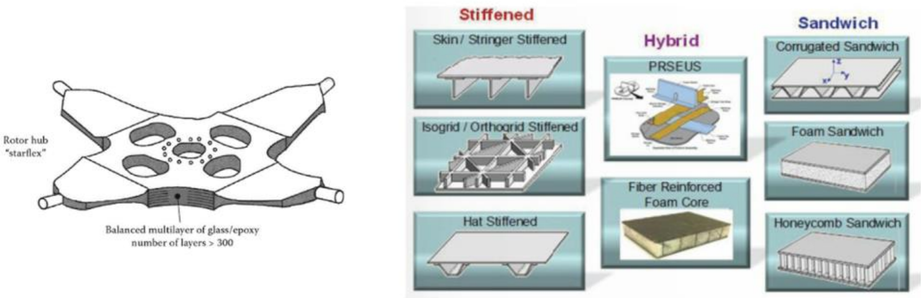


Figure 1: Architecture of composite structures

3.2 Some examples of study cases

Before describing the design process, we propose to focus very briefly on two study cases about the design of a composite part and illustrated in Fig. 2. The first study case concerns the design of the Starflex which was implemented in helicopter rotors in the 1990s. This is a concrete example of the redesign of a metallic part into composite materials: it led to a mass reduction of 50%, 80% reduction in number of parts, reduction of assembly operations and thus reduction in costs of approximately 50% in this example. However, this does not mean that switching from metallic to composite materials works in all cases. Parts made of complex structures combined with potentially costly safety factors and manufacturing processes may sometimes cut the benefits observed in the Starflex example. The case of Starflex is nevertheless a very good example of redesigning into a composite system with interesting outcomes. The second case was handled by NASA and involves the development of a rocket stage containing the payload. In this case study, the aim was to compare different types of composite technologies and this highlights the importance and abundance of architectural solutions when designing composite parts. This article also clarifies the selection process of the different solutions by introducing key performance parameters (such as mass, damage tolerance, etc.) and by assigning a factor of merit obtained after evaluating and scoring the key parameters. This method of selection can also be applied to the choice of concepts at the last stage of the methodology proposed in this article.



a) Starflex geometry b) Different composite architectures

Figure 2: Starflex design [7] and composite architectures studied by NASA [8]

4 THE GAP METHODOLOGY

4.1 Philosophy and objectives of the methodology

The GAP methodology (acronym for the attributes "Geometry", "Architecture", "Processes") is based on this triptych whose attributes are very inter-dependent. The core of the methodology is therefore based on the interactivity of these attributes, which will be explained in the remainder of this part. First of all, it is essential to define the framework of this methodology and what it aims to achieve in a generalized design process. A simple schematization of this process has been proposed by Ashby [9]: the GAP methodology (Fig. 3) particularly fits in the design phase for the creation of concepts and aims to approach the preliminary phase with many simple concepts in order to move towards the most relevant solutions for the next steps of the project.

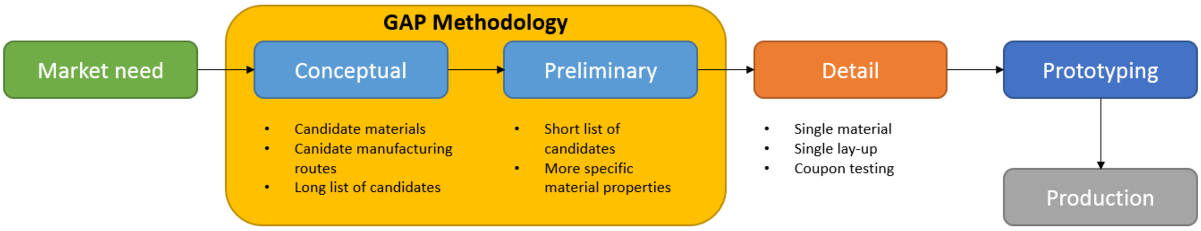


Figure 3: Integration of the GAP methodology embedded in Ashby's process of the creation of a composite part

It was seen in the first parts of the paper the importance of having several concepts and several "visions" to answer a given problem and it was also seen that the solutions of materials, architectures and manufacturing processes lead to many possibilities and therefore a “hyper-choice” for designers. The main idea of the methodology is thus to provide an approach to arrive at a set of coherent concepts on the three critical points identified: geometry, architecture and process. The question of the choice of materials remains secondary at this stage because this can be decided after the selection of concepts for the shortlist of candidate solutions to begin the dimensioning of the structures. The imagined design approach ultimately reduces to three main stages, which are established in the following order:

1. Search of geometrical candidates
2. Targeting of geometrical candidates
3. Design loop for selected candidates

Fig. 4 summarizes the reasoning of the procedure and the design loops necessary to arrive at the n-th geometry Vn. The article focuses on the first two stages only and these are outlined in the next section. Since design loops are ultimately a work of iteration and optimization that will lead to the final model of the part, it is not considered useful to develop those more precisely here.

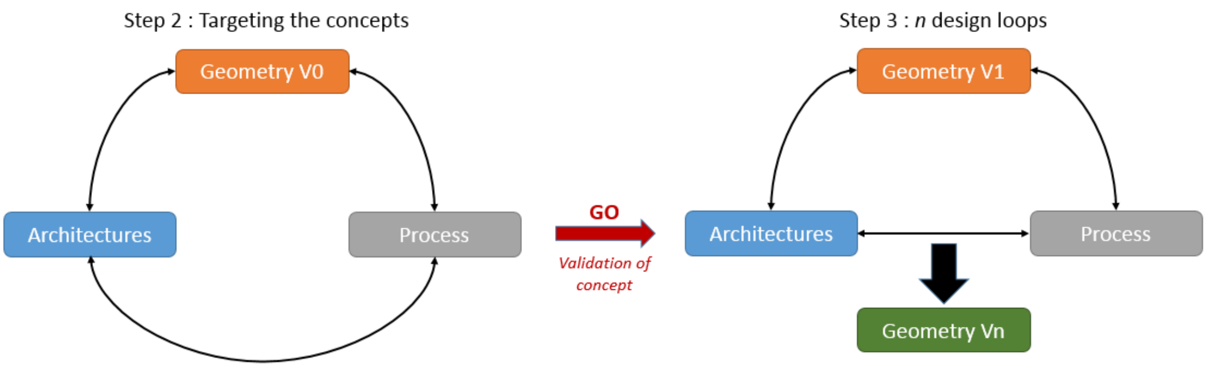


Figure 4: Steps 2 and 3 of the GAP methodology

4.2 Generation of concepts

It is preferable to start with the geometry of the piece, it is indeed this step that involves the creative process of designers and is therefore the most able to give the widest range of shapes and concepts. The guiding idea is therefore to leave the imagination free and sketch the first concepts without focusing on the specificities of composite materials. The results could therefore be extravagant and unfeasible, but it is a standard approach in a context of brainstorming. At this stage of the research of concepts, it might be advisable to think about geometries that can fit into one of these three categories: beam, plate (shell), solid. These three categories are indeed the three major families that make up the classification of forms (Fig. 5) according to the authors of the CES EduPack software [10].

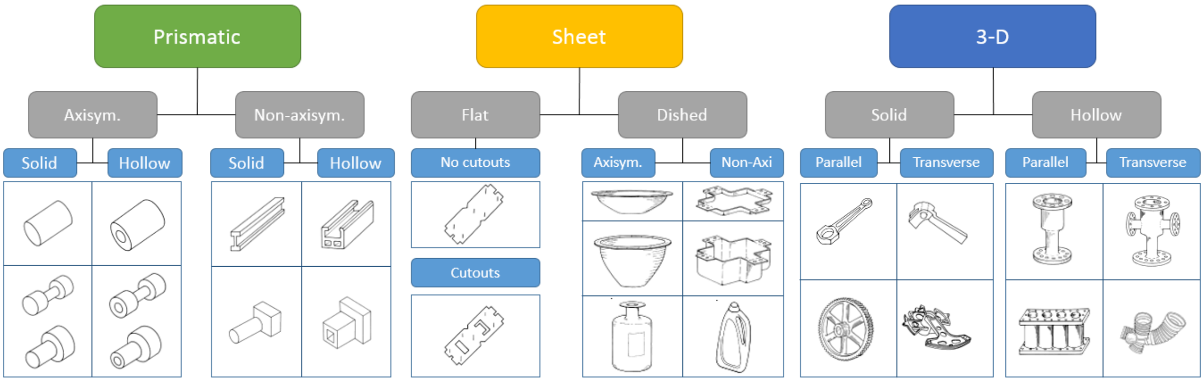


Figure 5: Shape classification

This classification was originally created to make links with the geometries achievable by the manufacturing processes for metal parts, but it is nevertheless relevant for the manufacturing processes of composite parts. We propose to use it as a starting point for the methodology since the nature of the shapes follows logically from the first geometries. From forms, we wish to define which technologies and architectures can match the geometry. This step weaves the first logical and rational link between the imaginary of the concept and the reality of the composite and participates in determining the feasibility of the proposed concept. Concerning composite technologies, we have identified six major classes:

- Thin laminates
- Thick laminates
- Sandwich
- Geodesic
- Profile tube
- 3-D composites

We remain voluntarily general in the framework of this article for the technologies and do not go into the details of the architectures, especially for the 3-D part that could be much more specific. A summary table listing the shapes and architectures can serve as a reference for determining the relationships between shapes and architectures. As the field of composites evolves rapidly, this table is also meant to be kept up to date when new technologies are available. The approach proposed here can thus be enriched by the designer who can integrate new technologies and architectures and make links with the accessible forms. The same reasoning is used to make links between architectures and manufacturing processes. Again, regarding the abundance of processes already there and those who will be developed in the future, continuous technological monitoring is essential to have an exhaustive list of processes. It should be noted though that some new processes are sometimes a variant of another process (example of the RTM process with Light RTM, VA RTM, HP RTM, etc.). Using these two tables of correspondences, it is then possible to output the genealogies for each concept and thus have a very clear representation of the possibilities offered by each concept. The figure (Fig. 6) shows on a generic case how to navigate from table to table in order to determine the genealogy of the solutions with the architectures and processes suitable for each concept (Fig. 7).

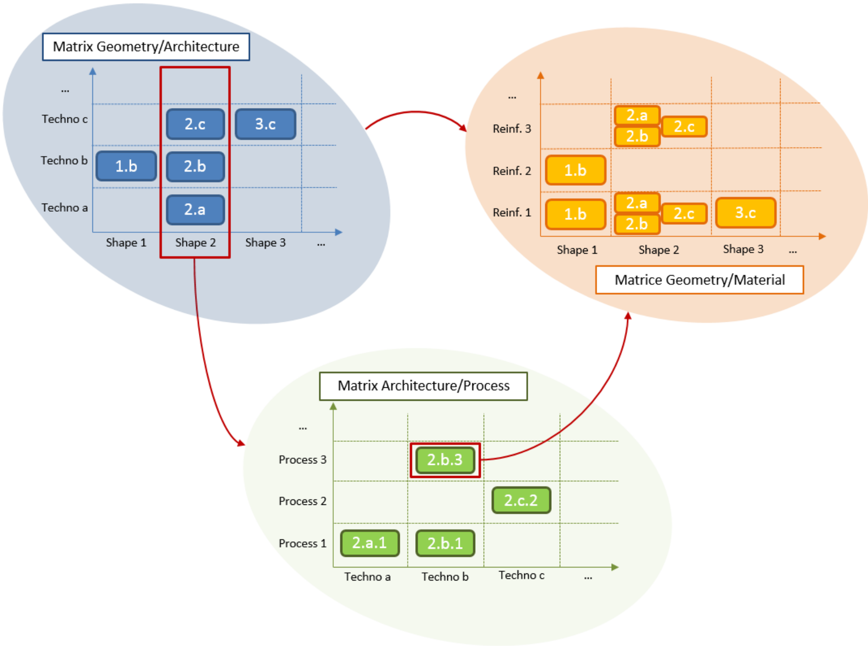


Figure 6: Loop between the geometry, architecture and manufacturing process

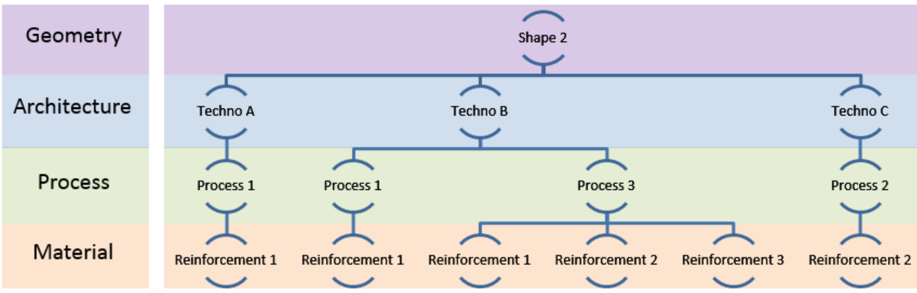


Figure 7: Generic tree of solutions for one concept

A possible integration of information about the material is included in the process. The choice of materials is so vast that it would be useless to list and match them for each manufacturing process. To integrate this problem related to the material, we propose to make the links between the types of reinforcements possible (mats, dry fabrics, UD, prepregs, short fibers) and the geometries. Each reinforcement has indeed a different shape factor and some shapes are thus more easily suitable for a given type of reinforcement. The designer now has at his disposal an explicit overview of the concepts that have been proposed and the selection of candidate concepts for the next design loop can be achieved. This selection can be done on the model of the NASA project discussed earlier in the article with the figure of merits. If the concepts are not mature enough to properly mark the selection criteria, other design iterations can be considered to facilitate this targeting step.

4.3 Application of the methodology through an example

This section proposes to study a generic designing case of a composite part as it could occur in any industrial project. The proposed case does not focus on the study of a specific product or component but is on the other hand very generic. The input data of the project are only functional surfaces, i.e. the geometry of the concepts must imperatively coincide on these surfaces. The functional surfaces for this case study are shown in Fig. 8. In order to give an order of magnitude of the composite part to be designed, let us specify that the dimensions between the corners are 700x400 mm.

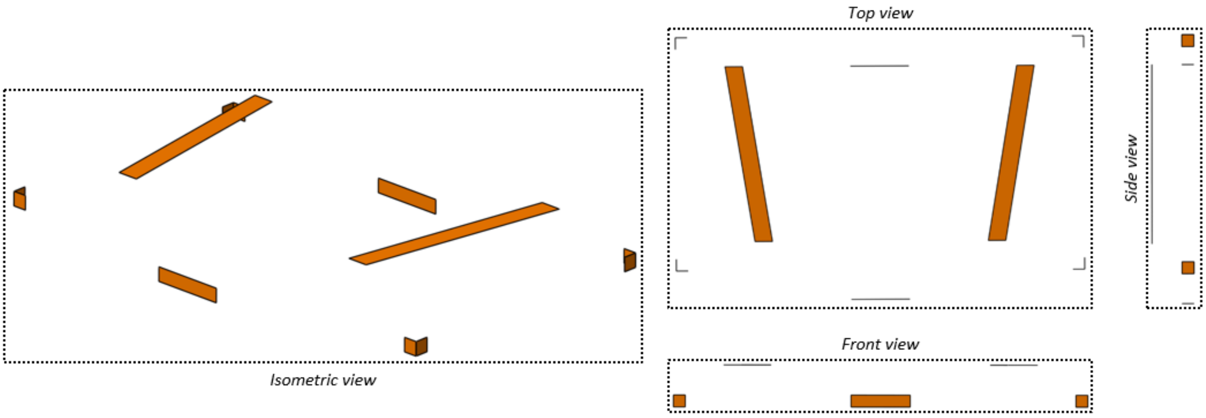


Figure 8: Functional surfaces given

The rules for designing the structure are simple: the geometry must necessarily coincide with the functional surfaces and the design volume falls within the limits set by these surfaces. The design remains free for the rest and all kind of shapes to join these surfaces can be imagined. There is no limit on the number of components, i.e. the structure could be imagined in one shot manufacturing or by assembling several parts. The generation of the first concepts must not impose limits on the possibilities of manufacture, the next targeting step will determine and eliminate the geometries considered as too difficult to manufacture. To illustrate the simplicity of the approach, Master students with approximately 20 hours of course on composites were asked to propose design solutions from the functional surfaces given in Fig. 8. An overview of the concepts created in the first instance is shown in Fig. 9 and Fig. 10: it is interesting to note the diversity of architectures and approaches that encompass the three families of forms defined above. A majority of these solutions tend to plate solutions, which is understandable insofar as composite structures are mainly oriented towards these forms. Another notable point is that there is only one proposed "one shot" concept whereas this would be the main goal to achieve in a composite structure as seen in the Starflex example. This is due to the fact there are few possible options with respect to the configuration given in this example. Concepts 9-a, 9-b and 9-c consist of two or three parts which belong to the "plate" family. The 9-d concept is manufactured in "one shot" with a continuous shell structure that manages to join all the functional surfaces. Each of these concepts have a good manufacturing potential, rather suitable for RTM, contact or vacuum molding.

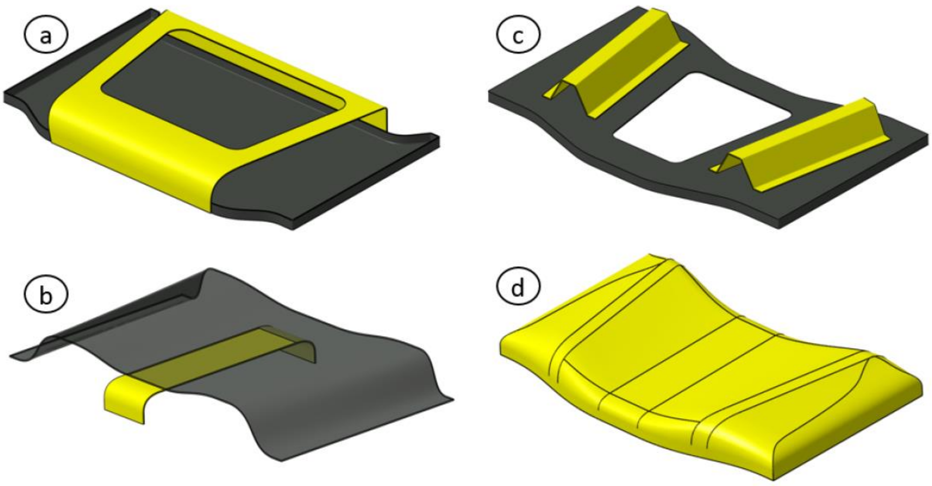


Figure 9: Plate concepts

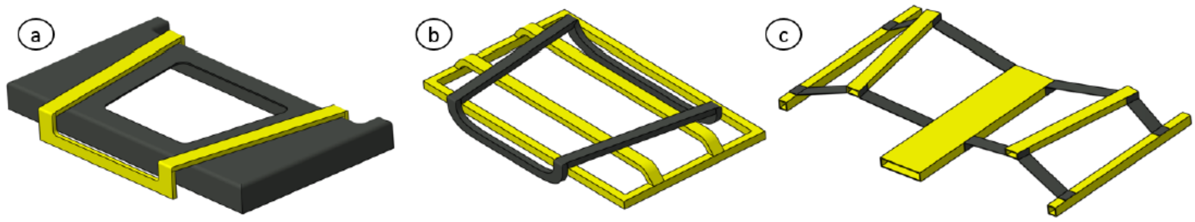


Figure 10: Beams and 3-D concepts

The 10-a concept combines a thicker plate, which could be a sandwich structure with a 3-D beam structure over it. Similarly, for the concept 10-b, two structures rather constituted of 3-D reinforcements rest on one another. Finally, the 10-c concept combines five pultruded beams interlinked by thin laminate slats. In all cases, the junction technologies between the different parts must be defined and taken into account in the evaluation of the concepts, but their integration is not framed in the GAP methodology. For each concept analysis we can define a technology tree linking the geometry, the architecture and the process as shown in the figure Fig. 11 below. The example is taken here for the "one shot" concept of Figure 9-d. This geometry consists entirely of a shell structure which can be made of thin laminates. The most suitable manufacturing processes for this type of architecture are the hand lay-up and the RTM, the spray lay-up if short fibers are considered. The types of reinforcements possible have also been listed for more details because the processes are not necessarily compatible with all the types of reinforcements that can be found in the market.

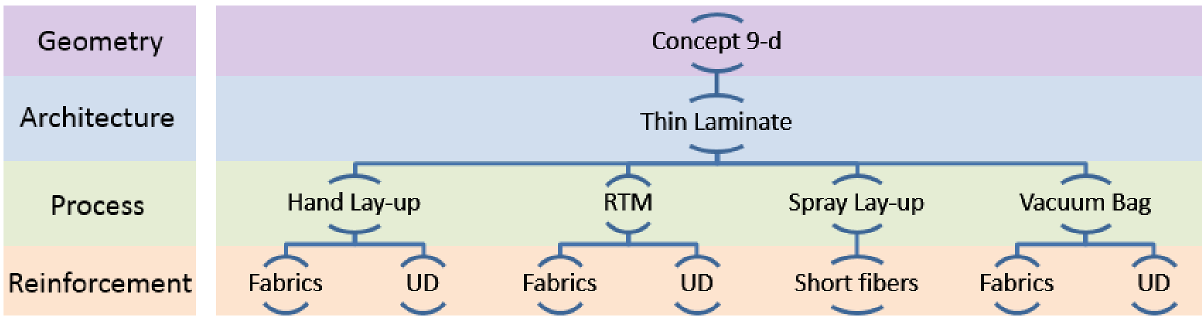


Figure 11: Tree of solutions for the concept 9-d

This technological summary should be done for each proposed concept and, according to the key parameters defined at the beginning of the project, the evaluation and the selection of the concepts can be carried out. The application example presented in this section ends here.

5 CONCLUSION

The GAP methodology presented in this paper provides a design approach for those who wish to design or redesign a composite part. This structured approach is necessary since both composite structures and their manufacturing processes are diversified. It has been shown that the creative process of design is the starting point of the approach and that it must allow generating enough concepts with different forms to envisage a maximum of possible solutions. From there, the methodology provides tools for generating concepts with consistent characteristics between their geometry, architecture and manufacturing process, and may even provide initial indications for the reinforcements to be used. The approach proposed in this article is simple to apply and fits perfectly into the first loops of design in order to bring ideas of coherent composite structures. While it is possible and recommended to be very creative in the geometry of concepts, it is nevertheless necessary to have prior knowledge on composite materials and their manufacturing processes in order to be able to determine the right matches and thus progress in the selection process of the designed concepts.

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