Computer-Aided Design of Aerospace Components
Tools and Implementation

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Introduction

After five years spent at selecting, specifying and implementing digital design tools for a large civil aircraft manufacturer, the author became an engineering professor three years ago. One of the author's first teaching assignments was a course entitled *Computer-Aided Design of Aerospace Components*. The content of this advanced CAD course draws on the practical experience gained while making digital design tools part of a business strategy to improve design productivity. The course thus aims at making engineering students understand both the tools and how to make them improve the design process. This paper presents the course original structure and content as well as some decisions made while defining it.

Context

Computer-Aided Design of Aerospace Components is an optional course intended for third or fourth year engineering students. This course is included in the standard curriculum for Automated Production Engineering students electing to specialize in Aerospace Production at École de technologie superieure, located in Montreal, Quebec, Canada. These students previously received formal training on basic Computer Aided Design (CAD) topics such as graphics systems, transformations, curves, surfaces and solid modeling, viewing and rendering, graphic exchanges standards, and so on. Thus, this optional CAD course departs from traditional basic CAD courses by focusing on practical aspects of design tools usage and implementation. Most students have limited or no prior knowledge of the aerospace field. The structure of this advanced one-semester course rests on three poles: formal teaching hours, labs and a project.

Course Objectives

The course conveys a few dominant ideas. First, there is a strong interdependence between design tools and design processes. Introducing new computer-aided design tools in an engineering organization necessarily impacts the engineering processes that support new product development. Students are expected to realize that current CAD tools do no support all phases of the product development process. Therefore, one of the course specific objectives is for students to be able to explain the role of each tool at each product development phase.

Second, one major aspect of CAD in aerospace design projects is the size of the organizations involved, where a single aircraft project easily draws on thousands of people creating ideas and sharing information. An adequate infrastructure as well as discipline is needed to efficiently share this evolving product data. Besides, there are as many ways to use CAD tools to document the product description as there are designers using them, some being more efficient than others. Modeling methodologies are used to standardize, to some extent, the methods used to create identified categories of parts. Two major classes of parts are Machined Parts and Sheet Metal Parts. Hence another specific objective of the course is for students to be able to use a Machined Parts Modeling Methodology and a Sheet Metal Part Modeling Methodology.

Third, design tools are constantly evolving and many a practicing engineer is bound to decide which ones deserve being implemented to bring benefits in term of cycle time, productivity, quality and cost of product and design processes. It is therefore necessary to be able to evaluate in a structured and rigorous manner the benefits that can be brought to a design organization by the potential introduction of a new design tool. Students are thus expected, as a third specific objective, to be able to design and execute such a systematic evaluation plan. They must also be able to design a complete implementation plan taking into account licenses, legacy data, training as well as financial aspects of a typical software tool implementation project.

These objectives are achieved through the study of the course content, described next.

Course content

The educational objectives are achieved by structuring this one-semester course on three poles: formal teaching hours, labs and a project. The following themes are studied during classes, where a unique combination of aerospace knowledge and design tools is proposed.

Introduction to aerospace -- First, since most students have limited background in aerospace, some data on this industry is provided. For example, aerospace accounts for nearly 50000 jobs in the Montreal area[1] and Canada is the fourth country in importance for this business[2]. A typical aircraft is presented, major components are identified and main manufacturing techniques are described. For example, a significant fact is that more than 50% of the part count of a typical civil aircraft is made of sheet metal. This general presentation helps students get familiar with this industry and the vocabulary it uses. A feeling for design compromises involving engine location, weight and stress is illustrated by discussing the rational behind selecting a T-Tail or a Conventional tail.

Aerodynamics and control -- Once students are familiar with aircraft components, it is appropriate for them to get some understanding of the aerodynamics that make flying possible. The physics of lift is explained based on Bernoulli's principle[3]. It is also illustrated using FoilSim, a 'simulation software that determines the airflow around various shapes of airfoils', available from the NASA web site[4]. A favorite question is to ask students to calculate how many people could 'fly' sitting on a standard sheet of press wood given an initial inclination of a few degrees and a constant 100 km/h wind. When students understand aerodynamics, we build on the newly acquired knowledge to appreciate the role of winglets and control devices such as spoilers and airbrakes, as well as the effect of dihedral angle on stability[3]. Through this discussion on aerodynamics and controls, students improve their basic understanding of an aircraft structure and specialized vocabulary.

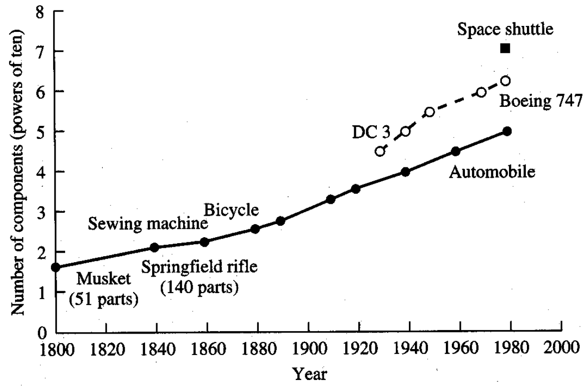

Figure 1 [from (6)]: Evolution of design complexity

Aircraft design processes – Once basic aircraft knowledge is acquired, the design process is formalized. Aerospace design is characterized by the size of design teams, product complexity and numerous technical constraints. We distinguish between Conceptual design, Preliminary design and Detail design and define the deliverables for each phase[5, 6, 7]. Here, students should realize that the process of designing is about exploring, documenting and modifying ideas. The CAD tools must therefore allow easy sharing and modification of product definition data. Current CAD tools essentially convey product geometry resulting from the design effort, generally both as drawings and as 3D solid models. However, current CAD tools capture nothing of the design intent. Despite these limitations, improving design tools contribute to allow design team to create increasingly complex design within shorter cycle time. Figure 1, from Ullman[6], illustrates the increasing complexity in mechanical design; it can be noted that there are over five million components in a Boeing 747 aircraft.

The digital mock-up as a simultaneous engineering tool -- The digital mock-up basically is a communication tool used for sharing the product definition between project participants, as well as with management for example during design reviews. Figure 2 shows a simplified version of the digital mock-up of the canopy of the cockpit of a jet aircraft. Considering that an aircraft design project involves thousands of people defining tens of

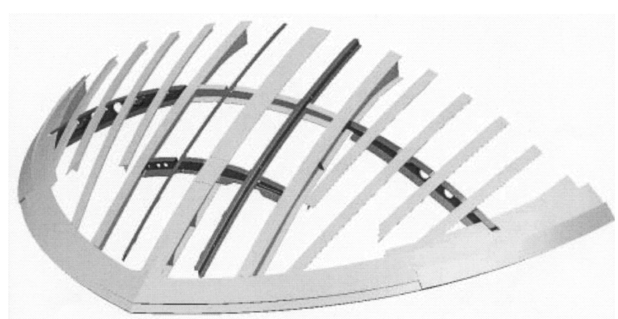

Figure 2: Simplified digital mock-up of an aircraft cockpit canopy

thousands of parts, sharing the product definition is key to success. While the project evolves from conceptual design to detailed design, the design solution is developed and documented to an increasing level of details. The CAD tool needed to capture product definition during conceptual design is basically 2D Drawing. The digital mockup starts being defined during preliminary design, thus relying on solid modeling capabilities to define 'rough' part geometry, so as to reserve space in the digital mock-up. The refined product definition is documented during the detail design phase, using solid modeling, drawing, and annotation tools since two deliverables, a solid model and a detailed drawing, are expected from the design team for each part. Figure 3 illustrates the evolution of solid models, from preliminary to detailed design.

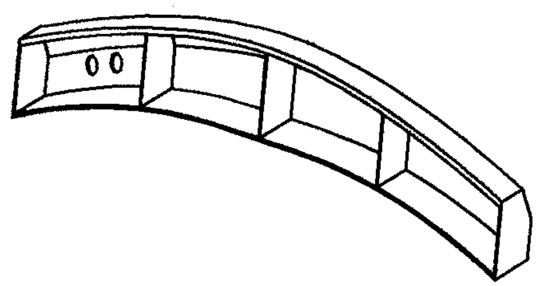

Figure 3a: Ongoing preliminary design

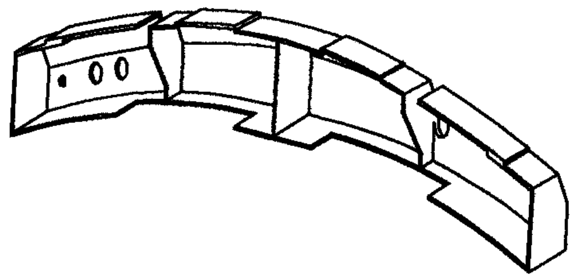

Figure 3b: Preliminary design completed

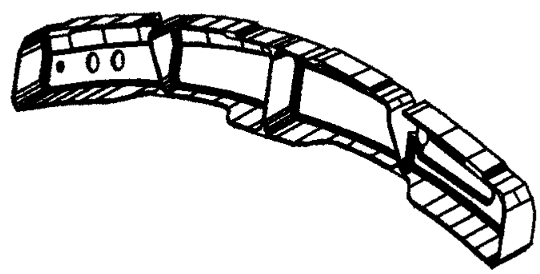

Figure 3c: Detailed design completed

Machined parts design and modeling – Design and modeling are considered as distinct activities. Design is about creating a solution to an engineering problem, while modeling aims at documenting the geometry of this solution. Both design and modeling are discussed in class.

On the design side lies, for example, adequately choosing corner radius sizes (the radius placed at the junction of two walls). This should be slightly larger than the radius of the cutting tool envisioned for machining the part so as to avoid including a full stop in the tool path, which would mark the part.

On the modeling side, students understand that high-end CAD tools are complex pieces of software that can be used in multiple ways to document a design, some being more efficient than others. One key to achieving modeling efficiency is to classify parts into majors groups and to devise specific modeling techniques. Machined parts make one such group. A typical aerospace machined part is shown in Figure 3.

A modeling methodology is defined to facilitate model creation and modification (since designing is a lot about modifying product definition…). Typical machined part modifications include changing wall location, modifying wall thickness, radii, joggle depth and location, etc. For the design process to be efficient, preferred modeling techniques, based on the best industrial practices, are discussed in class and practiced in the lab. Obviously, a modeling methodology is based on the functionality offered by the software used. Currently, the aerospace industry exploits CATIA V4, from Dassault Systemes, and so does the course. Students are led to fully realize this dependency through the implementation project, discussed later, where they benchmark two pieces of software for similar tasks.

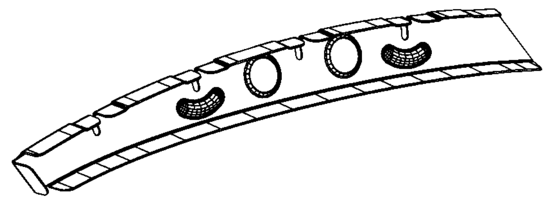

Figure 4: A typical aerospace sheet metal part

Sheet metal parts design and modeling –Sheet Metal parts make the second large group of parts that call for specific design and modeling rules. Figure 4 shows a typical aerospace sheet metal part. Basic sheet metal design rules are first defined. For example, student learn how to determine what is the minimum bending radius that can be used to form a metal sheet, given its thickness and condition, in order to avoid cracking the part. They also learn how to calculate minimum flange length based on the desired fastener size.

Next, general modeling methodology is described. As was the case for machined parts, this methodology aims at facilitating model creation and modification. Typical modifications include changing metal gage and bend radius, lightening hole location and size, joggle location and depth, mating surfaces, flange length, etc. This methodology, based on industrial practice, uses, amongst other tools, solid offsets from mating surfaces to define joggles and the CATIA V4 shelling operator to control wall thickness.

Design by features – The sheet metal modeling methodology mentioned above may be referred to as the 'Classical approach'; it is based on well-known Constructive Solid Geometry (CSG) tools and requires the designer to manipulate primitives such as extrusions, cylinders, and so on. However, design tools do evolve and therefore call for changes in the design processes. As an illustration, many CAD systems today offer specific "Design by features" products for sheet metal modeling. These recent tools impact the way designers create sheet metal parts by relieving them from the tedious, low-level work, generally involved with CSG manipulation, and rather allow them to describe parts as being composed of meaningful sheet metal characteristics such as web, flanges, lightening holes, beads, and so on. This theme is an excellent occasion to compare two software solutions to accomplish a given task, as is done later in the project.

Digital design tools implementation – The constant evolution of design tools forces engineers to measure the benefits they promise in a rigorous manner. As an example, is it worth investing in a Design-by-feature solution for sheet metal or is it too costly for the benefits it would bring? Should design organization switch from CATIA V4 to the newest CATIA V5? Answering such questions implies identifying key factors of a successful design tool implementation. Amongst the metrics considered are the productivity gains, expressed in man-hours and dollars saved, that can be measured by achieving rigorous testing based on modeling representative parts and assemblies. Careful design tool implementation planning must also take estimate the software

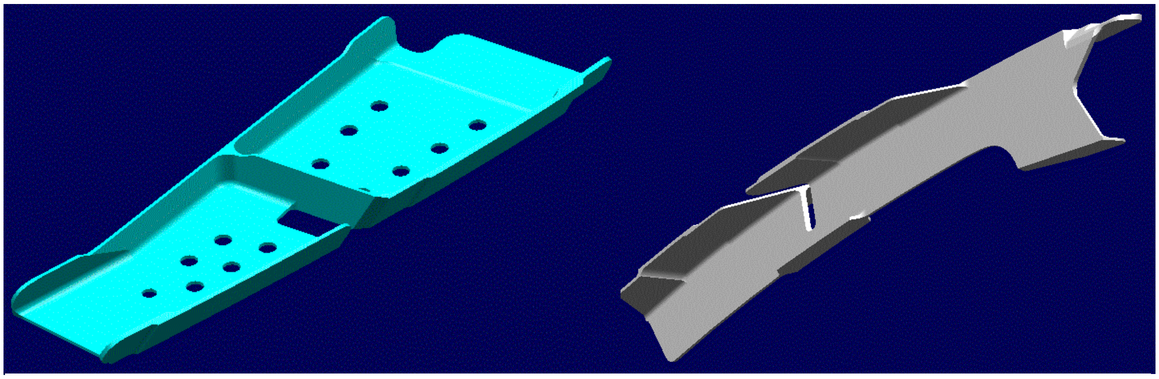

Figure 5: Representative machined parts used to conduct benchmarks

licensing needs, the management of legacy data (which is not a trivial issue!), and training of existing work force.

Laboratory

Most themes discussed in class are experimented in the lab. Lab activities are based on CATIA V4, the software currently used for many commercial aerospace design projects. Lab activities benefit from an agreement made with an aerospace airframe manufacturer who generously agreed to provide a subset of its digital mock-up as training material (Figure 2). Modeling exercises are based on parts drawn from this mock-up, as the ones shown in Figure 3 and 4. Since most students are familiar with CATIA V4 prior to this course, the lab can emphasize on (advanced) part modeling methodologies mentioned above for efficient creation and modification of aerospace parts. About one-third of total lab time is left for students to work on the project.

The Project

The project theme focuses on software selection and implementation principles, an important subject for many a practicing engineers. The course addresses this reality by providing students with metrics to evaluate the success of an implementation project by measuring the costs and benefits incurred by a design tool implementation, such as: measuring productivity gains, estimating the number of licenses required, estimating the costs of training, devising a migration plan for legacy data, etc. These notions are put to practice through a project. For example, students act as a team of engineers having to conduct a software evaluation and to design an implementation plan for a (fictive) company interested in replacing their CATIA V4 solution for machined parts with a CATIA V5 solution. Since the latter is not a simple evolution of the former but rather is a new, distinct product, and that industry is bound to abandon the old, soon unsupported V4, to embrace a more recent solution such as V5, this is a realistic project actually taking place in many design organizations.

As would be the case for an actual designer involved in such a benchmark, the evaluation phase requires each student to become familiar with both software solutions in order to decide on how to use the new software in the context of the company. Each student is given a representative part, as the aerospace machined parts shown in Figure 5, and is asked to model it at least three times with both tools. All results are reported and the best time is considered as representative of the productivity of an average user during the model creation process. It can be noted that such a test measures the modeling performance and involves no design work since the part is already designed. Tests are also performed to assess the performance of both solutions during model modifications work. To this end, students are provided with a few representative modification scenarios.

Of course, this project is by no means a full-scale benchmark between two software solutions. Students each spend the equivalent of about a week of work performing this evaluation and they are thus asked to focus on specific aspects of product modeling. For example, they are assigned to sheet metal parts or to machined parts, but are not expected to consider other areas such as drawing creation or assembly modeling. Even though this is a time-consuming exercise, students appreciate being exposed to multiple software solutions. It provides them with important skills that they can apply to real-world problems as soon as they graduate from school.

Discussion

This course balances, in a unique manner, knowledge belonging to three areas: aerospace, design rules and design tools (a comparable course is offered at Stanford University that focuses on yachts rather than on aircrafts[8]). Many questions arose while designing this course and the reasoning about some of them deserves being exposed.

Isn't this course too focused on CAD tool specific commands? –Modeling efficiency comes at the cost of mastering the specific commands of a given CAD tool. However, we expect the students to remember, say a year later, the general idea of what a methodology is helpful for, that is to standardize the most efficient methods available to create and modify identified categories of parts. Moreover, when conducting the project, students are asked to adapt the methodology they mastered with one software to another software. They are thus expected to understand the general concepts rather than to focus on specific details.

What is the pertinence of this course to graduates not working in the aerospace field? - -One can safely estimate that less than half the students attending this course will end-up working in the aerospace industry. This is why most of the course content relates to generic mechanical design practices and tools. Most examples, however, draw on aerospace industry methods and practices.

Isn't this course too CAD oriented? –This course looks at design from a structure designer perspective, which requires design skills as well as modeling skills. We therefore aim at teaching the basics of both (design and modeling) and to highlight the connections between them. For example, students are first expected to understand, from a designer perspective, that they have to avoid designing unnecessarily costly features such as a 5 axis surface if a 3 or 4 axis surface adequately fulfill the functional need. Next, they have to be able to define a 3 or 4 axis surface, rather than a 5 axis one, using the CAD tool at hand.

Conclusion

This course differs from traditional CAD courses by focusing on practical aspects of industrial implementation and exploitation of digital design tools for the aerospace industry. It examines the tools and how to effectively use them to actually improve the design process. It has received highly positive evaluations by students (more than 4.0/5.0), and discussions with industry representatives confirm that it fulfills an actual need.

Bibliography

1. R.A.Malatest & Associates Ltd, *Rapport sommaire - Enquête sur le marché de la main d'œuvre aérospatiale au Canada (Prévisions de main d'œuvre 2001-2004)*, Préparé pour CAMAQ, OAC et MAHRCC, Septembre 2001.
2. Daniel Chrétien, *Les ailes du Québec*, Québec Science, Juin 2001.Kroes, Michael J. and James R. Rardon, *Aircraft Basic Science*, 7th ed., Glencoe/McGraw-Hill, 1993, 414 pages.
4. http://www.grc.nasa.gov/WWW/K-12/FoilSim/index.html
5. Daniel P. Raymer, *Aircraft Design: A Conceptual Approach*, 3rd ed., AIAA Education Series, 1999, 923 pages.
6. David G.Ullman, *The Mechanical Design Process*, 2nd ed., McGraw-Hill, 1997, 340 pages.
7. McMahon, Chris and Jimmie Browne, *CAD/CAM - Principles, Practice and Manufacturing Management*, 2nd ed., Addison-Wesley, 1998, 665 pages.
8. Course ME 209: Computer-Aided Design of Model Yachts, Stanford University, Department of Mechanical Engineering (http://171.64.50.104/FMPro?-db=2001-2002coursedatabase.fp3&-format=detail.html&-lay=layout%20%231&-sortfield=course%20number&title=Computer-Aided%20Design%20of%20Model%20Yachts&-max=2147483647&-recid=33001&-find)

Biography

Louis RIVEST is a mechanical engineer. He holds a Ph.D. in the CAD/CAM field. He spent five years at Bombardier Aerospace in Montreal as a CAD/CAM specialist. He is now Professor at Ecole de technologie superieure in Montreal where is teaches Computer Aided Design. Amongst his research interests are the development of tools and methods to improve the mechanical design process and product data management.