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Computer Aided Process Planning in Aircraft Manufacturing

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ABSTRACT

Aircraft structural parts make around 1% of the total aircraft components. At present, the production cycle of several components families is within the range of few hours. Conversely, the production of structural parts is mainly a human-made operation with manufacturing complexity increasing with the part's morphology. The delicate thin elements and the presence of complex surfaces – mainly ruled surfaces which acquires the external aircraft body shape – sets the production time of mechanical structural parts ranging from few hours (for basic parts) up to over 20 days (for complex parts). The main loss of time is identified in the process planning field. This paper presents at first a review of the production numerical chain, and then offers a review of existing Computer Aided Process Planning (CAPP) software and their points of failures. We follow with the presentation of the USIQUICK project and the resulting CAPP software functions and prototype. We conclude the paper with a review of the main results setting the domain of our current and future research.

Keywords: CAD/CAM, CAPP, Process Planning, Numerical Chain, Aircraft Structural Parts.
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1. INTRODUCTION

The complex morphology of aircraft structural parts made it hard to automate the numerical chain of production. The current manufacturing process is time-consuming and requires an experimented process planner with good knowledge of the manufacturer workshop. This human analysis of the part induces additional visibility errors. The human operators might miss minor manufacturing features leading to a product unfaithful to the original design. Both reasons – Time saving and Errors reduction – forces aerospace industries to research on automated process planning systems. Whereas research in CAD/CAM fields debuted in the 1950's, the CAPP field was left over till the early 1980's. Original research in the CAPP domain treated revolution and 3-axis prismatic parts, once again leaving 5-axis structural parts for manual operations.

1.1 Context: Manufacturing of 5-Axis Aircraft Structural Parts

Aircraft 5-axis parts are geometrically complex and constrained by weight reduction needs. Figure 1 shows an example of a structural part and its location. The part is shaped in all directions with few prismatic areas. These multi-directional extrusions harden the capacity to identify the manufacturing fixtures and the minimal billet. The existence of multi-pockets and thin walls hardens the manufacturing operations sequences. The manufacturing of these particular areas is subject to a particular modus operandi. Ruled surfaces require the administration of flank milling processes and the machine kinematics and accessibility. These reasons – in addition to low production scales – discourage mechanical software industries to develop automated process planning software. This left-over creates a consequent disconnection in the numerical chain of production.

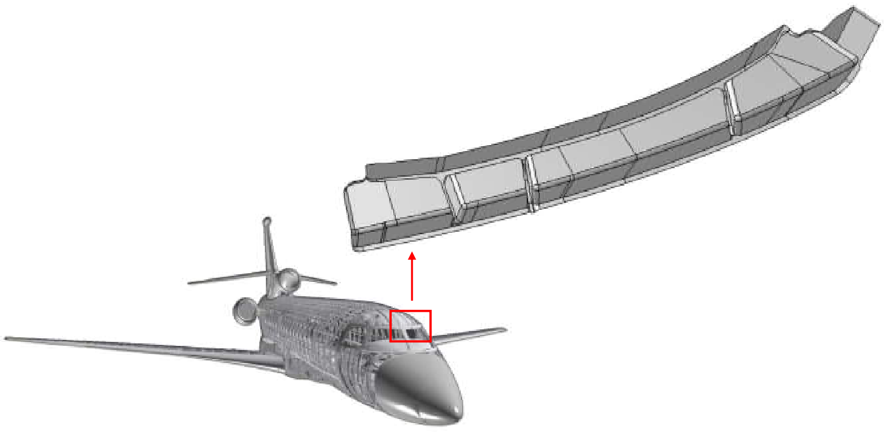

Fig. 1: Example of an aircraft structural part and its complex morphology (Falcon 7X – Dassault Aviation).

1.2 The Numerical Chain: From Specifications to the Product or from a Product to the Product

The positioning of Process Planning in the Numerical Chain is critical to the understanding of potential CAPP software. Figure 2 shows that there are two main numerical chains depending on the starting point. The first numerical chain starts with the specifications of a desired product and sequences design (CAD), process planning (CAPP), numerical manufacturing (CAM), Prototyping, Manufacturing and Quality Control to verify that the product answers the given specifications. The second numerical chain – often encountered in aircraft industries – is the re-manufacturing of an existing product. Older aircrafts do not have a numerical model of their mechanical parts. If a part needs replacement we proceed with the digitization and model reconstruction of the part to obtain the CAD Model. Then we proceed with the same sequence as the first chain.

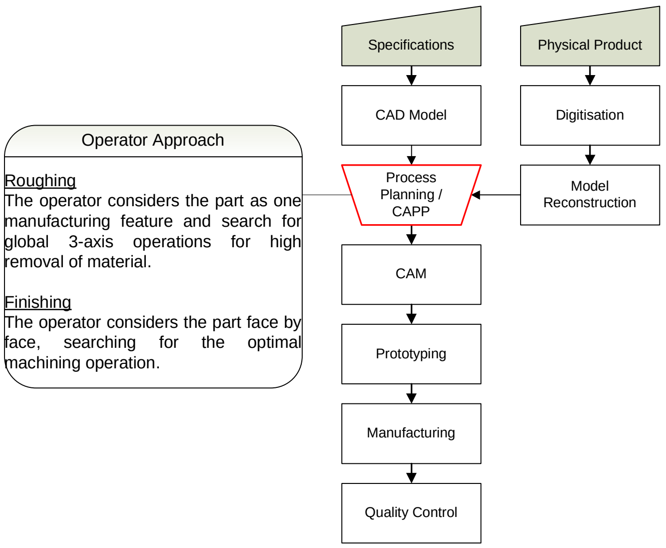

Fig. 2: CAPP in the Numerical Chain and the traditional operator approach.

In both chains, CAPP lies between CAD and CAM. The functionality of the Process Planning operator is to prepare the required information for the tool trajectory generation. The operator often divides his approach into two main parts: Roughing and Finishing. While the roughing part consumes a reasonable amount of time, the finishing one – with its intuitive approach – requires an average of 150 hours to generate one process plan for one part.

2. STATE OF THE ART

CAPP software should generate the Process Plan out of a CAD model. [1] defines a process plan as "all the relevant information required to manufacture the part". In a more detailed manner a process plan consists of (Fig. 3):

- Machining Operation: The manufacturing of one face by one manufacturing tool
- Machining Sequence: The un-interrupted manufacturing of a chain of faces by one manufacturing tool
- Machining Sub-Phase: The different Machining Sequences with the same Manufacturing Fixture
- Machining Phase: The different Machining Sub-phases with the same Manufacturing Machine

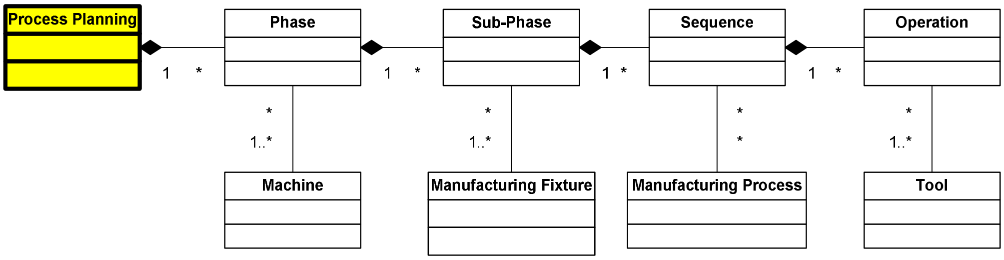

Fig. 3: Composition of a Process Plan.

[3-6] presents a comprehensive state of the art of Process Planning generation. Several CAPP software were developed in academic or industrial ventures: PROPEL [7], emPOWER–MACHININGTM [8], LURPA-TOUR [9], OMEGA [10], IMOLD CAPP System [11], PSG-CAPP [12], CIMSKIL TM (Technology Answers) [13]. These software are related to the general mechanical fields where parts are mainly 3-axis. Between the mentioned software, only [13] is adapted to aerospace industries where the parts are morphologically complex. Even though the final report [13] mention an 80% generation of the process plan, all demonstrations were made on 3-axis parts. We can, therefore, conclude with the lack of 5-axis CAPP software. [12] states that the main reason behind CAPP Software failures is the weak recognition of manufacturing features. A manufacturing feature relates a geometrical feature (face or group of faces) with its manufacturing process. Manufacturing features (MF) are recognized through different approaches: Topological, Heuristic, Volumetric and other less important techniques. However, the latter approaches often encounter problems such as multiple recognition and non-ending loops. Additionally, these approaches are not coherent with the operator approach. [3-6] offers complete details about the different manufacturing features extraction and their non-applicability to 5-axis structural parts.

As written before, during the finishing phase, the process planner doesn't see his part as a set of classical milling features but, in first attempt, considers each face of the CAD model as independent form each other [5]. However, these features are small size entities with much lower semantics than classical milling features. [3-5] call these features elementary milling features (EMF). The more actual definition of the EMF concept is the one proposed by [3], which we will adopt all along this paper: "An EMF is composed of one and only one face of the part CAD model. It is associated to at least one identified and validated finishing process, which must be independent from the other milling processes". The EMF concept is very important and is the core of the USIQUICK project [14]. Because it is based on a natural strategy adopted by the process planner, we clearly thought using this concept to build software could lead to a powerful assistance for the process planner.

However, building a fully automatic process planning software is far from being simple. The development of such a piece of software is a hard task because of the several problems, as mentioned earlier, linked to Manufacturing Features recognition and Process Planning definition. In fact, decision making in the manufacturing domain is difficult to model and even more difficult to instantiate (it is a well-known fact that filling up knowledge bases associated with expert systems is a long process, which can take up to 10 years). In a first attempt, the USIQUICK project aimed at developing a tool to help the process planner by doing some low level tasks and not developing a fully automatic system. The USIQUICK Project comes as an answer to the needs of a French aerospace company Dassault Aviation. This project is a consortium of 5 French research centers (CRAN - Nancy, IRRCyN - Nantes, L3S - Grenoble, LURPA - Paris, LGIPM - Metz) and 2 major companies (Dassault Aviation: Aircraft Manufacturer, and Dassault Systèmes: PLM Solutions). The major objective of the USIQUICK Project is to reduce the time needed for the process planning definition step. In order to do so, the consortium aims to propose software to help the process planner in his cognitive process. More particularly, this software is to be used during the finishing phase, which is the most time-consuming one.

3. USIQUICK: CAPP ASSISTANCE SOFTWARE

The following paragraph presents the usiquick 'transformer'. The latter is in charge of preparing the CAD part for process planning and manufacturing (see Fig. 4). We will present at first the traditional process planner approach of interpreting a CAD model. We will follow it with the presentation of the detailed USIQUICK approach. Then, we will present the resulting CAPP functions and the perspectives of our work.

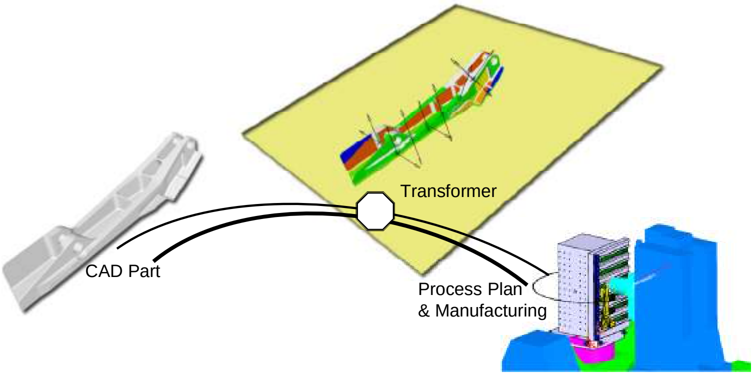

Fig. 4: The USIQUICK 'Transformer'.

3.1 The Operator Approach

The operator approach is based on intuition. The operator reasons in topologically discontinuous levels:

- 3rd level topology (Total Volume): The operator reasons on the part as a whole, identifies its family (3-Axis, 5-Axis, Revolution, Combined Revolution-5Axis …). He then tries to imagine the potential billet definition.
- 2nd level topology (Faces): The operator considers next the part face by face. He analyzes the geometry of the face, think of the potential manufacturing operation/tool combination. i.e. (in figure 5):
  - Face 1: The operator notices that this is a planar face with a particular depression. The face is thus closed. A closed planar face forces an end milling process.
  - Face 2: The operator notices that this is an open planar face with a very high area. The face will be used as a potential manufacturing fixture and will be made in a surfacing operation.
- 3rd level topology (Chain of Faces): The operator considers the part by areas. He selects a combination of faces and visualizes the chaining sequence. i.e. (in figure 5):
  - Chain 1: All the faces are machined in flank milling and they are adjacent 2 by 2, the faces will be chained as one manufacturing feature in flank milling.
  - Chain 2: The faces all-together make a wing top and should be manufactured at first and together.

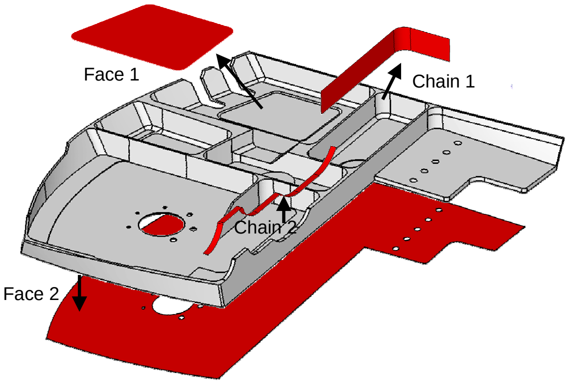

Fig. 5: Operator logic.

3.2 The USIQUICK Approach

The USIQUICK approach takes the operator logic and proposes a two level manufacturing feature extraction:

- Elementary Manufacturing Features (EMF): Low-level manufacturing features associated to one face,
- Manufacturing Features (MF): High-level manufacturing features associated to a chain of faces.

Throughout the conducted research, a pre-MF extraction step – Geometrical Enrichment – was identified. The main outputs of the latter step are:

- The identification of the planar and ruled faces that have special manufacturing processes,
- The identification of fillets that junction functional faces,
- The characterization of the edges' geometry (linear, circular, other) and their sharpness (closed, open, inflexion, other). Theses characteristics influence the manufacturing operations' selection.

The second step – Elementary Manufacturing Features Extraction – explores the information of the first step and computes technological data linked to the face. The latter is studied based on process planners' knowledge rules. At this stage, we study the manufacturability of the face: End Milling (EM), Flank Milling (FM), Sweep Milling (SM) or other. The manufacturability study is extended by the identification of non manufacturable zones (G-Zones & L-Zones). The proposed manufacturing directions will induce the existence of imperfect manufacturing at certain boundaries (E-Zones). The result of this step will transform the face into an elementary manufacturing feature (EMF) that links the face with its technological attributes.

The third and final step – Manufacturing Feature Identification – analyses the enriched B-Rep adjacency graph and determines the set of faces that can be manufactured in sequence. The sequence will thus constitute a high level manufacturing feature. Within this step, some particular Manufacturing Features (MF) are identified such as: Manufacturing Fixture Faces, Thin Features, etc. In the following paragraphs we will develop and present each step in details.

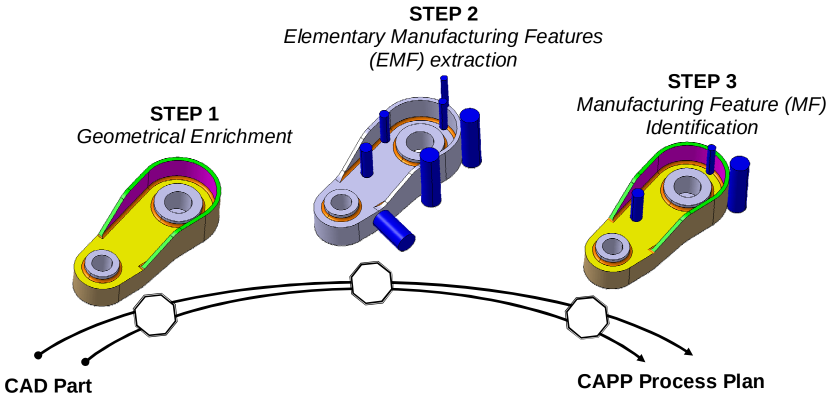

Fig. 6: The USIQUICK approach.

3.2.1 Geometrical Enrichment

CAD models lack the necessary technological knowledge required to automate the process planning and tool trajectories trades. Nowadays, process planners do not function on the same software as the mechanical designers. Adding up, the CAD model might – and most probably will – be generated from a neutral geometrical modeling format such as STEP. Hence, the design intentions and the design tree are lost as all the related geometrical attributes.

The first step of the 'Transformer' is to re-conceive the part according to the B-Rep (Boundary Representation) geometrical modeling. The B-Rep technique is most suitable for manufacturing since it characterizes the model with geometrical information by decomposing the object into the same topological levels as the process planner reasoning: Volume (3rd Level), Face (2nd Level), Edge (1st Level) and Vertex.

Once the B-Rep model is reconceived, we calculate the following attributes for each element:

- The object 'Volume' is enriched with the: volume, total surface area, number of faces and average surface area of a face. The latter trait serves for qualifying a face by "small" or "large" with respect to an average face surface ratio.

- The object 'Face' is enriched with the: surface, perimeter, open perimeter (access perimeter), minimal and maximal curvature, geometrical type, nature, fillets (non functional but necessary for determination of other functions as tool radius, sequencing extraction…), and narrowness.
  I.E. the face nature characterizes the access difficulty level of the face. In the fig.7 below, the green faces are of open access, the blue ones are accessible from one side, and the red ones are not accessible through the face itself.

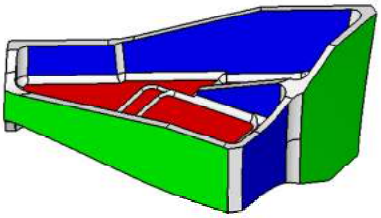

Fig. 7: Face Nature.

Another example, the face' narrowness that characterizes top of thin features. Fig 8 shows narrow faces computed through a formula extracted by made experiments.

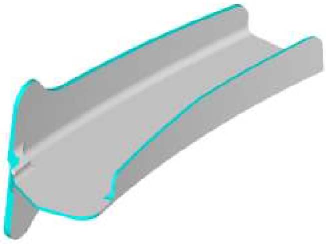

Fig. 8: Face Narrowness.

- The object 'Edge' is enriched with the: length, curvature, inclination angle necessary for manufacturing direction, adjacent faces, types and the sharpness (open, closed, extended, tangent open, tangent closed, inflexion).
- The object 'Vertex' is enriched with the Transition (open, closed, open-closed, closed-open, other).

At this stage, the part's B-Rep model is reconstructed and the different geometrical elements are enriched with attributes needed for the Elementary Manufacturing Features extraction step.

3.2.2 Elementary Manufacturing Features (EMF) extraction

In this step, we will transform the face into an elementary feature with technological attributes. We will study the ability of a face to be manufactured using specific manufacturing operation mode. The latter will propose a group of manufacturing access composed of manufacturing directions. The tool dimensions are then considered. The study is based on knowledge rules that summarize the process planner's know-how.

The face, now enriched with its technological attributes, will thus become the Elementary Manufacturing Feature. EMF are officially defined by [3]: An EMF is composed of one and only one elementary face which boundaries are solidified. It is associated also to at least one finishing process, identified, validated, and independent of the other processes.

In details, EMF have the following characteristics:

- Manufacturing Accessibility: based on experimentation done on planar, cylindrical and ruled surfaces the set of Manufacturing Access composed of Manufacturing Directions are specified. Fig 9 shows an example of Flank Milling Directions.

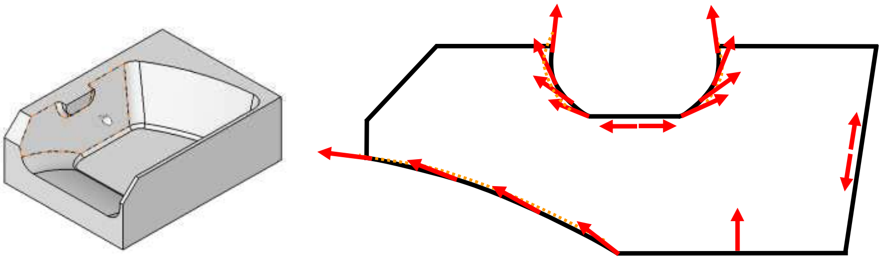

Fig. 9: Manufacturing Flank Milling Access.

- Manufacturing Mode: determine whether the face is manufacturable or not using the manufacturing accessibility results obtained in the previous step. The manufacturing processes that can be used are end, flank, simultaneous, and sweep milling. It is also important to know that the obstacles that might prevent the manufacturing of a certain surface are divided into groups: Local Zones, Global Zones … Operating using end and/or flank milling requires an analysis of the obstacles, and accordingly apply the most suitable solution relative to the group to where the obstacle belongs. Figure 10 shows that face F is sub-divided into two groups: F (in green) manufacturable in end milling, SF (in red) un-accessible in end milling.

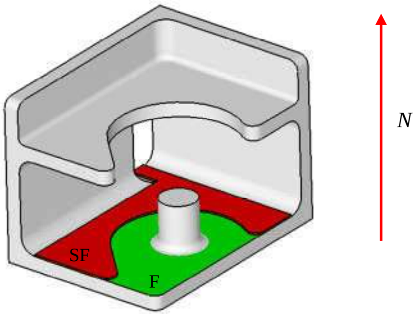

Fig. 10: End Milling Applicability.

- Manufacturing Tools (Figure 11): This step will determine the potential tools to be used in the manufacturing process. A standard tool is characterized by its cutting length, diameter, and corner radius (spherical and torus tools). It should not be too long or else it will be subject to vibrations and, as a result, might fail.

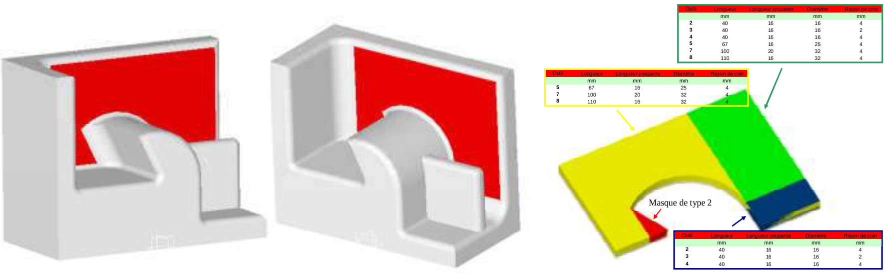

Fig. 11: Manufacturing Tool study.

This step of EMF extraction transforms faces into manufacturable ones. By applying the concepts of elementary manufacturing on a face, we are assigning information concerning its manufacturing process. And all the attributes such as accessibility, manufacturing mode, manufacturing tools that were previously analyzed and assigned will allow the sequencing later on to be done. These attributes are what separate faces into different manufacturing process division.

3.2.3 Manufacturing Feature Identification

The final step of the 'Transformer' is the sequencing of faces. The graph can be obtained from the part (P) using the Usiquick model (Fig 12 – on the left). The nodes on such a graph symbolize the face, and the arcs symbolize the common edges. The adjacency graph conserves the links between faces, but distinguishes faces in function of their type and edges in function of their sharpness. Each face is replaced by its EMF: C-labeled (red) faces are fillets, F-labeled (purple) are flank milled, B-labeled (blue) faces are end milled, E-labeled (light-blue) faces are thin features.
As a result, the original B-Rep model (Fig 12 – on the left) becomes split into sequences (Fig 12 – on the right).

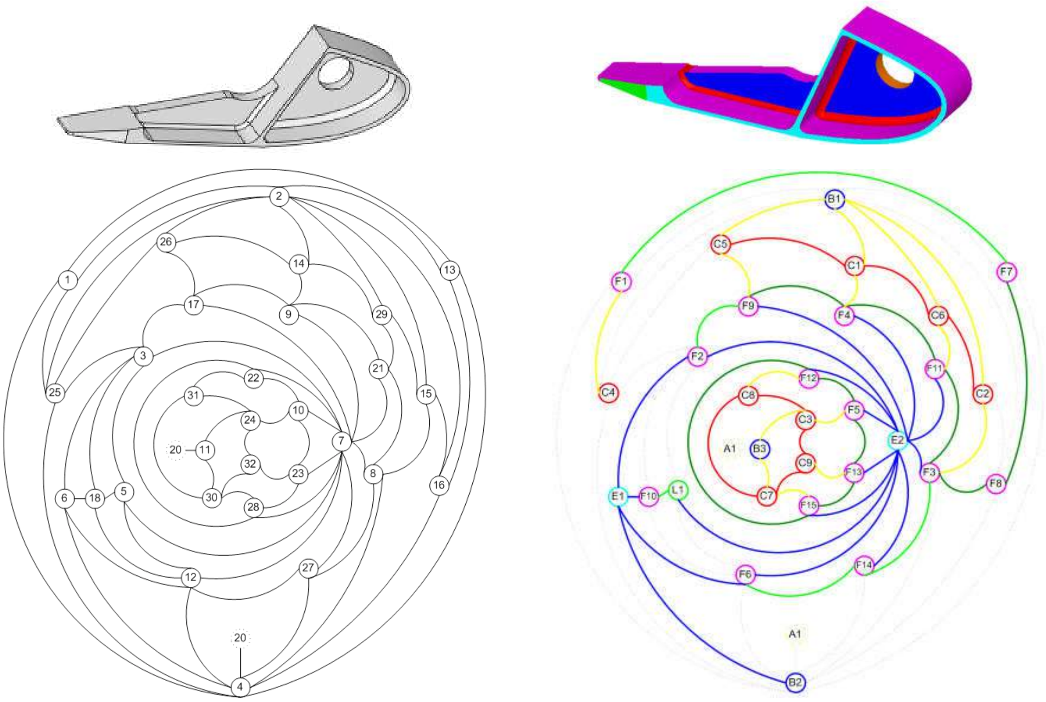

Fig. 12: Extraction of Manufacturing Features.

The new adjacency graph enables the identification of high level Manufacturing Features (based on the previous chains). The main recognized types of manufacturing features are:

- Surfacing feature: constituted by an end milling EMF, open, with the manufacturing direction collinear to the normal of the reference feature
- Pocket feature: constituted by sequence of flank pocket, fillets and end milling EMF.
- Multi-pocket feature: contains many pockets having the plane of the bottom of their pocket parallel.
- External flank feature: formed by external flank sequences.

3.2.4 Conclusion

Throughout the 3 different steps, we were able to extract high level 5-axis manufacturing features. At first we re-generated the B-Rep model of the part and enriched it with geometrical information. Secondly, we computed elementary technological information linked to the face. Third, we sequenced the Elementary Manufacturing Features into high level Manufacturing Features ready to be used as-is in the process plan generation of the part.

4. USIQUICK: DEVELOPMENT IN CAA V5 ®

The software development used the CAA V5 ® architecture provided by Dassault Systèmes. The platform made the software accessible from CATIA V5 ®, a leading PLM solution provided by the same company. In the following paragraph we will advance at first the software development architecture and results. In a latter stage we will present the test of the software by Dassault Aviation process planners.

4.1 Software Development and Results

The functions were integrated in the 'Machining' workshop of CATIA V5 ®. The software appears as toolbar giving the several options to the end-user. 21 different 5-axis structural parts were tested with an average treatment time of 59 seconds. The results are exploitable through 5 ways as seen in figure 13:

- Knowledge-based rules
- Manufacturing view
- Feature models
- 3D visualization of result (construction of elements in the PPR tree)
- Justification tree

The figure below shows different manipulations of the software. For full detailed results of the software check the different presentations and video available in [14], under the 'Bilan' link.

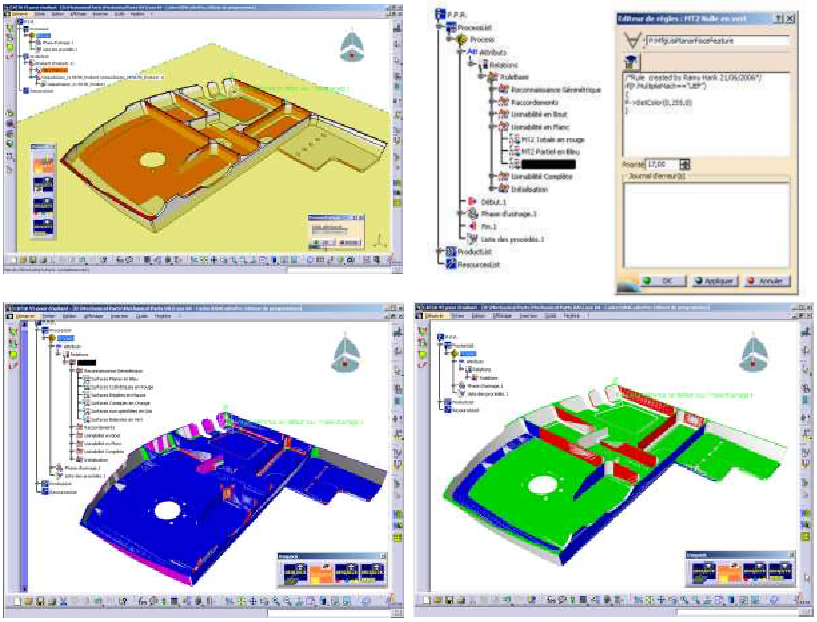

Fig. 13: (upper-left) Launching of the algorithms, (upper-right) Knowledge based rules for colored visualization, (lower-left) Geometrical function results, (lower-right) Manufacturability end-milling results.

4.2 Process Planner Testing

The software was tested by process planners from Dassault Aviation. The process planners noted the following remarks:

- The software reduces dramatically the analysis and comprehension time of the part from days to few hours,
- The software gives a powerful tool in its geometrical recognition function, where the visual output of the latter module helps the generation of a manufacturing fixture,
- The 5-axis manufacturing directions function enabled process planners to identify the manufacturing fixtures without seeing the part itself,
- The latter module permits the selection of the CNC machine to use from the workshop,
- The liability of the results reduces human errors drastically,
- The manufacturability function helps the fast generation of manufacturing strategies

In addition to the mentioned results, Dassault Aviation process planners noted that the current state of the software is of help to all the numerical chain from specifications to manufacturing.

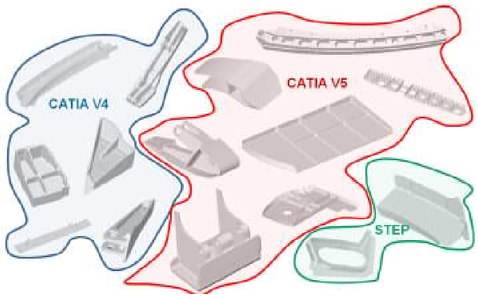

Fig. 14: Different tested mechanical parts and their origin.

5. CONCLUSIONS AND PERSPECTIVES

This paper presented at first a review of the production numerical chain, and offered a review of existing CAPP software and their points of failures. We followed with the presentation of the Operator approach of Process plan generation, and presented the USIQUICK project aimed at the generation of a CAPP software. We presented in details the 'transformer' step as concepts without the calculations for confidentiality agreement. The approach was split into three parts: Geometry, Elementary Features and Manufacturing Features. We then presented the resulting application coded in CAA ® and integrated within the CATIA V5 ® PLM software. Future works will study the robustness of the different proposed algorithms and the transformation of the CAPP defined functions into mathematical ones.

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