Knowledge based engineering support for aircraft component design

Knowledge based engineering support for aircraft component design

Proefschrift

ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft,
op gezag van de Rector Magnificus prof. dr. ir. J.T. Fokkema,
voorzitter van het College voor Promoties,
in het openbaar te verdedigen op 15 januari 2008 om 12:30 uur

door

Antoon Hille VAN DER LAAN
ingenieur in de luchtvaart en ruimtevaart
geboren te Wanroij

Dit proefschrift is goedgekeurd door de promotor:
Prof. dr. ir. M.J.L. van Tooren

Samenstelling promotiecommissie:

Rector Magnificus,	voorzitter
Prof. dr. ir. M.J.L. van Tooren,	Technische Universiteit Delft, promotor
Prof. Dr. R. Roy,	Cranfield University
Prof.ir. A. Beukers,	Technische Universiteit Delft
Prof.ir. J.J. Hopman,	Technische Universiteit Delft
Dr. R. Curran,	The Queen’s University of Belfast
Dr.ir. H.E.N. Bersee,	Technische Universiteit Delft

ISBN: 978-90-90225-56-2

Keywords: Knowledge Based Engineering, Cost Estimation, Aircraft Movables, Engineering Automation, Aircraft component design process

Printed in The Netherlands.

This research was financially supported by the Dutch Technology Foundation STW
(DLR.6054)

"The real problem is not whether machines think but whether men do."
B.F. Skinner

Contents

Acknowledgements

Special thanks goes out to all everyone involved in starting and finishing my PhD. First off all I like to thank Michel for giving me the chance of doing the research and guiding me through this sometimes difficult process. Our talks always gave me inspiration do go on. I would also like to thank Harald for giving me a job in the thermoplastic rudder project. Without this I would have probably left University a long time ago.

When doing your PhD. Research colleagues are always important. First of all to share your ideas with, secondly to give you support and finally just to have fun with. Therefore I would like to thank all my fellow struggling PhD students from the “Vliegtuighal”, Tai, Patricia, Witchuda, Giovanni, Darko, Sotiris, and Bas. I would also like to thank the other personnel that gave me support especially while designing and building the thermoplastic rudder, Bert, Marc, Sebastiaan thanks.

During my research I moved from the “Vliegtuighal” to the “Systems Integration Aircraft” group later called “Design of Air- and Rotorcraft”. Here I also met some fellow PhD. students who gave me inspiration to finish my PhD. Therefore I would like to thank Chiara, Gianfranco, Paolo, Lars, Giampietro, Marco, Jochem and Joost. I hope they all, except for Paolo who is already finished, finish their PhD soon. I should also not forget the people who supported me with my administrational duties, thanks Lin, and helped me with my computer trouble, thanks Michiel. Special thanks also goes out to Brent who helped me with taking many of the hurdles of finishing a PhD. thesis. Of Course I am forgetting a lot of people at the Faculty of Aerospace engineering, I’d like to thank all of them.

Life is not all about work one also needs support outside work to let of steam and make you remember that life is not all about finishing a PhD. Therefore I would like to thank all my friends who I might have neglected a bit over the last few months and my collegeus at Fokker who have had to put up with my whining. Finally I would like to thank my family for supporting me during my PhD research, thanks Toos, Annemarie, Rob and Ivo. Special thanks goes out to Femke and Jason who always managed to get my mind of work.

Summary

Currently improvements in the aircraft industry are seldom based on configuration changes of the aircraft itself. Instead the current evolutionary process in the aircraft industry is based on the continuous innovation and improvements of the aircraft components used in the aircraft manufacturing process. These aircraft component are often not designed and produced by the aircraft manufacturer themselves. Design and manufacture of the components is sub-contracted to suppliers. The level of sub-contracting is increasing with aircraft manufacturers focussing more and more on the integration of the different components and managing the aircraft supply chain. On the other hand aircraft component suppliers are forced to reduce design and manufacturing cost and lead times to remain competitive and to meet the demands of the aircraft integrators. To achieve these reductions in cost and lead time the aircraft component suppliers need to improve their development process. One method of improving the development process is the use of Systems Engineering in the design of new aircraft components. Systems Engineering consists of a collection of tools and techniques that allow the improvement of the design process. Part of Systems Engineering is the clearly defining what the requirements for a system are and checking to what degree these requirements are met. This is part of the so called the "Design for X" methodology, where X defines the sub-set of requirements that will be checked. The "Design for X" methodology can be used to improve the aircraft component design process. However "Design for X" can be time and resource consuming. This can be overcome by creating tools that automate part of the methodology. One of these automation techniques is Knowledge Based Engineering (KBE). Therefore the objective of this thesis is to prove the following: "Knowledge Based Engineering enables the application of the "Design for X" aspect of Systems Engineering for the aircraft component design process".

The design process of an aircraft component consists of a cycle of generating design concepts, analyzing these concepts and, using the analysis results, choosing the best concept, after which the whole process is repeated at the next level of detail. In this design process 3 actors are from the engineering perspective the most important. These are the design engineer, the structural engineer and the manufacturing engineer. Each of these actors each has a different view of the designed component. This can result in inconsistencies between the analyses of the different actors. These inconsistencies can result in analyses having to be re-done or in trade-off decisions not choosing the best design concept. Another issue in the design process is that the most important decisions have to be taken early in the design process. However in this phase the information on which to base the decisions is not very detailed. This can result in the wrong decisions being taken, which have disastrous consequences for the project. In addition to the previously discussed issues, creating and analysing a design concept can be so time consuming that not the whole possible design space can be explored.

Applying the "Design for X" methodology involves executing detailed analyses in specific analyses areas early in the aircraft component design process. In this thesis KBE tools are presented that can be used to automate part of the detailed analysis

process. Most potential for improving the aircraft component design process using these KBE tools are identified as being:

- **Automating the model preparation and analysis for the structural analysis of an aircraft component.**
- **Increasing the detail level of the manufacturability analysis of an aircraft component.**
- **Automating the modelling of the aircraft component design itself.**
- **Standardizing communication between the different analyses disciplines in the aircraft component design process.**

For the first three areas methodologies KBE tools were developed. The developed tools are positioned in a design framework, a so called Design and Engineering Engine (DEE). Improvement area four is addressed by standardizing the communication within this DEE using commonly used and accessible file types.

Automating the modelling of the aircraft component design itself.

A generative modelling engine for aircraft trailing edge movables has been developed. This modelling engine is capable of generating geometrical models of aircraft trailing edge movables based on a set of input parameters. The modelling engine is capable of generating both a structural view and a manufacturing view of the aircraft movable. Structural view means that the geometrical elements forming the movable are represented according to structural function. In the manufacturing view the geometrical elements are represented according to the way the movable is manufactured. Besides geometry the modelling engine also generates data needed for both structural and manufacturing analyses.

Increasing the detail level of the manufacturability analysis of an aircraft component.

A cost estimation tool for estimating the recurring manufacturing cost of aircraft movable has been developed. In the cost estimation process the required resources for manufacturing a component is related to characteristics of the component. There are many different ways of defining this relationship. Identifying the cost estimation method used for a cost estimate can be difficult however because there is no standard way of classifying cost estimation methods. Therefore a new method of classifying cost estimation methods based on there characteristics is devised. This classification system clearly states the characteristics of a cost estimation method. In the cost estimation tool developed a detailed cost estimation is performed based on the movable model created by the generative modelling engine for aircraft movables. The cost estimation relates geometric characteristics, such as a part area or volume, to manufacturing times required for manufacturing the part. The manufacturing times are determined for all the steps in the manufacturing process. The cost estimation tool creates detailed cost estimates, which fit in the “Design for Cost” methodology.

A tool has been developed that analyses the drapability of a composite movable rib. This drapability is an indicator for the chance of successful manufacture of such a rib. This tool illustrates how the chance of successful manufacture can be addressed early in the design process using sophisticated simulation tools. By addressing this chance the “Design for manufacturability” methodology is supported.

Automating the model preparation and analysis for the structural analysis of an aircraft component

For automating the structural analysis process a tool is developed which automatically generates the Finite Element (FE) model for an aircraft movable. This tool uses the movable model generated by the generative modelling engine. This tool is capable of creating a detailed structural analysis model. Using such a detailed model fits in the “Design for strength and stiffness” methodology. Because the structural analysis is based on the generative modelling engine for aircraft movables its results are consistent with the results from the cost estimation tool.

Standardizing communication between the different analyses disciplines in the aircraft component design process.

All communication inside and between the different developed KBE tools use standardized and transparent data formats, in this way communication is standardized. Standardizing data formats means that they are accessible without any specialized software. Transparent data formats means that they can by understood stand alone without access to any other files.

In the aircraft component design process actors from disciplines like design, structural analysis and manufacturing engineering have to cooperate to define a design which meets the requirements. To enable the “Design for X” methodology the disciplines must be able to perform a detailed analysis in a limited amount of time. It has been shown throughout this thesis that KBE can automate time consuming non creative tasks in the design process, significantly reducing the time it takes to perform detailed analyses. For the “Design for X” methodology to function properly the results from the different analyses must be consistent. It has been shown throughout this thesis that KBE can ensure consistency by standardizing communications between the different analysis disciplines.

One of the main contributions of this thesis is to identify where the problem areas in the aircraft component design process lie and how they can be solved. Furthermore methodologies have been developed to use detailed analysis methods earlier in the aircraft component design process. The main contribution of the work in the industrial context is to show how KBE tools handling multiple design aspects can be implemented in the context of a Design and Engineering Engine and how this implementation can improve the aircraft component design process.

Because KBE is able to create detailed results quickly and able to keep analysis results from different disciplines consistent it enables the application of the “Design for X” aspect of the Systems Engineering methodology for the aircraft component design process.

Nomenclature

Latin symbols

A_{double}	[m^2]	Total double curved area of a manufacturable part
A_{flat}	[m^2]	Total flat area of a manufacturable part
A_n	[m^2]	Area with induces geodesic curvature due to the nth curved sharp connection of a manufacturable part
A_{single}	[m^2]	Total single curved area of a manufacturable part
A_{total}	[m^2]	Total area of the manufacturable part
b_n	[-]	Sharp surface connections influence factor on manufacturing process acceleration
c_d	[-]	Double curvature influence factor on manufacturing process steady state speed
c_d	[-]	Influence factor on manufacturing process steady state speed of induces geodesic curvature due to curves sharp connection within a manufacturable part
C_m	[€]	Material cost
c_n	[-]	Single curvature influence factor on manufacturing process steady state speed
I_g	[-]	Geodesic curves information content
I_n	[-]	Normal curved information content
I_{sharp}	[-]	Sharp surface connections information content
L_{curve}	[m]	Curve length
P	[€/var]	Material price
sr	[-]	Scrap rate
t	[sec]	Manufacturing process time
t_{delay}	[sec]	Delay time in the manufacturing process
V_d	[m^2/sec]	Penalty factor for the steady state speed of a manufacturing process due to induced geodesic curvature on a manufacturable part
x	[var]	Variable on which the cost estimation is based for example volume or area

Greek symbols

α	[^{o}]	Angle difference in a connection curve
κ_g	[1/m]	Geodesic curvature
κ_n	[1/m]	Normal curvature
ν_{double}	[m^2/sec]	Steady state speed of a manufacturing process for double curves piece of a manufacturable part

$v_{overall}$	[m^2/sec]	Steady state speed of the manufacturing process for the total manufacturable part
v_{single}	[m^2/sec]	Steady state speed of a manufacturing process for single curves piece of a manufacturable part
v_0	[var/sec]	Steady state speed of the manufacturing process
θ_d	[^{o}]	Geodetic angle due to discontinuous curves connections
θ_{sharp}	[^{o}]	Angle between two surface elements of the same manufacturable part
$\tau_{overall}$	[sec]	Time it takes to reach 63% of the manufacturing process steady state for the total manufacturable part
τ_0	[sec]	Time it takes to reach 63% of the manufacturing process steady state

Abbreviations

CM	Capability Module
CS	Certification Specifications
COTS	Commercial Of The Shelf
DEE	Design and Engineering Engine
FE	Finite Element
FEM	Finite Element Modelling
GUI	Graphical User Interface
HLP	High Level Primitive
IGES	Initial Graphics Exchange Specification
KBE	Knowledge Based Engineering
MDEE	Movable Design and Engineering Engine
MDO	Multi-Disciplinary Optimization
MMG	Multi Model Generator
MML	MOKA Modelling language
PCL	Patran Command Language
PMM	Parametric Movable Model
RMMG	Rib Multi Model Generator
STEP	Standard for The Exchange of Product model data
WBS	Work Brake down Structure
UML	Unified Modelling Language
XML	eXtensible Markup Language

1 Introduction

Currently improvements in the aircraft industry are seldom based on configuration changes of the aircraft itself. Instead the current evolutionary process in the aircraft industry is based on the continuous innovation and improvements of the aircraft components used in the aircraft manufacturing process. These aircraft component are often not designed and produced by the aircraft manufacturer themselves. Design and manufacture of the components is sub-contracted to suppliers. The level of sub-contracting is increasing with aircraft manufacturers focussing more and more on the integration of the different components and managing the aircraft supply chain. On the other hand aircraft component suppliers are forced to reduce design and manufacturing cost to remain competitive and to meet the demands of the aircraft integrators. These suppliers face tough challenges especially in the initial development phases. First of all they have to compete with other companies for acquiring work share on every new aircraft project. Secondly they have to respond quickly to aircraft configuration changes initiated by the aircraft integrator company. To meet these challenges the suppliers need to improve the aircraft component development process in the initial phases.

To investigate how the development process of aircraft components can be improved first the aircraft components themselves will be characterized. This characterization not only involves looking at the components themselves, but also looks at the process used to manufacture them. Using this characterization, the aircraft component development process, and the important issues related to this process, will be discussed. Next the thesis objectives will be introduced and the approach taken to reach these objectives is discussed. Finally a these outline is given.

1.1 Aircraft components

An aircraft can be sub-divided in to several different groups (Figure 1-1). This thesis focuses on one of these groups; the airframe. The airframe contains the structural elements that build up the aircraft; the so called aircraft components. To investigate why the airframe is divided into different components first the history of airframe manufacture will be discussed. Next the different types of aircraft component are discussed.

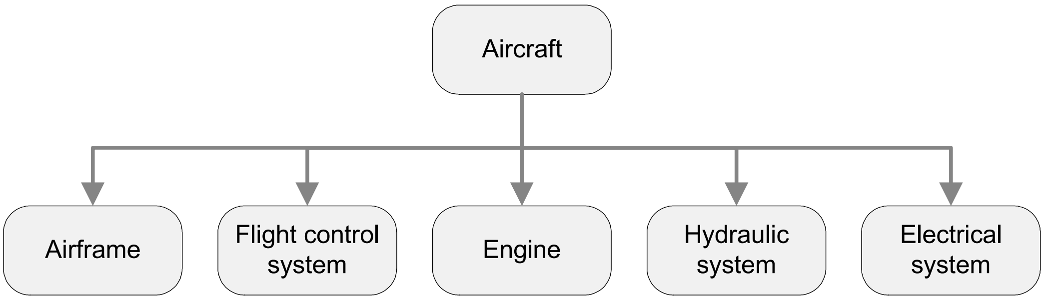


Figure 1-1 Typical division of an aircraft into different groups

1.1.1 History of aircraft components in the aircraft manufacturing process

Aircraft components have been around as long as aircraft have been manufactured. In the beginning of the 20th century the aircraft build were usually unique. Meaning the components for these aircraft had to be manufactured from scratch and were also unique. The component manufacturing was usually conducted in the same shop that was used for the manufacture of the aircraft itself. Even the most important sub-component of the aircraft, the engine, was sometimes developed and produced in house, as was the case with the Wright-flyer.

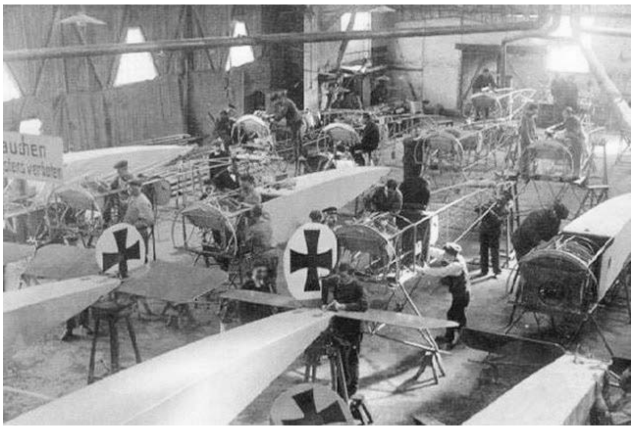


Figure 1-2 Fokker E-III assembly area

Because demand for aircraft rapidly increased during World War One, the production volume of aircraft had to be increased. To do this the efficiency of the production process had to be improved. This resulted in the adaptation of manufacturing techniques from other disciplines such as the automotive industry. Such adaptations meant for example the introduction of an assembly area and the standardization of the models produced. Because the aircraft models were standardized, aircraft components shape could be standardized and could be produced in batches separate from the aircraft assembly area. An example of a Word War One assembly area can be seen in Figure 1-2. Aircraft components could be produced separately from the actual aircraft. Therefore the production could also be performed in factories other than the aircraft factory. Because efficiency needed to increase to increase production output, components were often manufactured by specialist companies. For example almost all aircraft engines in world war one were produced by specialist engine builders or by automobile companies with experience in engine building. The use of component suppliers also had drawbacks in, for instance, the reliability of the supply. This can be illustrated by the acquisition of the Obursul engine company by the Fokker aircraft manufacturer to guarantee the supply of engines. Components could also be produced by less specialized companies to free up essential manufacturing capacity. This resulted, for example, in the production of aircraft components in the United States that were assembled in Great Britain or France.

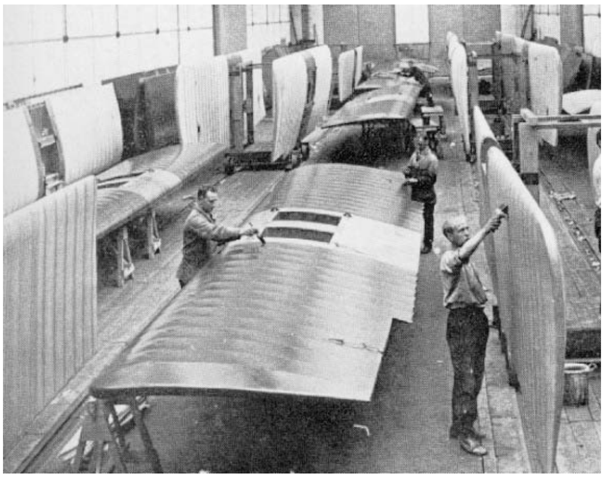


Figure 1-3 Painting of Fokker wings at Werkspoor


Figure 1-4 Fokker aircraft plant in Amsterdam, 1936

After World War One production volumes came down. However the adapted production methods kept being used and the focus slowly switched from military aircraft to civilian aircraft. Subcontracting work on the aircraft components also became more common, as can be seen in Figure 1-3, and the specialized engine companies remained. Most manufacturing work was still carried out in the aircraft factory itself though (Figure 1-4). Design of the aircraft and all its components was still very much the job of the aircraft manufacturer. This meant that the aircraft manufacturer also determined the material and technology for the production of the aircraft components.

Before World War Two most American aircraft manufactures were still using a job shop approach. This meant that an aircraft was assembled basically on its spot from relatively small aircraft components (Simonson, 1968). However the large number of aircraft needed for the war effort called for more efficient manufacturing methods. These were again found in the automotive industry, where the assembly line had been adopted (Figure 1-5). Automotive companies started manufacturing aircraft using their own manufacturing techniques, while aircraft manufacturers adopted manufacturing techniques from the automotive industry. Changing the production of aircraft to line production and increasing the production rate meant that the aircraft components used in final assembly had to become larger. This meant increasing the number of aircraft component levels which, by using several assembly steps, could be transformed into large sub-assemblies, used at the final assembly line of an aircraft. In many cases production of the aircraft components was sub-contracted so aircraft manufacturers could concentrate on the assembly of the aircraft itself. In later stages of the war 50% of airframe production was sub-contracted. These sub-contractors were also able to specialize on supplying certain components or performing a certain kind of work increasing the production efficiency and quantities. Manufacturing schedules of aircraft manufacturers and their sub-contractors were also synchronized to increased efficiency. Specialization could not prevent serious quality problems however, as many sub contractors had no experience with the tight tolerances required by the aircraft industry. An example of the increased size and the number of components in the American aircraft industry in the Second World War can be seen in Figure 1-6.

Figure 1-5 Lightning moving assembly line

Figure 1-6 Components for Martin bombers

After the World War Two demand for aircraft decreased and aircraft manufacturers concentrated on new technologies such as jet engines and pressurized cabins. Sub-contracting of aircraft components virtually died out because sub-contracting was considered to costly and, more importantly, sub-contractors could be unreliable. Not only aircraft technology changed, also the technology to manufacture aircraft changed. Production began to incorporate new machines that could automate or replace part of the labour intensive work. Another advance was the use of new jigging technology developed during the war in Germany (Bright, 1978). This new technology used standardized jigging components that could be easily combined into almost any jig configuration. This technology meant more flexible jigging reducing the tooling cost and the time is took to change a jig.

During the production ramp up for the Korean War sub contracting was again introduced in the American aircraft industry, pressurized by the government. Contrary to the situation after the World War Two, sub-contracting was sustained after the Korean War. As the number of both civil and military aircraft declined major aircraft manufacturers were forced to become sub-contractors. Contrary to earlier subcontractors that had no aerospace background, these former aircraft manufacturers had significant of engineering and manufacturing expertise. Engineering expertise meant they could take over part of the engineering effort from the aircraft manufacturer. Manufacturing experience meant that they knew how to manufacture aircraft components efficiently and to a high quality standard.

Over the years the sub-contractors that manufacture most aircraft components have gained more responsibility for example in the area of design. This has had several reasons. First of all the cost of aircraft development has become so high that the aircraft manufacturers that assemble the aircraft, the integrators, cannot carry the financial burden alone. Therefore the financial and, consequently, also the design and production risk is spread over several companies. Another reason is political; many countries expect technological and financial compensation for military, and in some cases, civilian aircraft orders. Aircraft component manufacturers also have become more competent in the engineering department due to an increase in experience and knowledge level. In today’s aircraft manufacture environment it is common practice for the aircraft integrator to subcontract not only the manufacture of the aircraft components, but also the complete design of these components. Aircraft components are also becoming increasingly “finished” when arriving at the aircraft integrator. This means that the electronic and other systems are already installed in the aircraft components. In the aircraft industry such a pre-installed component is called ‘stuffed’. Because the aircraft components are becoming more ‘stuffed’ and because of more efficient manufacturing techniques, final assembly time of aircraft is becoming shorter. For example the final assembly time of Douglas DC-9 designed in the sixties was 56 days, while in 1994 assembly of similarly sized a Boeing 737 took 31 days for similar move rates. Currently a Boeing 737 is assembled in 11 days. This short assembly time is achieved in part by adopting a moving assembly line last seen during the Second World War (Figure 1-7). Final example of a modern aircraft is the Boeing 787. This aircraft is planned to be assembled in 3 days. It is constructed from completely pre-stuffed aircraft components, delivered by companies from all over the world.

Currently the companies that manufacture aircraft components are highly capable companies. However to remain competitive the engineering and manufacturing efficiency of these companies need to increase continuously or the company needs to develop capabilities that set it apart from the competition. This can be achieved by specializing in development of a particular kind of aircraft component or by adopting advanced engineering and manufacturing techniques.

Figure 1-7 The Boeing 777 moving assembly line (Boeing)

1.1.2 Description of aircraft components

This thesis focuses on airframe components, these are the physical entities that form the aircrafts airframe and perform a structural function. In the aircraft structures industry it is common practice to subdivide the airframe into different levels as can be seen in Figure 1-8. Aircraft components can be found at all levels. However the aircraft components discussed in this thesis will usually lie at the installation level.

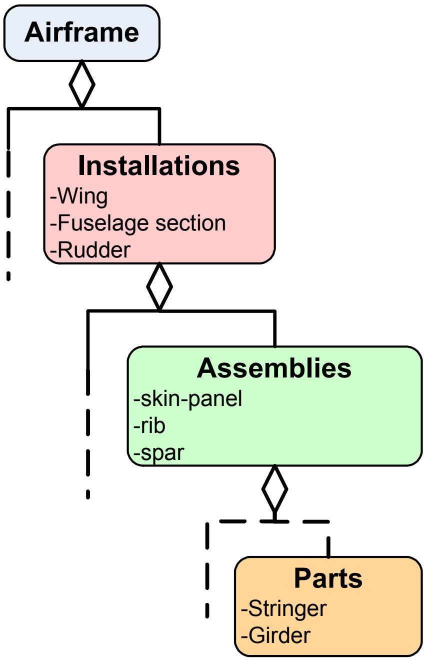


Figure 1-8 Schematic airframe built up

Besides detail level, airframe components can also be classified by the function they fulfil. Different aircraft component families are:

- Fuselage aircraft components, components like a fuselage barrel or a nose section that form the fuselage of the aircraft. (Figure 1-9)
- Wing aircraft components, components that form the wing of an aircraft. (Figure 1-12)
- Movables, components like a rudder or a flap that can move into the airflow around an aircraft. (Figure 1-10)
- Empennage or tail components like the horizontal stabilizer and the vertical tail that provide flight stability. (Figure 1-11)

Each of the component families has its specific characteristics and in the aircraft there is an interaction between components from the different families. The methodologies discussed in this dissertation will be applicable to all families. However the examples used to illustrate the methodologies discussed will use movables as example components.

Figure 1-9 Boeing 787 fuselage barrel (Boeing)

Figure 1-10 Euro-Enaer Eaglet General Aviation aircraft thermoplastic rudder

Figure 1-11 The A400M vertical tail (Airbus)

Figure 1-12 A wing at Airbus (Airbus)

1.2 *Aircraft components development process*

This section will introduce the development process of an aircraft component when it is being developed by a supplier in the aircraft industry. Development includes the complete design and manufacture of the component.

The development process usually starts with a tender from an aircraft manufacturer asking for bids or quotations for the development and/or manufacture of an aircraft component. In this tender the first preliminary list of requirements is also supplied. Once the tender has been received bidders generate design concepts of the aircraft component and the accompanying manufacture process. The bids

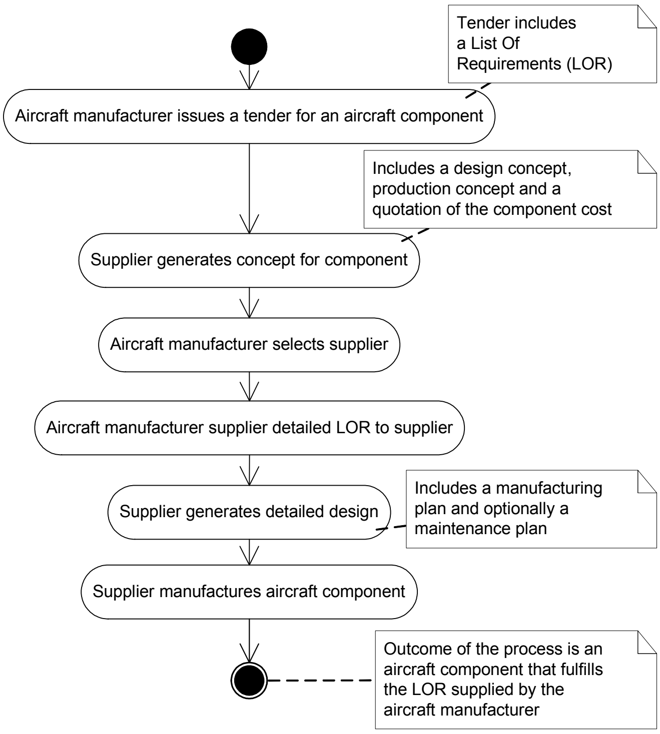


Figure 1-13 General overview of the aircraft component development process

also include a quotation of the cost as this is one of the most important trade criteria for the aircraft manufacturer. Once the supplier of the aircraft component has been chosen, the full scale development process of the aircraft component starts. This finally results in a detailed product design, a manufacturing plan and, optionally, a maintenance and support plan.

The actual design of the aircraft component follows the basic design cycle (Roozenburg, 1998) of generating design concepts, analysing them and selecting the one that best meets the requirements. This design cycle is run several times starting with the conceptual design performed in the bidding phase. Subsequent design phases go all the way to the most detailed level. In each subsequent step the level of detail of the design and the number of entities in the design concept increases. The number of design phases between the first conceptual phase and the final detailed phase is dependent on the number of design iterations, which in turn is dependent on the nature and characteristics of the aircraft component involved. The design effort for the aircraft component does not have to be performed by the supplier itself. It can also turn to sub-suppliers for aircraft components at lower levels. In this case the development process repeats itself at a changed aircraft component detail level.

In the development process for aircraft components there are several challenges and opportunities for the aircraft components developer/manufacturer:

- ***Quickly respond to market demands****.*
  Being able to respond quickly to market demands can give a manufacturer of aircraft components a competitive edge, because it enables the manufacturer to meet the aircraft integrators demand for lead time reduction.
- ***Meet the changing requirements for the aircraft integrator*****.**
  It is common that during the aircraft component development process the definition of the aircraft itself changes. This can result in changes to the requirements of the aircraft component. The changes in requirements can result in design changes which can hamper the development process.
- ***Create a design that can be produced profitably*****.**
  For the supplier designing and manufacturing the aircraft component it is important that a profit can be made. This can be difficult because the aircraft component market is very competitive. This competitiveness means that a competitive bid is important for acquiring the work. However when the bid is based on unrealistic figures it can result in an unprofitable project.
- ***Develop an aircraft component with a limited number of skilled personnel*****.**
  It is becoming increasingly difficult to find qualified and highly educated engineering personnel. In western countries many of the currently employed engineering staff is approaching retirement age. This can potentially result in a catastrophic loss of knowledge and capability for the companies facing this problem.

1.3 Thesis objectives and approach

Aircraft component development companies need to improve their development process to meet the challenges specified in the previous section. One method of meting these challenges commonly applied is the use of Systems Engineering (Hinte et al., 2008) for improving the design process. Systems Engineering consists of a collection of tools and techniques that allow the improvement of the design process. Part of Systems Engineering is the clearly defining what the requirements for a system are and checking to what degree these requirements are met. This is part of the so called the “Design for X” methodology, where X defines the sub-set of requirements that will be checked. The challenges specified earlier can be met by applying the “Design for X” methodology early in the design process. However “Design for X” can be time and resource consuming. This can be overcome by creating tools that automate part of the methodology. One of these automation techniques is Knowledge Based Engineering (KBE). Therefore the objective of this thesis is to prove the following:

Knowledge Based Engineering enables the application of the “Design for X” aspect of Systems Engineering for the aircraft component design process

Approach

To identify the possible application areas of the “Design for X” methodology and the tools developed using KBE enabling this methodology, first the aircraft component design process will be analysed. This analysis will result in a list of challenges encountered in the design process. These challenges will be translated into application areas for automation tools in the aircraft component design process. The application areas are:

- **Automating the model preparation and analysis for the structural analysis of an aircraft component**.
- **Increasing the detail level of the manufacturability analysis of an aircraft component**.
- **Automating the modelling of the aircraft component design itself**.
- **Standardizing communication between the different analyses disciplines in the aircraft component design process.**

Next all relevant developments for the applications areas will be identified. Finally methodologies will be developed, illustrated by the implementation of KBE tools showing how “Design for X” is applied in the identified application areas.

1.4 Thesis outline

The second chapter of this thesis looks at the aircraft component development process. The next chapter identifies the different improvement areas and specifies the tools that will be developed to illustrate the achieved process improvement. Chapter four will look at developments described in literature in the identified improvement areas and in automation methodologies. In the next five chapters the methodologies used and tools developed to implement these improvements are discussed. First of these chapters is chapter five which describes a generative model for aircraft movables. This generative model forms the bases for subsequent analysis tools. Chapters six and seven describe the methodologies and tools used for cost estimation, which is part of “Design for Cost”. Chapter six focuses on the commonly used cost estimation methods. In chapter seven the implementation of one of the identified methods in a cost estimation tool is discussed. Chapter eight handles the improvements to the structural analysis process, which is part of “Design for Strength/Stiffness”. In chapter nine the methods and tools to improve the process of analysing the manufacturability of an aircraft component are discussed. This is part of the “Design for Manufacturing” methodology. Finally in chapter ten conclusions are drawn and recommendations are made.

2 Detailed description of the aircraft component design process

To identify the possible application areas of the “Design for X” methodology and the tools developed using KBE enabling this methodology in the aircraft component design process, it is important to understand what the design process for these components looks like. Therefore a characterization of the design process is needed that addresses all important elements and issues in it. When the characterization is completed it can be used for identifying the opportunities where the methodologies can be applied. For the characterization created in this chapter the authors own experience with designing and analysing aircraft components has been used.

2.1 The aircraft component design process

The design responsibility for aircraft components has shifted in recent years from the aircraft integrator, the company that ultimately responsible for the total aircraft design, to the supplier, the company that builds to actual aircraft component. This can be seen in recent aircraft projects like the Boeing 787. Here the integrator manages the overall design of the aircraft and the final assembly, but outsources almost all component development work to its suppliers. For the suppliers the design responsibility offers opportunities, because technologies can be developed that can also be used in other projects. The design work also has value adding potential, but only when it is executed efficiently. The danger of accepting design responsibility for a supplier lies first of all in the dependence on the aircraft integrator for supplying the list of requirements. This list of requirements often changes during the development of the aircraft. Therefore the designs of the aircraft components have to evolve or be adjusted during the design of the aircraft. Pressure is applied by the aircraft integrator to keep the lead time for these design changes short, which can put a strain on the suppliers design capabilities. Pressure is also applied by the aircraft integrator to keep the cost of the aircraft component as low as possible. Therefore, to keep production of the aircraft component profitable, it is important that the component can be designed and produced as cheap as possible.

In the actual design process of an aircraft component different actors appear, each with different responsibilities and concerns. Because out-sourcing and sub-contracting are very common in the aerospace industry, these actors can come from different companies and therefore have different interests. The actors and their interests, or involvements, in the design process are represented in a so called “use cases”. The number of actors and the different nature of their interests also shows the multidisciplinary nature of the design process of aircraft components. In the use case of the design of an aircraft component the sub-suppliers are also included because the aircraft component manufacturer has the possibility to, instead of building all parts of the aircraft component itself, procure them from sub-suppliers. When procuring a sub-part the component manufacturer can supply the design of the sub-part to the sub-supplier, so called built to print, or leave the design and manufacture up to the sub-supplier. The aircraft component design use case can be seen in Figure 2-1. This and all other use case diagrams in this chapter use Unified Modelling Language (Alhir, 1998), the use of which is explained in chapter 3.

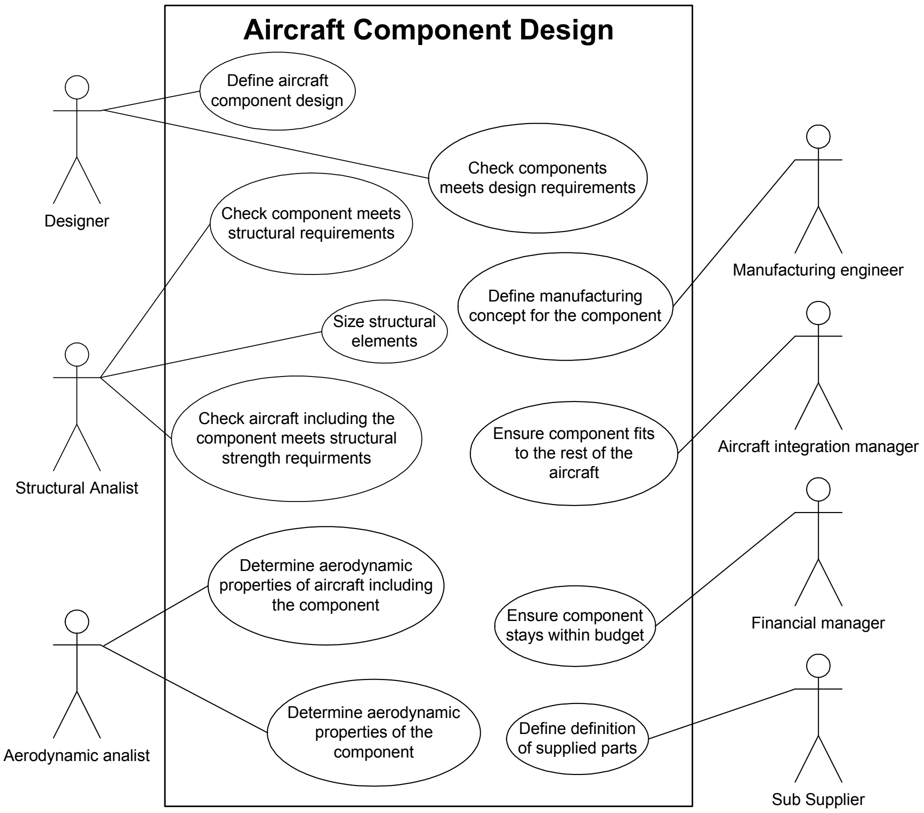


Figure 2-1 Aircraft component design use case

The design process of an aircraft component follows the basic design cycle as seen in Figure 2-2. This design cycle starts with the function the aircraft component has to fulfil. From this function follows the specification of the component in the form of a list of requirements. For meeting these requirements a number of design concepts are devised. These concepts are then analyzed and evaluated to see if they meet all the requirements and how well they perform. The analyses of the different concepts can be used to refine them in order to better meet the requirements or improve performance. Finally the performance of the design concepts that meet the requirements is used to select the final design.

The basic design cycle is usually run several times during the design process, in the different phases of the design process. These different design phases are usually the conceptual design phase, the preliminary design phase and the detailed design phase. However the number of times the design cycle is run and the name of these design phases is not fixed. In each subsequent design phase the design definition is more detailed and therefore in each subsequent design phase more lower level sub-designs are created.

Each of the phases or elements of the basic design cycle has its own characteristics. These characteristics not only consist of what happens in each phase, but also of which actors are involved in each phase. In the section below each phase of the basic design cycle will be briefly characterized and some aircraft component specific examples will be addressed. The design cycle discussed is one of an aircraft component procured by an aircraft integrator, where the design and manufacturing responsibility lies with the supplier.

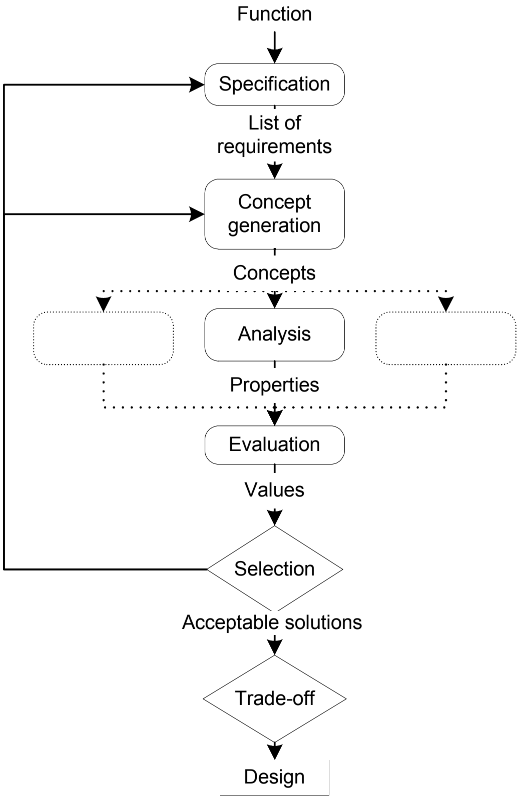


Figure 2-2 The basic design cycle (Roozenburg, 1998)

- **The function.**
  The function of an aircraft component is usually defined by the aircraft of which the component is part or by the customer who is procuring the component. The function of an aircraft rudder is for instance provide yaw control.

- **Specification**
  In the specification phase the function of an aircraft component is translated into a list of requirements. This list of requirements is more detailed than the description of the function of the component. Weight targets are for instance part of the list of requirements. In case of an aircraft component development process both the aircraft integrator or customer and the supplier that actually develops and manufactures the component are involved. The customer specifies his main requirements such as component shape or weight targets. The supplier uses or translates these requirements and adds new requirements to come up with the list of requirements that is used for the start of the concept generation phase. Actors involved in the specification phase come from all different disciplines and from different companies. Marketing for instance determines the sales or offer price while the suppliers engineering department, such as designers come up with the technical requirements. The list of requirements that is the result of the specification phase is by no means static. During subsequent design cycles it evolves as more information becomes available.

- **Concept generation**
  In the concept generation phase, design concepts for the aircraft component are generated. Usually different concepts are conceived. A concept has a certain level of detail. In the conceptual design phase the level of detail will be low while in the final design cycle, when the detailed design is determined, the level of detail must by definition be high. A concept for an aircraft component consists of a multi-disciplinary description of the aircraft components using illustrations and reports. A concept not

only consists of the structural description, in the form of, for instance, CAD files. It also consists of a manufacturing description of how the different parts that form the component are being manufactured and assembled. Because the concept is multidisciplinary most engineering actors are involved in the process; aerodynamics engineers defining the outer shape, structure and design engineers defining the structural topology and manufacturing engineers defining the manufacturing concept. Because the design cycle in iterative and run several times during the aircraft component development process, information about previously conceived concepts is re-used in the subsequent phases of the development process.

- **Analysis**

  In the analysis phase the concepts conceived are analysed to determine or predict their properties. All the different disciplines have different analysis methods and procedures. However the analyses are to a certain extent dependent on each other. For example in the structural analysis the thickness of the different structural elements are determined. This information is essential for the manufacturing engineer to asses the manufacturability of the concept in question. What analysis methods are used depend to a large extend on the design phase. In the conceptual design phase for instance a structural analysis might use simple analytic methods to analyse a design concept. When further on in the design process more detailed results are needed, numerical simulations or full scale structural tests might be conducted. One of the tasks of the manufacturing engineer is analysing the cost of the manufacturing concept. This can be done using various methods that again depend on the design phase. In the early phases statistical methods are used that provide high level results. In the later phases detailed methods can be used that determine the cost of each specific sub-part. Another job of the manufacturing engineer is determining the technical feasibility of a manufacturing concept. Methods for doing this range from judgement based on previous experiences to sophisticated manufacturing simulations.

- **Evaluation**

  In the evaluation phase the resulting properties from the different analyses are evaluated. First evaluation step is determining if the concept meets the requirements stated in the list of requirements. If not all requirements are met the acceptability of the discrepancies has to be judged. Furthermore the performance of the concept is evaluated. Performance can for instance be the manufacturing cost of the concept. Like in the analysis phase, the different engineering specialists have to conduct the evaluation of the concept in their own domain and, in cooperation with each other, in the multidisciplinary domain.

- **Selection**

  In the selection phase the results of the evaluation are used to see if a concept meets the requirements as stated in the list of requirements. If it meets the requirements it is deemed an acceptable solution and will be taken into consideration in the trade-off of different design concepts.

- **Trade-off**
  In the trade-off phase the best concept is selected. This is done based on the results from the evaluation phase. All concepts that reach the trade off phase meet the minimum requirements stated in the list of requirements. In the trade-off the values that indicate the performance of a concept such as weight or manufacturing cost are used to give a value to the overall performance of the concept. Values of the overall performance of the different concepts are compared and the best one is selected as the final concept. The different disciplines all play a role in the trade off phase. In case of aircraft components the aircraft integrator or customer also plays a role. For example, when a component is under weight, the matter of how this translates into overall performance relies on how much the customer is willing to pay for this weight reduction.

In this chapter the interest goes out to the engineering elements in the design process of aircraft components. Therefore the use cases of certain actors that operate in this area will be specified and described in greater detail. In the aircraft component design process three actors are the most important the design engineer, the structural engineer, sometimes called the stress engineer and the manufacturing engineer. In this case the design engineer is responsible for the design of the component. The structural engineer analyses the component to ensure that it meets the structural requirements. Finally the manufacturing engineer ensures that the design can be manufactured profitably. All three actors will be described in the sections below.

2.1.1 Designer use case

The designer determines what the aircraft component looks like and how it will perform the function it is required to. In Figure 2-3 a graphical representation of the designer use case can be seen. The designer does this by creating design concepts that could meet the list of requirements. Whether or not a design concept meets the list of requirements and the performance of the design concept is determined in other use cases where it is analysed. The designer use case therefore has significant interaction with use cases that perform the analyses, such as structural analysis, and also with use cases that determine how the aircraft component is manufactured and maintained. Another important part of the designer use case is to formalize or document the design. This is needed to communicate details about the design to the other actors involved in the design process and also serves as a starting point for these actors. It is important to keep this formal design description consistent for all actors in the design process. This can be challenging because the different actors in the design process have a different view on a model. This multi-view approach to the design will be discussed in the “Multiple views in the design process” section. A task included in this use case is also determining how the aircraft component should fit into the whole aircraft. This should be defined in the list or requirements and through interaction with the aircraft integrator. However it requires extra attention in the design process to ensure a right fit. Especially when the aircraft design is not fixed and therefore the requirements of how to fit the component change during the design process. In the use case diagram one design of an aircraft component is created however in the overall design process multiple concepts will be produced. For all these concepts and the re-design of these concepts the designer use case applies.

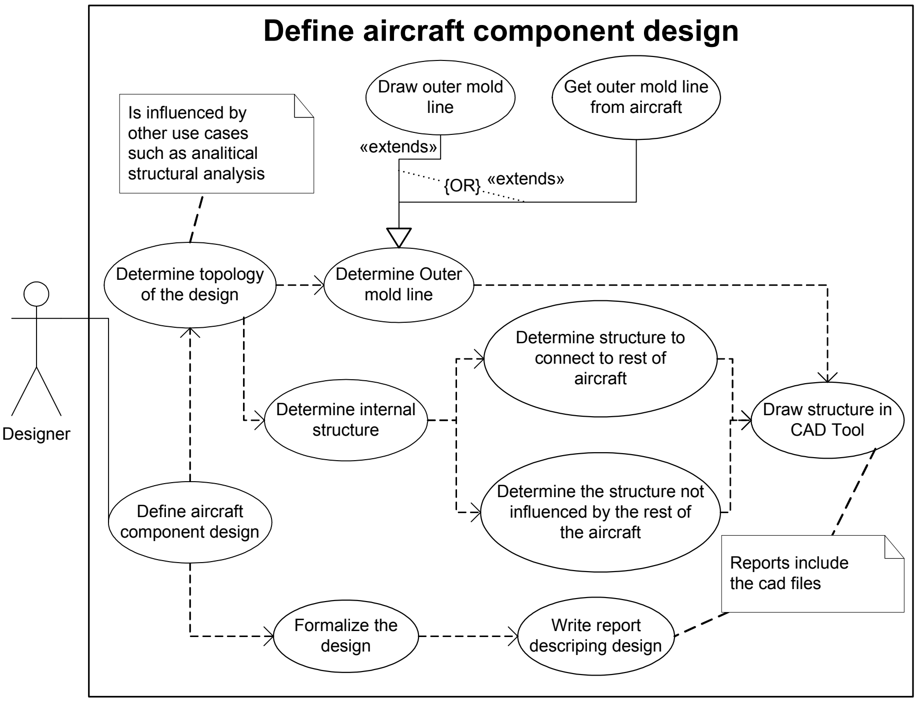


Figure 2-3 Designer use case

2.1.2 Structural engineer use case

The structural engineer has to verify that the design of the aircraft component meets structural requirements. To meet the structural requirements, the structural sizing of the aircraft component, meaning the material thicknesses, types and orientations, has to be determined. Besides this sizing, the load path concept, as defined by the designer in the definition of the aircraft component topology, has to be analysed and verified. All these tasks are included in the use case for the structural engineer, which is shown in Figure 2-4. During the structural verification of the requirements the structural engineer has to communicate to the different actors in the design process. Firstly communication with the designer is needed to get the shape and topology of the aircraft component. In fact the structural engineer also influences the shape and topology. Secondly there is also communications to the other specialists in the design process. This communication is two ways. For instance the structural engineer will provide the manufacturing engineer with the required thicknesses of the aircraft component. On the other hand the manufacturing engineer provides the structural engineer with information about the possible joints between the different sub-parts.

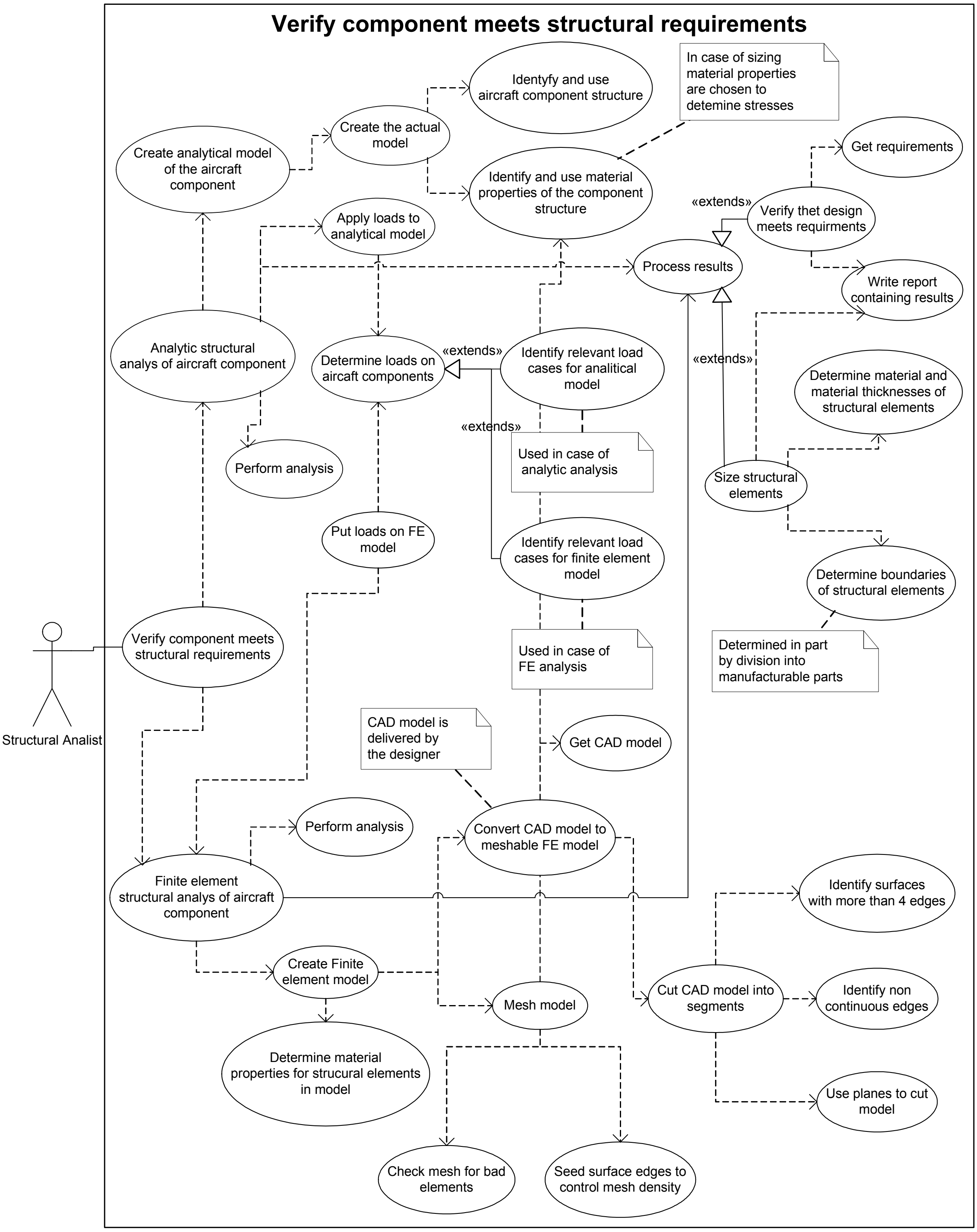


Figure 2-4 Structural engineer use case

Structural verification can be performed in two ways. Performing analytical structural analysis or performing a numerical analysis. The analytical methods can be very useful by providing a quick way to produce structural analysis results. However they usually use simplified models based on, but not linked to, the model provided by the designer. In the numerical analysis the model provided by the designer is used as a basis for the discretized model used in the numerical analysis. Keeping the models consistent can prove challenging however, because the models provided by the designer usually have to be reworked before they can be used in the numerical analysis. The amount of work it takes to generate the discretized model also limits the number of designs or design changes that can be thoroughly analyzed. The big advantage of the numerical methods is the results are very detailed and, when the model has been properly defined, reliable.

2.1.3 Manufacturing engineer use case

The manufacturing engineer determines the manufacturing concept of the aircraft component. The manufacturing concept determines how the aircraft component is manufactured and how quality can be controlled. The manufacturing concept entails defining different manufacturable parts of an aircraft component and how to manufacture them. The manufacturing concept also handles how to assemble the different parts. In order to chose the best manufacturing concept the performance of the manufacturing concept also has to be determined. This is done by running different analyses focussing on 2 aspects of manufacturability. First aspect is affordability, meaning how much the manufacture of the aircraft component costs. The second aspect is the technical feasibility of the manufacturing concepts. This technical feasibility determines the chance of successful manufacture of the design using the specific manufacturing concept. The use case of creating this manufacturing concept is represented in Figure 2-5. Activities in defining the manufacturing concept require the manufacturing engineer to communicate with the designer and also work together with the designer in the definition of the manufacturable parts. In this cooperation the manufacturing engineer will formalize the manufacturing concept with reports and drawings. Besides handling issues concerning the aircraft component itself, the manufacturing engineer also has to address issues concerning the different recourses used in producing the component. All these activities and reports have to be performed and written for all design concepts, because the manufacturing performance has a big influence on the overall performance of the design concept. In defining the manufacturing concepts the manufacturing engineer also has to make sure that all requirements concerning manufacturing are met. This is relevant with respect to certification of new or existing manufacturing methods.

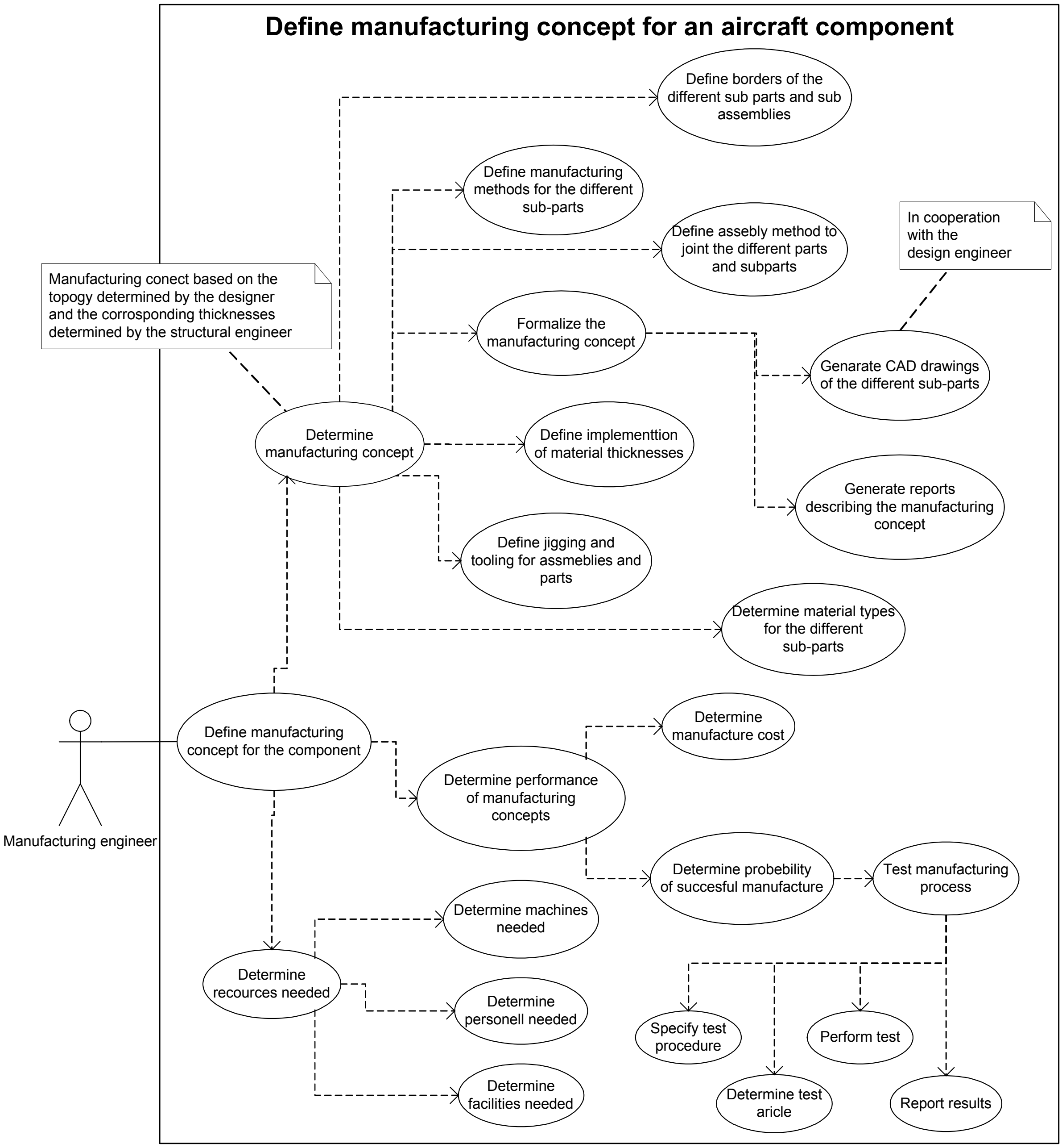


Figure 2-5 Manufacturing engineer use case

2.1.4 Multiple views in the design process

As was mentioned before, the different actors in the design process have a different view on the same aircraft component. In other words the different actors look for different aspects and details in the design of an aircraft component (Figure 2-6). These multiple views encountered in the aircraft component design process are analogous to the meta model approach described in Tomiyama et. al. (1989).

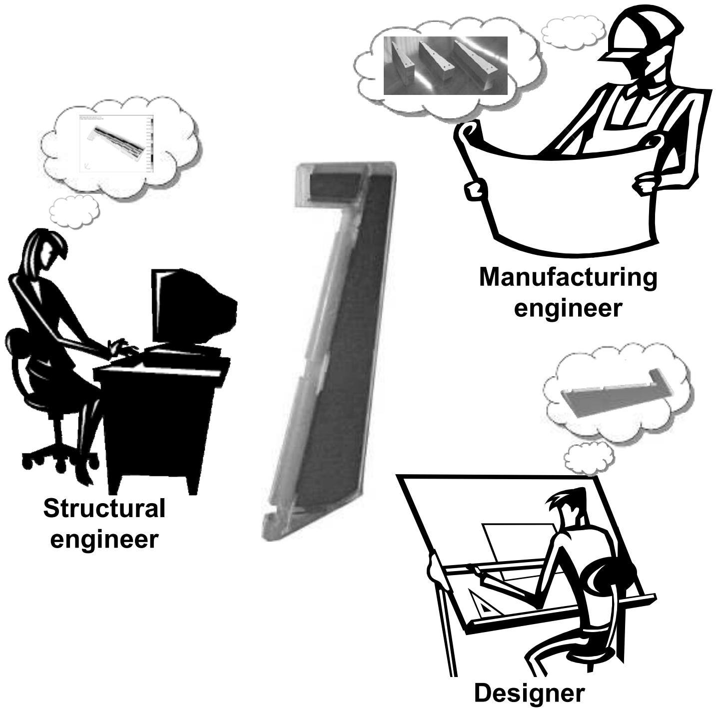


Figure 2-6 Multiple views on the same aircraft component by the different actors in the design process

How the different actors look at the component also depends on the phase of the design process. For instance in the early stages of the design process the structural engineer is not concerned about how the different manufacturable parts are defined as long as he has information about the topology of the design. The manufacturing engineer on the other hand has to know or define what the manufacturable parts will be or what they look like.

In the design process the designer usually provides the different actors in the design process with a model, usually a CAD model, which is then used to create the view needed by the specific actor. Creating this new view can be quite labour intensive and often has to be performed for all new design concepts and also for changes to existing concepts. The creation of the new view is labour intensive because the data format in which the design information is delivered often does not fit the required data format. The model that is provided also contains information for the other actors in the design process, making the provided model unnecessarily complicated. This can make it hard for each specific actor to find the data he needs.

Another problem is that the different actors all make their own translation to their desired view. In this translation assumptions, documented or hidden, are made. These assumptions are not the same for all the actors in the design process and therefore the different views that are created by the actors are no longer consistent. Because the subsequent analyses are based on models that are not consistent, the comparison and valuations of the results of these different analyses can be misconceived. This in turn can result in not selecting the best design concept or making design changes that to not improve the actual design concept.

2.1.5 Improving the existing design process

For aircraft component manufacturers to remain competitive, the existing design process described in the previous sections has to be improved. Improvement can be found in two areas, improving the quality of the design itself or improving the design process itself. Improving the quality of the design means that the final design better meets requirements or has better performance. Improvements to the design process means eliminating waste or non value adding activities from the design process.
Generating better designs can be achieved in several manners:

- ***Performing analyses that provide more detailed results for the selection process*.**
  When handled properly in the selection phase of the design process, more detailed analysis results gives a better chance of selecting the best design concept.

- ***Considering more design concepts*.**
  When there are more design concepts and the designs themselves are smartly chosen in the design space, the chances of selecting the optimal design are better.

- ***Optimizing design concepts*.**
  When the design concepts are optimized concurrently in the design process the design concepts from which to choose the final design are better.

Eliminating waste from the design process can be achieved in several manners:

- ***Eliminating miscommunications between the actors in the design process*.**
  Miscommunications in the design process result in of waste because it can result in analyses having to be re-run of analyses results being unreliable.

- ***Eliminating non value adding repetitive actions of the actors in the design process.***
  A substantial amount of work performed by the actors in the design process is repetitive, like translating data or searching for relevant data. Although these actions might be necessary to perform an analysis they can be considered waste because they do not add any value to the resulting design.

- ***Re-using data from high level data to lower level, more detailed, analyses***
  It is often difficult to re-use data from high level analyses in a lower level, more detailed, analyses. This means for example that analysis models have to be re-created from scratch throwing away higher level analysis models created earlier in the design process.

2.2 Conclusions

In this chapter the design process for aircraft components is investigated, to identify the areas where the “Design for X” methodology and the tools developed using KBE enabling this methodology can play a role. Different actors play a role in the aircraft component design process. From an engineering point of view the designer, the structural engineer and the manufacturing engineer are the most important actors. All these actors have to perform different activities to finally come to an aircraft component design concept that meets the requirements. During the activities of the different actors they each have a different view on the aircraft component. However there is also interdependency between the different actors. Mismatches in the view of the different actors and miscommunication or lack of communication can frustrate the design process.

Improvements to the aircraft component design process can be found in 2 areas, improving the quality of the final design or improving the design process itself. In improving the quality of a design, the “Design for X” methodology can play an important role. It provides a methodology which, when properly implemented in the design process, can result in better quality designs concepts being created. It also allows the improvements to focus on specific areas of the design that are deemed the most important. In the next chapter these specific areas will be identified for the aircraft component design process. The design process itself can also be improved by automating certain elements of it using automation tools. How these tools are developed is also discussed in the next chapter.

3 Using the Knowledge Based Engineering (KBE) methodology to improve the aircraft component design process

Knowledge Based Engineering (KBE) is a methodology that aims to automate certain steps of the engineering process by capturing the knowledge needed for that step and storing that knowledge in a software application. A formal definition of KBE is given by La Rocca, 2008:

> Knowledge Based Engineering (KBE) is a technology based on the use of dedicated software tools (i.e. KBE systems) that are able to capture and re-use product and process engineering knowledge. The main objective of KBE is reducing time and cost of product development by means of the following:
>
> - Automation of repetitive, non creative, design tasks
> - Support of multidisciplinary integration starting from the conceptual phase of the design process

In this chapter the possibilities of using the KBE methodology to enable the “Design for X” methodology in the aircraft component design process and improve this process will be investigated. This is done first of all by giving a short description of the KBE methodology in section one. In the next three sections the different steps for developing a KBE application are discussed. In section five the Design and Engineering Engine concept is introduced while in the final section conclusions are drawn.

3.1 Use of Knowledge Based Engineering in the design process

KBE is a methodology where certain aspects of engineering processes are automated based on the existing knowledge within a company. This automation is achieved by using software tools to mimic the actions normally performed by the engineers themselves. In these software tools the knowledge and methods of how the action should be performed are captured. The actions that are automated are usually repetitive actions that, although often complex, add little to the creative side of the design process. The software tools that are created will be called KBE tools.

The implementation of KBE tools results in changes to the design process because more computer tools will be used. A schematic view of the traditional design process and of one using KBE tools can be seen in Figure 3-1 and Figure 3-2. When using KBE tools the communication, information gathering and analysis actions, or part of these actions, are taken over by software tools, hereby reducing the amount of human resources needed to create a design.

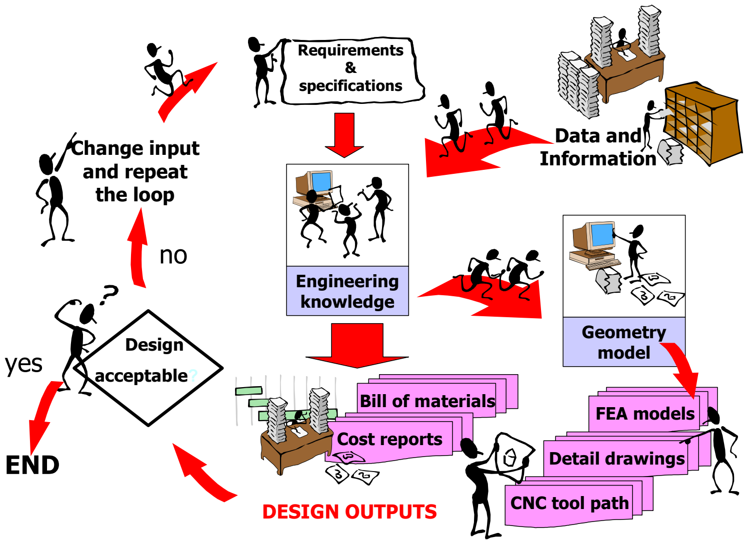


Figure 3-1 The traditional design process (LaRocca, 2006)

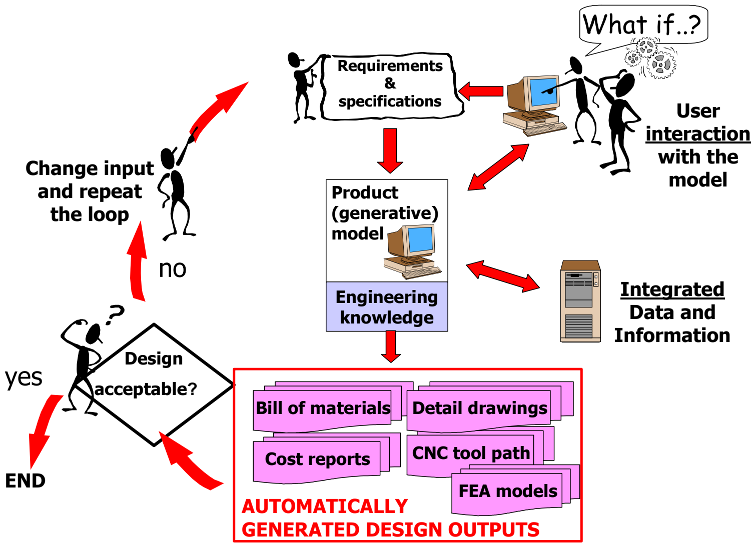


Figure 3-2 The design process incorporating KBE tools (LaRocca, 2006)

The use of KBE can have several advantages:

1. ***Existing knowledge is stored and is therefore made re-usable.*** Because the knowledge and methods are stored in a software tools, the knowledge will be accessible and re-usable even after the engineers that provided the initial knowledge and methods have left the company.
2. ***Design and analysis lead times are reduced***. Because the software tools usually perform the engineering actions quicker than the engineers that traditionally performed these actions, the total design lead time will be reduced.
3. ***Human engineering effort is reduced.*** Because some engineering actions will be performed by software tools the engineering hours traditionally spent on these actions can be used else ware in the engineering process.
4. ***Communication in the development process is more transparent.*** Because the KBE software tools communicate in a standardized way, using pre-

determined standardized data formats, human miscommunications or file incompatibilities will be eliminated.

5. ***More detailed information is available early on in the development process.*** Because the software tools perform analyses more quickly then traditional methods, more detailed analysis methods can be used earlier in the design process.

Although KBE tools can provide significant improvements to the design process of aircraft components one should not forget that development of these KBE tools itself requires a significant amount of human and financial resources. These resources are required for the development, use and maintenance of the software tools. Identification of the areas where the KBE tools will be most effective is therefore necessary.

The knowledge captured in the KBE tools can be different in nature, but it should in essence capture the knowledge that is available in the company for which it is developed. Two kinds of knowledge exist; factual knowledge and heuristic knowledge. Factual knowledge is widely accepted common knowledge that is publicly available. A factual knowledge rule could for instance be: “In steady flight the total lift of an aircraft equals the total weight of the aircraft”. Heuristically knowledge is based on experience and is a valuable asset of any company. Heuristic knowledge has been created by years of experience and can be difficult to quantify. A heuristic knowledge rule could for instance be: “Avoid sandwich constructions in flaps because they are hard to inspect”. KBE tools contain both kinds of knowledge however the heuristic, company specific, knowledge is what makes KBE tools effective and valuable.

Another method of distinguishing knowledge is dividing knowledge into product and process knowledge. Product knowledge links knowledge directly to an entity. Product knowledge is for instance: “The inner structure of an aircraft movable consists of spars, ribs and stringers”. Process knowledge is the knowledge about a process to develop or manufacture an entity. Process knowledge is for instance: “A Finite Element (FE) model is build by segmenting the surfaces of a CAD model into triangular and quadrangular surfaces”. Again KBE tools contain both kinds of knowledge. For instance a KBE tool for creating a aircraft movable must be able to model spars, ribs and stringers because it is known the movable structure consists of these entities. Furthermore, if the tool is used to create a FE model of the movable, it should be able segment the movable model into triangular and quadrangular surfaces.

Developing a KBE application consisting of different tools involves several phases. These different phases form the so-called KBE cycle (MOKA consortium, 2001, Figure 3-3). Although the KBE cycles looks like a closed cycle the steps in the cycle are iterative. The iterative nature of KBE application development can also extent over the boundaries of the KBE life cycle. In the sections below the different phases will be discussed and applied to the improvement of the aircraft component design process.

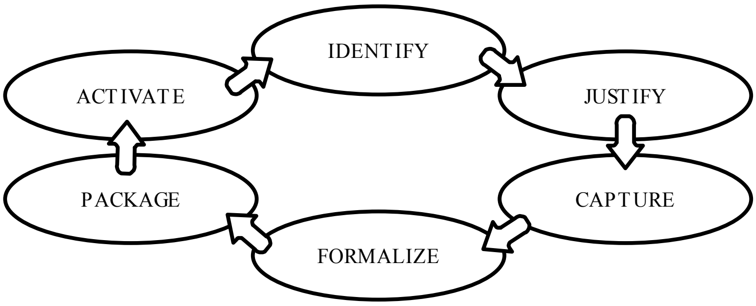


Figure 3-3 KBE application life cycle, the lifecycle starts with the Identify phase (MOKA consortium, 2001),

3.2 The identification and justification phases of the KBE cycle

The first two steps of the of the KBE lifecycle, the “identify: and “justify” steps are highly interwoven. The identification phase is the first phase in the KBE lifecycle. The identification phase can be described as:

- ***The identification phase***, using an existing business opportunity, the type of KBE application and the resources needed to build this KBE application are identified.

This phase specifically handles the “What kind of KBE application is needed?” question. It is important that all the resources and stakeholders or actors involved in development of the KBE application are involved in this phase. Involving all the actors early on in the development process increases the chance that the KBE application is accepted into the everyday work environment. Another issue in the identification phase is assessing the technical feasibility of the KBE application. Outcome of this assessment could be that the probability to successfully develop a KBE tool is low or that development of a KBE tool is too complex a solution for a simple problem. In both cases development of the KBE application will be stopped. Finally the objectives or requirements of the KBE application are formalized, so they can be verified once the KBE application is completed.

After the identification phase the justification phase is run. The justification phase can be described as:

- ***The justification phase***, a project plan is developed taking into account financial and cultural issues.

In this phase the project plan for developing the KBE application is written. The decision about whether or not to proceed with the development of the KBE application is taken by senior management based on this plan. The plan contains the technical issues handled in the identification phase and also assesses financial and cultural risks of developing the KBE application. A financial risk could be that the KBE application cannot be developed within the allocated budget. A cultural risk could be that the developed KBE application will not be used by the actors involved. Because these issues are dependent on the technical characteristics of the project determined in the identification phase, iteration between identification and justification phase is required.

When developing a KBE application for aircraft components both the identification and the justification phase have to be run. These phases start with the opportunities identified in the previous chapter. One step of the identification phase is to identify the actors that will play a role in the development and use of the KBE application. In the overall picture these actors will be the same as those specified in the previous chapter, with one addition, the knowledge engineer. This knowledge engineer will build the actual KBE application and is also responsible for extracting the available knowledge form the experts. The business opportunities of KBE applications for aircraft components lie in the area of design, structural analysis and manufacturing analysis. Therefore the actors in the use case for the identification phase will be limited to the structural engineer, the manufacturing engineer, the design engineer and the knowledge engineer. The identification phase use case can be seen in Figure 3-4.

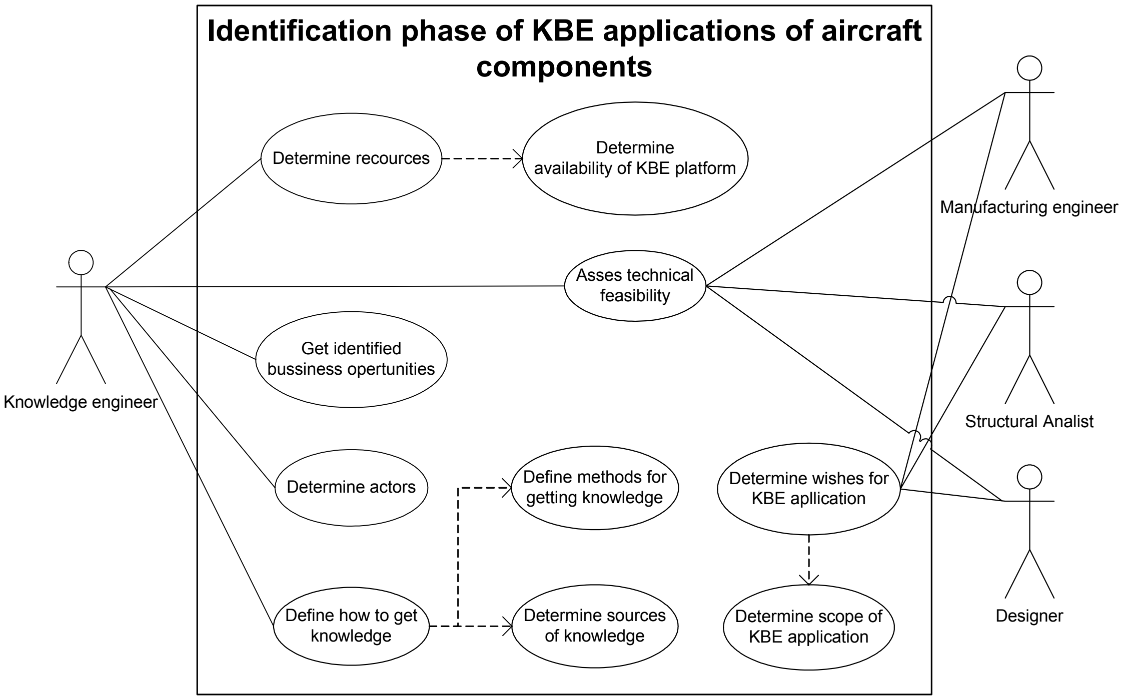


Figure 3-4 Use case of the identification phase of the development of KBE applications for aircraft components using UML

One activity in the identification phase is the assessment of the technical feasibility. In case of aircraft components this means identifying where the technical risks might lie and defining the methods on how to minimize these risks. As can be seen in Figure 3-4 all actors are involved in the process of assessing the technical feasibility. This is necessary because only the expert know the pitfalls and risks in their particular fields. The knowledge engineer is also involved in the process because he has to asses how the pitfalls and risks affect the KBE application and how they can be countered.

One technical risk that applies to KBE applications for aircraft components is that by increasing the level of detail of the aircraft component model and of the different analyses, the model and analyses become very complex. First problem is that this complexity can hamper the implementation of the aircraft component model on the KBE platform. Second problem is that the complexity decreases the transparency of the KBE application for the users to the extent that they might be reluctant to use it. These problems can be countered first of all by using an iterative approach for the development of the KBE application. In this iterative approach firstly a model is created with a low level of detail, but which already entails a lot of the required functionality. This functionality can be evaluated by the users of the KBE application, who can guide the application developers to a transparent and usable application. During the consecutive iterations to develop more detailed models, insurmountable problems in the iteration process result in a model that does not have the expected level of detail, but is still functional. This development strategy is a form of rapid prototyping.

Another problem during the development of the KBE application is that some modelling or analysis methods specified by the experts become obsolete. When the KBE application developed is a fully integrated system this might render the whole system useless. Therefore the KBE application should be modular as much as possible. This has the advantage that, if a modelling or analysis module does become obsolete, it can be replaced quickly. It also has the advantage that the KBE application is already usable, while not all modules are finished and that the KBE application is easily expanded later on. On the other hand modules can also be made interchangeable between KBE applications. In this manner the knowledge stored in a module is made available to other or future KBE applications.

The different modules that are developed for the KBE application should use commercial software and tools, which are familiar to the expert that provides the applications knowledge and the users of the application. This will improve the acceptance of the application and encourage use of the application. In the case of aircraft components it also ensures that certified software tools are used. This reduces the certification time of any design concept, which can be critical in decreasing the design lead time. When commercial software and tools are not available or not detailed enough, new modules will have to be developed. These modules should represent the knowledge from experts captured by the knowledge engineer. What this capturing process could look like is explained in the appropriate section below.

The modular approach of the KBE application mains that a standardized communication scheme between the different modules should be implemented. To limit the risk of un-transparency of the results the file types used for communication between the different modules should be accessible by common software tools such a text editors, browsers and CAD programs. Not all software tools will be able to use the universally standardized file formats. Therefore translator modules that can be coupled to the software tools to interpret the standardized file formats should also be implemented.

In the identification and justification phases it is important to recognize the areas where the most gains can be made. This allows, first of all, to focuses the available resources on the most important areas. This improves the chance that the significance of the KBE application will be shown early in the development process through prototypes of the application. Recognizing the most important areas also helps to justify the required financial and other resources for the project. For the design of aircraft component the most important improvement areas were identified in the previous chapter. The identified business case consisted of creating better quality aircraft component design concepts and eliminating waste in the design process. These goals can be achieved by reducing design lead time, improving detail level of the design analyses. Specifically for aircraft components the following issues should be addressed:

- ***Automating the model preparation and analysis for the structural analysis.***
  Structural analysis and especially the model preparation is a very time consuming operation that requires valuable resources like a structural engineer. Automating the model preparation and analysis will reduce lead time and can, when executed properly, also improve the quality of the analysis. When lead time is not an issue, automation allows for more detailed analyses.

- ***Increasing the detail level of the manufacturability analysis.***
  In the current design process manufacturability analysis of the aircraft component is limited. However manufacturability determines to a large amount the financial and technical success of a project. Furthermore design decisions that have the most impact on the manufacturability of an aircraft component are often taken early on in the design process. Increasing the level of detail of the manufacturability analysis in the early stages of the design process therefore increases the chance on a financially and technically successful project.

- ***Automating the modelling of the design itself.***
  Generating design concepts models and implementing design changes to these models can be a time consuming job. By automating the modelling process or part of it, the design lead time can be reduced. Reducing the lead time per design concept also allows for more design concepts to be generated, ultimately resulting in a better final design.

- ***Standardizing communication between the different disciplines****.*
  Misunderstandings resulting from miscommunication between the different disciplines can result increased design lead time or reduction off the chance of generating the best design concept. Miscommunication can result in waste of resources. For instance time spent on the analysis of wrong concepts can be considered wasted time, increasing the design lead time or eating up time that should have been spent on the analysis of other design concepts.

3.3 The capture and formalize phases of the KBE cycle

The next two phases of the KBE cycle are the capture and the formalize phases. In these phases the knowledge that is available is captured and later reordered and restructured into formal knowledge rules, methods and models. The capture phase is described as:

- ❖ ***The capturing phase,*** the knowledge needed for the KBE application is gathered and structured in order to get a solid knowledge base for the KBE application.

This phase handles the “capturing of knowledge” issue. Capturing the knowledge that is available is an important and challenging step in the development process of a KBE application. Because the captured knowledge forms the backbone of the developed application, the knowledge captured should be properly defined and applicable to the tools that will be developed. Before the knowledge capturing starts the knowledge engineer should have a clear understanding of what kind of knowledge he needs for the development of the KBE application. Realizing what knowledge lies in- or outside the scope of the KBE application ensures that no resources are spent on acquiring and formalizing unnecessary knowledge. The scope of the KBE application should be determined by the project plan for the KBE application written in the justification phase. Once the available knowledge is gathered an informal model is devised. In the process of creating the informal model the knowledge available is structured and documented.

Once the informal model is complete the model can be formalized, this is done in the formalization phase:

- ***The formalization phase,*** the informal model is translated to a formal model, which is easily understandable for software engineers.

Though the informal model is representing all the available knowledge, it will be difficult to base the KBE application on this model, because the knowledge is inconveniently represented. To change the knowledge representation a translation step is needed. This translation step changes the knowledge of the informal model into the formal model. This formal model is a model of the entities and processes involved in the proposed KBE application, represented in a format that is usable for software development engineers. To create the formal model, standardized modelling languages should be used. This can for example be Unified Modelling Language (UML) (Alhir, 1998). This is a standardized modelling language widely accepted in the software development industry. UML allows for the modelling of all categories of knowledge using different graphical formats. Examples of UML diagrams can be found throughout this thesis.

In case of a KBE application for aircraft components the capturing phase will consist of gathering the available knowledge about the aircraft component in question. The knowledge needed for the development of the KBE application comes in many categories all of which are needed for the development of the KBE application. Some of these categories are:

- *Illustrations,* These can for instance be relevant examples of aircraft components that are in the same family as the component handled in the KBE application.
- *Entities,* These are objects that describe the system. In case of aircraft components they can for instance be the structural elements that form the component.
- *Constraints*, These are limitations on the entities. Limitations for aircraft components are for example the shape in order to make sure the components fit to the rest of the aircraft.
- *Activities,* These are descriptions of development processes. An activity can for instance describe the steps in the certification process of an aircraft component.
- *Rules,* These guide or bound the activities. A rule can for instance be a certification regulation to be applied in the certification activity.

The knowledge available in these categories comes from different kinds of sources. Sources can for instance be documents, books, computer software or people. Each of the different sources asks for a different knowledge extraction technique. These knowledge extraction techniques can, in case of humans, consist of multiple interviews to gather all the knowledge available from an expert. This knowledge gathering process requires determination from both knowledge engineer and domain expert. It is therefore important to make the domain expert aware of the importance on the KBE application and schedule multiple appointments in which to extract the available knowledge. In case of the KBE application for an aircraft component the knowledge acquired should handle the issued identified in the first phase of the KBE cycle.

The knowledge that is acquired form the knowledge sources needs to be structured and documented. Structuring is needed to determine the usefulness of the knowledge and to identify where knowledge gaps exists. Structuring also helps in finding relations between the different knowledge entities. In case of aircraft component this can for instance mean identifying what activities are needed to design an entity. During the knowledge structuring the knowledge also has to be documented in a standardized way. This improves the accessibility of the knowledge and also enhances the usability of the knowledge. In (MOKA consortium, 2001) standardized forms are used to store the knowledge. For each of the different knowledge categories a form exists in which the knowledge can be documented. Links between these forms can also be made. Of course this is only one example how the knowledge can be documented.

The documented and standardized model will form the so-called informal model. Of course the creation of this informal model is again iterative, because, as was shown before, part of structuring is identifying where more knowledge is needed. It can also appear during the capturing phase that the scope of the KBE application should be changed. In which case one should go back even further in the KBE cycle and redefine the scope of the application by re-running the identification and/or justification phases. The informal model can be used in the iterative process because it can be used to show experts what the extracted knowledge is. Because the knowledge is structured the experts should get a clear view of where his knowledge is misrepresented or where knowledge is missing. This is an important role of the informal model; giving the domain expert insight in the captured knowledge.

In the formalization phase the informal model of the aircraft component itself and of the aircraft component development process has to be translated in the formal model. The most important function of the formal model is to form the bases for the software tools that will form the KBE application. To make this possible a modelling language should be used that is understandable for software developers and can represent all the knowledge stored in the informal model. Such a language can be UML. The UML diagrams created for the formal model also form part of the documentation of the KBE application and they will be used to check the correctness of the KBE application. UML is easy to understand by people who have had training in this area such as software engineers. However it can be difficult to understand by the domain experts. Therefore it is important to use the informal model in the checking of the knowledge with the expert before formalizing the knowledge.

The formal model consists of many models, some of which are describing actual aircraft component. However the models are not only describing shape of the physical entities but also other aspects associated with the aircraft component. These different aspects can for instance be:

- Structure, describing the actual physical entities of the aircraft component.
- Function, describing the function of the aircraft component, what it does in operation and how it does it.
- Behaviour, how do the entities of the aircraft components behave in operation and what is needed to change the behaviour.
- Technology, what technology will be used to manufacture the aircraft component.

- Representation, how will the design of the aircraft component be visualized and used.

All the different aspects are important and also related to each other. Examples presented in chapters 5 to 9 will clarify the different aspects and also how they will be modelled using UML.

3.4 The package and activate phases of the KBE cycle

Final two phases of the KBE cycle are the package and activate phases. These phases deal with the developments and use of the software tools that form the KBE application. The packaging phase is described as:

- ***The packaging phase,*** use the formal model to create actual working software tools that represent the formal model.

In this phase the software tools forming the actual KBE application are developed. The tools developed should have all the characteristics specified in the formal model. The software tools that are created should use a platform and fit the requirements drawn up in the identification phase. This means that the software tools that are developed should be checked using the project plan from the justification phase. Before actually using the developed software tools in daily practice they should be tested to verify that they meet the expectations of the actors involved in the development process and in the actual use of the software tools. When everybody is satisfied the developed tools can be put to work in the activation phase of the KBE cycle.

The activation phase can be described as:

- ***The activation phase,*** the software tools developed in the packaging phase are put to work in daily practice.

The activation phase deals with how the get the developed software tools to work issues. The first issue handled in this phase is to get the software tools to the people that will be working with them in daily practice. These people should have been involved in the development process. However this does not ensure that they know how to use the newly developed software tools. Therefore it is important to have training programs and user manuals available for this phase. The quicker the user gets to know the tools and learns how to work with them, the quicker they will get actual results and will see how it can make their lives easier. This will greatly enhance the social acceptance the software tools. Finally activation does not mean the end of the development of the software tools; continuous maintenance is needed to keep the software tools forming the KBE application operational.

The packaging and activation phases for the KBE application for aircraft components do not involve special issues. These phases will be illustrated throughout this thesis in the descriptions of the development of the various software tools that will form the KBE application examples.

3.5 Introduction of the Design and Engineering Engine (DEE) concept

As was described earlier the KBE application for aircraft components is a combination of modular software tools to automate activities in the areas where the biggest opportunities lie. In this KBE application communication between the different modules is an important aspect. To make the KBE application accessible and useful, all communication should be reliable and transparent. The availability of the different modules and where they fit in the design process should also be clear. To facilitate the operation of, and communication between, the different modules, a framework in which they will operate has to be devised. This framework in itself has as its main goals facilitating communication between the different modules of the KBE application and ensuring the right sequence of using the modules in the design process.

The framework software tool discussed in the previous paragraph is called a Design and Engineering Engine (DEE). The concept of the DEE has been proposed and implemented at Delft University of Technology as is shown in (La Rocca, 2002), (Lisandrin, 2002) and (van Tooren, 2003). In these references DEE's for various design and engineering areas were proposed and implemented. The DEE for aircraft components will not differ in concept from the existing DEE's however it will be usable in the design process for aircraft components. In Figure 3-5 a schematic overview of the DEE can be seen. Because, with the right modules implemented, the DEE can form a closed loop it can also be used for optimization purposes. However this requires highly reliable modules and should only be implemented when the software tools involved in the optimization are thoroughly tested and validated. The DEE guides the transport of data between the different modules. It does this by mimicking the different activities that exist in existing, non KBE, design processes. What activities are performed in the DEE for aircraft components can be seen in Figure 3-6.

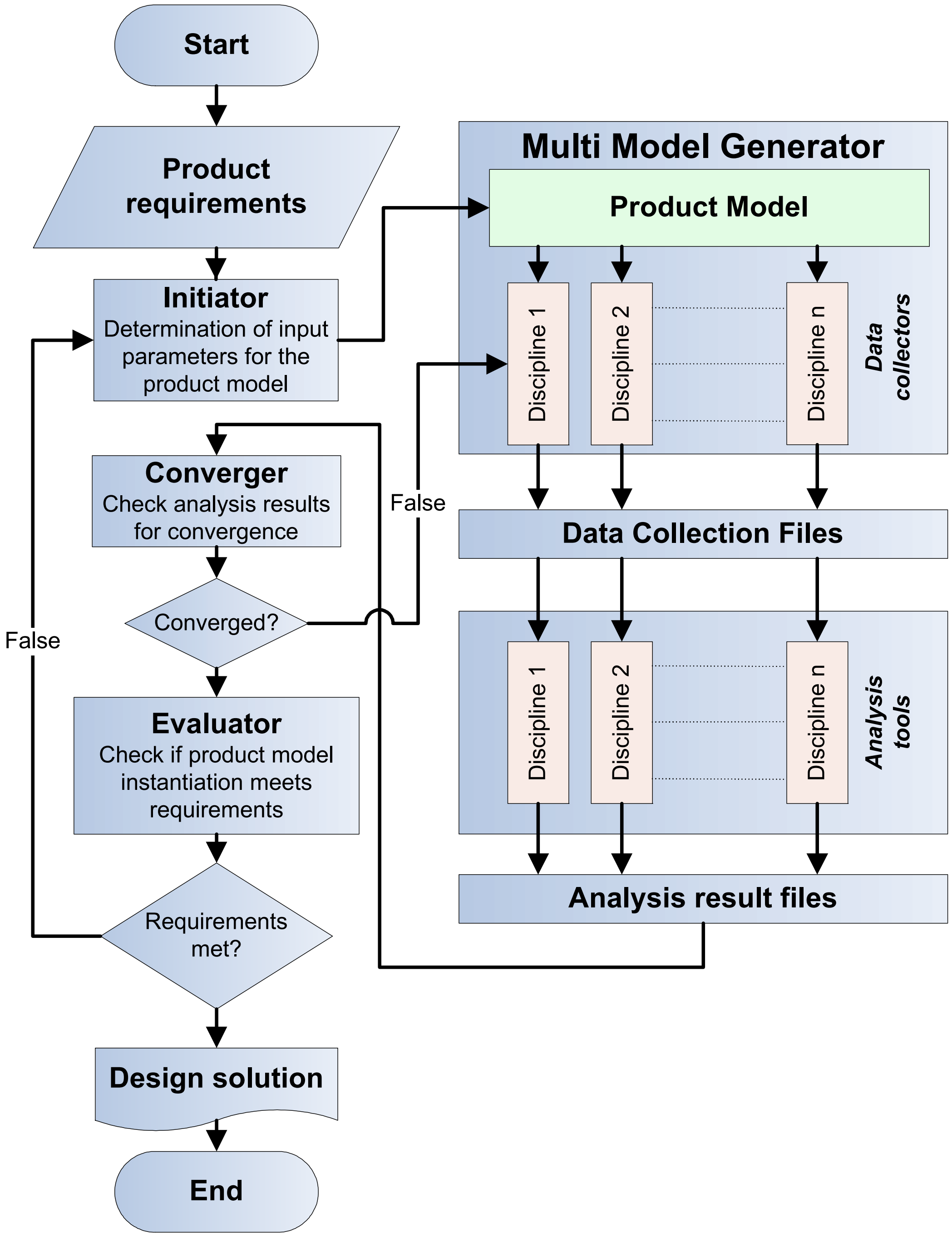


Figure 3-5 Schematic representation of the DEE framework

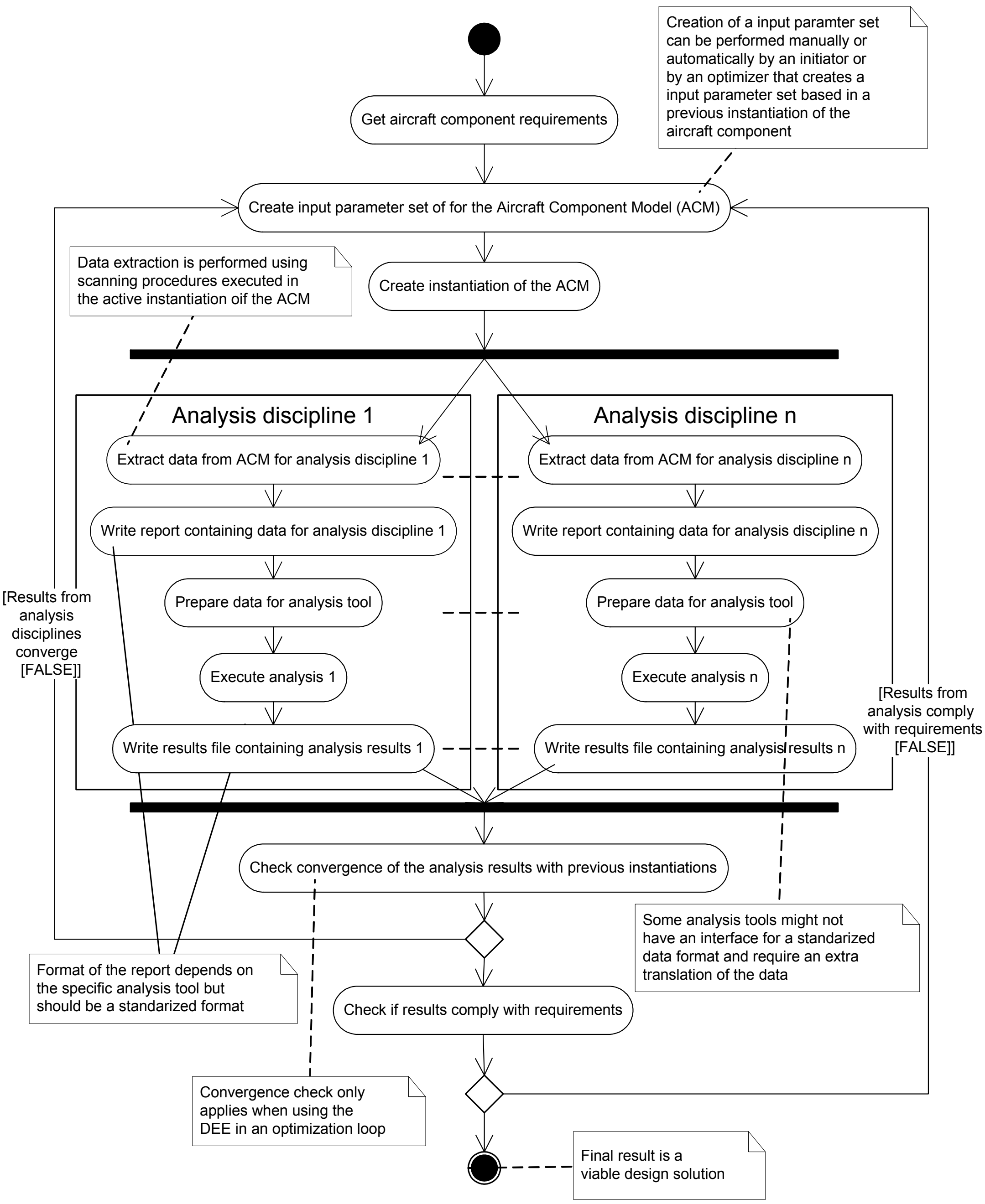


Figure 3-6 Aircraft component DEE activity diagram using UML

Of course the activities in the DEE are not only performed by the facilitating framework but also by the modules that operate in this framework. Key modules operating in the framework are:

- ***Initiator***
  The initiator determines the initial configuration of a product. In case of an aircraft component this is done using the requirements for the aircraft component and knowledge about the initial sizing of the aircraft component. The initial configuration is stored in a set of input parameters that are used by the Product Model to generate a model.
- ***Multi Model Generator (MMG)***
  This module consists of the Product Model to create a model and data collectors to extract relevant data from the Product Model. In case of an aircraft component

the Product Model generates a model of an aircraft component, using input parameters provided by the initiator and modelling methods based on existing knowledge. From the model generated by the Product Model relevant data needs to be collected for the various analysis disciplines. So called data collectors do this. These data collectors are also part of the MMG. These collectors scan the Product Model for relevant data and create collections containing the data for specific analysis disciplines.

- ***Analysis tools***
  Analysis tools perform the analyses in the different disciplines. They are developed using the knowledge of experts in the different analysis disciplines. As was shown before, analysis tools should be build as much as possible using Commercial Off The Shelf (COTS) tools that are familiar to the experts that help to develop them. The analysis tools not only consist of software tools to perform the actual analysis but can also contain translators to translate both the in- and output into the required data format.
- ***Converge and evaluator tools***
  Tools that check the convergence of the different analyses and evaluate the results of these analyses are needed to judge how the evaluated design concepts meet the requirements that were used to initiate the DEE. When automated they can be used to close the loop of the DEE and facilitate optimization routines. This requires that they can also compile a new input set for the Product Model.

It is not necessary for all the DEE elements described above to be finished modules for the DEE to work. Activities in the different modules can also be performed by human interaction. For instance the initiator can be a designer specifying a particular parameter set representing a design concept. The converger/evaluator can also be a designer or expert checking the convergence or results and using the results to create an updated parameter set. In fact making human interaction possible is very important especially at the beginning of the DEE development process to facilitate testing and also to evaluate the usefulness of the DEE concept.

In this thesis the actual development of the DEE will not be discussed. However the different modules developed for improving the aircraft component design process will fit in such a DEE. Where the modules developed for solving the identified issues fit is discussed below.

- **Automating the model preparation and analysis for the structural analysis of an aircraft component**.
  Structural analysis will be one of the analysis disciplines. The automation of the model preparation will take place in the Multi Model Generator. This ensures that the structural model is based on the same Product Model as the model generated for other analysis disciplines. The model preparation for structural analysis is in this case extracting the right “view” from the Product Model and collecting the structural analysis data from this model. This data collection is performed by one of the data collectors in the Multi Model Generator.
  Automating the structural analysis requires automation of the analysis process itself. This can be done by using the expert knowledge about the structural analysis process to automate this process. This will use existing or newly

developed structural analysis tools. In the DEE this takes place in one of the analysis tools.

- **Increasing the detail level of the manufacturability analysis of an aircraft component**.
  Increasing the detail level of the manufacturability analysis first of all requires that analysis tools are implemented to perform the manufacturability analysis. Because of the many aspects of manufacturability analysis this will probably mean that several independent analysis tools need to be developed. These analysis tools also have to be fed data. Like with the structural analysis, this data will be extracted from the Product Model using one of the data collectors in the Multi Model Generator.

- **Automating the modelling of the aircraft component design itself**.
  Automation of the modelling of the design of the aircraft component itself is implemented by the Product Model. This is a parametric model that should be developed using the available knowledge about the aircraft component in question. The Product Model should have the possibility to model all the required features for the different analyses. It therefore in itself generates a substantial amount of information; this is used to create the different discipline views. The model created by the Product Model is based on a set of inputs that is supplied to the Product Model by the initiator. Methods implemented in the Product Model then ensure that the right model is created. These methods are based on design knowledge acquired in the knowledge capturing phase.

- **Standardizing communication between the different analyses disciplines in the aircraft component design process**
  Standardization of the communication between the disciplines is achieved by the Product Model. The Product Model produces multiple views on the same aircraft component ensuring that the subsequent analyses are consistent and therefore comparable. Standardization is also realized by using standardized file formats for communication between the different modules in the DEE framework. This will make communication transparent, increasing the chance that any miscommunications are noticed early in the design process. In this way the errors can be corrected before any time consuming analyses have been performed.

3.6 Conclusions

The identified areas for improving the aircraft component design process focus on improving the communication between the different actors in the design process and automating repetitive activities of these actors. Automating some of these activities allows using more detailed analysis at an earlier stage of the design process enabling the “Design for X” methodology. The tools that will be developed fit in a so called Design and Engineering Engine (DEE). This DEE ensures that communication is consistent and that the position of the tools in the design process is consistent. In chapter 5 to 9 the different automation modules developed will be discussed. These modules will be using an aircraft movable as an example of an aircraft component. The aircraft movable is chosen because the author has experience in designing and analysing such a component. Furthermore aircraft movable are detachable from an aircraft and therefore prime example of aircraft components that are sub-contracted by aircraft integrator companies. The tools that actually will be developed can be seen in Table 3-1.

Table 3-1 Tools developed to show the possible improvements to the aircraft components design process

Tool developed	Description	Chapter
Parametric Movable Model (PMM)	This tool generates a model of an aircraft movable. Model means a geometrical representation of an aircraft movable. The Parametric Movable Model (PMM) will have 2 views, a structural view and a manufacturing view. The models created by this tool will be used a data provider for subsequent analysis modules.	5
Cost analysis estimation module	This module facilitates the cost estimation of aircraft movables modelled with the PMM. It consists of elements extracting the relevant data from the manufacturing view of the PMM and of elements which perform the actual cost estimation.	6,7
Structural analysis module	This module facilitates the structural analysis of aircraft movables modelled with the PMM. It consists of elements extracting the relevant data from the structural view of the PMM and of elements which perform the actual structural analysis.	8
Manufacturing feasibility analysis module	This module facilitates a drapability analysis of composite aircraft movable ribs. It consists of one element extracting the relevant geometry from the PMM. Another element in this module is a new model generator which creates a more detailed model of the rib which is used to prepare data for the actual drapability analysis. The actual drapability analysis module itself will not form part of this module.	9

4 Knowledge based Engineering tools for design of aircraft components; an overview

In order to develop KBE tools that can enable the "Design for X" methodology it is important to understand what kind of KBE tools have already been developed in the application areas identified in the previous chapter. Knowledge Based Engineering (KBE) tools have been developed at different levels of product detail and also for different phases of the design process. This is visualized in Figure 4-1 in the so called scale cube. Here the different levels of detail, the different disciplines considered during a design and the different design phases are represented. KBE tools have been developed for different areas of this cube and also combining these different areas. In this chapter an overview will be given of KBE tools, which are relevant to the development of KBE tools for the design process of aircraft components. This does not automatically mean that they focus on aircraft components or at the same area of the scale cube. Especially tools that lie outside this domain might provide valuable new insights for the developments of new KBE tools.

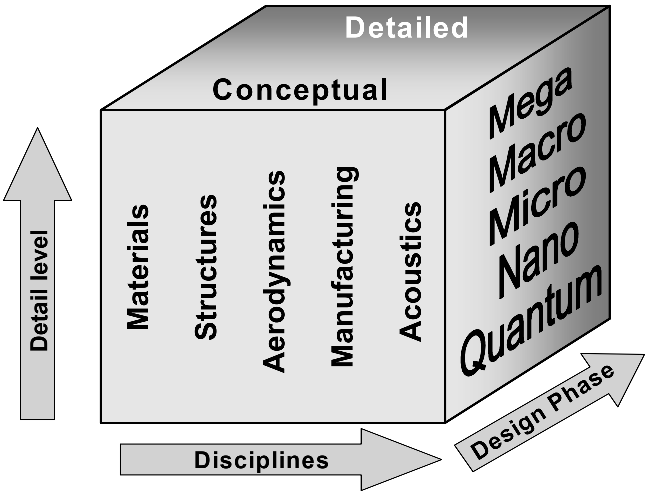


Figure 4-1 The design scale cube showing the different levels and disciplines in the design process

Some of the tools that will be discussed are developed to fit in automated frameworks. In this overview the focus will lie on the individual tools or modules and what they can be used for. In the last section of this chapter the frameworks in which they operate will be discussed. In total four different kinds of tools will be discussed:

- ***Model generators***, tools that generate geometrical and other representations or models of structural components or systems.
- ***Structural analysis tools***, tools that facilitate quick structural analysis of structural components or systems by using either analytical or numerical methods
- ***Manufacturability analysis tools***, tools that determine the manufacturability of a component or system. These kind of tools are split in two subgroups:
    - Cost estimation tools, these tools determine the manufacturing cost or manufacturing time of a component or system.
    - Technical feasibility tools, tools that determine whether or not a component or elements of the component can be manufactured using a certain manufacturing technique. Or a tool that determines what the technical difficulties are in manufacturing the component or elements with the specific manufacturing technique.
- ***Multi disciplinary tools***, frameworks that combine several tools or integrated tools that perform a multidisciplinary analysis

4.1 Model generators

When determining the performance of a mechanical component design concept the different actors in the design process need information about the design concept to run their respective analyses. This actor specific information set describes the design concept in the view of the actor. For most analysis disciplines the geometrical description of the component forms an essential part of the information set. This geometrical information is usually stored in a CAD model. However for most analysis disciplines geometrical information is only part of the information set needed. The other part is the view specific information that is not stored in the geometric representation. For a manufacturing engineer this can for instance be how a component is manufactured and what the material properties of the component are. A schematic overview of a model generator can be seen in Figure 4-1.

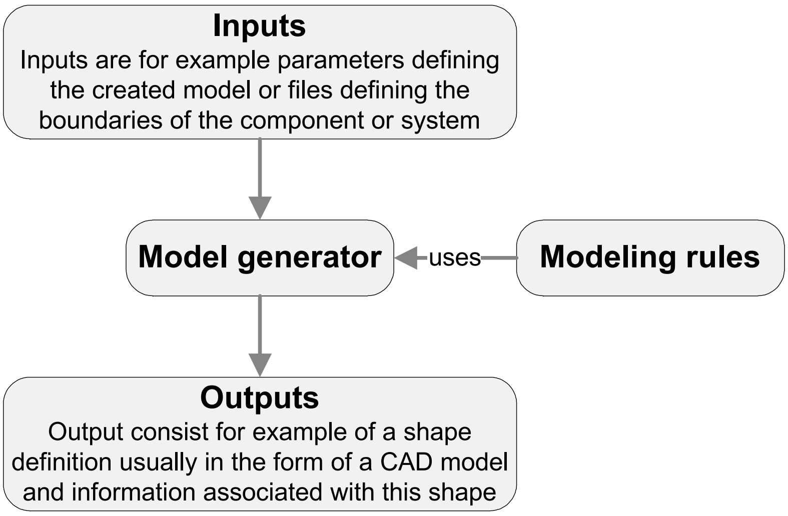


Figure 4-2 Schematic overview of a model generator

The information sets used by the different disciplines need to be consistent to make sure that the analyses results are consistent. In a KBE environment the information sets for the different analysis disciplines are generated by a single entity based one set of inputs to make sure all view specific information sets are consistent. This entity is called a model generator. Essential part of the model generator is the geometric model which forms the shape representation of the mechanical component. Usually this geometric model is created using specialized CAD software.

For geometry models many different CAD tools exist. Well known CAD systems are:

- Catia from Dassault Systems http://www.3ds.com/products-solutions/plm-solutions/catia/overview/ [cited 01-09-2005]
- NX from UGS, formally known as Unigraphics http://www.ugs.com/ products/nx! [cited 01-09-2005]
- Pro/Engineer from PTC, http://www.ptc.com/avvserver/mkt/vroducts/home.isQ?k=403 [cited 01-09-2005]

Main use of these CAD tools is interactively defining the geometrical definition of a system or component. Most CAD packages also have additional add-ons that facilitate the automatic generation of models and the addition of more information to the models.

However the functionality of the add-ons can be limited and most add-ons are aimed at developing specialized extra functionality to be used interactively in the CAD platform, not for developing integrated KBE solutions.

Besides CAD tools also specialized KBE packages exist, three of these packages are ICAD by Dassault System (http://www.ktiworld.com/ our_products/icad.shtml [cited 01-09-2005]), AML by Technosoft (http://www.technosoft.com/aml.php [cited 01-09-2005]) and GDL by Genworks (http://www.genworks.com/ [cited 27-01-2007]). All these software packages provide geometric modelling, automatic or interactive, while also allowing other information to be generated and connected to the geometry. Furthermore common interfaces and the ability to run in batch mode are provided. All these features are enabled by using a coding layer that runs on the background of any model. This coding layer allows for smart generation of the needed information, using mathematical expressions and algorithms. The added coding layer does impair the user friendliness of the software. To counter this all packages also have the ability to develop specialized Graphical User Interfaces (GUI's). By implementing these GUI's, KBE tools can be made more usable. However they decrease the accessibility of the coding layer of these KBE tools. Because of the additional functionality added by the coding layer, the specialized KBE software tools are suitable for the implementations of model generators, which generate both the lay-out of a component or system and information related to the component or system. It should be noted that the interactive possibilities of these tools are not as extensive as with dedicated CAD tools.

In literature several examples exist of model generators at different levels of detail. A gear model generator is presented by Aziz et al. (2002), this generator generates helical gears for finite element structural analysis based on a parametric model. In Chen et al. (1998) a model generator for mechanical parts is presented. The parts created by the model generator are prepared for a manufacturability analysis. Several model generators deal with moulds, for instance in Lee et al. (1998) a model generator for moulds is presented used as a basis for a manufacturability analysis. Ma et al. (2003) presents a model generator for cooling channels in existing mould geometries. Final example of a mould model generator comes from van der Laan et al. (2004), which presents a model generator that produces geometries of rib moulds for the thermoplastic rubber forming process. An automotive application of a model generator can be found in Chapman et al. (2001). Here a model generator for a car frame based on the cars outside surface, is presented. In the aeronautical field model generators of whole aircraft and parts of whole aircraft have been presented by LaRocca et al. (2002) for blended wing bodies, Krakers et al. (2003) for fuselage sections and Meijer (2003) for conventional aircraft configurations.

As can be seen most model generators lie or at the lower or at the upper scale of the design cube. At the aircraft component or installation level no model generator exists so this will have to be developed from scratch.

4.2 Structural analysis tools

As was described in chapter two structural analysis is an essential part of the design process of structural elements such as aircraft components. Structural analysis can be used for both initial sizing and for structural verification of the component or system. For the structural analysis first the topology of the component or system that is analyzed has to be determined. Initial sizing means determining the material kind, thicknesses and, in case of composites, orientation for the given topology of a component or system. In the case of verification the stresses, strains, deflection and stability characteristics of a component are estimated and compared with the requirements for the component. A schematic overview of a structural analysis tool can be seen in Figure 4-3.

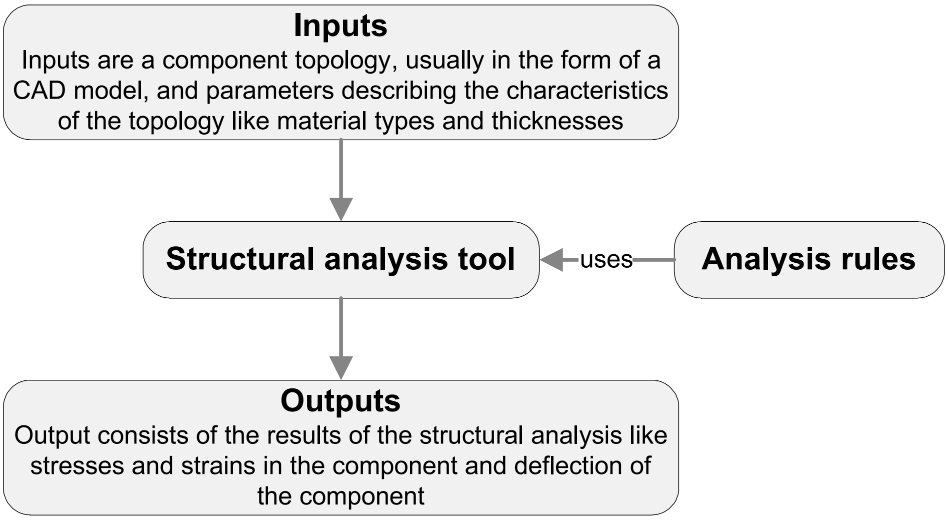


Figure 4-3 Schematic overview of a structural analysis tool

Two main groups of structural analysis exist, analytic and numerical analysis. The analytic methods use analytic formulas to predict the stresses and strains in, and the stability characteristics of, a construction. Advantage of these methods is that they use simple parameters such as length or thickness and do not need a detailed geometric model for the analysis. Disadvantage can be that the geometry of a product limits the applicability of the analytical formulas. Therefore these tools are usually limited to specific applications. In Kassapoglou (1999A) analytical methods are used to analyse helicopter frames for a multidisciplinary cost optimisation. In Curran (2004A) analytic methods are used to analysis stiffened panels in a multidisciplinary optimization.

The second method for structural analysis is the numerical method, usually a finite element method. In this case a discretization of the structural domain is used, not necessarily coinciding with actual structure of the analyzed system. The discretization often consists of a mesh, build up of points or nodes and elements used for the Finite Element (FE) analysis. Usually this mesh has to be build using a software programs that have specialized meshing algorithms. Such a meshing program can for instance be Patran (http://www.mscsoftware.com/products/products_detail.cfm?PI=6 [cited 23-09-2005]). The mesh of a product is usually based on a CAD representation of the product. However CAD representations can usually not be used directly for mesh generation and needs a substantial amount rework in preparation for the mesh generation. This is a time consuming and repetitive task and therefore a prime candidate for implementation in a KBE tool. The mesh that is generated is used by a structural solver such as Nastran (http://www.mscsoftware.com/products/products_detail.cfm?PI=7 [cited 23-09-2005]) for the actual analysis, which consists of determining the stresses, strains and deflections of all the elements. Interpreting the results from the finite element analysis can be challenging.

Advantages of the finite element method are that the structure that is analyzed is presented by surfaces, bars, beams and solids that can closely match the actual construction. The analysis should therefore produce accurate results that can be mapped to the actual construction. Second advantage of the finite element analysis is that it usually involves software tools; these tools usually have interfaces that allow for integration into larger frameworks such as KBE frameworks or tools.

A disadvantage of the finite element method is that many different solution and simulations methods exist of which the right one must be chosen to get a proper result. This selection requires expert judgement and experience that, if the finite element analysis is to be incorporated in a KBE tool, must be condensed into simple rules, which can be incorporated in the tool. Another disadvantage of the finite element method is that it produces a large amount of data. This large amount of data has to be interpreted in the right way using experience and expert knowledge that has to be incorporated into the KBE tool.

Examples of automated or partly automated FE analysis in a design or optimization cycle can for example be found in Komarov et al. (2002). Here finite element modelling is used for both the generation of the initial load path concept and the structural analysis of the resulting aircraft construction. Another example can be found in Bayandor (2002) where finite element analysis was used for the topology optimization of a Krueger flap. Examples of connections between CAD or KBE software tools and finite element software can also be found in literature. For example in Herencia (2000) where a coupling between a generative wing model and finite element mesh preparation software is described. In Sues et al. (2001) a framework for seamless coupling of CAD and mesh generation software tools is presented. In Nawijn et al. (2006) the principle of linking different model generators and a mesh generation software tool is presented using transparent interface formats.

4.3 Manufacturability analysis tools

The emphasis of the big aircraft integrators such as Boeing and Airbus has in recent years moved from technical performance to improving the affordability of aircraft. As a consequence suppliers have been pressured into delivering more cost effective services and supplying cheaper aircraft components. Because much of the manufacturing cost are the result of the product design, a large part of the manufacturing cost are determined at an early stage of the design process. According to Rais-Rohani et. al. (1996), Rush et al. (2000), Curran et al. (2004B) and Boothroyd et al. (2002), 70% of the total production cost of a product is determined in the conceptual stage of the design process. It is therefore important to be able to estimate the production cost of a design concept. However for complex parts such as aircraft components little information exists about the manufacturing of the component in question. For the generation of this information more detailed design information is needed, however this is outside the scope of the conceptual design. Therefore only a limited cost estimation or no cost estimation at all is performed. The cost estimation that is performed is usually executed by an experienced cost engineer that uses his years of experience. However when new production processes are used his expert judgement can be flawed. Another problem with this practice is that they provide little or no feedback to the designers of the aircraft components. Final issue with using the experience of a cost engineer is that when the engineer leaves the company all knowledge about cost estimations is lost. It is therefore important to develop cost estimation tools that can be used at the early stages of the design process.

Other part of the manufacturability analysis is the feasibility analysis. Determining the probability that a part can be successfully produced by a specific manufacturing method filters out unfeasible manufacturing concepts at an early stage of the design process. This filtering saves valuable analysis time that can be used for a more in dept study of other, more feasible, manufacturing concepts.

Feasibility analyses can for instance be:

- Accessibility analysis of a product during assembly of the product.
- Flow analysis of a vacuum infused product to see in the whole product is properly filled.
- Press analysis of a rubber press product to see if wrinkling occurs.
- Lay-up analysis of composite parts to see if there are no problems in the lay-up process.
- Analysis of a milled part to see if no undercut area’s exists.

As can be seen the type of analysis and thus the information needed for the analysis differs with different manufacturing techniques. In other words each manufacturing system requires another view on the system. Therefore many different tools are used for the feasibility analysis, however most tools use simulation of a manufacturing process as a means of analysis.

In the sections below the different approaches used in cost estimation tools will be discussed first followed by a section in which tools used to determine the technical feasibly of design concepts are discussed.

4.3.1 Cost estimation tools

Estimating the cost of an aircraft component is a complex process. There are many variables that determine the cost of an aircraft component and part of these variables are not constant but can change over time. This is for instance the case with material and energy prices. Furthermore the origin of cost, the manufacturing or design process of the component, are themselves not fixed processes. Therefore a cost estimate has to take into account these uncertainties.

The cost of producing an aircraft component can be split in two main areas: recurring cost and non-recurring cost. The recurring costs consist of costs that are made for all the parts separately, such as labour and material. Non-recurring costs are costs that are made for the whole production line, such as tooling cost and machine cost. Another element of the non-recurring cost is the design cost of a product. A recurring cost estimation is usually required to determine the cost effectiveness of a product once it is in production. The non-recurring costs are usually incurred in the product development and production start-up phase. For estimating total product cost, the non-recurring cost can be treated as an addition to the recurring cost. The height of this addition depends on the estimated production run of the aircraft component.

One of the issues in the cost estimation is which cost elements must be incorporated in the estimation. This depends on what the information is used for and on what information is needed by people involved in the design process. This in turn is also dependent on the phase of the design process in which the estimation is made and what kind and how much information is available.

For performing the actual cost estimation several methodologies exist of which the three most important are:

- *Parametric cost estimating*. Cost of a product is linked to technical parameters such as weight, size or part count.
- *Analogous cost estimating*. Product cost is estimated by comparing it to previously produced similar products.
- *Bottom up cost estimating*. In this approach the cost of all entities in the Work Breakdown Structure (WBS) of the product are determined based on the actual manufacturing processes used.

Each of the methodologies has its specific characteristics and sub variants. All methodologies can be used in cost estimation tools. Usually these cost estimation tools use inputs describing the product analyzed and the manufacturing techniques used to produce the product. In Figure 4-4 a schematic view of a cost estimation tool is shown. In this view also a “manufacturing database” is present. In most cost estimation tools such a database is used to store parameters, such as historical cost data, used in the cost estimation process.

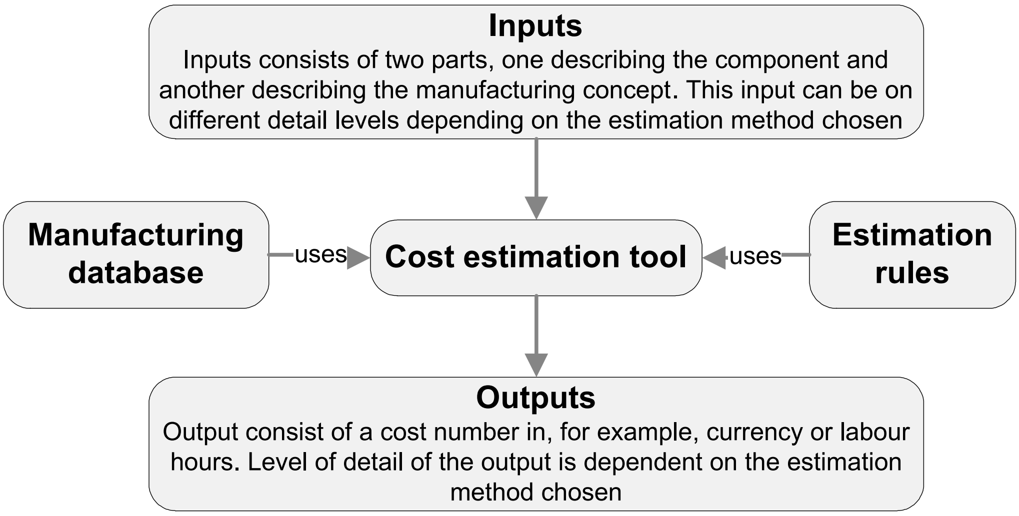


Figure 4-4 Schematic overview of a cost estimation tool

In the section below all three identified cost estimation techniques and the cost estimation tools using these techniques will be discussed. Finally in the last section a short description of other cost estimation tools or techniques will be given.

4.3.2 Parametric cost estimating

Parametric cost estimating is a cost estimation methodology that uses Cost Estimating Relations for cost estimation. The definition for parametric cost estimating from the Parametric Estimating Handbook of the International Society of Parametric Analysts (2003) reads: *“Parametric estimating is a technique that develops estimates based upon the examination and validation of the relationships which exist between a* *project's technical, programmatic, and cost characteristics, and the resources consumed during its development, manufacture, maintenance, and/or modification".* In this section a description of parametric cost estimating will be given however for a more in dept review one is referred to the previous mentioned reference (Parametric Estimating Handbook (2003)) and Curran et al. (2004B).

The Basic principle behind parametric costing is that the cost of manufacturing a product is linked to one or more parameters or characteristics of the product. These parameters are often geometric parameters such as weight, length or thickness. However other parameters such as number of drawings determining a design are also used (Collopy et al. (2001)). The mathematical formula determining the cost using the parameters is called the Cost Estimating Relation (CER). In the aerospace industry these CER's are commonly developed using linear regression (Curran et al. (2004B)) using historical data and databases. A CER for an aircraft elevator could for instance be:

$$C_{man} = C_w * W^{C_a} + C_s * S + C_b \qquad (1)$$

C_{man} = Manufacturing cost of the elevator

C_w, C_s, C_a, C_b = Factors determining the total cost, determined by regression

W = Weight of the elevator

S = Span of the elevator

During the development of CER's it is important to be aware of the limitations of the CER and document these limitations. Users of the parametric model should be made aware of these limitations to prevent the wrong use of the parametric model. Furthermore the parametric model should be validated to ensure that the results are useful and sensible. The whole lifecycle of a parametric model and all the activities involved can be seen in Figure 4-5.

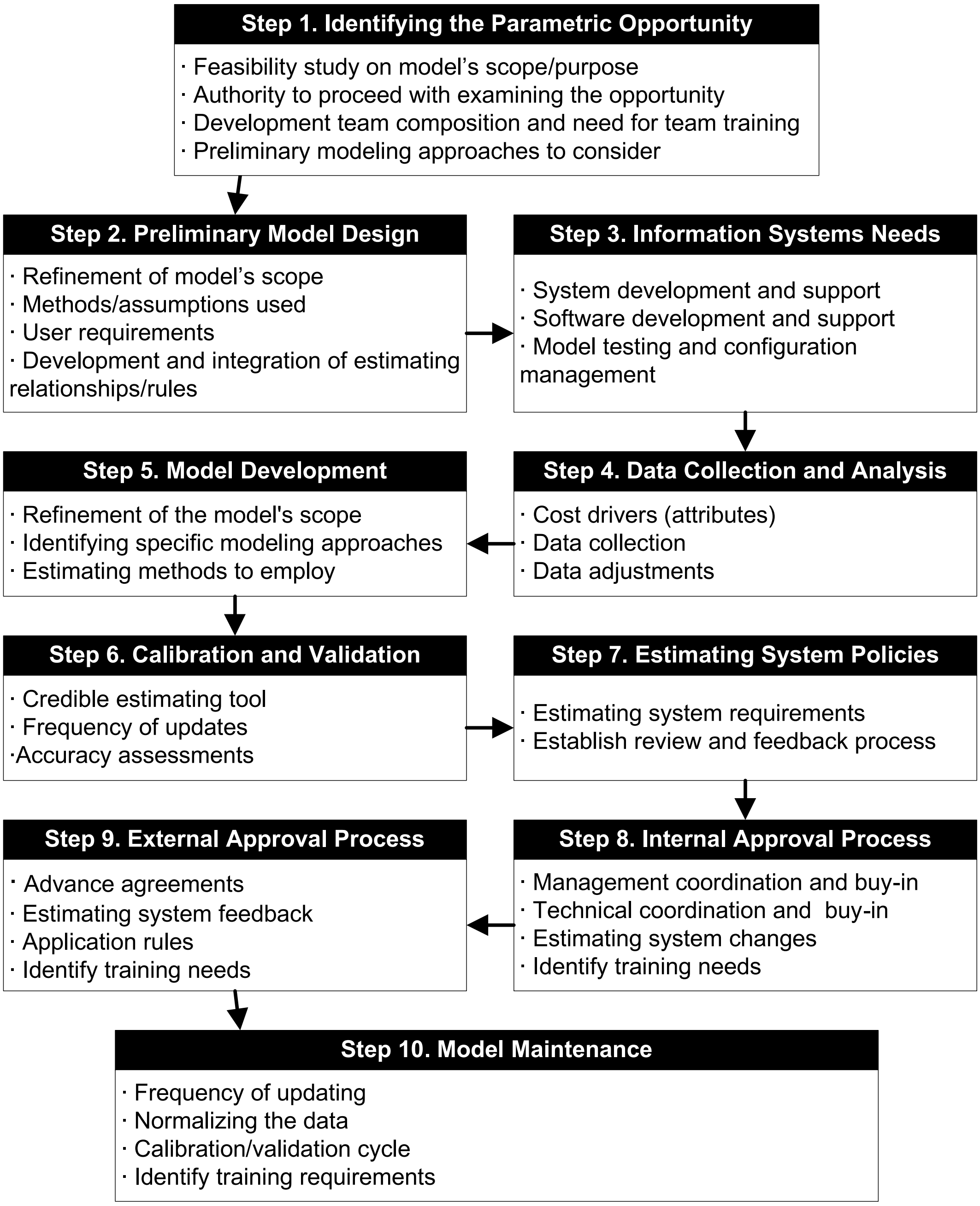


Figure 4-5 Typical parametric cost model development, adjusted from Parametric Estimating Handbook (2003)

Several commercial software packages that use parametric cost estimating have been developed. A summary of these packages with a short description is given below. For a more thorough description one is referred to the companies' websites or the Parametric Estimating Handbook (2003):

- *Price H*® from Price systems. This software tool generates system acquisition cost estimates. The cost estimates are based on quantitative and qualitative parameters. Main parameters are size, weight and manufacturing complexity. *Price H*® uses mostly non linear mathematical equations. *Price H*® has a built in risk analysis capability. http://www.pricesystems.com/products/price_h.asp [cited 26-08-05]

- *Seer-H^{tm}* from Galorath incorporated. This software tool generates a life cycle cost estimation of advanced systems using knowledge bases that can be expanded and adjusted. *Seer-H^{tm}* uses a combination of metrics and analytic techniques to perform the cost analysis. Risk analysis is built into the software tool.
  http://www.galorath.com/tools_h.html [cited 26-08-05]
- *Seer-DFM^{tm}* from Galorath incorporated. This software tool generates a cost estimation at a manufacturing process level. The generated cost estimation has a probabilistic character meaning it has upper and lower ranges. These ranges also account for the risk analysis.
  http://www.galorath.com/tools_dfm.html [cited 26-08-05]
- *NAFCOM* from NASE/US air force. The NASA/Air Force Cost Model (*NAFCOM*) is a parametric cost model for space systems. There are 2 versions of NAFCOM, one restricted version limited to authorized government users and one unrestricted for potential suppliers and educators. The parametric formula’s implements are based on space program data of over 100 different projects.
- *ParaModel®* from Mainstay Software Corporation (marketed as ACES in Europe). *ParaModel®* is parametric cost estimation tool that is not database driven but uses CER’s based on data collected from industry over many years. *ParaModel®* can be used for the whole lifecycle analysis of a product or system.
  http://user1128512.sf2000.registeredsite.com/paramode.html [cited 21-07-05]

The advantages of the parametric cost estimation method are firstly that very little has to be known about a product to get an estimate. Secondly parametric cost estimation tools can be used by people who are not expert cost estimators such as designers. Disadvantages of the parametric cost estimation method are firstly that the method works as a black box. This makes it difficult to see where certain cost come from or if a mistake is made (Duverlie et al. 1999). Second disadvantage is that it is difficult to judge by a non-expert if a parametric model applies to the system or product it is used for. Third disadvantage is that historic data is needed to calibrate the parametric cost estimation. Therefore the cost estimation is based on history and new processes, or innovations to processes, are difficult to implement. Parametric cost estimation methods also need constant maintenance to keep them up to date, reflecting the latest developments in the area covered by the estimation method. If this maintenance work is not done the parametric model can produce misleading cost estimation results. A pitfall in developing parametric models can also be that irrelevant data is used for determining the CER’s. This results in a useless cost estimating model (Curran et al. 2004B). Final disadvantage is that parametric cost estimation is not always causal, meaning that estimated cost increases and decreases are not the direct result of changes in the manufacturing process. For instance a weight reduction can be achieved by removing more material using milling. When weight is the governing estimation parameter in a CER this removal of material will result in a reduction in the estimated manufacturing cost. This cannot be correct because the milling machine will have to operate longer.

In literature parametric cost estimation tools can for instance be found in Kassapoglou (1999B), where a parametric cost estimation, in combination with structural analysis, is presented for helicopter fuselage frames. Another example of parametric cost estimation methods from literature is the tool used by Castagne et al. (2004) for estimating the cost of stiffened fuselage panels.

4.3.3 Analogous cost estimating

Analogous cost estimating uses historical data to perform a cost estimate. Analogous cost estimating sometimes also called “case based reasoning”. The historical data consist of information from previous projects that dealt with products of an approximately similar shape as the product for which the cost estimate is made. Because the analysis is made using historical data, expert judgement is needed to determine which historical data is relevant and which is not. Expert judgement is also needed in determining the differences between the project for which the cost estimation is performed and the historical projects. To take these differences into account these corrections, factors reflecting them are used in the actual cost estimating process.

According to Curran et al. (2004B) the process steps of performing a analogous cost estimation are as follows:

- *Definition.*
  In this phase the definition of, and assumptions about, the system for which the cost estimation is performed and the cost estimation itself are determined.
- *Practical preparation.*
  In this phase the availability of historical data is assessed and the data of the system for which the cost estimation is performed is put in a similar format as the historical data.
- *Data collection*.
  In this phase the actual data about the historical cases is collected.
- *Factor generation.*
  In this phase factors are generated that characterize the system of which the cost has to be estimated.
- *Actual cost estimate*.
  In this phase the actual cost estimation is performed.
- *Total program cost estimate*
  In this phase all cost estimates are combined and profit and other additional factors are added to produce the final estimated cost for the whole program.

The formulas used for the cost estimation process for an analogous cost estimation have the following form:

$$C_N = C_H \cdot F_C \cdot F_M \cdot F_P \qquad (2)$$

C_N = Cost of the new system

C_H = Cost of historical cases

F_C = Complexity factor, determined by experts

F_M = Miniaturization factor, determined by experts

F_P = Productivity factor, determined by experts

The complexity, miniaturization and productivity factors are determined by experts in the specific fields.

The advantage of analogous cost estimation is that, when historical data is available that has a good analogy with the new project, a relatively accurate cost estimation can be produced quickly. Main disadvantage is that expert judgement is needed to judge analogous historical data and to determine the adjustment factors for using the historical data (Asiedu et al. (1998)). This expert judgement is inherently subjective. Another disadvantage is that analogous cost estimation is not always causal, meaning that estimated cost increases and decreases are not the direct result of changes in the manufacturing process.

From literature reports on several analogous cost estimation tools and systems are known. In Duverlie et al. (1999) a case based reasoning cost estimation system is presented for pistons and also a comparison is made with a parametric cost estimation tool. In Kulkarni et al. (2003) a system is presented that uses reference objects to determine the manufacturing cost of milled objects. In Rehman et al. (1998) a methodology is presented for using case based cost estimation in the conceptual design stage. An example of using analogous cost estimating for aircraft parts can be found in Curran et al. (2004C). Here a system is presented for the cost estimation of aircraft engine nacelles incorporating complexity factors.

4.3.4 Bottom up cost estimating

In bottom up cost estimation manufacturing cost is related to all elements of a component or system and all the activities related to these elements. Bottom up costing can also be called process based costing or the engineering build-up method. Basic principle behind this estimation technique is that the whole manufacturing process is split into chunks that present actual physical activities and entities. For these activities or entities cost estimations can be made. When the different cost estimations for the activities and entities are added, a cost estimation for the whole system or component is produced. This cost estimation method is usually used for the cost estimation of the recurring cost of a manufacturing process. The cost related to, for example, the design of the system or component is usually added as a factor on top of the estimated cost. Because all activities and entities in the manufacturing process are handled this cost estimation method produces very detailed results. However in order to reach these detailed results the cost estimator also needs detailed information about the processes used for manufacturing and about the actual system or component for which the cost estimation is produced. Therefore this cost estimation is usually information intensive and used in the detailed design phase when most decisions about cost are already made and the influence on the cost is limited.

In bottom up cost estimation the formulas that describe the different activities for manufacturing the system or component are important. Usually the formula’s used in the cost estimation mimic the actual physical process. For instance in Neoh (1995) it is stated that manufacturing operations performed by humans or machines can often be represented as dynamic systems with first order velocity response to a step input. This representation can then be used to formulate an approximation using a hyperbolic expression:

$$t = t_{delay} + \sqrt{\left(\frac{X}{v_0}\right)^2 + 2 \bullet \tau_0 \bullet X} \qquad (3)$$

t = Total manufacturing time

t_{delay} = Delay time before the operation

v_0 = Steady state speed of the process

τ_0 = Time it takes to reach 63% of the steady state speed

X = Variable on which the analysis is based, for example areas or length

This hyperbolic expression with the addition of some expressions for delay and setup times can be used to simulate most manufacturing processes. The factors determining the actual behaviour of the process are limited to the steady state speed, an expression describing the acceleration phase of the manufacturing process and factors describing the static delay and setup time. These factors can be determined by using historical data such as data about previous processes or, because they are actual physical factors, by performing tests.

The advantage of bottom up cost estimation is that it is causal, meaning that changes in the cost estimate are caused by changes in the actual manufacturing process of the system or component. Furthermore the cost estimation is very detailed because all elements in the work break down structure for manufacturing the system or component are handled. This gives the opportunity to localize the cost drivers, which in turn can be used to improve the design. Another advantage is that in principle no historical data about a manufacturing process is needed, because the essential factors for the estimation can be determined by doing test or by using characteristics from, for example, the machine involved in the process. However it should be noted that using historical and expert judgement for determining the essential factors will improve the model, because of possible discrepancies between the actual manufacturing process and the test setup used to determine the manufacturing factors.

Disadvantage of the bottom up cost estimating method is first of all that a huge amount of data is generated. This data has to be filtered and interpreted to get a proper cost estimate. For this job expert knowledge is needed. Second disadvantage is that a substantial amount of data is needed as input for the cost estimation. This data consists first of all of the factors that determine the different manufacturing methods and secondly the data that describe the system or component for which the cost estimation is made. The data about the different manufacturing methods are usually stored in databases that need to be maintained, which can take quite some effort. The data about the system or component for which the estimation is made has to be extracted from the design. Usually this data is not available at the conceptual design stage or it takes a great deal of effort to extract usable data from the design. Therefore the role bottom up cost estimation can play in the conceptual design stage is usually limited.

In literature several implementations of the bottom up cost estimation method can be found. An example of a framework for cost estimation of composite laid up structures can be found in Neoh (1995). This framework uses formulas to estimate manufacturing times for each step in the composite lay up manufacturing process, including positioning of parts and incorporates methods for the influence of complexity on the manufacturing process. A more detailed view of the formulas used can be can be found in Ilcewicz et al. (1996). In Kumar et al. (1998) a theory is presented on how to incorporate complexity of a part into a cost estimation. Stockton et al. (1998) deals with automatic tape laying and presents a cost estimation model for this manufacturing technique, while Barlow et al. (2002) presents a cost estimation system for liquid moulded composite structures. An expansion of the Neoh (1995) model using the same principle but for many more manufacturing processes can be found in Haffner (2002). Besides composite manufacturing methods this publication also handles assembly manufacturing techniques. Finally a cost estimation model for a new manufacturing technique is presented by van der Laan et al. (2005). In this publication a cost estimation technique for the friction stir welding assembly technique is presented.

4.3.5 Cost estimation summary

Table 1 Cost estimation summary table

Method	Characteristics	Advantages	Disadvantages
Parametric	Based on relations between product characteristics and costs	• For use no expert knowledge needed • Not much about product has to be known	• Black box appearance, gives no direction for improvements • Historic data is needed • Expert knowledge needed to judge if parametric model applies to product • Not always causal
Analogous	Based on similarities between the product and previous projects	• Relatively good estimation can be produced • Quick results	• Expert judgement needed for product conversion factors • Historical data needed • Not always causal
Bottom up	Based on adding all the cost from actions needed to manufacture the product	• Causal • Detailed results • In principle no historic data needed	• Data intensive • Detailed product data needs to be available

4.3.6 Other estimation techniques

Besides the previously described cost estimation methods some other methods are also described in literature. These methods usually fit into one of the previously described methods but use specialized algorithms for creating the relations used in the cost estimation.

Expert opinion

When using expert opinions as a cost estimating tool, a manufacturing expert is asked to produce a cost estimate of the system or component involved. The cost estimate is purely based on the experience of the engineer involved. This technique can also be called an intuitive cost estimation technique, because the intuition of the engineer is used to create the cost estimation. Big advantage of this method is that it is usually fast. Biggest drawbacks are that the cost estimation is subjective and that, for good cost estimates, highly experienced costing engineers are needed.

Feature based modelling

In feature based modelling a system or component is described by design features, these features can for instance be holes or slots. Manufacturing these features usually account for a large part of the manufacturing cost of a system or component. Therefore the characteristics, such as size and tolerance, of these features can be used for the cost estimation of a system or component. A feature based cost estimation model for machined parts can be found in Ben-Arieh (2000).

Fuzzy logic

Fuzzy logic is a tool that can be applied for cost estimating. Fuzzy logic means that certain values are not expressed quantitatively but qualitatively. For instance a hole with a diameter of 3mm can with fuzzy logic be assessed as "small" instead of using the actual diameter. Advantage of fuzzy logic is that it can better handle human knowledge that is qualitative. Due to the non-deterministic character of fuzzy-logic it is also good at handling the probabilistic issues involved in cost estimating. An example of a cost estimating system using fuzzy logic is presented in Shehab (2002).

Neural network

Neural network is a technique that can be used to develop a cost estimation tool. The technique simulates the human thought process to produce cost estimating relations. To do this it needs historical data to train itself and learn what the cost estimating relations must look like. For the learning process to be effective the quality and quantity of the historical data should be large. However even when the historical data meets this requirement the resulting cost estimating relations will still not be transparent and the whole method will seem like a black box to the user. Performance increases over regression based parametric cost estimation have been shown in Bode (2000) and Cavalieri et al.(2002), while the pitfalls of using neural networks are discussed in Smith et al.(1997).

4.3.7 Technical feasibility analysis tools

Technical feasibility can be defined as the chance that a system or component can successfully be produced. This chance is dependent on the manufacturing processes that are used and the lay-out or geometry of the system or component that is produced. Determining the technical feasibility is essential because when the chance of successful production of a system or component is low, it can result in a technical and financial catastrophe. The assessment of technical feasibility of a system or component design should be performed as soon as possible in the design process. This will ensure that unfeasible concepts are filtered out early in the design process and valuable resources can be allocated to the designs that show the most promise. Most technical feasibility assessment in the early stages of the design process is performed using common sense or expert judgement. However for more complex systems and components such an approach is no longer workable. Additionally such an approach usually favours known and tested manufacturing methods harming the chances of new innovative design concepts. Therefore tools have been developed that help designers and manufacturing engineers to judge the technical feasibility of their designs.

The technical feasibility analysis tools can be divided into 2 main groups:

- Tools that store expert data and/or empirical rules and use these to automatically asses the technical feasibility of a design.
- Tools that simulate the actual manufacturing process and use the results of this simulation to asses the technical feasibility of the design.

Both groups of tools are in practice not only used to assess technical feasibility but also to provide information about the ease of manufacture of a particular design concept. Both groups of tools will be discussed in the next paragraphs. A schematically view of a technical feasibility tool can be seen in Figure 4-6.

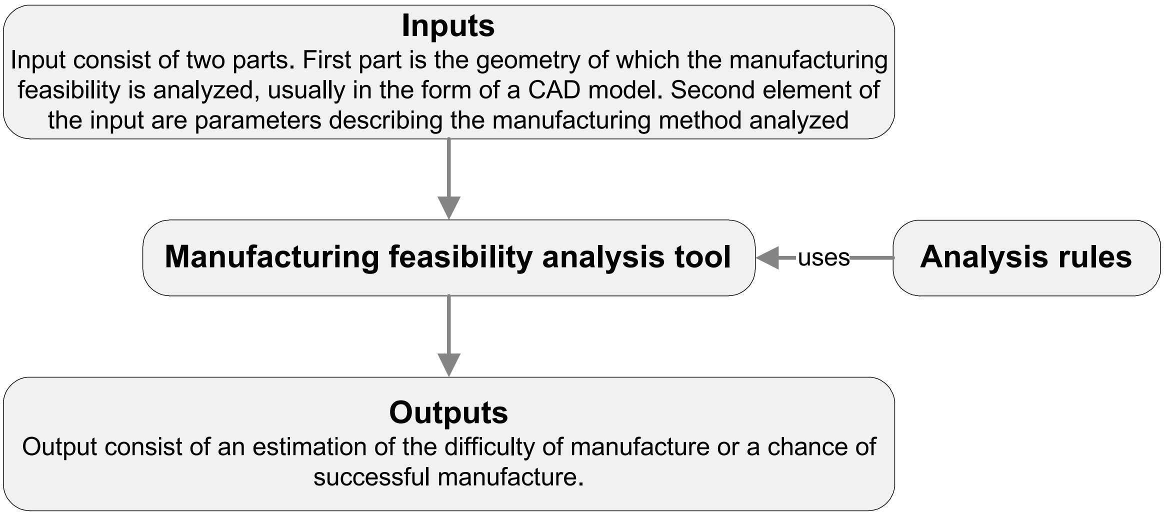


Figure 4-6 Schematic overview of a tool for determining technical feasibility

Tools that store expert data and/or empirical rules are usually used as advisory systems for designers. Basic objective of these tools is to provide the knowledge of manufacturing experts in an easy to use format to design engineers or novices in the area of manufacturing. That is why these systems are often called expert-(knowledge) systems. The expert knowledge stored in the tool cannot only be used to judge the technical feasibility but also to suggest changes that might improve the design concept. For the development of these systems formalized expert judgement is needed meaning knowledge from experts or experience gained by previous projects must be transformed into rules. In literature a number of systems are described, firstly Leake (1999) describes a case based system for the design of a front side panel of a car. Borg (1999) shows the prototype of a system that helps designers assess the manufacturing and life cycle consequences of their design decisions. In Tang (2003) a framework is shown that supports the multidisciplinary development of sheet metal parts. One element of the framework is the stampability analysis, which is performed by analysing the part geometry using simple manufacturing rules. Finally in Chen (1998) a system is presented for simple mechanical parts that analyzes the parts geometry by utilizing simple engineering rules. This system also suggests improvements to the design.

The second group of tools consists of manufacturing simulation tools. These simulate the actual manufacturing behaviour of a system or component. Because the different manufacturing methods have a different nature, the simulation tools also have a different nature. Simulation tools are usually numerical and closely related to structural finite element models and to aerodynamic fluid dynamics models. Simulation tools are usually commercially developed tools that can be classified as Commercial Of the Shelf Tools (COTS) tools. Some models are also under development by academia, such as DRAPE which is described in Bergsma (1995).

The manufacturing simulation tools are especially important when the behaviour of the manufacturing process or the material used in the process is hard to predict using existing knowledge about the manufacturing process. For manufacturing methods where the structural properties are influenced during the manufacturing process it is even more important to have proper simulation tools, because these can provide simulations validating the structural integrity of the product. The behaviour of manufacturing methods handling composite materials is both difficult to predict and defines the structural properties of a system or component to a high degree. Therefore many simulation tools exist to simulate composite manufacturing methods. For instance injection processes can be simulated by tools such as Moldflow (http://www.moldflow.com/stp/ [cited 31-08-2005]) and RTM-Worx (http://www.polyworx.com/ [cited 31-08-2005]). Another example of composite simulation tools can be found in tools that simulate the lay-up process of composites. These tools usually also calculate the orientation of the fibres after the system or component has been manufactured. Examples of these tools are FiberSim (http://www.cdt.com/ [cited 31-08-2005]) and the previously mentioned DRAPE.

In addition to these stand alone simulation tools, CAD packages such as Catia, Unigraphics and Pro-Engineer have add-on tools that can provide simulation capability. The use of tools integrated in CAD tools has the advantage that preparation time of the CAD model can be limited. This preparation can take a significant amount of time similar to preparing a CAD model for a structural finite element analysis. Disadvantage of using integrated tools is the lack of flexibility and interoperability; add-ons are usually limited to one CAD-package.

4.4 Multi disciplinary tools

The tools described in the previous section all handle one aspect of the design and analysis process. In other words only one discipline from the design cube (Figure 4-1) is handled. However when designing an aircraft component or system there is interaction between the different disciplines. Therefore for an optimal design this interaction must be taken into account during the design process. This can be done by using multidisciplinary design tools or by using combinations of design tools from various disciplines in a framework combining these tools. For instance an aerodynamic design tool can be used to determine the air flow and pressures around a structure. The pressures in turn can be used to perform a structural analysis and determine the weight of the design. Using the results of these analyses, design changes might be implemented. Because the interaction between disciplines is often two way, multidisciplinary tools often have an iterative character.

Multidisciplinary tools described in literature are almost without exception used for Multi-Disciplinary Optimization (MDO) purposes. In a multi disciplinary optimization a model generates information for different analysis disciplines. The design space investigated is limited by putting constraints and boundaries on the parameters and variables describing the design. An objective function is used to judge the performance of a design concept. Convergence checks of the objective function in subsequent design iterations are used to steer the optimization process. Problem of MDO tools is that they only cover part of the design space so the optimal solution must lie in this design space.

Furthermore when the optimization criteria are not properly defined local optima might be found in the design space, which do not represent the optimum design.

Multidisciplinary tools vary in level of tool integration, level of flexibility and the component or system they help designing. Integration levels vary from fully integrated tools with one user interface to systems that require manual actions for communication between the different elements. The level of flexibility usually determines the range of products and shapes the multidisciplinary tools can be used for. The level of flexibility is also closely linked to the integration level of the tool in question. Fully integrated tools are usually limited to one type of product with limited differences in shape and specification. Non-integrated frameworks built up of various modules can be used for different products at different scale levels. Designs generated by multidisciplinary tools vary from stiffened panels, spars or ribs to complete aircraft.

In literature multidisciplinary tools are usually used for multi objective optimization proposes and usually consist of frameworks combining various tools or tools that use analytical analysis methods to perform optimisations. Examples of framework combining various tools can be found in Gern et al. (2001) where a multidisciplinary design framework is presented for the design of a strut braced aircraft. Tools from different disciplines, like structural analysis, aerodynamics and aero elasticity, are used to devise an aircraft design with optimal performance. In the MOB project (Morris, 2002) the multidisciplinary design of a blended wing body configured aircraft was investigated, combining among others structural and aerodynamic high fidelity analyses. Another example of a multidisciplinary design framework using different tools is presented in Zweber (1998). This framework is used for the optimization of a wing design, using tools from the structural analysis and cost estimation disciplines. Multidisciplinary tools using analytical expressions can be found in Castagne et al. (2004) for aircraft fuselage panels and in Rais-Rohani et al. (2005) for wing spars. Both use simple analytical expressions for structural analysis and cost estimation to come to an optimal design. Other papers handle the shape of a multidisciplinary framework and the communication in such a framework. In Engels et al. (2004) a traditional sequential dataflow approach is presented while in Cuthosky (1993), Madhusudan (2005) and Sun et al.(2001) agent based systems are proposed. In agent based systems, agents assure proper communication between the different tools. The systems presented in these publications use facilitator agents to steer all the different tools. Finally an agent based framework without a facilitator agent is presented in van Tooren et al. (2005).

5 Development and description of the Parametric Movable Model (PMM)

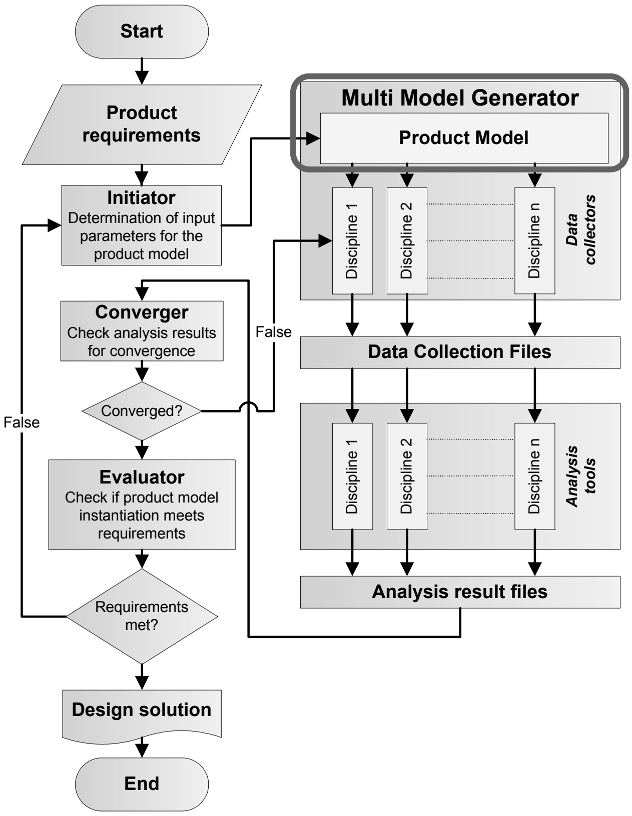


Figure 5-1 Part of the DEE discussed in chapter 4

Essential part of the Design and Engineering Engine (DEE) for the design of aircraft components is the Multi Model Generator (MMG). It generates data about the aircraft component that will be used by other the tools performing analyses in the different disciplines, enabling the “Design for X” methodology in these analyses disciplines. The concept of the MMG will be explained by showing an example of such an MMG for the family of aircraft movables. It is called the Parametric Movable Model (PMM) and will form the basis of all the other tools discussed in this thesis.

The PMM’s function is to provide data to all the other tools analysing aircraft movables. Secondary function of the PMM is to generate visual representations of a movable. To perform the first function the requirements of the analysis tools to which data is provided have to be determined. As was shown previously different engineering disciplines can have different views on the same component, therefore the PMM should be able to support these views. The element of the PMM discussed in this chapter is strictly the product model. The data collectors that are part of the PMM will be discussed in the chapters handling the specific analysis disciplines for which they collect data. Which part of the DEE is discussed in this chapter is depicted in Figure 5-1.

In the first part of this chapter the requirements for MMG development that ensure re-usability of elements of the MMG will be discussed and the definition of views in an MMG is discussed. Second issue handled in this chapter are the requirements for the PMM. In the second section the general requirements for the PMM will be handled followed by the requirements of the structural and manufacturing views of the PMM. When the requirements have been determined the PMM can be implemented. The discussion of the implementation is again separated in a general part and two part discussing the structural and manufacturing views of the PMM. Finally some examples of instantiations of the both the structural and the manufacturing view of the PMM will be shown.

5.1 MMG developments guidelines

An MMG is a complex software tool, developing it from scratch can be a time consuming exercise. Therefore it would be useful is elements of an MMG could be re-used in other MMG's reducing the development time for these new MMG's. To achieve this re-using of MMG elements, it is necessary that these elements are modular. Modularity means that a module that performs an operation in the MMG has clearly defined in- and outputs.

Two different types of modules can be distinguished within an MMG: A High Level Primitive (HLP) and a Capability Module (CM) (La Rocca 2007B). Both HLP and CM consist of a set of classes and/or methods which are used in the MMG. The definitions for a HLP and CM are:

High Level Primitive (HLP): A parametric model of a primary design option element, generic enough to be re-used in other MMG's and specific enough to support the MMG user properly.

Capability Module (CM): A set of methods or classes that can be added to a High Level Primitive or to another Capability Module. The Capability Module can be applied to multiple High Level Primitives and/or Capability Modules.

Because HPL's and CM's will be re-used in other MMG's they must be extendible. This means that a developer must be able to add more capabilities in the form of classes or methods, but that the new module must still function properly in the original MMG. This ensures that only one version of the module needs to be maintained and can be used by all MMG's.

In a MMG the HPL's and CM's are used to interpret a dataset and translate it in such a way that it can be used for further analysis of the product or it visualizes the product for the user of the MMG. The interpreted dataset is created by the initiator in the DEE. This dataset consists of parameters, variables and files describing the design concept. How this is actually implemented in the PMM will be made clear further on in this chapter. A dataset can be interpreted in different ways analogous to how the different actors in the aircraft component design process look at a component. In this chapter such an interpretation will be called a view.

View: An interpretation or translation of the MMG input dataset describing a design concept for one engineering discipline.

It is important to stress that the different views of a product originate from the same dataset. Therefore the different views on a product based in this dataset will produce consistent results for the different views.

The definitions of High Level Primitives, Capability Modules and Views will be used throughout this thesis to describe the PMM.

5.2 General requirements for the movable product model

The PMM is used to generate the different discipline views of the family of aircraft movables. Movables are elements of an aircraft that can be moved into the airflow around the aircraft. Different movable types exist as can be seen in Figure 5-2. The PMM will be limited to generating the trailing edge movables. This branch of the movable family was chosen because members of this branch show many commonalities, which makes representing them using one and the same modelling engine sensible. The movables that can possibly be modelled with the PMM therefore lie in the top branch of Figure 5-2.

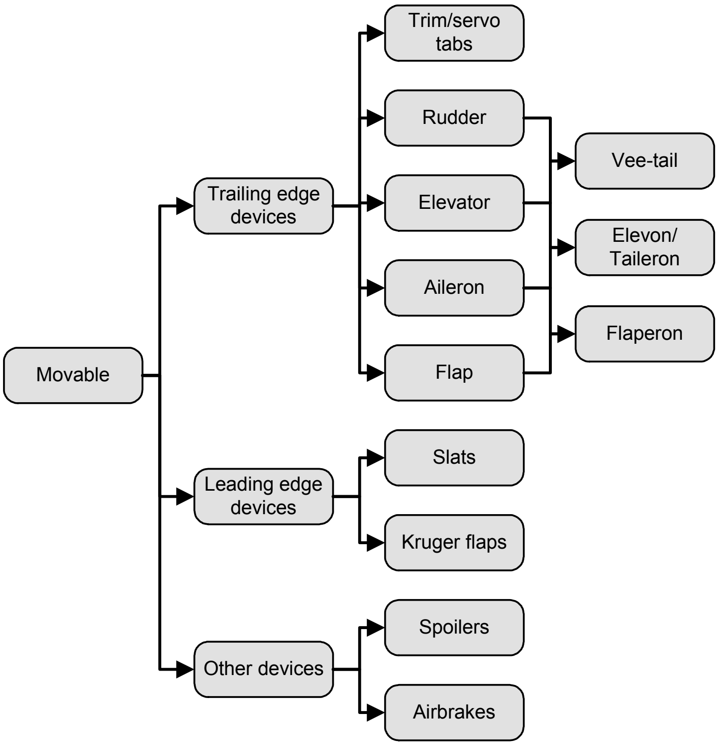


Figure 5-2 The movable family tree

Essential characteristic of trailing edge movables is firstly that they lie at the trailing edge of a wing like element. Such an element can be a wing, but also elements of the empennage. In the case of trim tabs or multiple elements flaps it is even possible that the movable lies in the trailing edge of another movable. The PMM should also be able to generate the particular shapes commonly encountered in movables. Features determining this shape and therefore required to be implemented in the PMM can be seen in Figure 5-3. All surfaces and features dealing with the outer shape or outer mould line of the movable will be called “shape” features. The shape features that the PMM is required to represent are:

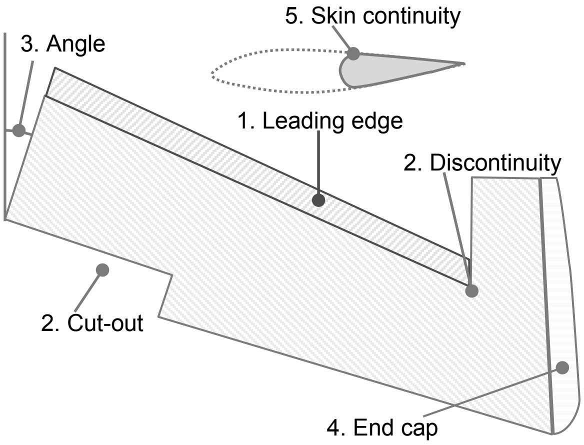


Figure 5-3 Movable shape features

1. The leading edge, this is the part of the movable in front of the first spar of the movable, it must have an aerodynamically smooth connection to the rest of the movable.
2. Cut outs and discontinuities, these features are needed to accommodate, for example, trim tabs or to create a horn in which the balance mass of the movable can be positioned.
3. Arbitrary angles at the beginning and end of the movable and between the discontinuities.
4. End cap, these aerodynamic fairings at the end of the movable assure smooth aerodynamics of the top and bottom of the movable.
5. Skin continuity, this ensures that the movable lies flush with the wing surface to ensure good aerodynamic properties when the movable is not deflected.

The shape of the wing like entity in which the movable will fit is determined by the design of the overall aircraft. This usually means that an outer mould line is supplied to the movable manufacturer by the aircraft integrator. To accommodate this, the PMM should be able to handle surfaces in which the movable should fit, supplied from outside the Movable Design and Engineering Engine (MDEE). The tools that supply the outer mould line can for example be CAD tools or higher level DEE's. In order to fill this requirement it is essential that the format in which the outer mould line is delivered is standardized. The PMM should also function when no outer mould line is known. Therefore the PMM should be able to generate an outer mould line in itself, based on inputs from the DEE user. This means that the PMM should be able to model the shape of the wing in which the movable should fit.

Summarizing the general requirements for the PMM are:

- The PMM should be able to generate all shapes commonly encountered in trailing edge movables.
- The PMM should be able to fit the movable into an outer mould line supplied by external sources.
- The PMM should be able to generate the outer mould line of the wing like element in which the movable will fit.

5.3 Structural view requirements for the PMM

One view the PMM needs to generate is the structural view. In this view the movable topology is represented. This view is used by a designer to visually check a design concept and can be used by a structural engineer to check the load path definition. This view will also be used as a basis for supplying data to structural analysis tools. In order to generate this data, structural details will have to be implemented in the PMM. These structural details are dependent on the structural concepts that are implemented. The view in the PMM in which the structural entities are visualized will be called the structural view.

Four main structural concepts for trailing edge movables can be distinguished: a stiffened skin construction, a sandwich construction, a multi-rib construction and the full dept foam/honeycomb. Three of these options will be incorporated in the PMM: the stiffened skin option, the sandwich option and the multi-rib option. The difference between these three options is the way the skin surfaces are stiffened. The PMM should be able to combine several different structural options in one instantiation of the movable model.

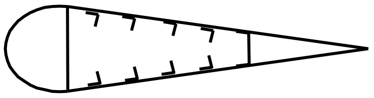


Figure 5-4 Stiffened skin example

Stiffened skin The stiffened skin structure consists of two types of elements: shape elements and stiffening elements. The shape elements form the external shape of the movable. Shape elements are for example skins, leading edge and end-caps. The stiffening elements make sure that the shape is retained when the moveable is loaded. Stiffening elements are for example ribs, spars and stiffeners. The stiffened skin variant refers to the concept where most stiffening is provided by longitudinal stiffeners as can be seen in the cross section in Figure 5-4.

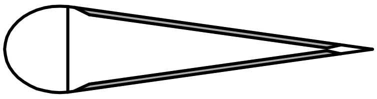


Figure 5-5 Sandwich example

Sandwich panels With a sandwich panel construction shape and stiffening element are integrated in one element. The skin surface consists of two facings and a core. The distance between the two facings ensures that the skin surface has enough bending stiffness to prevent buckling. An example of the sandwich construction used for the movable skins can be seen in Figure 5-5.

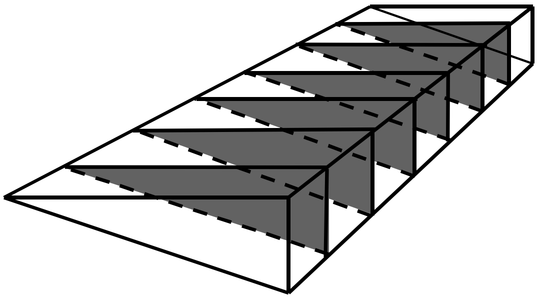


Figure 5-6 Multi rib example

Multi-rib The multi rib construction is essentially a version of the stiffened skin construction. Main difference is that the stiffening elements consist of many ribs and that no stiffeners exist. The stiffening itself is based on a different principle compared to the previously described concepts. Instead of increasing the bending stiffness of the skin the buckling length is shortened. By shortening this length the buckling load increases. To shorten the buckling length the ribs have to divide the skin into many sections, which are short enough to withstand the loads exerted on it. An example of the multi-rib construction can be seen in Figure 5-6.

All the structural concepts presented above should fit inside the movable shape. Therefore the PMM should ensure that the outer mould line supplied externally or created by the PMM is used as a boundary for all the structural entities.

Another important element of the structural view of the PMM is the possibility to award the different structural elements different types. This can for example mean that there are hinge ribs and light (structural) ribs. In this way a distinction can be made the between the structural elements, this is essential for the structural analysis of the movable. The different types will be determined by interpreting specialized inputs from the input dataset. The different types should also be visible in the PMM. Making them visible will allow the user of the DEE to see the impact of the initial input and changes to these inputs on the movable model.

Summarizing the structural requirements for the PMM are:

- The PMM should be able to generate structural entities representing the stiffened skin, sandwich panel and multi rib structural concepts.
- The PMM should make sure that the structural elements of the movable lie within the outer mould line of the movable.
- It should be possible to award structural types to the structural elements and this should be visualized.

In Figure 5-7 the use case diagram of the structural view of the PMM is presented. In this diagram all the functions of the structural view of the PMM are presented. During the actual implementation of the PMM this diagram is used as a guide. In this diagram an additional element is present namely the preparation of the structural model for numeric analysis. This element of the PMM is not discussed in great detail in this chapter it will however be handled in chapter 8 where the structural analysis tool is discussed.

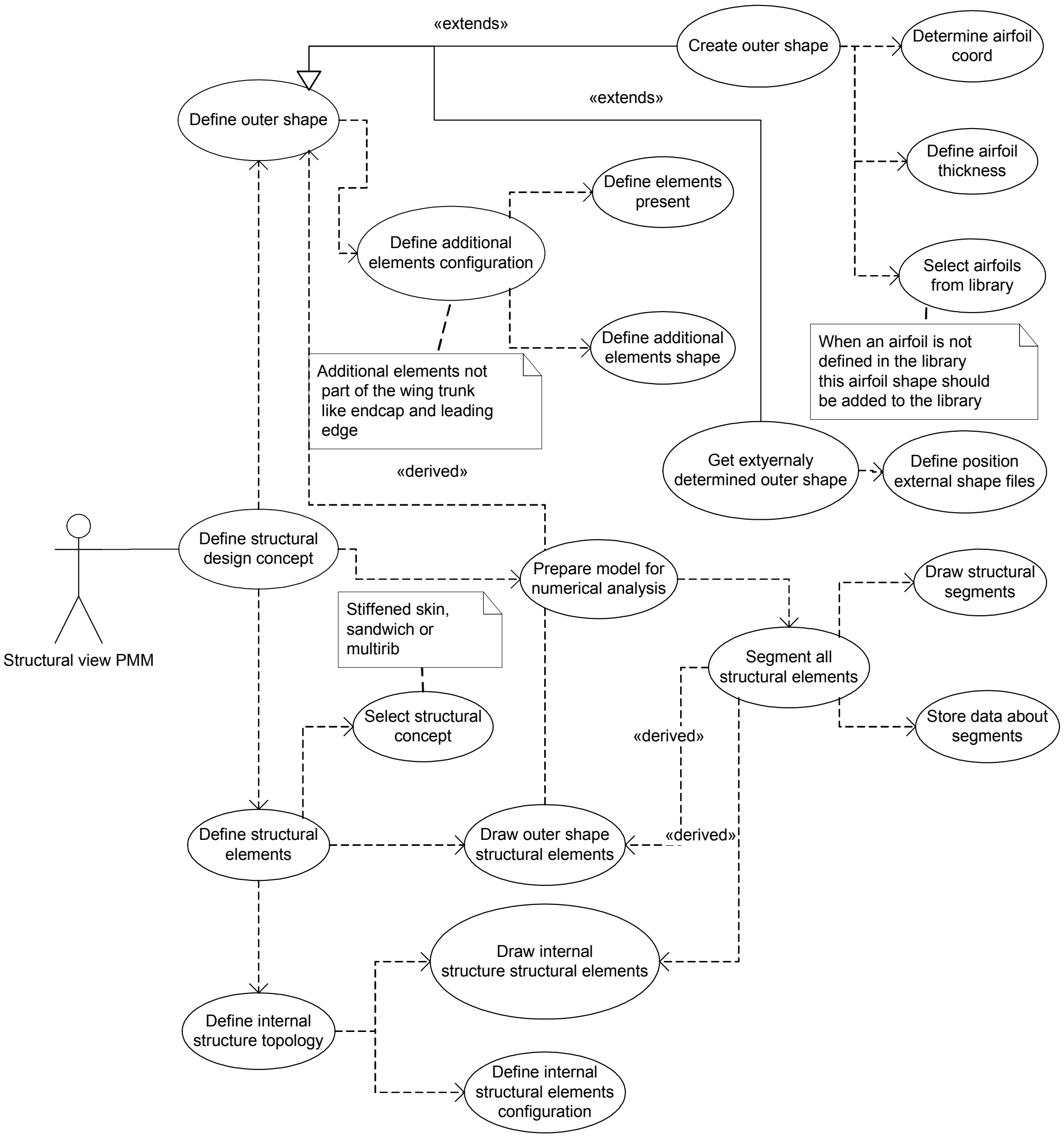


Figure 5-7 The use case diagram of creating the structural view of the PMM

5.4 Manufacturing view requirements for the PMM

Another view generated by the PMM is the manufacturing view. This view will visualize the movable manufacturing concept. This view is also used as a basis for the manufacturability analyses. For the manufacturing analysis it is important to know what the manufacturing process looks like. The first issue that has to be addressed is what parts are being used to manufacture the movable; these parts will be called manufacturable parts. These parts will in reality form the structure of the movable and can therefore be built up using the structural elements from the structural view of the PMM. The structural entities can be re-ordered to form the manufacturable parts that are used in the manufacturing analysis. Re-ordering in this case means specifying the structural elements that, when combined, form a single manufacturable part. For the manufacturing analyses additional details might also be required. These details will have to be modelled using information about the structural entities and additional inputs provided by the PMM input data set.

Different manufacturing techniques exist. These manufacturing techniques can be split into two groups: production techniques and assembly techniques. Production techniques are used to produce the parts from which the movable will be build. Assembly techniques are the techniques that are used to join the parts that will form the movable. Which manufacturing techniques will be implemented in the PMM is determined in the “Manufacturing technique definition and the manufacturing database” section of this chapter.

The structural entities that will form a manufacturable part and what method is used to manufacture them is determined in the PMM input data set. In case of the MDEE this input data set is created by the DEE user. However if the assembly method for each assembly joint would also be a separate input for the DEE user, the user could become overwhelmed by the number of inputs in case of many movable parts. Therefore smart algorithms have to be implemented based on existing manufacturing knowledge to solve this problem. These algorithms will make the manufacturing view “smart” and reduce the number of inputs the DEE user has to supply. The algorithms should be transparent and well documented however to ensure the resulting manufacturing concept is understood and not the result of rules that might no longer be valid.

Summarizing the requirements for the manufacturing view of the PMM are:

- The PMM should be able to re-order structural entities into manufacturable parts and visualize them.
- The PMM should be able to determine assembling methods for the different sub-parts and identify the different joints. The joints should also be visualized.

In Figure 5-8 the use case diagram of the manufacturing view of the PMM is presented. This diagram will be used as a guide during the implementation of the manufacturing view.

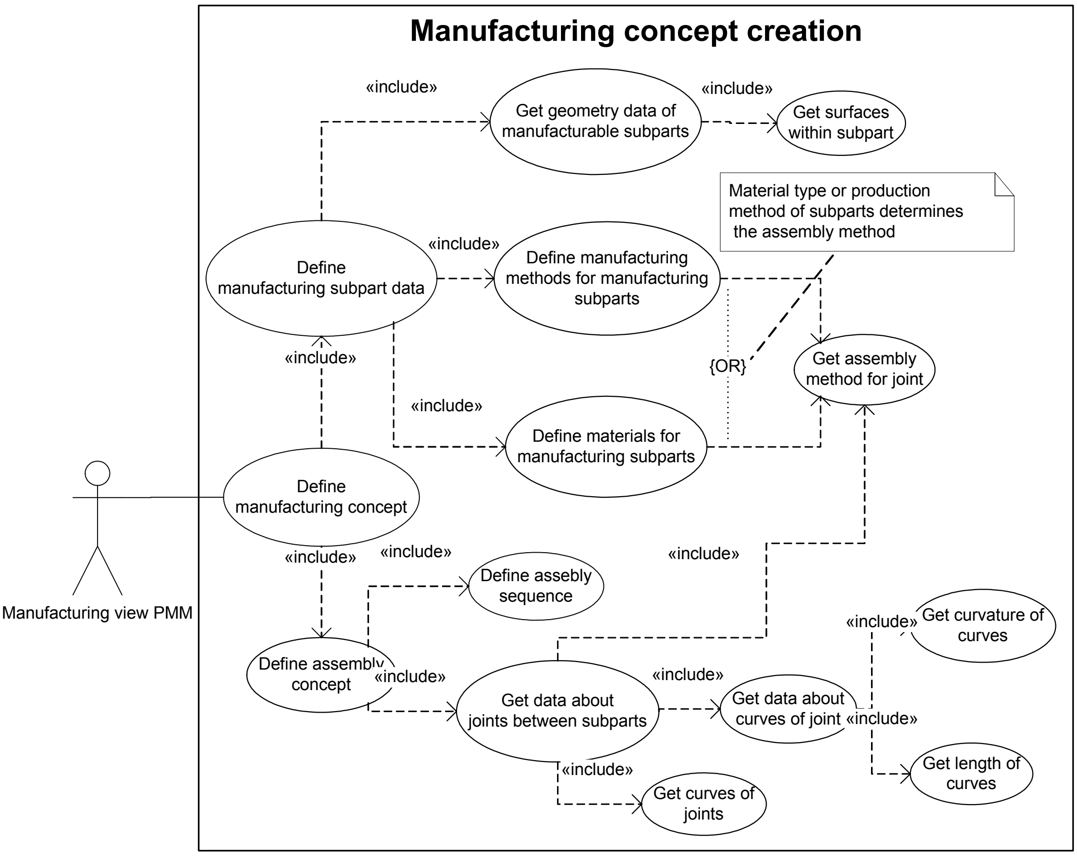


Figure 5-8 PMM manufacturing view use case

5.5 General implementation of the movable product model

For the implementation of the PMM first the structure of the PMM must be determined. This structure will be built up of HLP's and CM's. This structure can then be used for the development of the actual PMM application software using a particular KBE platform. The application on this platform stores the methods used to generate views of the movable input data set. In this chapter first the general structure of the PMM will be discussed. Secondly the software platform on which it is developed and the consequences this has are discussed. In the third section the actual implementation details are handled.

5.5.1 PMM general structure

First the HLP's that will be used to model a movable will have to be determined. These HLP's will have to be able to create a representation of a movable which can be used to create structural and manufacturing views. In Figure 5-9 the HLP's used in the PMM are represented. In total these will be 4 different HLP's which also interact with each other. The Wing Trunk HLP will create most elements of the movable wing box. The Movable Leading Edge HLP will represent the leading edge including its underlying structure. The Hinge HLP will represent the hinges where the movable connects to the wing like entity in which it is positioned. Finally the End Cap HLP is used to generate the aerodynamic caps at the top and bottom of the movable.

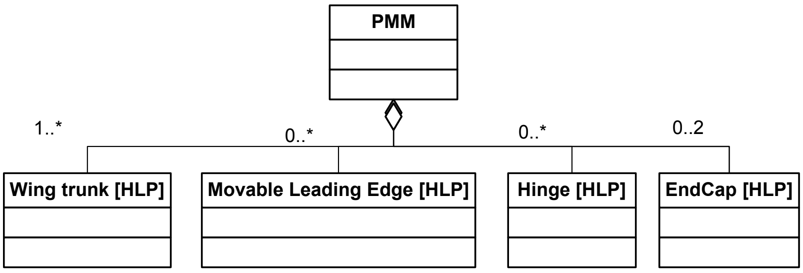


Figure 5-9 High Level primitives used in the PMM

The Wing Trunk HLP in the PMM is an adjusted version of a HLP developed for a Blended Wing Body Multi Model Generator described in La Rocca (2002). Using this already developed structure and code for a wing trunk reduces the amount of work needed for the PMM development, while enhancing the compatibility of the PMM to higher level DEE's that use wing trunk elements. These DEE's can provide outer mould line surfaces which are used by the PMM.

The HLP's used for the PMM will be interwoven, meaning that HLP's have dependencies between each other. To show these dependencies and also to show the HLP details Figure 5-9 can be further expanded. When this detailed representation uses a standard representation language like UML it can also serve as a basis for software development of the PMM. In this case the elements that are graphically represented can the translated one-on-one to objects in the software. A graphical UML representation of the PMM with all the shape features and structural elements implemented can be seen in Figure 5-10. In this diagram the in and outputs of all the elements and the methods contained in these elements are also represented. An added benefit of the graphical UML representation of the PMM is that it is not software dependent. This means that if during the development process the KBE platform changes the represented structure can still be used as a basis for the development of the application on a different platform. This also means that the migrating process of an already developed application from one KBE platform to another is simplified by using an UML diagram that represents the structure of the application.

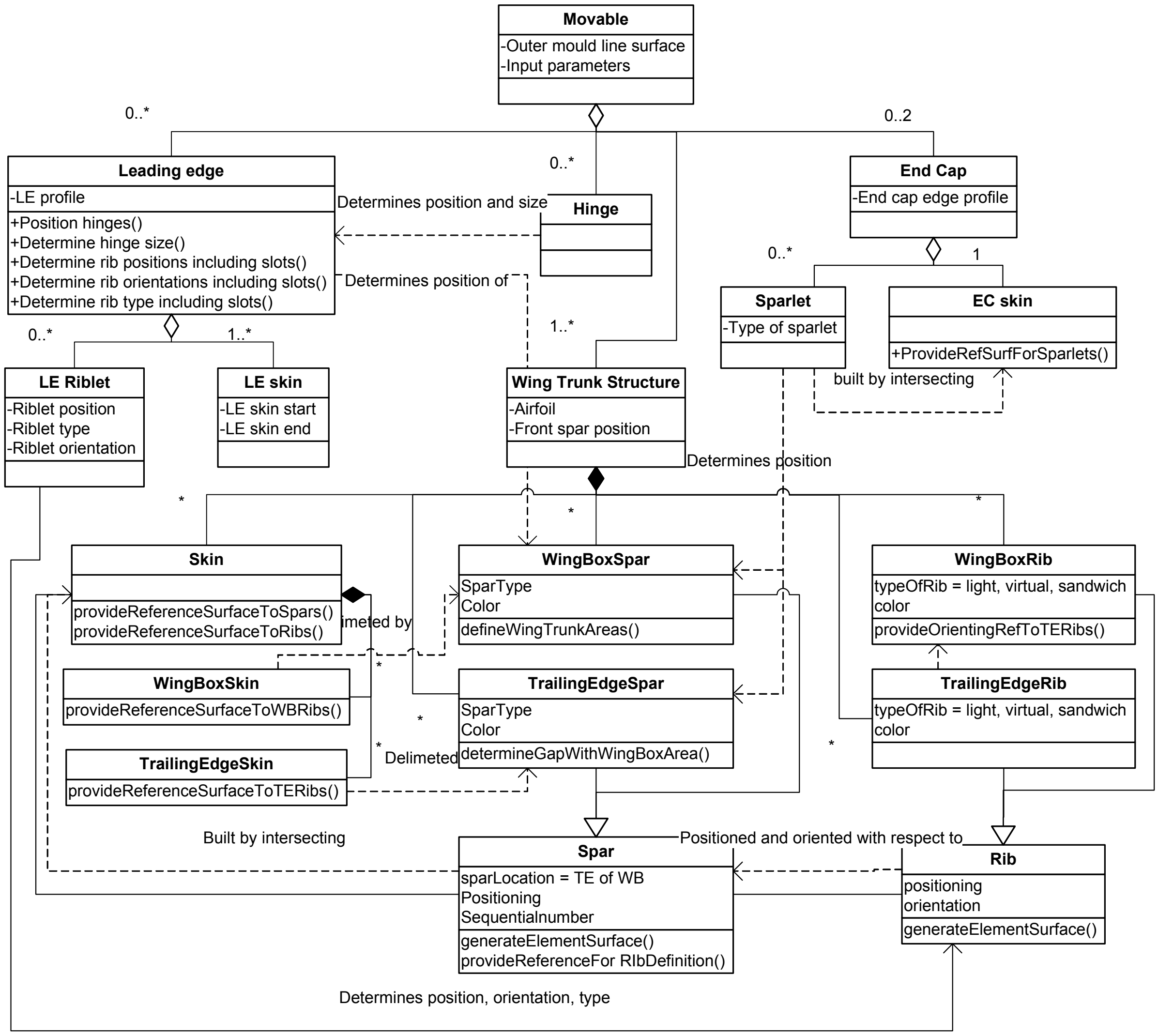


Figure 5-10 PMM structure including shape and structural elements

As can be seen in Figure 5-10 the input for the movable consists, besides the input parameters that will be discussed later on, of an outer mould line surface. As was discussed in the requirements this outer mould line surface can be determined in two manners. Firstly an external surface can be used. In this case the external surface is part of the input data set supplied to the PMM. In addition to this external surface the connection or hinge points with accompanying parameters should also be part of the input data set. This ensures that the structure generated in the movable fits the connection points and therefore the structure in the wing like element in to which trailing edge movable is connected.

The other option for creating an outer mould line surface is to create it from scratch. In this case the input data set should contain inputs defining the airfoils used to create an outer mould line surface. These inputs can be used to create airfoil curves. Through these curves a surface is lofted that will form the outer mould line surface. The connection or hinge points are determined in this case by selecting certain options in the inputs for the structural elements. A diagram representing the process of generating the outer mould line surface can be seen in Figure 5-11.

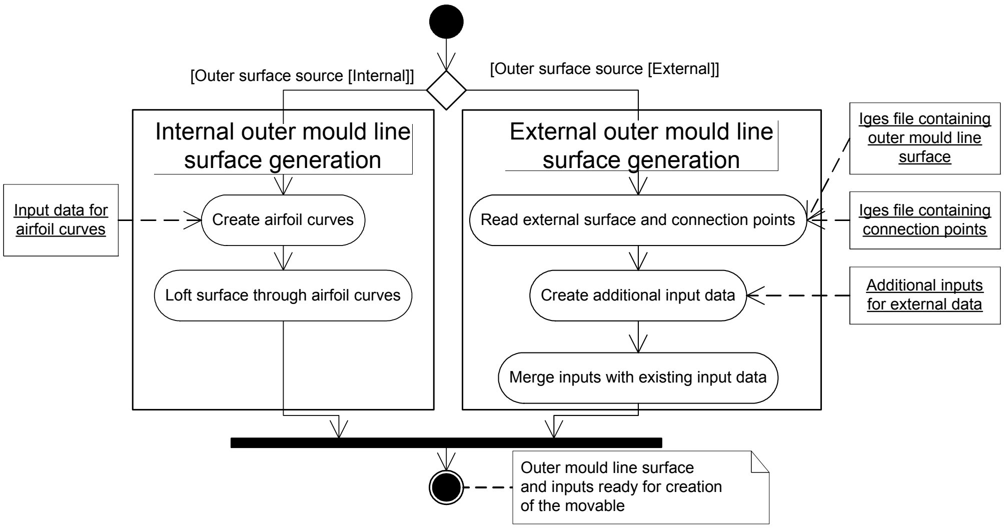


Figure 5-11 Outer mould line surface generation activity diagram

5.5.2 PMM Development platform

It is important for the development platform to provide a robust basis for the development of the PMM. The development platform should provide geometric modelling possibilities but also provide the possibility for the implementation of smart algorithms. Furthermore the platform should have the possibility to work independently without user interaction. In chapter 4 several KBE platforms were identified. Of these platforms ICAD fits the above stated requirements. Furthermore modelling engines have already been developed for other higher level entities such as complete aircraft using this KBE platform (La Rocca, 2002). Therefore ICAD software was chosen as the platform on which the PMM will be implemented.

The ICAD platform uses an object oriented programming language to model the different classes in a DEE. These classes can be physical entities such as ribs and spars but can also be of a different nature. The object oriented nature of ICAD facilitates the fast implementation of the previously described PMM structure. It also ensures that only the needed classes will be active in any instantiation of the PMM. This means that when a structural view is requested, only the entities for the structural view are created. Entities only needed for the manufacturing view will not be instantiated. ICAD also has the capability of generating output in the form of different file types. This output capability is needed in the MDEE to transfer data from the PMM to the analysis tools. Output tools that are available in ICAD are, for instance, geometry output in the form of IGES or STEP files. Another output tool available is the text writer that can be used to write ASCII text files containing data for the different analysis tools.

5.5.3 PMM general implementation details

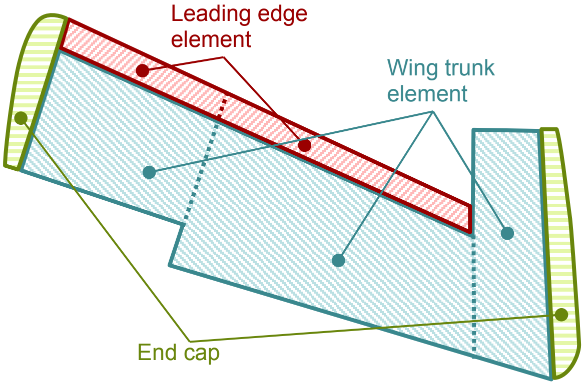


Figure 5-12 PMM elements

The basis of the PMM is and adjusted version of the Wing Trunk HLP developed by La Rocca (2002). Of this entity the definition of the wing box is used. The wing box in this case consists of skins, ribs and spars. These elements can lie in the leading edge, main wing box or trailing edge. In case of the PMM only the main wing box and trailing edge are used. The leading edge is discarded and replaced by a new, specialized, leading edge. This new leading edge is a separate HLP. Discarding the original leading edge however does not mean that is removed from the HLP, it is only switched of. This ensures that the wing trunk is only extended and that the adjusted Wing Trunk HLP can also be used in its original applications. The movable generated by the PMM will use multiple instantiations of the wing trunk, in this way the requirements for discontinuities and cut outs will be met. Finally end cap HLP’s will be added to satisfy the shape requirements. The wing trunk elements, leading edges and end caps can be seen in Figure 5-12.

Internal outer mould line surface definition

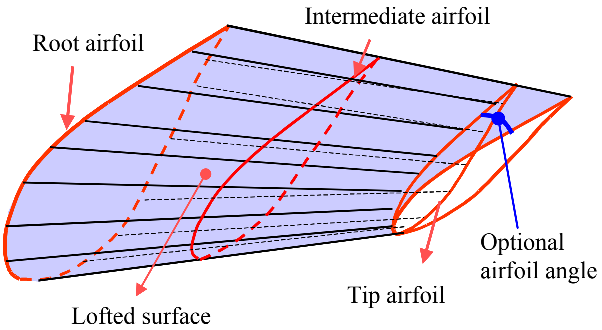


Figure 5-13 Outer mould line surface definition

Part of the original Wing Trunk HLP is an outer surface definition. This definition is used in an adjusted form in the PMM. As was discussed before when the outer mould line surface is created by the PMM itself it uses airfoil curves. These airfoil curves are based on parameters in the input data set. These parameters in fact specify airfoil types, the points of which are read from a library. Through these points a curve is fitted, which will form the airfoil. Additional input parameters are incorporated to adjust the shape of each airfoil curve. They can for instance be used to scale the thickness of the airfoil. In each outer mould line surface multiple airfoils can exist, though a minimum of 2 is required. A schematic example of an outer mould line surface created using these airfoils can be seen in Figure 5-13.

Multiple outer mould line surfaces can exist in the PMM as each of the instantiations of the wing box structure requires another outer mould line surface. Options for the input parameters have been added to guarantee the transitions between the different outer mould line surfaces is smooth when required. This for instance means that in case of two wing trunk instantiations, the middle cord length where the two wing trunks are connected is determined based on the outer tip and root cord lengths. The determined middle cord length ensures that leading edge line and trailing edge line are smooth. To enable root and tip airfoils to be put at an angles the original wing trunk HLP has been adjusted. The angles themselves are defined by input parameters in the PMM input data set.

External outer mould line definition

When the outer mould line surface is determined externally, three geometrical elements are needed. Firstly the outer mould line surfaces itself. This element is delivered to the PMM in the form of an IGES file containing the surface. Second element is the hinge line. This line determines where the movable will hinge with respect to the wing like entity in which it is positioned. The hinge line is also delivered to the PMM in the form of an IGES file. Final geometrical elements are the connection or hinge points. These are points that lie on the hinge line where the movable will be connected to the wing like element. These points are also delivered to the PMM in a separate IGES file.

Besides the geometrical elements also additional inputs are needed for the use of the external data. First essential input is the wing trunk number in which a movable should fit. This input is needed when the IGES files are delivered by a higher level DEE. In this case it is possible that the IGES files contain multiple surfaces for instance of outer and inner wing. When this is the case the PMM user should specify in which wing trunk to fit the movable. Other inputs include inputs about the connection points. The PMM automatically positions ribs to provide support for these connection points. The additional inputs determine the configuration of these ribs. The inputs for the connection ribs are blended with the “regular” wing trunk inputs to ensure that the input data set for the PMM remains consistent.

Wing trunk HLP structural elements

The wing trunk HLP structural elements consist of spars and ribs that will be positioned inside the outer mould line surface defined earlier. Ribs and spars have been defined in such a way that they always fall within the outer mould line surface. In this way a proper definition of the wing trunk structure and therefore of the movable structure can be guaranteed. Position, function and other characteristics of the spars and ribs are determined by input parameters in the input data set. The implemented input parameters are flexible. Meaning the positioning can be defined in several different ways. The differences lie in the way references are used. For example in some cases it can be helpful to use absolute positioning, meaning actual measures to position a rib or spar. In other cases relative position, so positioning length relative to the length of another spar or rib, is more convenient. By allowing several options the PMM is flexible and able to meet differentiated needs of different PMM users. Because several input parameters exist for each rib and spar it is important to keep the inputs consistent, this means for example that each rib should have a positioning and an orientation input. Keeping the input parameters consistent can be challenging because the inputs are fed to the PMM in the form of list of parameters, each entry in the list representing a different spar or rib. A part of an input file for the PMM can be seen in Figure 5-14 and Figure 5-15. Shown in this figure are the inputs for the movable spars and part of the inputs for the ribs. In Appendix A all the inputs for the PMM are described.

```
:type-of-spar-wb-ns               (list(list 'h     'r    'v  )(list 'r    'v  ))
:spar-position-list-root-wb-ns    (list(list 0.24   0.69  0.93)(list 0.69  0.93))
:spar-position-list-tip-wb-ns     (list(list 0.31   0.69  0.93)(list 0.69  0.93))
:cap-sparlet?-wb-ns               (list(list 't     nil   nil )(list nil   nil ))
:production-group-spars-wb-ns     (list(list 6      7     nil )(list 7     nil ))
```

Figure 5-14 Main box spar inputs for the PMM

```
:type-of-rib-ns                   (list(list 'r )(list 'h    'r     'h   'r    'h  ))
:rib-positioning-referred-to-spar-ns (list(list 0  )(list 0     0      0    0     0   ))
:rib-orienting-referred-to-spar-ns (list(list 'te)(list 0     0      0    0     0   ))
:rib-positioning-offset-list-ns   (list(list 0.3)(list 0.05  0.27   0.5  0.72  0.95))
:rib-orienting-angles-list-ns     (list(list 0.1)(list 90    90     90   90    70  ))
```

Figure 5-15 Part of the main box rib inputs for the PMM

One of the inputs for the spars and ribs defines the function of the spar or rib. Defining a function can be used to indicate that a spar or rib is not a real physical entity but used as a help entity in the model. In this case the structural function of the spar or rib will be indicated as virtual. This means the physical representation of the spar or rib will not be collected for structural or manufacturing analyses. Virtual entities are used purely as help entities to solve or avoid problems in the model. In the structural view the virtual elements are distinguished by using a different colour, in the manufacturing view they are not present.

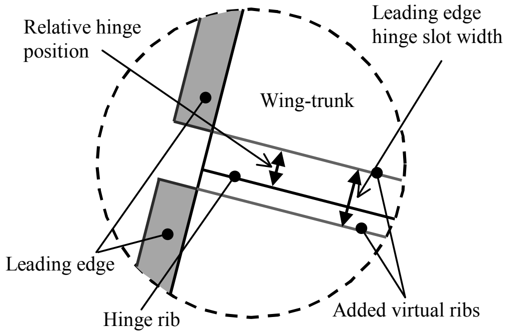


Figure 5-16 Leading edge slots lay-out

The function of a spar or rib can also be used to trigger actions in the PMM. For instance once the PMM detects a hinge rib, a routine contained in the movable leading edge HLP automatically generates a slot in the leading edge. This slot is essentially a hole in the leading edge in which a hinge can be placed. An example of a leading edge slot can be seen in Figure 5-16. Additional input parameters determine the position and size of the slot. The PMM also adds a virtual rib on each side of the hinge rib. These virtual ribs are needed to ensure that the movable is properly segmented when the output for the structural analysis is generated. Segmentation in this case means cutting up all the structural elements into smaller surfaces that, when used in structural numeric analysis software, form a proper structural model. The details of the segmentation process are discussed in chapter eight.

Input parameters can also have “smart” options. For example entries in the input parameters defining the positioning and orientation of a rib can be “root” or “tip”. This indicated that the rib should lie in the root or tip of the movable. Another option is to lay the rib in the flight direction. These and the other “smart” options discussed above are implementations of the knowledge acquired from designers regularly involved in aircraft component design. Formalizing and applying the existing design knowledge makes the PMM more useful and increases the status of the PMM from “just another modelling tool” to a smart and useful design tool.

The original wing trunk consisted of 3 elements: the leading edge, the wing box and the trailing edge. In case of the PMM the leading edge is replaced by a newly defined leading edge that is discussed in the next paragraph. In the original Wing Trunk HLP leading edge, wing box and trailing edge are separated in the “cord-wise”. Therefore each element has a separate set of spars defined by separate input parameters. This separation expands the definition possibilities such as gaps between them. This can however result in problems in the connections between the different elements if the input options are not handled carefully. For instance to guarantee the connection between wing-box and trailing edge the last or rear wing box spar should have the same position as the first or front trailing edge spar. When both these spars would be defined “real” there would be a problems because the 2 spars would overlap, therefore one of the spars should be labelled “virtual” ensuring that it is not taken into consideration when creating the structural analysis models. The original Wing Trunk HLP lay out can be seen in Figure 5-9. The leading edge from the original wing trunk HLP is discarded and a new leading edge is attached.

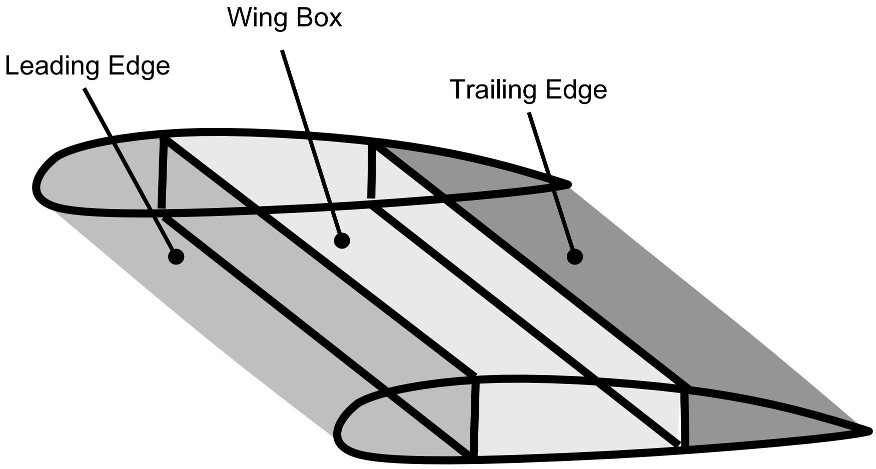


Figure 5-17 Lay-out of the original Wing Trunk HLP

Movable Leading Edge HLP

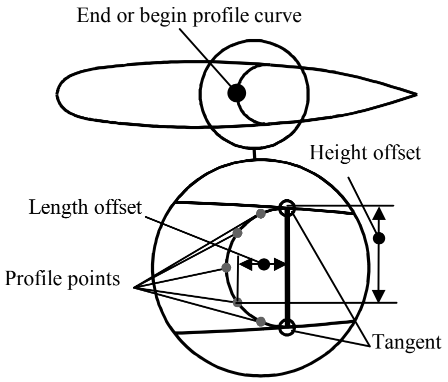


Figure 5-18 Leading-edge profile lay-out

The Movable Leading Edge HLP is a collection of surfaces that are added in front of the front or first spar of the wing box. The surfaces ensure good aerodynamic properties and can also be used to enclose mass balance elements that are located in front of the front wing box spar. The collection of surfaces that make up the leading edge are based on one mother surface. The mother surface is generated by lofting a surface through two curves at the end and beginning of the relevant section. The curves for the mother surface are built by lofting a curve through points. The position of these points is determined in the input data set which is controlled by the PMM user. The profile point’s offset is always related to the upper point of the spar to which the leading edge is connected. Offset lengths are normalized with the height of this spar. This for instance means that if a point is defined at a length position of “1.0” and a height position of “0.0”, the point lies on the same height of upper point of the spar and, in absolute terms, length wise lies the value of the spar height in front of the front spar. During the surface loft the upper and lower spar curves of the front wing box spar are used as guide curves to ensure a good connection to the wing box. The definition of the points and curves can be seen in Figure 5-18.

The number of different leading edge surfaces is dependent on the number of hinges. At each hinge there is an opening to accommodate the hinge. This opening is cut from the mother surface resulting in several smaller surfaces. Finally nose ribs are added to the leading edge. These are basically extensions of the ribs in the wing trunk. However input parameters are available to control whether or not they should be created and whether or not they should have an angle to the relevant rib in the wing trunk. A nose rib can also be added without adding a rib; this is done by specifying the relevant rib to be "virtual". When a hinge rib is detected and a nose rib is specified, a nose rib is created on each side of the hinge slot. An example of a movable leading edge with a hinge slot and several nose ribs can be seen in Figure 5-19.

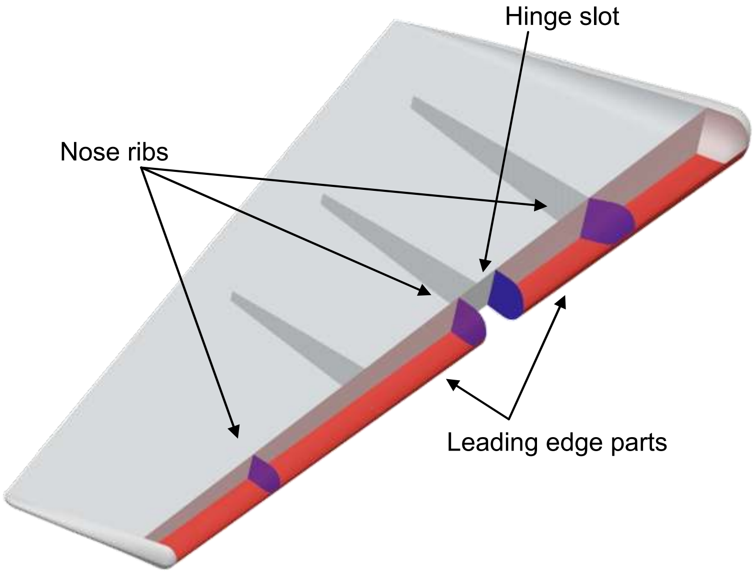


Figure 5-19 Movable with leading edge segments, nose ribs and hinge slot

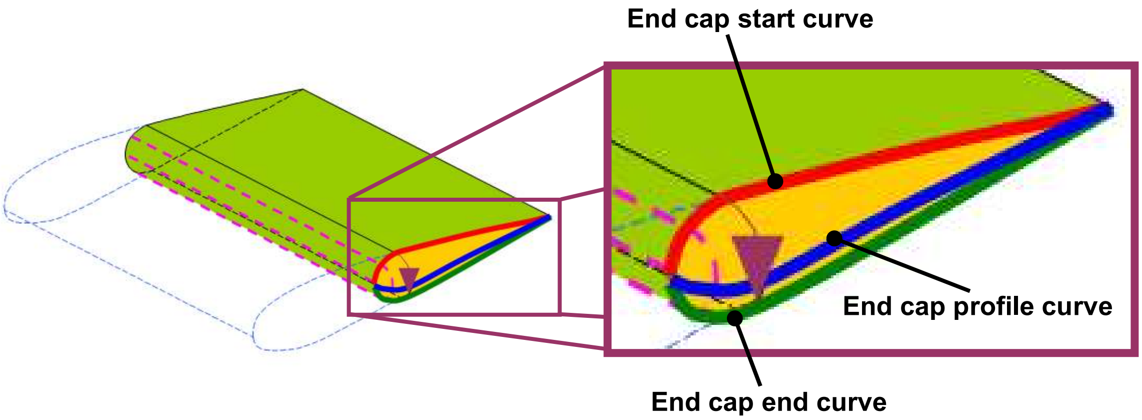


Figure 5-20 End cap definition

End Cap HLP

The End Cap HLP's can be added to the tips of the movable. The end-caps consist of a surface that ensures the aerodynamic properties and optional extensions of the spars that exist in the wing trunks. For the creation of the end cap first two curves are created at the lower and upper part of the movable to which the end cap is connected. These curves will be called the end cap start and end curves. They are build-up by merging curves from the wing trunk and leading edge into one. Another curve is created at the tip of the end cap. This curve will be called the end cap profile curve. It is based on a profile that is stored in a library and is called through a parameter in the input data set. The end cap is created by lofting a surface through the 3 curves in the sequence: end cap start curve, end cap profile curve, end cap end curve. This lofting is influenced by 3 control surfaces that determine tangency of the end cap to the wing box and direction of the end cap at the end profile. Finally extensions of the spars can be created; these extend from the spar to the end cap skin. The spar extensions are optional, whether or not to create them is determined in the input data set. An example of an end cap and the definition of the curves needed to create the end cap can be seen in Figure 5-20.

5.6 Structural view implementation in the movable product model

Now the parametric model of the movable has been defined using HLP this parametric model has to be interpreted in such a way that the structural view on a moveable can be created. The generated parametric model already fulfils most of the requirements for the structural view. Using the elements of the PMM HLP's many structures can be represented. The spars and ribs are used in all structural concepts. However to represent all the required structural concepts some additions are needed. An important addition is the possibility to award material properties, thicknesses and orientations to the structural elements. This is achieved by expanding the input data set and interpreting this dataset in a proper way. This interpretation is not implemented in the HLP's themselves by added CM's. The implementation details of how a material type and thickness is awarded to a structural element can be found in chapter eight.

In this section first the different structural concepts stated in the structural requirements section will be discussed. Final issue that is discussed will be the visualization options that have been implemented to improve the transparency of the PMM.

Stiffened skin

The stiffened skin structural option is modelled largely by using elements in the PMM. However there is one element missing in this definition. This is a stiffener that can be attached to the upper and or lower skin. Because these stiffeners are often encountered in the movable design environment, it is essential to generate them as they have a big influence on the structural performance. To account for this structural option the wing trunk HLP needs to be extended to also have the possibility to model a stiffener.

In order to add these elements to the wing trunk HLP it is essential to know what information about the stiffeners are required by the structural analysis and will therefore be collected by the structural analysis data collector. The structural analysis tools that will be used in the MDEE will accept a simplified representation of the stiffener. The actual stiffener geometry, for example height and width, does not have to be modelled in detail. Instead it is important to specify the location of the stiffener and the essential structural characteristics such as stiffener area. These structural characteristics can be handled by an extension of the movable input data set and therefore be left out of the modelling part of the PMM. Because usually only longitudinal stiffeners are used, the positioning of the stiffeners is analogous to the positioning of spars. Therefore the stiffeners can be defined in the input dataset as spars with a special function. Using these functional inputs, spars are defined as being stiffeners on the upper, lower or on both skins. Representation in the wing trunk HLP is also the same as the spars, with the addition of stringer curves. These are curves at the edges of the spar surfaces. When the data is extracted for the structural analysis tools only these curves will be used, the spar webs associated with them will be discarded. In this case the stiffeners can be used in the structural analysis models. With the implementation of stiffeners all elements for the stiffened skin structural concept have been defined and it can be used effectively in the PMM.

Sandwich panels

To implement the sandwich panel structural option in the PMM, the sandwich panels have to be identified and the geometric representation of the panel has to be defined. This will result in certain surfaces that will form the sandwich panels. Because the structural analysis in the MDEE does not require an actual solid model of the sandwich panels, the surfaces defined in the PMM can be used. The sandwich characteristics can then be awarded to these surfaces in the structural analyses tools using the CM's handling the material properties and the input dataset.

In movables sandwich panels occur in different ways, although they can mostly be found in the skin panels of the movable. Therefore the sandwich panel implementation was applied to these skin panels. However the principles behind the sandwich panel implementation can be used for all surfaces, and can be applied to these surfaces, this will however require some extra development effort.

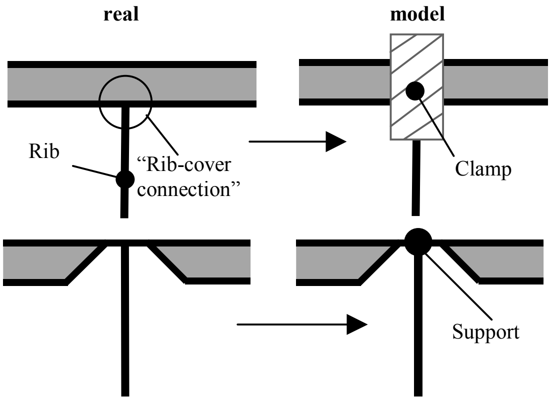


Figure 5-21 Different sandwich skin-rib connection options, real and how they should be modelled

One option to define the sandwich panels in the movable model is to give all surfaces representing the skin a sandwich panel layout. This can be done by adjusting an input parameter that determines the material properties of these surfaces. This will result in a "rib-skin connection" as represented in the upper part of Figure 5-21. For certain constructions this definition suffices. However in converting the movable model to a structural analysis model this definition of the "rib-cover connection" will result in a clamped rib-skin connection. For certain structural options this is not a realistic representation and can distort the results from the structural analysis. The constructions shown in the lower part of Figure 5-21 must be modelled in the structural analysis model with a simply supported joint between cover and spar/rib. In the PMM this is made possible by splitting the skin surfaces into sandwich and non-sandwich.

For splitting the surfaces in sandwich and non-sandwich elements a CM has been developed and the Wing Trunk HLP has been expanded. The Wing trunk HLP has been expanded in such a way that it is possible to award ribs and spars the “sandwich” function. In this case a rib or spar is considered virtual and defines the boundary of a sandwich panel. The CM developed uses these ribs and spars and collects the surfaces within these boundaries. This group of surfaces can be given the sandwich material properties by adjusting the right input parameter. In Figure 5-22 a schematic model including the sandwich spars and ribs can be seen. In the figure the intersection points of sandwich ribs and sandwich spars are indicated by a dot. To determine if a surface belongs to the sandwich panel group, all four corners of the surfaces are compared, automatically in the CM, with a list of all intersection points of sandwich ribs and spars. When all 4 corners of the panel coincide with an intersection point the panel is marked as a sandwich panel and collected and exported as such by the structural analysis data collector.

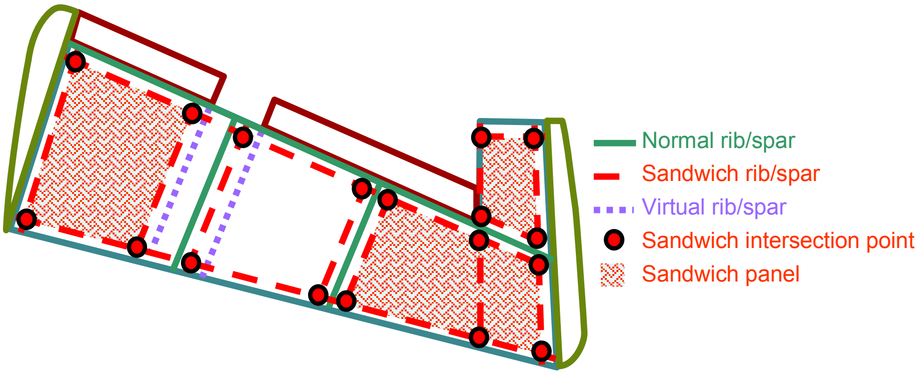


Figure 5-22 Sandwich panel determination

Multi-rib

The multi rib structural option can be generated using the standard definition of spars and ribs from the Wing Trunk HLP. In the input parameter set for the PMM the functionality and properties of the different ribs are be determined.

Structure visualization

Visualization on the KBE platform, in this case ICAD, of the structure view is achieved by awarding different colours to the different elements. This option of awarding colours to all the structural elements is implemented for all the HLP’s used in the PMM. For example upper and lower skin panels of the wing box have different colours, which are also differ from the colours of the trailing edge skin panels. By using different colours the different surface groups can be easily identified. For several structural entities its colour identifies the structural function of the entity. For instance a “hinge” rib has a different colour than a “light” rib. Using colours to identify the different entities in the PMM and their functionalities improves the transparentness of the PMM and allows the user to quickly asses the changes he or she makes to the input parameters. Examples of the structural view of the movable can be seen in the Product model examples section of this chapter.

5.7 Manufacturing view implementation in the movable product model

The implementation of the manufacturing option in the PMM requires a completely different interpretation of the input data set describing the movable design concept. In this view the entities that form the movable will be re-ordered so they form a manufacturing concept. This requires besides the extension of the input data set, the implementation of CM's capturing the knowledge and algorithms needed to generate a manufacturing concept. The manufacturing view itself can be considered a High Level Primitive as it is a model of a generic manufacturable part. How the different CM and the HPL fit in the PMM can be seen in Figure 5-23. As can be seen in this figure it also includes a CM for segmenting the PMM for structural analysis. This CM will be discussed in chapter 8. However the result form this CM is that all structural elements are cut into surface segments at all the element intersections.

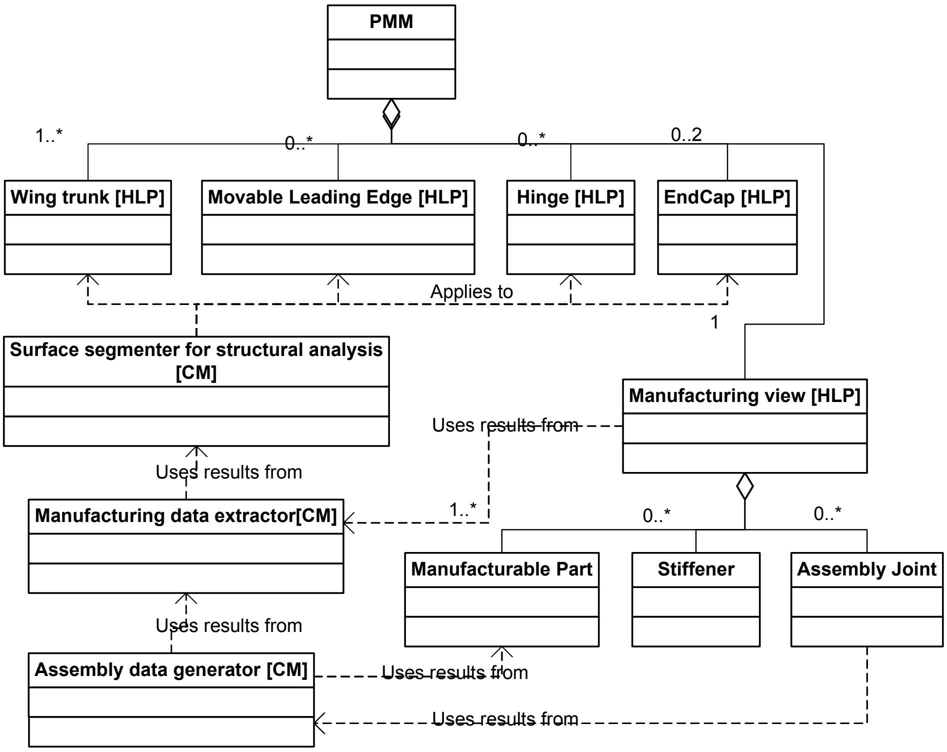


Figure 5-23 Overview of the HLP's and CM's in the PMM including the manufacturing view

5.7.1 Manufacturing concept definition

Generating a manufacturing view essentially consists of two steps the first one is the determination of the production groups or manufacturable parts. These manufacturable parts are collections of entities that in production will form one sub-part. Second step in generating a manufacturing view is the definition of the assembly joints or connections between the manufacturable parts. The structural view is taken as a starting point for both steps. This means that when a manufacturing view is created all the HLP's and

CM's used in the structural view will automatically also be used. A schematic overview of the manufacturing concept generation process can be seen Figure 5-24.

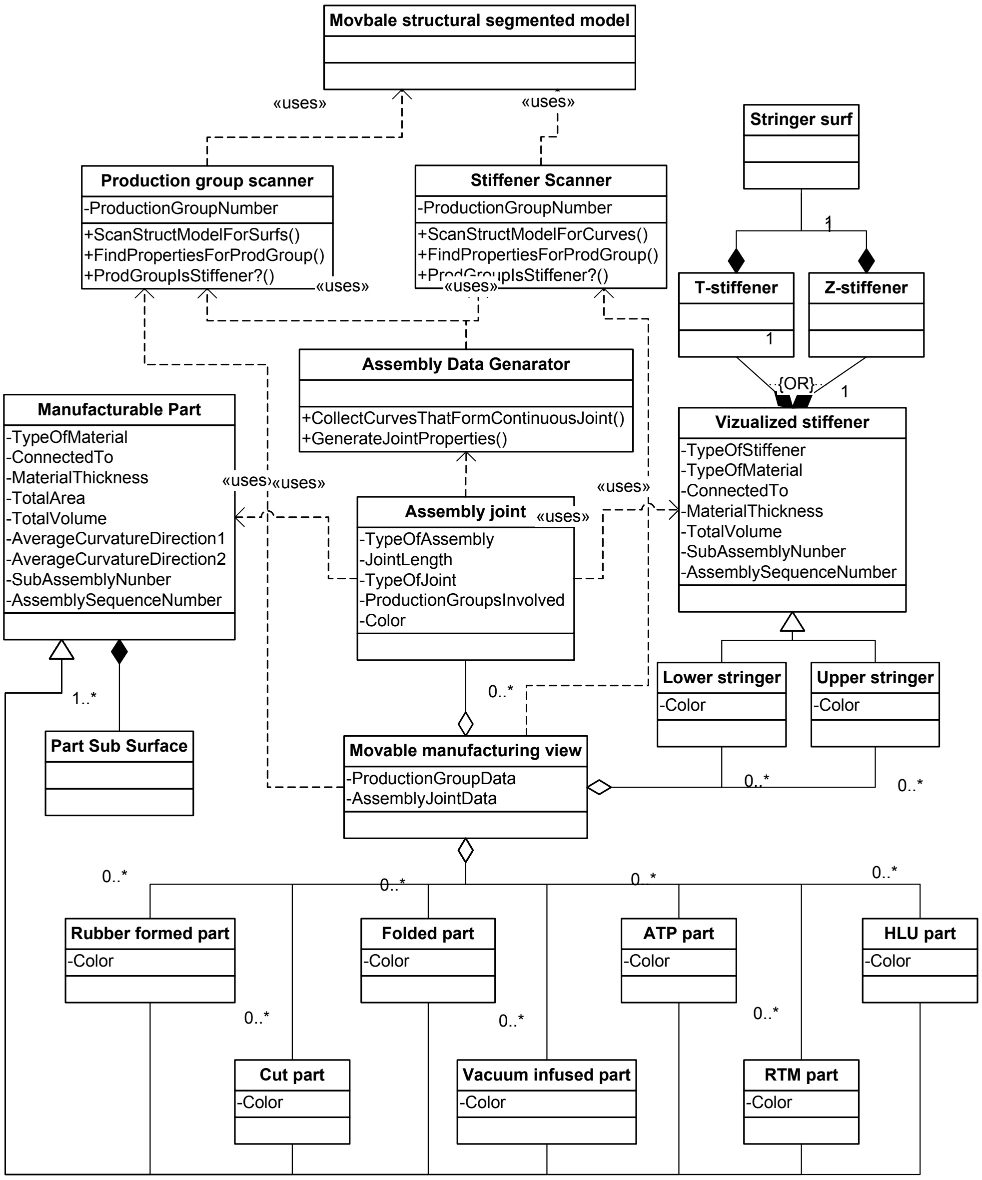


Figure 5-24 Schematic overview of the manufacturing view based on the segmented movable model

For generating a manufacturing view so called scanner classes, which are part of the manufacturing data extractor CM, scan the segmented model to extract relevant data. In addition inputs contained in the PMM input set are used. For the scanner classes to operate properly the HLP's used in the structural view are extended. This extension entails adding an identification parameter to all the structural entities. This parameter identifies the manufacturable part to which an entity belongs. This identification parameter is inherited by the surface segments created by the surface segmenter CM.

With the extended HLP's the "production group scanner", which is part of the Manufacturing Data Extractor CM, shown in Figure 5-24 checks all segments and collects the ones with corresponding production group numbers. This results in several groups of segments that each will form one manufacturable part. In Figure 5-25 an activity diagram visualizing the operations in the production group scanner is shown. Information and data from the scanners is eventually used to generate the manufacturing view.

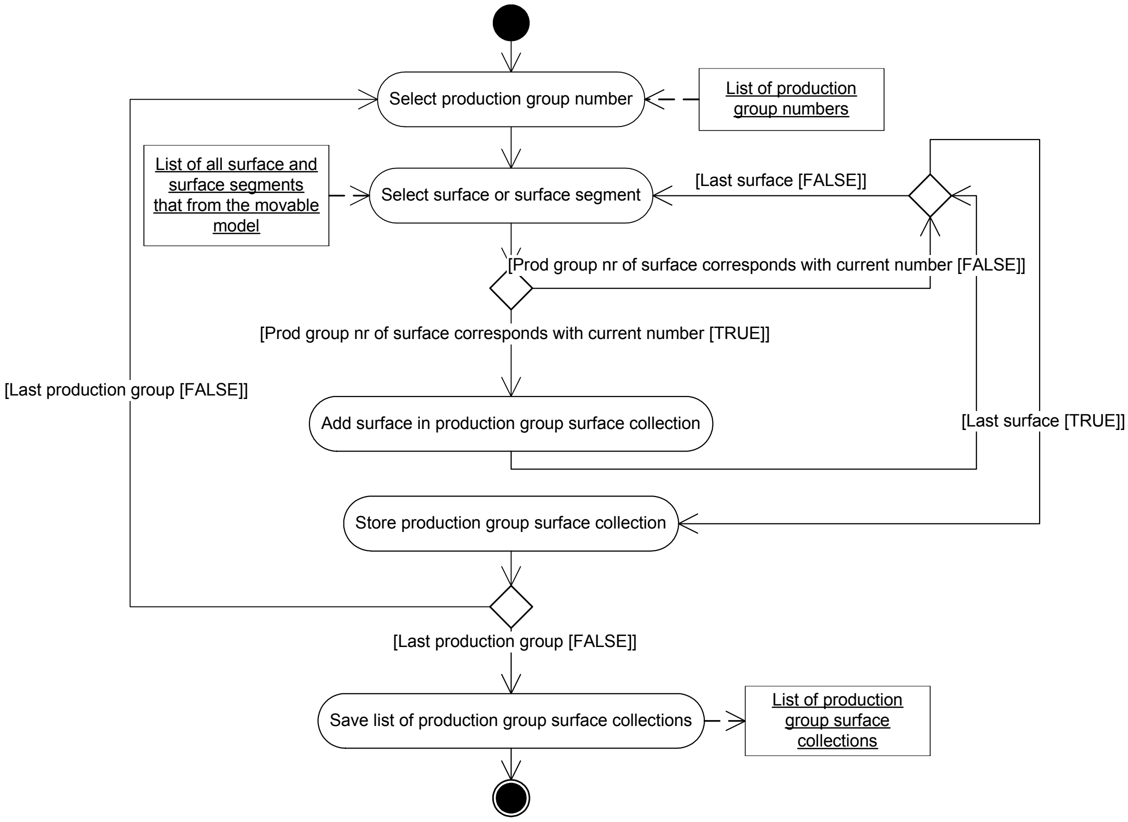


Figure 5-25 Activity diagram showing the operations executed by the production group scanner

Structural entity transformation into manufacturable parts

As was stated before the structural HLP’s have been extended with an identification parameter identifying the manufacturable part for each structural entity in the HLP. This identification parameter is used as a way to integrate certain structural entities in the manufacturable parts. For instance the skin of the main wing box and the trailing edge are commonly produced as one panel. Using the “production group” parameter facilitates this integration by specifying the same production group number for both structural entities. This principle can be used throughout the movable to integrate structural entities. In this way the amount of part integration can be addressed in early stages of the design process when the PMM is used.

Although the Manufacturing Data Extractor CM is ‘smart’ in scanning the movable model and grouping the surface segments, awarding the right production group number to structural entities is still a process that requires intelligence. For instance the Manufacturing Data Extractor CM will not recognize if 2 structural entities are not physically connected it simply selects them and puts them in the same production group, meaning that they will form one manufacturable part. The intelligence of making sure that the different production groups are consistent has been provided by human interaction. In future smart modules can be implemented that take over this task.

To increase the transparency of the manufacturing view the different manufacturable parts in it can be visualized using different colours. The colours are based either on the manufacturing technique used for the different manufacturable parts or on the materials the manufacturable parts are made of. Which option is used is dependents on the manufacturing view requested. Examples of the visualization of the manufacturable parts can be seen in the last section of this chapter.

Contrary to the other structural elements such as spars and ribs the geometric information about stiffeners available from the structural view of the PMM is not enough for the different manufacturing analyses. Therefore extra geometrical information has to be created. To add this extra information to the PMM input data set is extended with parameters that specify the geometric features of the different stiffeners. These features can for instance be the type of shape of the stiffener but also the geometric dimensions such as height and width. In the Manufacturing View HLP these stiffener parameters are used to generate a stiffener visualization. This visualization helps the user of the PMM to better understand the created manufacturing concept and therefore makes the manufacturing concept more transparent. An example of stiffeners visualized in the manufacturing view of the PMM can be seen in Figure 5-26.

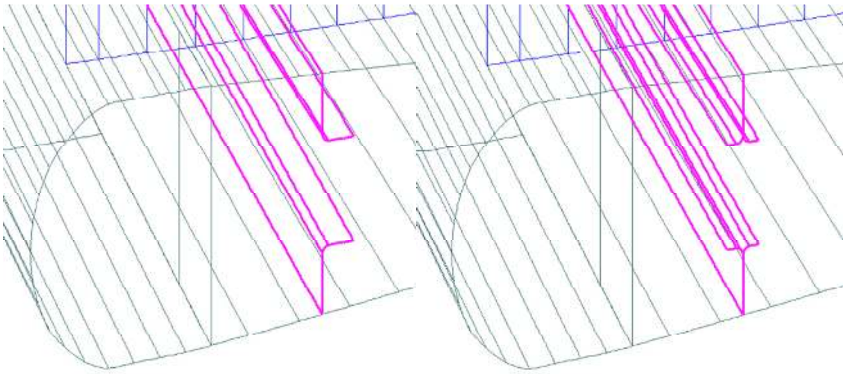


Figure 5-26 Stiffeners visualized in the manufacturing view of the PMM, Z-stiffeners on the left, T-stiffeners on the right

Many assembly methods require flanges to be added to the manufacturable parts. Adding these flanges to the structural or manufacturing views of the PMM would however make it unnecessarily complicated. Not adding them could mean that the analyses based on the manufacturing view of the movable are not accurate enough because features that add considerable manufacturing complexity to the PMM are not considered. To make it possible to consider them in the sub-sequent analyses but not complicate the PMM model any further the flanges are added to the Manufacturing View HLP in a simplified fashion. This simplified representation consists of added parameters that specified a flange on a manufacturable part. To keep the PMM simple they are not represented geometrically and only used when data is collected for subsequent analyses. The added parameters consist per manufacturable part of a flange width, a flange angle and a fill percentage.

Assembly joints definition

Contrary to the manufacturable parts the assembly joint definition is not based on parameters for each structural entity. This would become un–practical because with the increase of manufacturable parts the number of combinations requiring an assembly method definition would increase dramatically. Furthermore during the definition of the parameters for the manufacturing view it might not be clear which manufacturable parts have to be assembled. Therefore the assembly method for each joint in the manufacturing view is determined based on a preferred assembly method for a material or production method combination. In practice this means that an assembly joint scanner, which is part of Manufacturing Data Extractor CM, scans the segmented structural model and collects all assembly joints. Assembly joints in this case meaning boundaries of a manufacturable part that is shared by another manufacturable part. In this way each assembly joint gets 2 or more manufacturable parts as members. These members provide the information about production method or material and based on this information an assembly method is determined using the Assembly Data Generator CM. The whole process of determining the assembly joints can be seen in Figure 5-27.

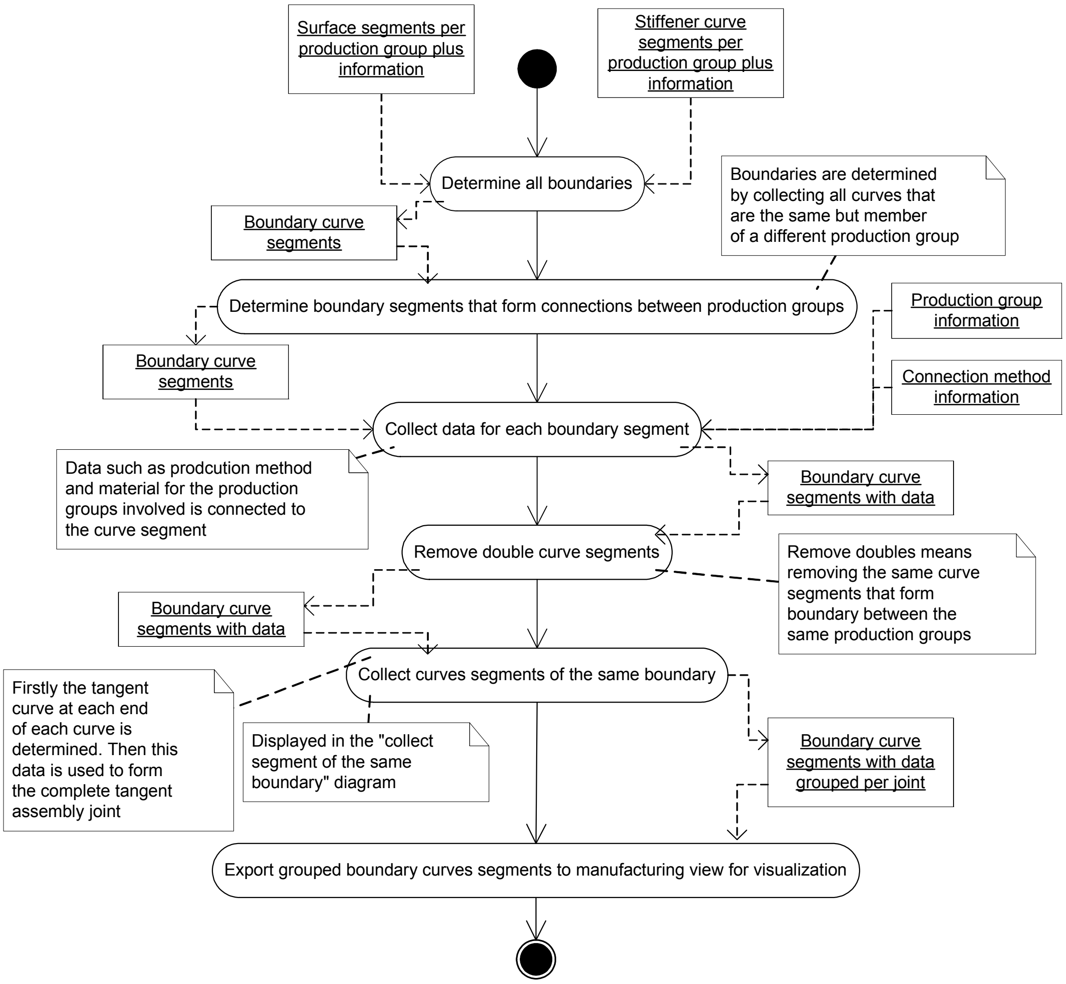


Figure 5-27 The process of determining continuous assembly joints

Because the manufacturing view uses the segmented structural model as a basis the assembly joints, when collected, consist of a collection numerous curve segments which are unsorted. This means that double curves exist in this collection and that the position of each curve in the collection is unstructured. This means that the structure of the collection of curves does not resemble the actual physical structure of the assembly joint. In other words 2 subsequent assembly joint segments in the collection do not have to be subsequent in the physical appearance of the assembly joint. However unstructured nature of the segments collection forming the assembly joint impairs the clarity and transparency of the manufacturing view. In addition analysis tools using data collected from the manufacturing view also require data about the un-segmented continuous assembly joints. Therefore an algorithm was implemented in the Assembly Data Generator CM that sorts the assembly joint segments into continuous assembly joints. This algorithm uses the principle that when 2 assembly joint segments are tangent they belong to the same continuous assembly joint. How this algorithm works can be seen in Figure 5-28.

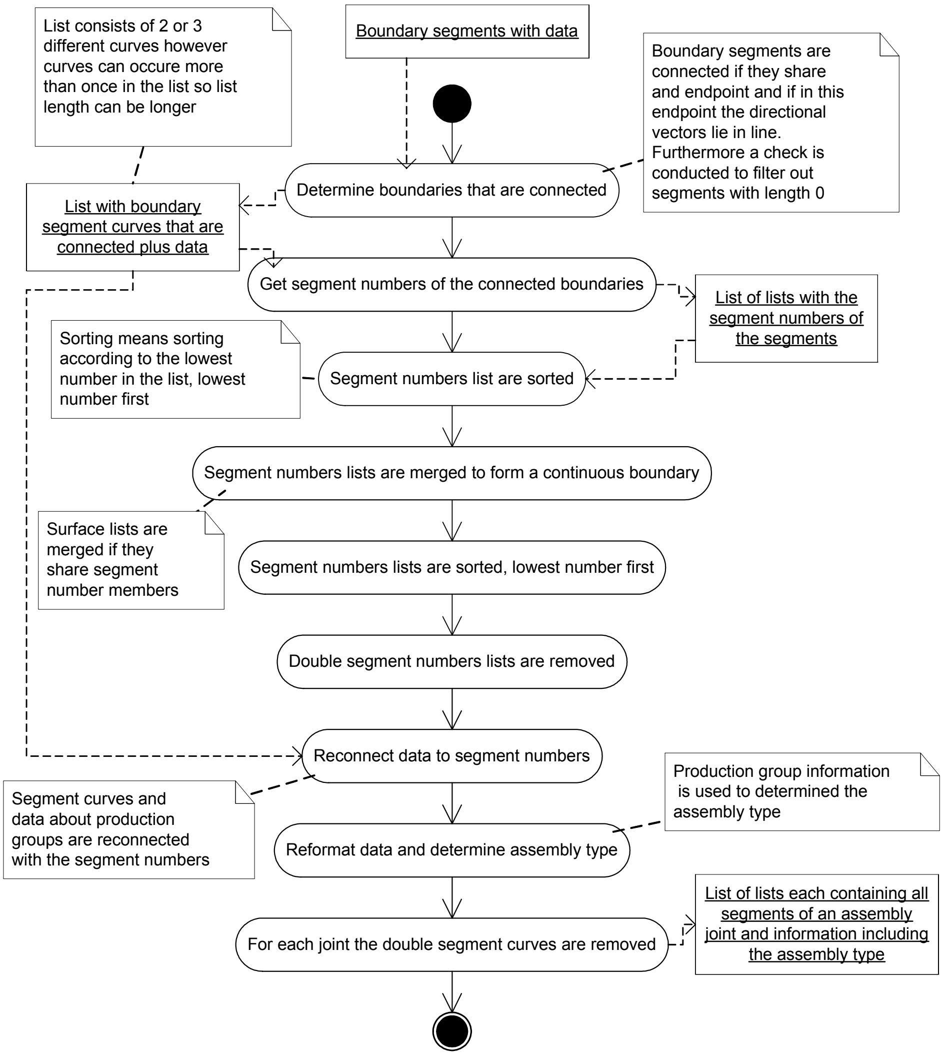


Figure 5-28 The process of collecting the segments for a continuous assembly joint

Determining the assembly method using the production method or material characteristics of the joint members requires that the system knows which production method or material combination results in which assembly method. Therefore the PMM input data set must contain parameters that determine the assembly method for each production method and material combination. Because this input parameter is usually determined by the manufacturing environment or the manufacturing engineer and not by the designer this input parameter is stored in the so called manufacturing database.

From this manufacturing database an extract is made which is added to the PMM input data set.

Visualization of the assembly joints in the manufacturing view HLP is achieved by representing the assembly joints with extra thick curves. The colour of these lines is determined by the assembly methods. Visualization of the assembly joints is extra important because they are a result of the movable model, entries in the manufacturing database and the manufacturable parts. The user of the PMM will therefore probably want to check what kind of assembly joints result from his decisions.

5.7.2 Manufacturing technique definition and the manufacturing database

For the manufacturing view of the PMM to work properly, the definition of manufacturing techniques and materials that are used in it, have to be extended and maintained. The definition of new manufacturing techniques and materials in the MDEE requires work in the manufacturability analysis tools and in the PMM. For now a limited number of production and assembly techniques have been implemented for the manufacturing view of the PMM. A list of these techniques can be found in Table 5-1.

Table 5-1 Manufacturing techniques and materials implemented in the manufacturing view of the PMM

Production techniques	Assembly techniques	Materials
Hand lay up of composite materials	Resistance welding of thermoplastic composite materials	2024 Aluminium
Automated tape laying of composite materials	Bonding	7075 aluminium
Cutting of sheet material	Mechanical fastening	Carbon fibre reinforced epoxy composite
Rubber forming of thermoplastic composite materials	Friction stir welding	Carbon fibre reinforced PEI thermoplastic composite
Resin transfer moulding of composite materials		Glass fibre reinforced PA6 thermoplastic composite
Vacuum infusion of composite materials		
Folding of thermoplastic composite materials		

Implementation of new manufacturing techniques or materials not only involves changing the PMM but also involves changing the so called manufacturing database. This database forms an important part of the manufacturability analysis tools and is described in detail in chapter 7. In the manufacturing database information is stored about the manufacturing processes that can be used to produce a movable. Information is stored in this database because it is essentially the responsibility of the manufacturing engineer and not the responsibility of the designer using the PMM. The PMM user can change the movable design and also the manufacturing concept of a movable by adjusting the PMM input data set. The manufacturing engineer can change the manufacturing environment in which the subsequent analyses are going to be performed by adjusting the manufacturing database. Changing the manufacturing environment essentially means changing the configuration of the production plant where the movable will be manufactured. Separation of the design inputs and the manufacturing environment inputs helps to keep the PMM input data set transparent. Storing the manufacturing information in a database also ensures that when an assessment between different design concepts is made the manufacturing environment remains the same and does not influence the subsequent analyses. On the other hand when a user of the MDEE wants to investigate the influence of changes to the manufacturing environment, only the manufacturing database has to be changed and the PMM input data set can remain constant. Final advantage is that the manufacturing database can be used for many model generators; it is not limited to the PMM. The PMM input data set on the other hand is unique and only fits the PMM.

The manufacturing database consists of a collection of tables, a number of which influence the operation of the manufacturing view of the PMM. The tables that influence the PMM are the tables in which the preferred assembly methods for production method combinations and material combinations are stored and the tables in which the production methods and materials themselves are stored. When adding a new production method or material these tables have to be updated so all possible production and material method combinations are represented. Adding an assembly method simply means selecting the production methods combinations or material combinations for which it is applicable. Other actions that have to be performed when adding a production method, assembly method or material are actions that manipulate the manufacturing database in such a way that it fits the manufacturing analysis tools. What they mean and how they should be performed is handled in the chapter dealing with these analysis tools, chapter 7. As can be seen adding or adjusting manufacturing methods or material is maintenance intensive. However because the manufacturing database is not only needed for the MDEE, but can fit to different design frameworks, the maintenance effort needed can be divided between different projects.

5.8 *Product model examples*

In this section examples will be given of movables created using the PMM. It is divided into two parts; one showing examples generated by the PMM structural view and another one showing examples generated by the PMM manufacturing view. A general aviation rudder will be used to show the different features of the PMM. This rudder stems from the Euro-Enaer Eaglet 2-seat aircraft.

5.8.1 Structural view examples

The visualization generated by the structural view of the PMM should show the user of the PMM the impact of his decisions on the structure of the movable. To do this colours have been used to define the functions of the different elements in the structural view. In Figure 5-29 the multi rib base line version of the Eaglet rudder can be seen. Here the virtual ribs are painted blue, which means that they don't have a structural function and are not part of the manufacturing concept.

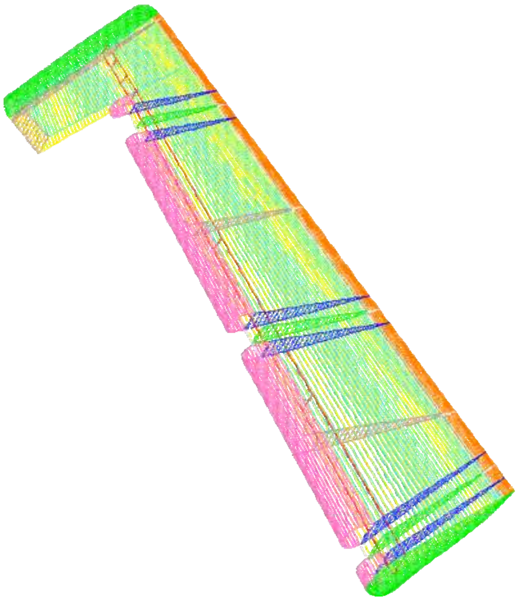


Figure 5-29 Structural view of the multi rib Eaglet rudder

The PMM has the possibility to generate many different movable shapes and structural concepts. In Figure 5-30 to Figure 5-36 renderings of models generated with the structural view of the PMM are shown. The number and diversity of the different examples proves the modelling potential of the PMM. The modular build up of the PMM and the re-usability of the PMM are shown in Figure 5-36 were the model of an elevator is shown. In this elevator a cut out is created in which another instantiation of the PMM is positioned to represent the trim tab of the elevator.

Figure 5-30 Airbus A320 flap model

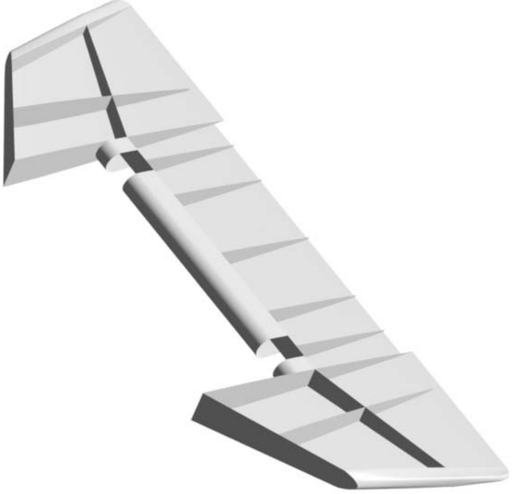


Figure 5-31 Model of an imaginary movable

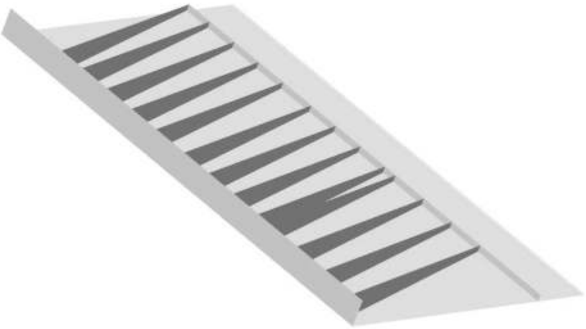


Figure 5-32 Lockheed Tri-Star flap model

Figure 5-33 Eaglet rudder model

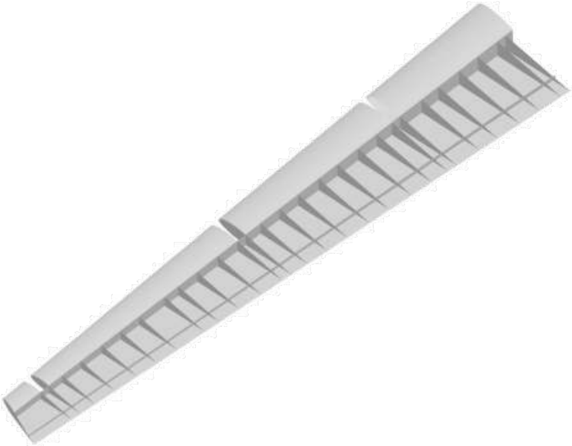


Figure 5-34 Fokker 100 elevator multi-rib model

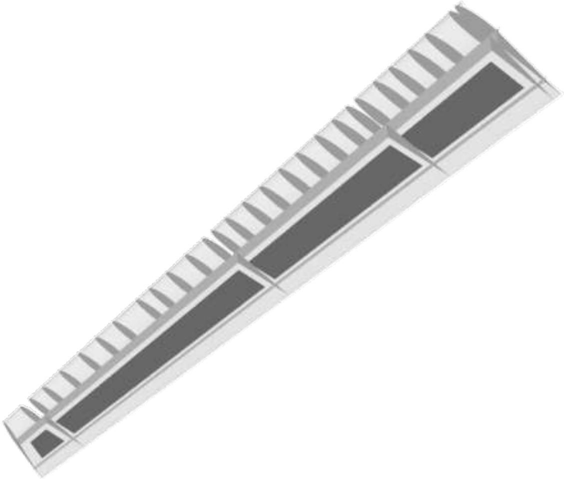


Figure 5-35 Fokker 100 elevator sandwich model

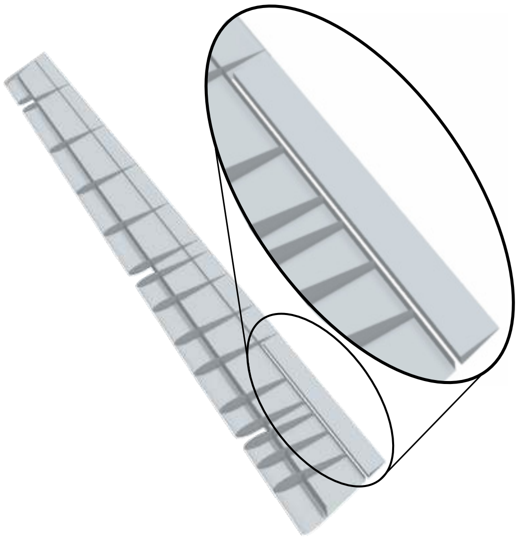


Figure 5-36 Elevator with cut-out and instantiation of the PMM resembling a trim tab

5.8.2 Manufacturing view examples

The visualization generated by the manufacturing view of the PMM should show the user of the PMM the impact of his decisions on the manufacturing concept of the movable. Again colours are used for visualization as can be seen in Figure 5-37. In this case each colour represents a manufacturing method for a part. Colours are also used to visualize the different assembly joints in the manufacturing concepts. These are represented by thick lines the colour of which represents the assembly method determined for the particular assembly joint.

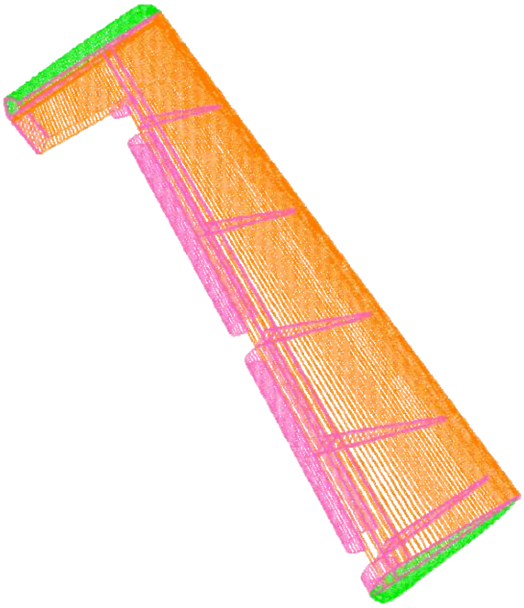
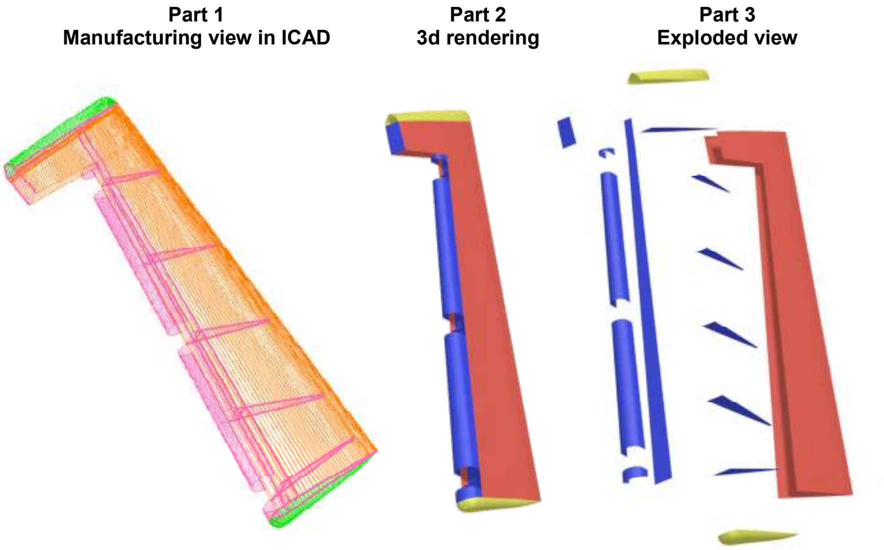


Figure 5-37 Manufacturing concept representation of the Eaglet rudder baseline

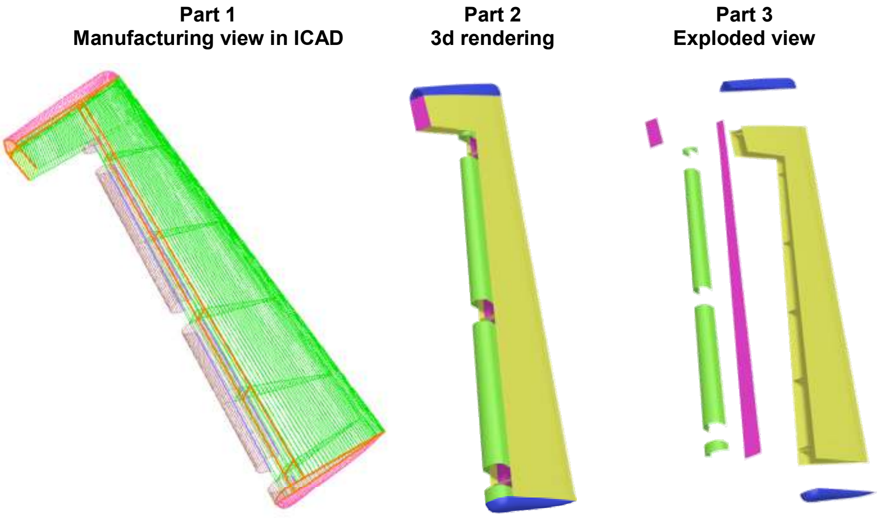
In the manufacturing view the structural elements are redistributed into manufacturable parts. The same structural elements can be distributed in completely different manufacturing concepts. This is shown in Figure 5-39 where the structural elements from the baseline Eaglet manufacturing concept (Figure 5-38) are redistributed to form a highly integrated wing box, which can be produced using vacuum infusion techniques. This new manufacturing concept eliminates many assembly joints. However the resulting parts are much more complex.


Part 1
Manufacturing view in ICAD

Part 2
3d rendering

Part 3
Exploded view

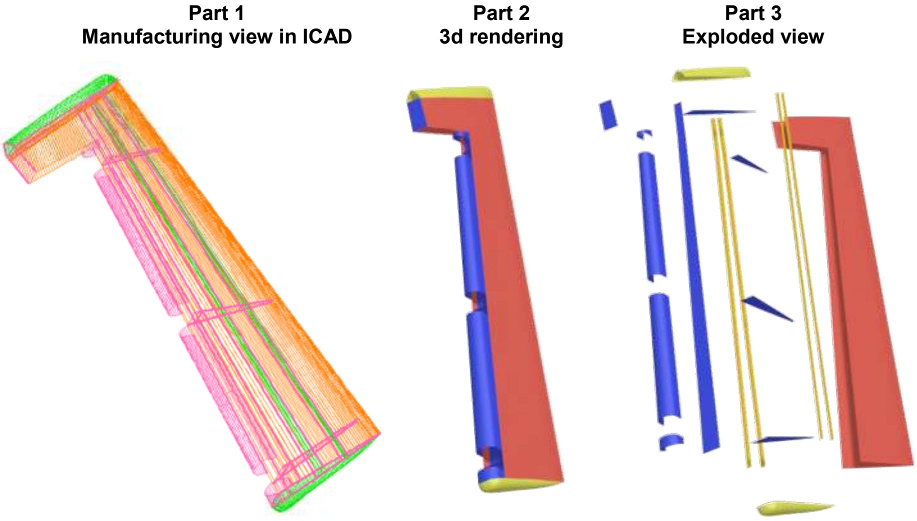
Figure 5-38 Base line Eaglet manufacturing concept, separate parts


Part 1
Manufacturing view in ICAD

Part 2
3d rendering

Part 3
Exploded view

Figure 5-39 Eaglet manufacturing concept using highly integrated parts


Part 1
Manufacturing view in ICAD

Part 2
3d rendering

Part 3
Exploded view

Figure 5-40 Eaglet manufacturing concept using stringers

In the manufacturing view information is added about the stiffener lay-out so they can be modelled in more detail. These details are needed for the different manufacturing analyses. An implementation of these stiffeners can be seen in Figure 5-40. Here another structural and manufacturing concept is presented for the Eaglet rudder.

5.9 Conclusions and recommendations

In this chapter the Parametric Movable Model (PMM) is discussed. This model will provide the bases for the analyses tools discussed in the following chapters. These tools will in turn enable the “ Design for X” methodology in the different analysis disciplines. The different views of the PMM generate models of a family of aircraft components, the trailing edge movables. The model generated by the PMM consists of geometric entities and information attached to these geometric entities. The PMM provides two views; the structural view and the manufacturing view, both based on the same input data set. In these views the information for the structural and manufacturing analyses respectively are represented.

In the model generated by the PMM structural view the aircraft movable is represented by structural entities. In the model generated by the PMM manufacturing view the aircraft movable is represented as manufacturable parts, meaning the parts that will be assembled to form the finished aircraft component.

The PMM is capable of modelling most commonly encountered trailing edge aircraft movables with most structural and manufacturing options. The outer shape of the movable can be determined in two separate ways. First of all the outer mould line can be created by the PMM itself using airfoil shapes loaded from an airfoil library. Secondly the outer mould line can be determined by an IGES file generated externally.

The PMM developed is fully functional and is already a very useful tool however there are several areas where it can be improved. First of all the user interface for defining the PMM input dataset is text based and not very user friendly. This problem can be largely solved by creating a Graphical User Interface (GUI), which helps the user create the inputs. This GUI would then essentially form the initiator part of the Movable Design and Engineering Engine.

For the PMM to be complete and handle the full range of trailing edge movables the full depth honeycomb structural option should also be implemented. However implementing this structural option is not easy as it will require the use of solids whereas the PMM for now is solely based on surfaces.

Finally the same model structure used for the PMM could be used for other generative modelling engines used to model aircraft components. This means adopting the multi-view approach. This approach ensures that the generated views can create data for structural and manufacturing analyses. Using the multi-view approach in a way similar to the PMM also simplifies the use of the analysis modules that will be described in the following chapters.

6 Discussion of cost estimation methods and the selection of the appropriate method for the Movable Design and Engineering Engine (MDEE).

One part of the “Design for X” methodology enabled by the Movable Design and Engineering Engine (MDEE) is “Design for Cost”. This means that the design concepts created must fulfil the sub-set of cost requirements. To analyse how a design concept fulfils this sub-set, a cost estimation of the design concept must be executed. Therefore a cost estimation method will be implemented in the MDEE. The cost estimation method selected for implementation in the DEE must fulfil certain requirements to ensure that the “Design for Cost” methodology can be enabled. Therefore the cost estimation method chosen must be selected carefully. This selection is made in this chapter.

The cost of an aircraft movable design and manufacturing project can be defined as the amount of financial resources it takes to develop and manufacture the aircraft component, or in other words the development and manufacturing cost. In this thesis only the manufacturing cost will be considered. Manufacturing cost consists of 2 parts: recurring cost and non-recurring cost. Recurring costs consist of costs that occur every time a part is manufactured. Non-recurring costs are costs that are incurred for the whole production line. This can for example be tooling cost and machine cost. A division of the manufacturing cost in recurring and non-recurring cost and some cost elements can be seen in Figure 6-1.

Although the non-recurring cost makes up a large part of the manufacturing cost of an aircraft component, it will not be considered in the module that estimates the cost of an aircraft component. Non-recurring cost is not considered because it can be difficult to link design features that determine the characteristics of the design to non-recurring cost elements. For the recurring cost elements this is much easier because the design features that determine the characteristics of the design can be linked directly or indirectly to the cost elements. For example the area and thickness of a part determines the total amount of material needed for this part, predicting the material cost.

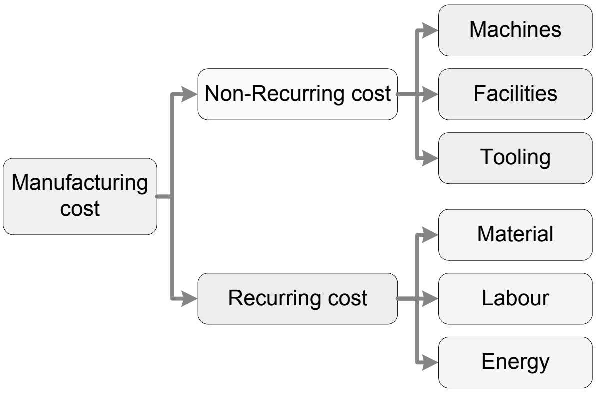


Figure 6-1 Manufacturing cost tree

In this chapter different cost estimation methods will be discussed to find out which cost estimation method is best suited to fit in the Movable Design and Engineering Engine (MDEE). Focus in this discussion lies on how the different cost estimation methods work, what the differences are and if they fit in a Design and Engineering Engine (DEE). During the investigation of the different cost estimation methods it became clear that the distinction between, and description of, the different cost estimation methods is not very precise. Therefore a new classification system for cost estimation methods is proposed in this chapter. Finally the cost estimation method that is going to be used in the MDEE is selected. The actual implementation of this method will be discussed in the next chapter.

In the first section of this chapter the characteristics of cost estimation methods identified in chapter 4 are discussed. In the second section a new classification system for cost estimation methods is proposed. Final section of this chapter consists of the selection of the cost estimation method that is going to be implemented in the MDEE.

6.1 Overview and summary of existing cost estimation methods

Different cost estimation methods have been identified in chapter 4. These methods have different characteristics that have far reaching implication for how and where they can be applied. In this chapter the three most commonly used methods are discussed: analogous, parametric and bottom up cost estimating. Because the definition of these methods is not always clear, and in literature different names are used, a definition that is applicable to this chapter is given:

- ***Analogous cost estimating***. In analogous cost estimating the cost of the total project for producing a product or system is related to the cost of previous similar projects. Factors determining the relation between the project of which the cost is estimated and previous projects provide the possibility to tune the cost estimation.
- ***Parametric cost estimating.*** In parametric cost estimating, statistical relations based on characteristics of a product or system or of the project to manufacture such a product or system are used to predict the cost of the product or system. The parametric cost estimation method can also be used to generate cost estimates of sub-parts or sub-assemblies of a product or system.
- ***Bottom up cost estimating.*** In bottom up cost estimating the cost of each element in the Work Break down Structure (WBS) of a product or system is estimated. Different methods can be used to determine these costs, but the outcome is usually a large amount of data consisting of cost information about all the elements of the WBS. Different techniques can be used to perform a bottom up cost estimation. It can for instance consist of a combination of parametric cost estimations. However in this chapter bottom up cost estimation is defined as a method where the cost is determined of each process and material element used to create the final product.

6.2 Product description in cost estimating techniques

Most cost estimation techniques use relations or formulas to estimate the manufacturing cost of a product or system. In these relations parameters describing the system of which the cost is estimated play an important role. These parameters, in essence, determine the final outcome of the cost estimation and the difference in estimated cost for different design concepts. For the different estimation techniques the parameters that describe the product or system are different in name and expression:

- ***Analogous cost estimating.***
  The parameters which describe the product or system are parameters that describe the global characteristics of a product or system or the project to produce this product or system. These parameters are for example complexity, miniaturization and productivity factors. The factors describe the difference between the system that is analyzed and a reference system or a database of reference systems that is used as the basis for the cost estimation.
- ***Parametric cost estimating***.
  In this case parameters are used that describe the actual physical appearance and characteristics of the product or system or the project to produce such a product or system. These parameters can for instance be, weight, length or number of drawings of a product or system. These parameters are then used in a formula that has factors, determined by statistical techniques, to relate these parameters to cost. The factors are determined using data from previous projects dealing with products or systems of similar characteristics.
- ***Bottom up cost estimating.***
  In this case the focus is on lower level elements of the product or system. In this chapter this estimation method is being defined as a method where the cost is determined of each process and material element used to create the final product. The parameters that are used therefore describe a smaller element of the product or system. For example parameters like “sub-part area” that describe the area of part of the product can be used to estimate the manufacturing time of this part. These parameters are then used in a formula together with factors that determine the actual physical behaviour of the manufacturing process used.

Although the used parameters have different names they have the same basic function; they describe the product or system that is analyzed. They do this however at different levels of detail, highest level being the analogous method, one step down the parametric method and finally the bottom up method. The level of detail a design is described has an effect on the outcome of the cost estimation. The detail level also influences the reliability of the cost figure that is created. Rule of thumb in this case is: “the higher the level of detail of the design information used in the cost estimation the higher the reliability of the cost estimation results and the higher the data content of the in and output of the cost estimation”. Of course this rule of thumb only applies to well calibrated and verified cost models.

6.3 Differences between the cost estimation techniques

In Figure 6-2 the different level of detail of a product or system can be seen. The different cost estimation techniques use or are related to different elements in this tree. Analogous cost estimation is by definition positioned at the top level of the tree. This is because it by definition compares the cost of the whole program to produce a product or system with other programs of similar characteristics. Therefore the outcome of the analogous cost estimation includes the cost for all branches of the product tree. Parametric cost estimation can be performed at different levels of detail. However usually it is used to estimate the cost of the complete product, of a sub-assembly or of a manufacturable part. When using a parametric cost estimation technique to estimate the cost of a certain element, all leaves and branches below this element are also included in the cost estimation. Bottom up cost estimation is positioned at all levels of detail. The cost has to be estimated of all the leaves and branches of the product tree. To get a cost estimation of the whole product all elements of the bottom-up cost estimation have to be summed.

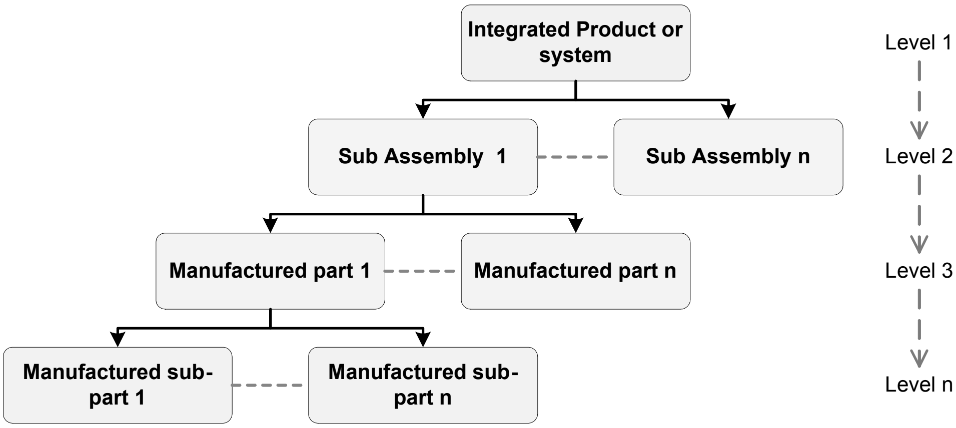


Figure 6-2 Product or system tree layout and built up

The classification of cost estimation techniques can also be based on the difference in relational and compilational methods. Compilational methods are methods that add different cost elements to form the final cost of a product or system. Relational methods link cost to attributes of the total product or system. Bottom up cost estimation is a compilational method, because it compiles the cost of all elements of the WBS to determine the cost of the product or system. Analogous and parametric cost estimation techniques are relational, because they link the cost of a product or system to the attributes discussed in the previous section. The results of several parametric cost estimation concerning sub-parts of a product or system can be compiled to form the overall cost estimation for this system or part. However this does not make the parametric methods that lay at the basis of this estimation compilational.

Cost estimation methods can also be distinguished as being process or product based. Process based means relating the cost of a product or system to the processes that are used to manufacture this product or system. Product based cost estimation bases the cost of a product or system to the characteristics of the product or system itself. Relational methods are automatically considered product based costing methods, because by definition the cost is estimated is based on attributes of the product or system itself. Therefore analogous and parametric estimation techniques are product based cost estimation methods. Compilational methods are not per definition process based. However bottom up cost estimation is process based, because bottom up cost estimation looks at all the elements of the WBS for producing the product or system that add manufacturing cost. These elements can be labour cost needed to perform a process and the material used in this process. All the cost elements are summed to determine the final cost estimate.

The type of cost estimation method influences its applicability. Relational methods use statistical relations between product and cost. The statistic relevance of these relations is only valid for a limited area of the design space. For example when looking at a parametric cost estimation model for aircraft fuselage skin panels, one needs to know something about this aircraft. A parametric model for an un-pressurized sub-sonic aircraft will, for example, probably not be applicable to a supersonic pressurized aircraft. Bottom up cost estimation is process based, meaning that it uses only the activities and materials used in the manufacturing of a product or system to estimate the cost of this product or system. The activities involved in manufacturing the product or system do largely not depend on what it is used for or what it looks like. Therefore the cost estimation techniques used in the bottom up method are applicable to a wide range of product or systems.

Process based cost estimation methods are also more suited for new or innovative manufacturing techniques and/or products. For these manufacturing techniques or products no data is available, therefore creating a statistical relation for estimating cost is almost impossible. This means that analogous and parametric cost estimation methods are not applicable to these innovative manufacturing methods and products. For creating a process based cost estimation method only the innovative part of the manufacturing method or product has to be analysed. This can be done on a smaller scale, for instance by performing test runs or by using prototype data. For example for the friction stir welding assembly method only the actual joining of the two parts is innovative. The positioning and clamping procedures are quit similar to other assembly methods. Therefore when creating a process based cost estimation method for friction stir welding only the joining speed of the friction stir welding process has to be investigated. This speed can be determined in a test set-up in a laboratory. By combining the estimation results for the innovative part of the manufacturing method with the already known well known elements a cost estimation method for the complete process can be devised.

Another issue defining the difference between cost estimation methods is the causality. Causality means that a change in the inputs for the cost estimation model results in a change of estimated cost that corresponds to the actual cost change of the product or system. In bottom up cost estimation the methods used for the estimation look at the actual manufacturing physics of the product or system. This can for instance mean how is a connection made and also what material is bought. This has the advantage that it is inherently causal, after all when an action has to be performed or a material has to be bought this adds to the actual manufacturing cost of the product or system. Big advantage of such a causal system is that the cause of adding cost is easily apparent and can therefore be identified and, when needed, adjustments can be made. It is also intuitive, more work and materials ads more cost, and therefore useful for people that are not cost estimation experts, such as designers. Parametric and analogous methods don’t have a connection to the actual production process of the product or system; they are based on statistics. They have the advantage of working quick and can produce good results. However parametric and analogous methods are not inherently causal and can act like a black box. Therefore they can be difficult to understand by non-experts, especially because, in the case of parametric methods, the results of some design decisions can be puzzling. For instance in order to reduce weight, lightening holes are added to a rib, because weight of the rib is reduced a cost estimate based on weight will predict lower cost. However common sense dictates that adding holes adds work and therefore increase manufacturing cost.

When looking at the differences between cost estimation methods data intensity and actual usability of the methods should also be considered. In this case the lower the data intensity the more easily usable the model will be in every day practice and the earlier in the design process the required input data will be available. Combining this with the rule that more detailed information adds more reliability this results in the statement that easy to use cost estimation methods have a low reliability. Low detail methods such as analogous or high level parametric cost estimating can produce good results, when applied to the right products, and are effective at the beginning of the design process when limited data is available. Data intensive methods, such as bottom up costing, require a substantial amount of data. This is usually not available at an early stage of the design process and therefore this method is rarely used at this stage. When the data is available this is usually at an advanced stage of the design process when the possibility to influence the manufacturing cost of a product or system is limited. Bottom up cost is usually implemented in automated systems because the numerous calculations can then be automated. These automated systems can however require a great deal of maintenance.

In the section above the characteristics and problems of the different cost estimation techniques were discussed. In Table 6-1 a summary of the most important characteristics is shown.

Table 6-1 Cost estimation characteristics summary table

	Analogous cost estimation	Parametric cost estimation	Bottom-up cost estimation
Level of product tree elements used	High level elements	Depending on method used high level or lower level elements	All elements ranging from low level to high level elements
Estimation method type	Relational	Relational, can be combined into compilational	Compilational
Estimation basis	Product based	Product based	Process based
Applicability of the estimation method	Applicable to products closely resembling the products used to create the estimation method	Applicable to products similar to the elements used to create the estimation method	Applicable to products created using processes covered by the method
Suited for innovative or new processes or products	No statistical basis	No statistical basis	Yes, as long as new processes are properly analysed
Causality	No inherent causality	No inherent causality	Inherently causal
Data intensity	Low	Depending on the level of product tree elements used ranging from low to high	Very high

6.4 Cost estimation classification

The definition given above for the 3 main cost estimation methods is a summary of the information found in literature discussed in chapter four. However literature is not consistent about the definition and different names or terms can be used for approximately the same cost estimation method. For example parametric costing uses statistical relations. Different techniques can be used to define these relations. Sometimes the statistical techniques are also used to name the cost estimation method. An example of this can be found in the neural network cost estimation methods that use neural networks to define the statistic relation.

Because the names of the different cost estimation methods are not always consistent it can be confusing, especially for non experts, to appreciate what the used cost estimation method is and, more importantly, what the limitations and assumptions of this cost estimation method are. This confusion can result in misuse of cost estimation methods. To eliminate this confusion, cost estimation methods should be classified according to what really happens inside the method, “inside” in this context meaning the actual operations that are performed to produce the cost estimate.

First element of the classification will be the attributes on which the cost estimation is based. Attributes are the parameters in the cost estimation relationships that are used to describe the product or the system to manufacture the product. In the sections below the important attributes will be identified. Another issue that has to be dealt with in the classification is what kind of relations is used. Here “kind of relation” means the nature of the relationship, whether purely statistical or based on something else.

6.4.1 Using attributes and a means or classifying cost estimation methods

All cost estimation methods link attributes describing the entity of which the cost is estimated or the system used to manufacture the entity with the actual cost of this entity. The link between the attributes and the cost of the entity is usually a mathematical relationship. For understanding how such a relationship works first the relevant attributes and how they relate to cost have to be identified. These attributes exist on 3 levels:

- ***Project level.*** Attributes in this level describe the whole project of developing and producing a product, from design of the product to decommission of the product.
- ***Product level*****.** Attributes in this level describe the physical product that is manufactured.
- ***Process level.*** Attributes on this level describe the processes that are used to manufacture the product.

In the next sections the 3 different levels are described and the relevant attributes of each level are identified.

Project description and attribute identification

At the project level the complete project of developing, manufacturing and decommissioning a product is handled. However the interest in this thesis lies only in determining the manufacturing cost of a product. Therefore the phases in which decisions about the manufacturing are taken or actual manufacturing takes place are of the most interest. These phases are primarily the design phase and of course the manufacturing phase. These phases are described by attributes or characteristics. Only a few of these attributes actually influence the manufacturing cost of the product and are therefore relevant in the context of product cost estimation. Examples of these attributes are:

- ***Part definition complexity,*** With this attribute the administrative complexity of a part definition is described. This can for instance be quantified as the number of drawings needed to formalize the product design. This attribute is influenced not only by the product that is designed, but also by requirements formulated by, for example, a certification agency. This attribute is a cost indicator meaning that it does not directly influence the manufacturing cost, but can be an indicator for product complexity which influences cost.
- ***Assembly philosophy,*** Assembly philosophy used in the design process is dependent on the company that manufactures the product and also other actors, such as the higher level manufacturer that will use the product. Assembly philosophy is primarily determined by previous experience and the competences of the company that is manufacturing a part. Assembly philosophy is a purely qualitative attribute guiding the design of the manufacturing concept. Assembly philosophy influences cost by determining the configuration of assemblies.
- ***Manufacturing philosophy,*** Manufacturing philosophy is quit similar and related to the “Assembly philosophy” attribute; only in this case the type of manufacturing processes chosen to manufacture a part is handled. This is again determined by previous experience and company competences. It is purely qualitative and influences the product cost by determining the manufacturing methods of manufacturable parts.
- ***Manufacturing location,*** The manufacturing location is an important part of the manufacturing environment specified for the product. It can influence the manufacturing cost via manufacturing environment related issues such as hourly labour rate. This attribute is purely qualitative.
- ***Technology used,*** Technology used is closely related to the assembly philosophy. In this case it indicates which manufacturing technologies are being used in the product manufacturing process. This influences the production techniques of the different manufacturable parts, which in turn influence the cost of the product. This attribute is again pure qualitative.
- ***Make or buy philosophy,*** Make or buy philosophy determines which parts of manufacturing a product should be sub-contracted and which should be kept in house. It influences cost because it determines what kind of cost should be determined for a part or assembly. If a part is manufactured in house this is the actual manufacturing cost, while if a part will be bought this should be the market price, which is related to, but not the same as the actual manufacturing cost.

The list compiled above should not be considered complete but is an indication of what process attributes look like.

Project attributes mainly influence cost by influencing manufacturing process and product attributes. In practice project based attributes are usually used in combination with product attributes to form statistical relations to estimate product cost. This is understandable because the product attributes are needed to describe what is actually manufactured.

Product description and attribute identification

Aircraft components are usually build assembling smaller elements which are in turn assembled from even smaller parts. This principle of building the aircraft component using smaller building blocks is shown in Figure 6-3. For some cost estimation methods it is necessary to clearly describe the different leaves and branches of the product tree.

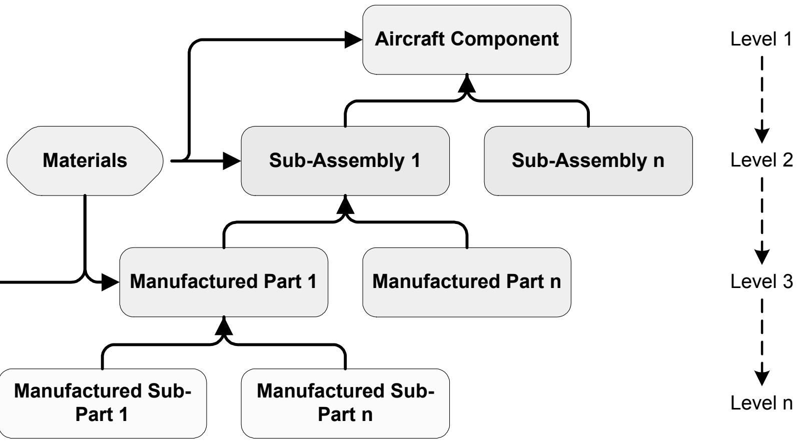


Figure 6-3 Hierarchical structure of an aircraft component

In Figure 6-3 the elements used to manufacture a product are clearly defined. In every day practice it might not be so easy to distinguish the different elements. Determining the boundaries between the different elements is usually arbitrary. The boundaries of the different elements can be determined by the product appearance and/or the characteristics of the manufacturing processes used to manufacture the elements. An element boundary can for instance be created when an element is removed from jigging or is transported to another processing site. Another method of determining the element boundaries is to use manufacturing processes. When a manufacturing process is finished a new element is created. The issue then becomes where the boundaries of the manufacturing processes lie.

The number of levels in the product hierarchy is usually determined by the characteristics of the component and the manufacturing environment in which it is produced. In the product hierarchy the manufacturing environment and characteristics of each ‘branch’ can vary meaning that the number of levels for each ‘branch’ can also vary. Different manufacturing concepts of the same aircraft component design can also have different manufacturing environments or element definitions. If this is the case the number of levels in the product hierarchy can also change.

Two distinctly different element groups exist in the product structure. First group are the elements that are at the bottom of the tree. These elements will be manufactured using only materials and not other sub-elements. These elements are created using so called production processes. Elements of this group will be called manufacturable parts. The second group consists of elements that are composed of different lower level elements and, optionally, materials. Manufacturing this second group of elements usually involves assembling different manufacturable parts using assembly processes. The elements that are members of the second group will be called assemblies. The difference between production processes and assembly processes is not clear cut however, hybrid manufacturing techniques, such as co-curing of composite structures, exist.

In the previous paragraphs the element materials was mentioned several times. These materials come in different forms. These are 2 distinct groups of material. The first group contains the consumables. The second group contains the product materials. The consumables are the materials that are used in the manufacturing processes and are not present in the finished product. The production materials are present in the finished product. This group comprises of three sub-groups. First sub-group is the production basis material. This is the material used to form manufacturable parts. This can be metal sheets or composite pre-pregs. The second sub-group is the group of bought parts. These are basically manufacturable parts not produced in house. The difference between production basis materials and bought parts is not clear cut however. For example pre-pregs are built from composite fibres and uncured resin elements so could also be considered a bought part. The third and final sub-group of the production material group are the fastening material. These can closely resemble both production basis materials, for example bonding resins, and bought parts, for example hi-locks. The resulting materials tree can be seen Figure 6-4.

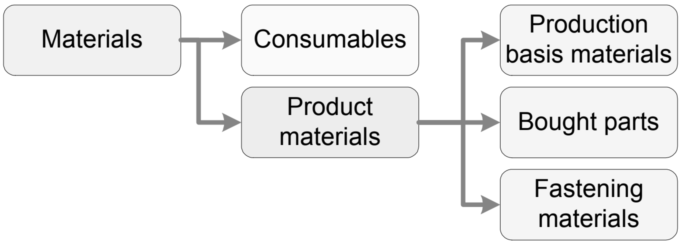


Figure 6-4 The materials tree

Each element of the product tree can be described using attributes. Some of these attributes influence the manufacturing process of the specific elements, which in turn determines the cost of the element. Attributes can be manufacturable part specific, assembly specific or shared by both manufacturable parts and assemblies. Examples of important attributes that influence the manufacturing process of aircraft component elements are:

- ***External Size,*** The external size of a product can be expressed in actual values for the length, width and height of the element. External size of an element can be quantified expressing the measurements in meters. Both manufacturable parts and assemblies have an external size and therefore external size is a shared attribute.
- **Mass,** The mass of en element is dependent on the dimensions of the elements; external size, cut outs and local thicknesses. Mass of an element can be quantified by expressing it in kilograms. Both manufacturable parts and assemblies have a mass and therefore external size is a shared attribute.
- ***Shape complexity,*** The shape complexity of an element can describe many things and is also different for different kinds of elements. If the element is a manufacturable part the shape complexity can for example entail the curvatures of the part or the number or different surfaces. If the element is an assembly element, shape complexity can for example be the curvature of the connection joints. Shape

complexity is difficult to quantify because there are many types. Shape complexity is an attribute shared by both manufacturable parts and assemblies although the actual meaning can be different.

- ***Material type,*** For a manufacturable part the material type is the main material sort that is used in production process. For assemblies it is a combination of the material types of the manufacturable parts used in the assembly. Therefore, even though material type is a shared attribute, the material type attribute has a different definition for manufacturable parts and assemblies. Material type itself cannot be quantified, however material characteristics, such as specific weight, strength or stiffness, could be used as a quantification measure.
- ***Part thicknesses,*** Part thickness is an attribute of each manufacturable part. When this manufacturable part is used to create an assembly, this assembly inherits the thickness attribute from the manufacturable part that is used. Part thickness does not have to be constant in an element. Quantification of the part thickness therefore consists of a collection of length expressions, usually in millimetres. Part thickness is a shared attribute.
- ***Production process used,*** The production process used determines how a manufacturable part is produced. This attribute is purely qualitative and specific for manufacturable parts.
- ***Assembly processes used*** Assembly processes are used to join different sub-assemblies and manufacturability parts into an assembly element. Because different connections exist in an assembly, this attribute consists of a collection of different processes, one for each connection joint. This attribute cannot be quantified and is assembly specific.
- ***No of sub-elements involved*** For an assembly element the number of sub-elements combined in the assembly is an important attribute. The number of elements to a degree determines the complexity of the assembly. This attribute is quantifiable because it consists of a single number. Only assemblies have different elements and therefore this attributes is assembly specific.
- ***Connection lengths*** In an assembly, connections between different elements have to be made. An important attribute of assembly elements therefore is the length of these connections. Each assembly usually entails different connections; the quantified expression of this attribute therefore consists of a set of length measures. Connections are only present in assemblies and therefore this attribute is assembly specific.

The list compiled above should not be considered complete but is an indication of what product attributes look like.

There is also a certain amount of inheritance in the different attributes. This means that high level assembly attributes are influenced by attributes from the lower level elements that are involved in the assembly. For example the weight of an assembly is the summation of all the weights of lower level elements plus the materials added to the assembly. In case of shared attributes, the attributes of lower level elements always influence the attributes of the assembly in which they are used to a certain degree.

Manufacturing process description and attribute identification

The manufacturing process of an aircraft component is a complicated process. The manufacturing process itself can however be split into sub-processes like the aircraft component can be split in elements. The complexity of these sub-processes is smaller than that of the higher level manufacturing process, which can be useful for certain analyses. The hierarchical built up of the manufacturing sub processes, shown in Figure 6-5 resembles the hierarchical product tree shown in Figure 6-3. Analogous to assemblies and manufacturable parts a distinction can be made between assembly processes and production processes. In an assembly process an assembly element will be created while a production process results in manufacturable parts.

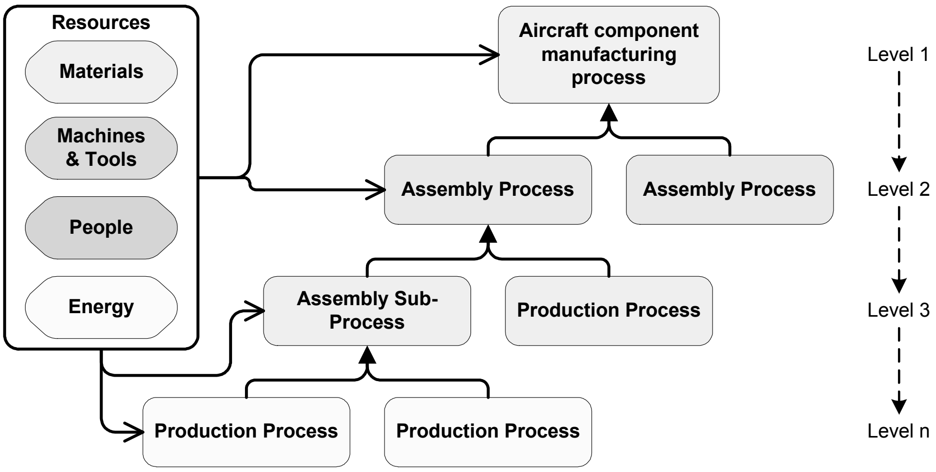


Figure 6-5 Hierarchical structure of the aircraft component production process

As is shown in Figure 6-5 the different manufacturing processes require resources. In this case only the resources that are active in these manufacturing processes are shown. These are:

- ***Materials*** The products that are manufactured consist of a material, that's why this resource is also present in Figure 6-3. Material for manufacturing processes also includes scrap and manufacturing process consumables. Materials are consumed in the manufacturing process; they are either lost or transformed into a product.
- ***Machines & Tools*** Machines and tools are aiding the manufacturing process. They are not consumed in the manufacturing process and can be used in subsequent manufacturing processes.
- ***People*** People perform activities in the manufacturing process. These activities can also mean interaction with other resources such as machines and tools.
- ***Energy*** Machines and other elements of a production process require energy in the form of electricity or fuel. Energy is consumed in the manufacturing process.

Each of the manufacturing processes can be described using attributes. These can also be related to the resources used in the manufacturing process. Examples of attributes that are the most important for the cost estimation will be discussed below. First the resource related attributes will be described, followed by the manufacturing process attributes. In the attribute description, the influence of the attribute on the manufacturing cost will also be discussed.

- ***Material,***
    - *Type,* The material type determines the price of the material. It also implies certain boundary conditions on the manufacturing process that can influence the cost of the process.
    - *Price,* The material price determines the specific material price. Together with the amount of material used it determines the material cost of a manufacturing process.
    - *State,* This attribute entails the state of the material. This can for instance mean the curing state of the resin in a composite material or the heat treatment of a metallic material.
    - *Amount,* The amount of material used in a manufacturing process is a value. This value can be determined by looking at the part or assembly dimensions and applying a scrap rate. Together with the specific price of a material the amount will determine the total material cost of a manufacturing process.
- ***People,***
    - *Skill level,* The skill level required from the people involved in the manufacturing process is influenced by other attributes such as which machine is used in the process. Skill level is usually related to the wage level of an employee and hereby influences the cost of the manufacturing process.
    - *Number used,* The number of people used in a process together with hourly rate of these people and the hours spent on the manufacturing process results in the total labour cost of a manufacturing process.
    - *Actions performed ,* The actions performed by the people involved in the manufacturing process directly influence the process time and hereby influence the cost of the manufacturing process.
    - *Labour hours,* The hours spent on the manufacturing process by a man together with the hourly rate and the number of people used determines the labour cost of a manufacturing process.
    - *Hourly rate ,* The hourly rate of the people involved in the manufacturing process together with the number of hours and the number of people involved determines the total labour cost of a manufacturing process.
- ***Machine,***
    - *Type,* The machine type influences the hourly rate of the machine though depreciation. This can be used in the cost estimation together with the process time to determine the machine cost.
    - *Speed,* Machine speed influences the process time. This is especially true if a process is machine intensive. Process time is an important factor in the total cost of a process.
    - *Machine hours,* Machine hours together with the machine rate determines the machine cost of a manufacturing process.
    - *Machine rate,* Machine rate is a term combining machine depreciations and other factors determining the cost of a machine into an

  hourly rate. This rate together with the machine hours determines the machine cost of a manufacturing process.

- ***Tools,***
  - *Type,* As with machines the tooling type, in part, determines the depreciation of the tooling. The tooling type can also influence the process time.
  - *Size,* Tooling size determines how easily the tooling can be manoeuvred when necessary. This influences the process time. Tooling size can also influence the space necessary for the manufacturing process.
  - *Tool rate,* Depreciation, expected life of a tool and other factors are combined to into an a tool rate. Together with the time a tool is used this factor determines the tool cost of a manufacturing process.
- ***Energy,***
  - *Type* The type of energy used in a manufacturing process determines the unit cost. Energy type also has other influences such as delays when changing an energy container.
  - *Amount* The amount of energy together with the unit cost determines the energy cost of the manufacturing process.
  - *Unit cost* Unit energy cost is dependent on the type of energy and also on the location of the manufacturing process. Together with the total amount of energy used in a manufacturing process it determines the total energy cost of the process.
- ***Steps involved in process,*** A single manufacturing process usually takes different steps. These steps can for instance be: position material, use machine to create element, unload element. All the different steps add to the total cost of the manufacturing process. In each different step many of the other attributes or resources of the manufacturing process will be active. This attribute influences the cost of the manufacturing process via these other attributes.
- ***No of elements involved,*** In case of an assembly process the number of elements that have to be assembled influence many of the other attributes such as the number of steps involved in the manufacturing process and the kind of tooling. In this way the number of elements involved in the manufacturing process influences the cost of this process.
- ***Process time,*** Process time of a manufacturing process is to a large extent dependent on all the other process attributes. Process time is very important in determining the total process cost because it, combined with machine and labour rates, determines the machine and labour cost of the process.

The above described attributes of manufacturing processes are interdependent. Furthermore the attributes of the manufacturing processes are also dependent on the attributes of the manufacturable parts or assemblies that are involved in the manufacturing process. This means that it can be difficult to determine how the different attributes influence the cost of the manufacturing process. However understanding how attributes influence cost is essential when modelling cost using manufacturing process and product attributes. In the next section a further investigation will be conducted on the origin of cost and how it can be related to the different attributes described in this and the previous sections.

6.4.2 Proposal of a new system of identifying cost estimation methods

The attributes identified above can be used to identify four cost estimation classes. This new definition divides the cost estimation techniques according to expressions or formulas that are used. Defining element is what these expressions or formulas describe. Four types have been formulated:

- **Project based cost estimation**, Formulas and expressions used in this technique use attributes that are related to the product life cycle as a whole.
- **Product based cost estimation**, Formulas and expressions used in this technique use attributes and variables that are related to the manufactured product itself.
- **Process based cost estimation**, Formulas and expressions used in this technique use attributes that are related to or describe the manufacturing processes used to create the product.
- **Hybrid models**, Formulas and expressions used in this technique use attributes that are related to different categories.

Project based cost estimating

In project cost estimating the cost estimating expressions are related to the attributes of the complete project to manufacture a product. Cost is determined by relating the cost of a complete project to the cost of other projects dealing with similar products. In the relation between the projects, attributes describing the project to manufacture the new product form one part of the expressions. The other part of the expression is formed by statistically determined expressions using data from previous projects. In literature project based cost estimating is commonly called analogous cost estimation or case based reasoning. The actual relations between the project attributes and cost is determined using data from previous projects. The techniques used to determine the relations are arbitrary. Traditional curve fitting techniques can be used but also more advanced methods such as neural networks. Project based cost estimation always works at the highest level of the product tree and incorporates a complete project. The cost estimation can be performed quickly but the level of detail of the results is low. Reliability of the results is determined by the measure of commonality between the project of creating the new product and the projects on which the statistical relations are based.

Product based cost estimating

In product based cost estimating the cost estimating expressions are related to the attributes of the product itself. These attributes can be found throughout the product definition. Meaning the product attributes can be found in different levels of the product tree. For example, in an aircraft movable a product attribute can be the size of the complete finished product, but can also be the size of a rib that is part of this aircraft movable. Product based cost estimation therefore covers estimation techniques from the highest to the lowest detail level. It for example covers a statistical method that relates the size of a product to cost, but also a method that uses characteristics of all sub-elements of a product to estimate the cost of these elements, and determines the cost of the total product by adding the cost of all these elements. Product based estimation covers a large range of different estimation techniques. As long as an estimation method relates product attributes directly to cost it is considered a product based cost estimation method. Level of detail and reliability of the cost estimation results is determined by the type of the cost estimation, which product attributes are used and which technique is used to relate these attributes to the cost of the product.

Process based cost estimating

In process based cost estimation the cost estimating expressions are related to the attributes of the manufacturing processes used to manufacture the product. These attributes can be found throughout the product manufacturing tree. However, contrary to product based costing, the processes at all the levels have to be taken into account to estimate the cost of the product. Therefore process based cost estimation is always compilational. The manufacturing process attributes are in part closely related to the product attributes. For example, the lay up area in a hand lay up process is determined largely by the area of the product that is produced. The actual expressions that relate the process attributes to cost can be based on different principles such a statistics or simulation of the manufacturing process. Because the manufacturing processes at all levels have to be taken into account to estimate manufacturing cost of a product, the in- and outputs of this cost estimation techniques are very detailed. Reliability of the results depends on the appropriateness of the relations used in the actual cost estimation process.

Hybrid models

In hybrid models attributes from all three previously mentioned categories can be combined in a cost estimating expression. Because this cost estimation method combines different cost estimation categories it also combines the characteristics of these categories.

6.4.3 Relating project, product and manufacturing process attributes to cost

Relations between the project, product and manufacturing process attributes lie at the basis of most cost estimation techniques. Essential question is therefore how these attributes influence the cost of manufacturing a product. To answer this question first the sources of cost have to be identified. These sources of cost lie in the use or consumption of resources. These are in this case the resources of the manufacturing process: materials, machines, tools, energy and people. The cost incurred by acquiring these resources essentially determines the cost of manufacturing a product or system. Determining the influence of the product and manufacturing process attributes on the cost of a product therefore involves determining the influence of these attributes on the resources. For example the size of a product captured in the length width and height attributes of the product directly influence the amount of material needed to manufacture the product.

The influence of an attribute on the resources can be twofold, direct or indirect. Direct influence means that the attribute describes the consumption or use of a resource and therefore directly influences cost. Indirect influence means that the attribute influences an attribute with direct influence and hereby indirectly influences cost. Direct attributes can only be found in the manufacturing process attributes describing the resources, because this is where the actual manufacturing costs are incurred. An example of a direct attribute can for instance be the material specific cost and the amount of material used. Indirect attributes can be found in both process and product attributes. Indirect attributes are for example the size of a product or the material kind used. Indirect attributes usually also interact or influence each other, in this way a chain of influences between indirect attributes can exist finally linked to a direct attribute. This can for example be the number and size of elements in a product influencing the assembly connection lengths. The connection lengths in turn influence how much material and labour is needed to create these connections.

To determine the manufacturing cost of a product all cost estimation methods have to estimate the direct attributes or part of them. In the early stages of product development the values of the direct attributes are usually not known or unreliable. The attributes that are known at this stage of the development are usually product attributes that stem from the product definition conceived in the early stages of the development process. Most cost estimation methods used at this stage of the product development process use indirect product or process attributes to describe the product or process for which the cost is estimated. Essential step in converting these indirect attributes into a viable cost estimate is to determine the relationship of these indirect attributes to the direct attributes. Such a relationship can for instance be the size of a product determining the amount of material needed or the material type determining the specific material cost. With some cost estimation techniques the cost of a complete product is determined, meaning that the cost of a product or even a whole project is determined and represented with a number without any reference to direct attributes. In this case the values for the direct resources are encapsulated in this number. Therefore the determination of this number in a sense represents the determination of a collection of direct attributes.

The relationship used in cost estimation tools between indirect attributes and direct attributes can be determined in different ways. Two techniques used for determining the relationship between indirect and direct attributes are:

- *Statistics* Using data from previously performed projects, products or processes, relationships are determined between the indirect attributes from these projects, products or processes and the direct attributes of the manufacturing processes used to manufacture the product. In determining these relationships common statistical techniques are used.
- *Simulation* A manufacturing process used to create the product is simulated. The simulation can be real, in which the manufacturing process is actually conducted, or digital, in which the simulation is performed with a computational model. Results from the simulation can be used to determine relationships between the indirect and direct attributes of the product in question.

Knowledge about how the relationship between indirect and direct attributes is determined is essential when using the cost estimation tool, because it influences the applicability and reliability of the used tool. For instance a statistical relation determining the cost for a low speed general aviation movable is not applicable to a supersonic jet fighter.

The definition of a manufacturing cost estimation tool becomes:

A manufacturing cost estimation tool for a product is a tool that relates attributes describing the project of manufacturing a product, attributes describing the product itself and/or attributes describing the manufacturing processes involved in manufacturing the product to the consumed resources used to manufacture the product.

6.5 Formalization of the proposed cost estimation classification system

The previously described characterization of cost estimation methods based on the attributes that are used and the modelling method used results in a formal classification method for cost estimation methods. The first part of the classification method consists of which type of attribute is used. The attribute itself must also be specified. Whenever possible the method of quantifying the attribute should be added to the classification. The second part of the classification entails the type of relation used in the cost estimation method. As was described previously this can be a statistical or a simulated relation. In the cost estimation classification method a further description of the relation is also be added. Final part of the classification is the applicability range of the cost estimation method. Examples of classification according to the proposed method can be seen in Table 6-2.

Table 6-2 Examples of cost estimation methods in the proposed classification system

Method name	Type of attribute	Attribute specification	Attribute quantification	Relation type	Relation specification	Applicability range
Cost estimation method 1	Project	1. Assembly definition 2. Manufacturing location	1. Fuzzy logic 2. nil	Statistical	Stochastic	Subsonic medium sized aircraft movable
Cost estimation method 2	Project	1. Project complexity	1. Number of drawings in project	Statistical	Neural network	Sheet metal rib of a transonic large scale airplane
Cost estimation method 3	Product	1. Product length 2. Product width 3. Product height	1. Length in mm 2. Width in mm 3. Height in mm	Statistical	Data mining	Integrally middle skin panel of a regional jet
Cost estimation method 4	Product	1. Product features	1.1. Number of features 1.2. Feature characteristics, fuzzy	Simulation	Milling of features	Hinge bracket of business jet movable
Cost estimation method 5	Process	1. Injection volume 2. Resin viscosity	1. Volume in mm3 2. Viscosity in poise	Simulation	Formula modelling the injection process	Vacuum infused product with no complex corners
Cost estimation method 6	Process	1. Assembly joint length	1. Length in mm	Statistics	Stochastically	Assembly joint using high lock fasteners in aluminium material

As can be seen many cost estimation methods cover only part of the whole product or process. In these cases the cost estimation of the total product usually consists of a compilation of cost estimation methods. Being used in a cost compilation is however not a characteristic of the cost estimation method itself.

The proposed classification of cost estimation methods is by no means the ultimate solution for recognizing and judging cost estimation methods. However it helps people, especially people not familiar to cost estimation, to recognize what a cost estimation method entails and also helps them to judge if a particular cost estimation method is applicable to their specific problem. Adding boundary conditions is in this sense very useful. However the boundary conditions should be described in simple terms so they are understandable. The result of using the new classification system should be that actors in the design process of a product, which are not cost estimation professionals, are able to recognize if a cost estimation method is applicable to their design. If this can be made possible cost estimation tools can be used more often and at different places in the design process than is currently common practice. Increasing the use of cost estimating methods should ultimately result in more cost effective designs.

6.6 Identification of the cost estimation method to be used in the Movable DEE

The cost estimation method that will be used in the MDEE will have to meet certain requirements. These requirements are the result of what the MDEE is being used for and requirements that are imposed by the cost estimation tool itself. The requirements for the cost estimation method are:

1. Able to model new innovative manufacturing methods.
2. Take advantage of the available models in the MDEE.
3. Provide understandable, transparent results.

As was shown before relational cost estimation methods that use statistics to define the relations on which their cost estimation is based have a limited applicability. These cost estimation techniques use existing product and projects to define the statistical relations. Therefore they are not applicable to new innovative manufacturing methods. Cost estimations based on simulations of manufacturing processes are able to model new innovative manufacturing methods. This is done by simulating the manufacturing method using the physical characteristics of the manufacturing method.

Main advantage of the MDEE is that the data needed by the cost estimation method will be generated automatically. In the cost estimation tool the data will also be processed automatically. Because the steps are automated it is possible to handle more data than would by practical if hand cost estimation was implemented. This opens the possibility to use data intensive cost estimation methods. These data intensive cost estimation methods should have the advantage that they provide more detailed and more accurate cost estimation then less data intensive cost estimation. Of course this is only true when the cost estimation methods used are suited to the product or system of which the cost is estimated. Important issue in using high data content cost estimation methods is to keep the data that is used accessible and transparent to ensure that it can be checked and verified. Furthermore the estimation method must be properly maintained to incorporating the latest developments of the manufacturing processes and materials covered by it.

The cost estimation that best fits the requirements for the cost estimation in the Movable DEE is a cost estimation method based on process attributes, using relations that simulate the process physics of the manufacturing processes used. This method can model innovative manufacturing methods because an estimation can be made on the physical behaviour of these manufacturing methods. It therefore fulfils the first requirement for the cost estimation method implemented in the MDEE. The method is data intensive, because it needs process attributes of all the manufacturable parts and assembly joints in the product. However this data will be generated by the manufacturing view of the Parametric Movable Model (PMM). Therefore the estimation method takes advantage of the available models in the MDEE, the second requirement for the cost estimation method implemented in the MDEE. The process attributes used in the method are attributes generated by this view and other attributes that are provided in the form of input parameters to the MDEE. The cost estimation method will simulate all the sub-processes involved in manufacturing a part or assembling parts. This will provide cost results for each of these processes. When the results are formatted properly they provide a cost estimation that runs from the top level to the bottom level of the manufacturing process tree. The results will be formatted in such a way that they are easily accessible and understandable fulfilling the third requirement for the cost estimation method implemented in the MDEE. A classification of the method used in the MDEE can be seen in Table 6-3.

Table 6-3 MDEE cost estimation classification

Method name	Type of attribute	Attribute specification	Attribute quantification	Relation type	Relation specification	Applicability range
MDEE Cost estimation method	Process	1. Surface area of the produced part 2. Complexity factors per produced part 3. Length of the assembly	1. Area in of the manufacturable parts mm^2 2. Different types of complexity exist per manufacturable part each type is quantified differently 3. Length of assembly connections in mm	simulation	Formula modelling each sub-process of the production or assembly process	Aircraft movable manufactured with the supported production and assembly methods

When properly implemented, the above described cost estimation technique will produce reliable cost estimation results because it stays close to the manufacturing flow of a movable. In this manufacturing flow the costs are incurred, therefore staying as close as possible to it will increase the reliability of the results. Implementation details of the movable cost estimation tool using this estimation technique are discussed in the next chapter.

6.7 Conclusion

In this chapter firstly the different cost estimation methods identified and described in literature are analysed and characterized. The three methods identified are: analogous cost estimating, parametric cost estimating and bottom-up cost estimating. Unfortunately differences between and characteristics of these cost estimation methods are not always clearly and consistently described in literature. This can be problem for people not familiar with cost estimation methods when judging if an estimation method is applicable to their particular problem. Therefore a new cost estimation method classification is proposed. This classification method describes cost estimation methods in a more descriptive way, which is better understandable for people who are not estimation experts. The cost estimation methods are classified based on, input attribute characteristics, relation characteristics and applicability range. Using this classification system the best estimation method for the Movable Design and Engineering Engine is selected. This estimation method is a data intensive automated estimation system based on process attributes using formulas simulating the manufacturing process. This methods best fits the Movable Design and Engineering Engine requirements of being able to model new and innovative manufacturing methods using the advantages of an automated KBE system.

7 Implementation of cost estimation in the Movable Design and Engineering Engine (MDEE)

In this chapter the actual implementation of the cost estimation method selected in chapter 6 will be discussed. As was stated in chapter 6 only recurring cost estimation will be supported. Similar to previous chapters the family of aircraft components used for illustrating the different tools and methodologies will be the family of aircraft movables. Purpose of this chapter is to present a cost estimation methodology that fits in an automated framework; enabling the “Design for Cost” methodology.

Several issues will be discussed, first of which will be the position of the cost estimation tool within the Movable Design and Engineering Engine (MDEE) and the interaction of the cost estimation tool with the other elements of this DEE. The next section of this chapter contains a thorough description of the cost estimation method itself. The third section describes how the cost estimation method is implemented within the MDEE, each element added to the MDEE is described. In the fourth section improvements to the cost estimation module in the MDEE are suggested. In section five an example is shown of a cost estimate of a general aviation rudder. Finally in section six conclusions are drawn.

7.1 Position of the cost estimation elements in the MDEE

Elements of the cost estimation can be found throughout the MDEE. They can be divided into 5 groups:

1. **Input parameters for the cost estimation tools,**
2. **Data collectors in the Parametric Movable Model (PMM),**
3. **Data collections containing information needed for the cost estimation.**
4. **Cost estimation tools estimating the cost of design concepts,**
5. **Cost estimation result, contained in data collections.**

Where these five elements are positioned in the MDEE is visualized in Figure 7-1.

The first group of elements used in the cost estimation are the estimation inputs. Two types of inputs are needed. Firstly the inputs describing the aircraft component

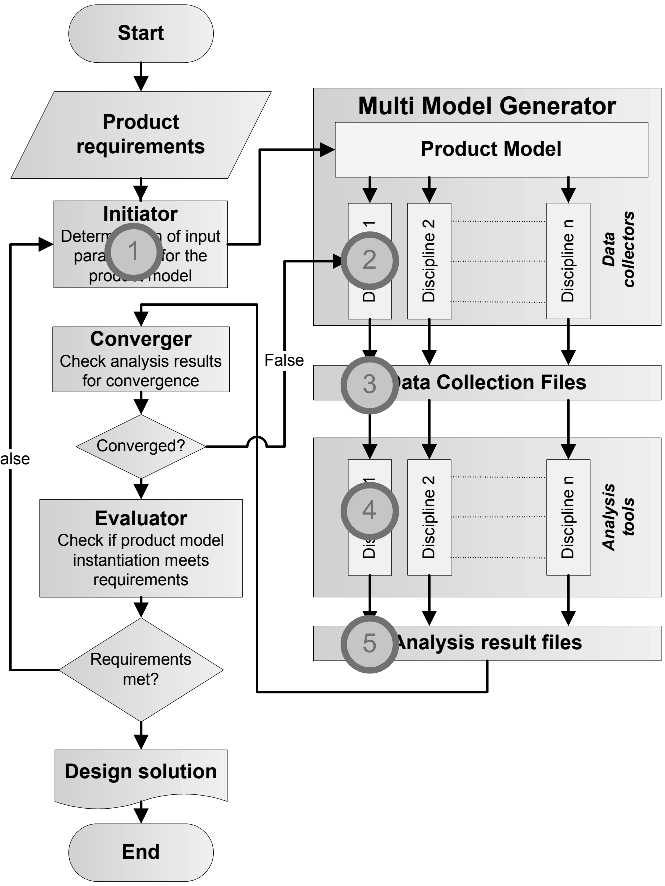


Figure 7-1 Position of cost estimation elements in the Movable Design and Engineering Engine (MDEE)

manufacturing concept, these are part of the input dataset for the PMM and are described in chapter 5. Secondly the manufacturing environment where the aircraft component is manufactured needs to be described. This manufacturing environment is a dataset containing all parameters influencing the cost of manufacturing the movable, but not describing the design concept of the movable itself. In case of the MDEE the manufacturing environment is stored in the Manufacturing Database, which was introduced in chapter 5 and is thoroughly described in the section “Input parameters for cost estimation”. The two different input groups should be kept separate because in the aircraft component design process different people will be responsible for them. The product specific inputs are the responsibility of the designer, while the manufacturing engineer is responsible for defining the manufacturing environment inputs.

The second group of elements used in the cost estimation are the data collectors that are part of the PMM. These elements are added to the PMM in the form of Capability Modules (CM’s). These collectors extract manufacturing data from the manufacturing view of the PMM described in chapter 5. This data is stored in data collections that can be used by other elements of the MDEE. These data collections should be of a of a common file format so they can be interpreted and understood by different tools or people using the tools. In case of the cost estimation all the needed data can be represented as numbers or text, so the only requirement for the data collector is that it should be capable to write ASCII type files.

The third group of elements used in the cost estimation are the data collections containing data extracted and collected by the data collectors discussed previously. Most important requirements for collections are that they should be easily accessible and transparent and that they should store the manufacturing data in a structured way. A way to make the data collection accessible is to make sure that they can be viewed with software commonly available. Commonly available software can for instance be a text viewer/manipulator or an internet browser. The data collections should also represent the data in a structured way.

To keep the data collections structured an additional layer defining the structure of the data should be part of the data collection. This additional data structure layer can be defined MDEE specific, which would make it possible to incorporate features especially suited for this MDEE. However using a newly defined format might limits the re-usability of the reports themselves and the data collectors generating the data collections. A better way of adding the structure layer is to use a structured text file formatted according to a commonly accepted standard. Big advantage of this approach it that users of the MDEE are probably familiar with the way the data is structured and therefore can easily understand the data structure, ensuring that the data collections are accessible and understandable. In case of the MDEE the XML-file format was chosen for as the format of the data collections. This has, besides the advantage of structured data representation, the advantage that it can be interpreted by many software tools. This simplifies the MDEE by, in some cases, eliminating the need for data translation modules.

The fourth group of elements used in the cost estimation are the cost estimation tools themselves. In these analysis tools the actual cost estimation is performed. Cost estimation in this case means determining and quantifying the resources needed to manufacture and assemble the aircraft component. This is done using the manufacturing data stored in the data collection described above and algorithms based on the physics of the manufacturing processes used. Output of the cost estimation should be the amount of resources used or a translation of these resources into actual financial cost.

The fifth and final group of elements used in the cost estimation is the cost estimation data collection storing the cost estimation results. Just as the data collections containing the manufacturing data this data collection should be accessible and transparent. It should also store the cost estimation results data in a structured way, structured meaning that the cost estimation results should be available on different levels. These different levels range from the highest level, in which the total cost of the aircraft component is represented, to the lowest level, in which the cost of a sub process needed for the manufacture of the components part is represented. As format for this data collection the same XML-file format as the manufacturing data collections was chosen.

7.2 Cost estimation characteristics

The dev elopement of a new cost estimation method is not the objective of this chapter. Therefore an existing cost estimation method will be adjusted to fit as a basis for the cost estimation tool in the MDEE. The cost estimation method implemented in the MDEE is based on the method described by Neoh (1995) and Haffner (2002). This method was chosen because it fulfils the requirements for the cost estimation method devised in chapter 6. It is an estimation method based on process attributes, using relations that simulate the process physics of the manufacturing processes used. In this section a short description of the fundamentals of the cost estimation method will be given. Originally the method was only used for the cost estimation of manufacturing processes involving composite materials. However it can also be applied for other manufacturing methods. The implemented cost estimation method determines the process time of a certain manufacturing process. In the cost estimation method implemented in the MDEE this method is used to determine the process times for all sub-processes involved in manufacturing a part or assembling two parts. These process times can be used to estimate the resources used in each sub-process. In addition to the process times, materials used in the manufacturing process also have a big influence on cost. Therefore the cost estimation method was expanded to also determine the amount of material used in a manufacturing sub-process.

7.2.1 Determining the process time

In the cost estimation method implemented in the MDEE the process time of a production or assembly sub-process is calculated with a Cost Estimating Relation (CER). This is a generic formula that describes the relation of process time to a process attribute. The generic form of the CER is:

$$t = t_{delay} + \tau_0 \sqrt{\left(\frac{x}{v_0 \cdot \tau_0} + 1\right)^2 - 1} \quad (1)$$

x = Variable on which the cost estimation is based, for instance area or length

t_{delay} = Delay time in the manufacturing operation

v_0 = Steady state speed of the manufacturing operation

τ_0 = Time it takes to reach 63% of the steady state speed

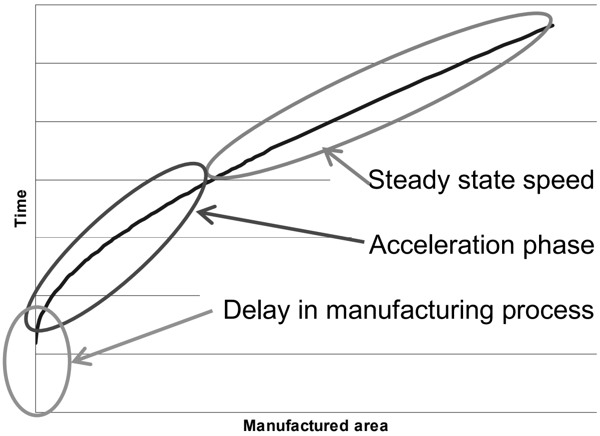


Figure 7-2 Graphic representation of the relation used to estimate process times, identifying the three main contributors to process time.

The process attribute has to be determined using a model of aircraft component. In case of the MDEE this attribute is extracted from the manufacturing view of the PMM. What the process attribute is depends on the manufacturing process. This can for example be the total area that should be laid up in a hand lay-up process or the volume that should be injected in an injection process.

The three attributes in the process time estimating CER describing the physics of the manufacturing sub-process are stored in the manufacturing database. For many processes the values of these three attributes are available in literature. There are also methods of determining these three attributes. First of which is the manufacture of test samples using the manufacturing process for which the attributes should be determined. Second method of determining the attributes is deriving them from other process attributes. For instance the steady state speed of a milling machine will to a large extend determine the steady state speed of the milling manufacturing sub-process. Although the attributes of many of the sub-processes are available in literature, for a properly functioning and up-to-date cost estimation tool they have to be calibrated and maintained. Calibration means that the attributes should be based on the processes that are, or will, actually be used in a particular company or factory. Maintenance means that the attributes should be kept up-to-date to reflect changes in the manufacturing sub-processes or the factory where it is used.

When the process attributes of all production and assembly sub-processes involved in manufacturing an aircraft component are known, the total manufacturing time of the aircraft component can be determined. The sub-process times can also be used to determine some of the consumed resources, such as labour hours and machine hours. Other resources require a different approach. One of these different resources is the amount and type of materials used in the different sub processes. How this resource can be determined is explained in the next section.

7.2.2 Determining the amount of material used

Materials used in the production and assembly sub-processes consist of two types:

- *Product materials*, materials that remain in the finished product

- *Consumables*, materials that are used in the manufacturing process of a product but do not remain in the finished product.

In the cost estimation the amount and type of both groups of material will be determined. The relation used to determine the material cost of a sub process relates a process attribute to the total amount of material used. The CER used is:

$$C_m = x \cdot \left(1 + \frac{sr}{100}\right) \cdot P \qquad (2)$$

C_m = Estimated material cost
x = Variable on which the cost estimation is based, for instance area or length
sr = Scrap rate percentage
P = Material unit price

The process attribute *X* is defined in the same way as for the process time determination. The additional attributes needed for the cost estimation are the scrap rate and the unit price of the material. Both are considered input parameters for the cost estimation and are stored in the manufacturing database. The scrap rate has to be determined for each sub-process in which a material or consumable is used. The material unit cost is related to the specific type of material. This material type is determined differently for the two groups. The consumables are process specific. This material type can therefore be linked to the applicable processes in the cost estimation software. Product Materials on the other hand are determined by the manufacturing concept. In case of the MDEE the types of these materials is therefore defined in the data set describing the movable design concept.

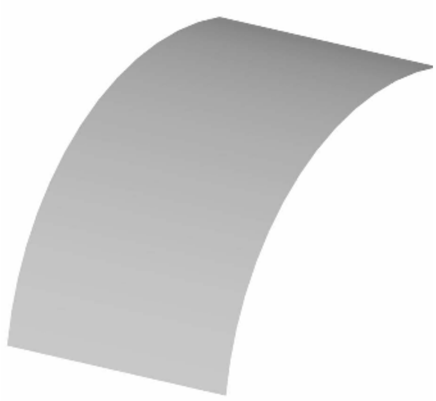
7.2.3 Incorporating complicity issues in the process time determination

In the CER for determining the process time of the different sub-processes, geometric part complexity does not play a role. However for some sub-processes geometric part complexity can have a profound influence on the process time. This is for instance the case during the lay-up phase of the hand lay-up manufacturing process of composite materials. To ensure that the cost estimation module remains accurate for complex parts the existing CER was extended to include complexity issues. In this case the new CER was applied to the lay-up sub-process, however with some minor adjustments they can also be used for other sub-processes. A thorough description of the theory behind the geometric complexity determination and the adjustments to the existing CER can be found in the first and second sections of Appendix B. In this section an overview will be made.

Geometrical complexity of a part is defined by several geometric characteristics. The most important ones are:

1. ***Complexity due to continuous curvature both in the normal and geodesic direction.***
   Continuous curvature is one of the most commonly occurring geometric complexity phenomena. Curvature can occur in 2 directions. First of these directions is the normal direction. Normal curvature in a point means the biggest curvature or smallest radius in this particular surface point. Geodesic curvature is the curvature perpendicular to the normal curvature. Normal curvature is sometimes called single

curvature because a surface that has only normal curvature is a single curved surface. When a geodesic curvature occurs somewhere on the surface the surface is double curved. In the hand lay-up process normal and especially geodesic curvature can make it more difficult to lay-up the materials. This results in a slower lay-up speed ultimately resulting in increased process times. Examples of single and double curves surfaces can be seen in Figure 7-3 and Figure 7-4.



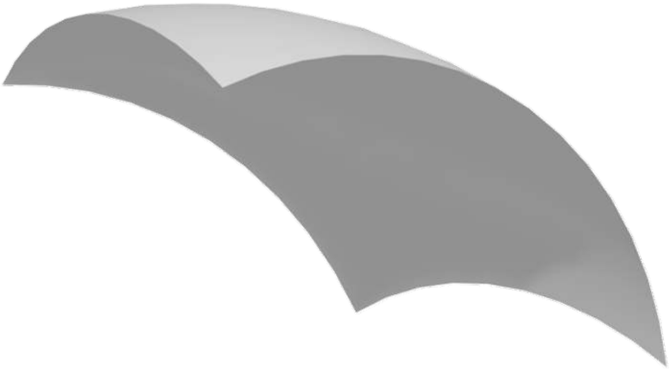


Figure 7-3 Single curved surface **Figure 7-4 Double curved surface**

2. ***Complexity due to discontinuous surface normals.***
   In the PMM it can happen that different surfaces are combined into a single manufacturable part. This can result in connections between areas that have discontinuities in the surface normals. These connections can result extended process times because it can be difficult to let the material follow the sharp contour of the connection. Another issue is that the lay-up process essentially restarts at this connection. These factors result in an increase of process time.

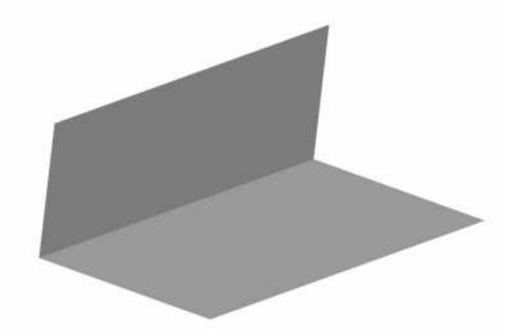


Figure 7-5 Surfaces with a discontinuous surface normal vector

3. ***Complexity due to geodesic material curvature imposed by discontinues surface normals.***
   Contrary to the previous 2 cases this complexity cannot be identified by looking at the different surfaces that make up the part. In fact this complexity only occurs in the material that is laid up. However because the complexity is the result of the part geometry it is still called a geometric complexity. This complexity occurs when the connection between areas with discontinuous surface normals is curved. For instance in a part consisting of two surfaces, the material lay-up will start in one surface of the connection. This fixes the orientation of the material. When the material is laid up over the connection, the material will have to be stretched or shrinked to fit the second surface. This stretching or shrinking is a result of the imposed geodesic curvature of the material and makes it more difficult to lay-up the material resulting in an increase of the process time.

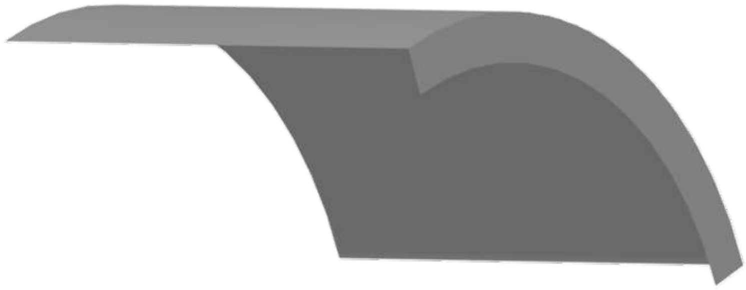


Figure 7-6 Two surfaces forming a part with a shrink flange

Complexity is quantified in the form of a value for information content. For each of the complexities a different definition of information content exists. How these information contents are derived can be found in Appendix B in this section only the resulting expressions and a short description of the complexity will be presented.

The information of the normal and geodesic curvature (complexity type 1) is determined by integrating the curvature over the surface in question. This results in the following expressions for the information content. Normal curved-information content of smooth surfaces:

$$I_n = \iint_{surface} \kappa_n ds \tag{3}$$

Geodesic curved-information content of smooth surfaces:

$$I_g = \iint_{surface} \kappa_g ds \tag{4}$$

For sharp connections (complexity type 2) the assumption is made the that angle between the areas involved in the connection remains constant, the expression for sharp connection information content then becomes:

$$I_{sharp} = \left|\pi - \theta_{sharp}\right| \cdot L_{curve} \tag{5}$$

Information content for induced geodesic curvature (complexity type 3) is somewhat different than the information contents discussed before, because it is dependent on the initial material orientation of a part. The information content is defined as the maximum geodesic curvature possible in a curved connection and is dependent on the angle difference between the surfaces involved in the curved connection. Expression for the information content of induced geodesic curvature is:

$$\theta_d = \frac{\alpha}{2} \tag{6}$$

To determine the process time of the lay-up process of a complex part an extended CER based on the hyperbolic function is used. In Haffner (2002) an extension of the standard hyperbolic function is presented:

$$t=\left(\tau_{single}\cdot\sqrt{\left(\frac{A_{single}}{v_{single}\cdot\tau_{single}}+1\right)^{2}-1}\right)+\left(\tau_{0}\cdot\sqrt{\left(\frac{A_{double}}{v_{double}\cdot\tau_{0}}+1\right)^{2}-1}\right) \qquad (7)$$

Where:

$$\tau_{single}=\tau_{0}+b_{n}\cdot I_{sharp} \qquad (8)$$

b_n = Factor determining the influence of sharp edges on the acceleration phase

$$v_{single}=\frac{v_{0}}{1+\left({}^{v_0}\!/\!_{c_n}\right)\cdot I_{n}} \qquad (9)$$

c_n = Factor determining the influence of normal curvature on the steady state speed

$$v_{double}=\frac{v_{0}}{1+\left({}^{v_0}\!/\!_{c_g}\right)\cdot \theta_{d}} \qquad (10)$$

c_g = Factor determining the influence of geodesic curvature imposed by discontinuous connections on the steady state speed

The expression presented above has some shortcomings. The two main short comings are:

- It does not incorporate the geodesic curvature of smooth surfaces, while this can have a profound effect on process times.
- Complexity due to imposed geodesic curvature is treated as a new process start. This seems quite odd because complexity resulting from sharp connections is not treated as a new process start.

To counter these shortcomings the expression was adjusted. The resulting expressions can be seen below:

$$t=\tau_{overall}\cdot\sqrt{\left(\frac{A_{total}}{v_{overall}\cdot\tau_{overall}}+1\right)^{2}-1} \qquad (11)$$

Where the acceleration parameter is determined by the sharp connection information content:

$$\tau_{overall}=\tau_{0}+b_{n}\cdot\sum_{n}^{NoOfShrpConnections} I_{sharp} \qquad (12)$$

The normal and geodesic curvature of smooth surfaces and the induced geodesic curvature influence the steady state speed parameter:

$$v_{overall}=\frac{v_{0}\cdot A_{flat}+v_{single}\cdot\left(A_{single}+A_{double}\right)+v_{double}\cdot A_{double}+V_{d}}{\left(A_{flat}+A_{single}+2\cdot A_{double}+\sum_{n}^{NoOfCurvedConnections} A_{n}\right)} \qquad (13)$$

Where:

$$v_{single}=\frac{v_{0}}{1+\left({}^{v_0}\!/\!_{c_n}\right)\cdot\sum_{i}^{NoOfSurfaces} I_{n_i}} \qquad (14)$$

$$v_{double} = \frac{v_0}{1+\left({v_0}/{c_d} \right) \cdot \sum_{i}^{NoOfSurfaces} I_{g_i}} \qquad (15)$$

c_d = Factor determining the influence of smooth geodesic curvature on the steady state speed

$$V_d = \sum_{n=1}^{NoOfCurvedConnections} \frac{v_0 \cdot A_n}{1+\left({v_0}/{c_g} \right) \cdot \theta_{d_n}} \qquad (16)$$

The new expressions are extended in such a way that it can still use process attributes determined for the original expression. The new extended CER's characteristics are:

- Complexity due to imposed geodesic curvature is separated from the actual connection it is related to. This means that a curved sharp connection not only adds complexity through induced double curvature but is also considered as a normal sharp connection, increasing sharp connection information content.
- The expression considers the lay-up of the surface as one continuous process and does not separate normal and geodesic parts. This means that the expression has the form of a single adjusted hyperbolic function.

The new extended expression also considers smooth geodesic curvature. This requires that an extra process attribute determining the influence of geodesic curvature on process time has to be determined. This attribute will be called c_d.

In the expressions presented above process parameters (b_n, c_n, c_d, c_g) determine the influence of the various complexities on the process time. Of these parameters b_n, c_n and c_g are known from literature while c_d has to be determined. When all the process parameters are determined for any process resembling the lay-up phase of the hand lay-up process the extended CER can also be used for these processes.

7.3 Implementation details of the cost estimation module

In this section the details of the modules that have been developed to enable cost estimation in the MDEE will be discussed. The implemented modules are those shown in Figure 7-1.

7.3.1 Input parameters for cost estimation

The input parameters for the cost estimation are stored in the manufacturing database. This database can be filled and kept up-to-date by the manufacturing engineer. In the movable design process it can be accessed and used without checking its contents. The attributes in the manufacturing database should be used to model the manufacturing environment in which the movable is being manufactured. In the MDEE the manufacturing environment is modelled as a collection of attributes or parameters. This manufacturing environment consists of three types of attributes:

1. ***Process attributes*** These describe the manufacturing processes that can be used to manufacture an aircraft movable. A parameter stored here could for instance be the steady state speed of the milling manufacturing process.
2. ***Material attributes*** These describe the product materials and consumables used in manufacturing a movable. A parameter stored here could for instance be the material price of the Aluminium 2024 material.

3. ***General attributes,*** These describe other elements influencing the movable manufacturing process. A parameter stored here could for instance be the typical labour rate.

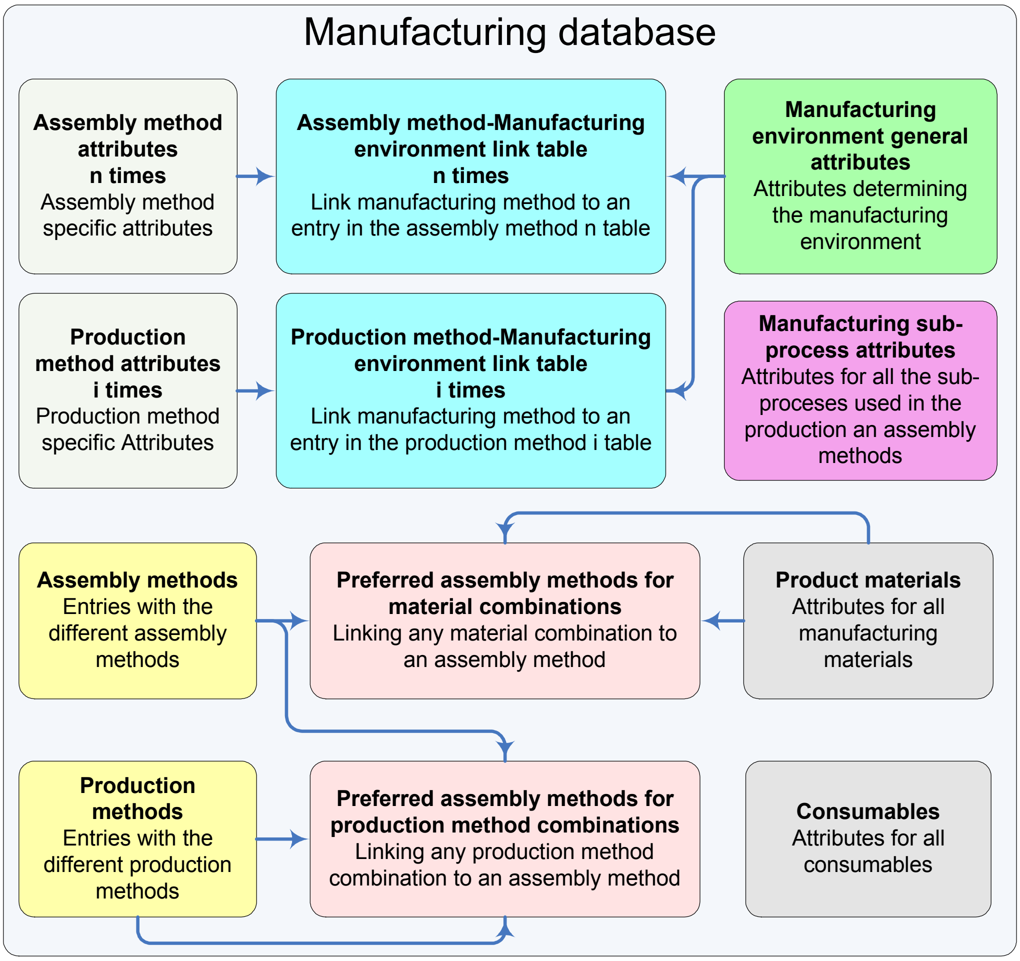


Figure 7-7 Graphical representation of the manufacturing database showing all the tables

The manufacturing database is a relational database. Such a relation database consists of several tables, each of which fulfils a specific function. In these tables the columns are formed by the attributes. Each row in the table represents an entry set for all the attributes. The names and functions of the different tables are shown in Figure 7-7 and are described below:

- ***Assembly methods***

  In this table all the assembly methods are represented with name, description and ID number. Each assembly method should also have a separate table in which the attributes for this assembly method are stored.
- ***Production methods***

  Analogous to the previous table this table stores the production methods with name, description and ID number. Each production method should have an entry in this table and should also be represented by a separate table storing the production methods attributes.

- ***Assembly method attributes, n times***
  This table is present for all the assembly methods that are implemented. So in case of n different assembly methods implemented there are n different tables. In these tables process attributes such as scrap rates and weld widths are defined. The table also defines for each of the sub-processes specified for the assembly process whether or not it should be used in the cost estimation. The attributes stored in each of these tables are assembly method specific, meaning that each table stores different attributes.
- ***Production method attributes, i times***
  This table is analogous to the previous table only this time for production processes. Again one table is present for each production methods, so in this case if there are i production processes there will be i tables. The attributes stored in each of these tables are production method specific, meaning that each table stores different attributes.
- ***Manufacturing environment general attributes***
  In this table specific attributes of a manufacturing environment are stored. This can for instance be the labour rate or the labourers' skill level. Each entry in this table represents a new manufacturing environment. In this way different geographical locations or factories can be represented as different manufacturing environments.
- ***Assembly method-Manufacturing environment link table, n times***
  This table is present for all different assembly methods. It links an entry in the corresponding assembly methods variables table to an entry in the manufacturing environment table using the unique ID's of the entries in the "assembly method attributes" and "manufacturing environment" tables. This table is used to link manufacturing environments to specific characteristics of assembly methods in these manufacturing environments.
- ***Production method-Manufacturing environment link table, i times***
  This table is analogous to the previous tables only this time it links an entry in the corresponding "production methods attributes" table to an entry in the "manufacturing environment" table.
- ***Preferred assembly method for production methods combinations***
  This table is actually not part of the cost estimation inputs however, for the completeness of the manufacturing database description a description of the table is included here. In this table the preferred assembly methods for production method combinations are stored. Each entry in the table consist of 4 attributes; the manufacturing environment ID, the assembly ID, the first production method ID and the second production method ID. For each manufacturing environment all possible production method combinations should have an entry in the table.
- ***Preferred assembly method for material combinations***
  This table is analogous to the previous one except that the production method ID's are replaced by manufacturing material ID's. Again for all manufacturing environments, all possible manufacturing material combinations should have an entry in the table.
- ***Product materials***

In this table the attributes of the materials that make up the product are stored. It consists of identifying attributes, such as ID number and name, and of the unit price of the material.

- ***Consumables***
  In this table the attributes of materials used in the manufacturing process of the product but not actually making up the product are stored. This table is analogous to the previous one except that this table stores attributes of materials only used as consumables.
- ***Manufacturing sub-process attributes***
  In this table the attributes of all the sub processes used in the assembly and production methods are stored. Most of these attributes are taken from literature. Attributes are for example the steady state speed of a process, the delay time and a factor determining the acceleration phase. Furthermore attributes about the influence of complexity and the number of machines or people needed for the sub-process are included in each entry of the table.

The attributes stored in the manufacturing database form an important part of the cost estimation, because they determine what the manufacturing processes used to manufacture the movable will look like and therefore what the cost of manufacturing will be. Keeping the manufacturing database well maintained is essential for producing consistent and reliable cost estimates. Maintenance consists first of all of keeping all the attributes up-to-date. Second maintenance issue is expanding the manufacturing database. When new manufacturing methods or material are added all the tables will have to be kept consistent to keep the whole cost estimation process running smoothly.

The manufacturing database should be a distributed entity; this means that it should be accessible from outside the cost estimation system. Accessibility of the manufacturing database is needed because part of the data stored in it is supplied by manufacturing experts. To keep the cost estimation process up-to-date this manufacturing data should be updated when new data becomes available or when manufacturing process characteristics change. Keeping the data up-to-date is the responsibility of the manufacturing experts which should therefore have easy access to the database. This can be achieved by making the database accessible via the web. In case of the manufacturing database it was implemented using MySQL software. Using a basic user interface the MySQL database is made accessible via any common internet browser. Therefore data in the database can be accessed and changed by anyone with an internet connection and the right privileges. Privileges for changing any piece of data should only be granted to the manufacturing expert responsible for this data.

7.3.2 Cost estimation data collectors in the PMM

Cost estimation data collectors are added as CM’s to the PMM. They collect the data needed by the cost estimation module and store this data in data collections. The collections are always based on the manufacturing view of the PMM. How this manufacturing view is constructed is explained in chapter 5. Four separate data collections with different characteristics can be identified. These collections are:

1. Collection storing manufacturable part data

2. Collection storing stiffener data
3. Collection storing assembly connection data
4. Collection storing general manufacturing data

The first three of these collections are created by cost estimation data collectors. The position of the cost estimation data collectors that are part of the PMM is shown in Figure 7-8. This figure also shows how the capability of the manufacturing view of the PMM is extended by applying the “Complexity data generator” CM. This module enables the determination of complexity parameters in the manufacturing view.

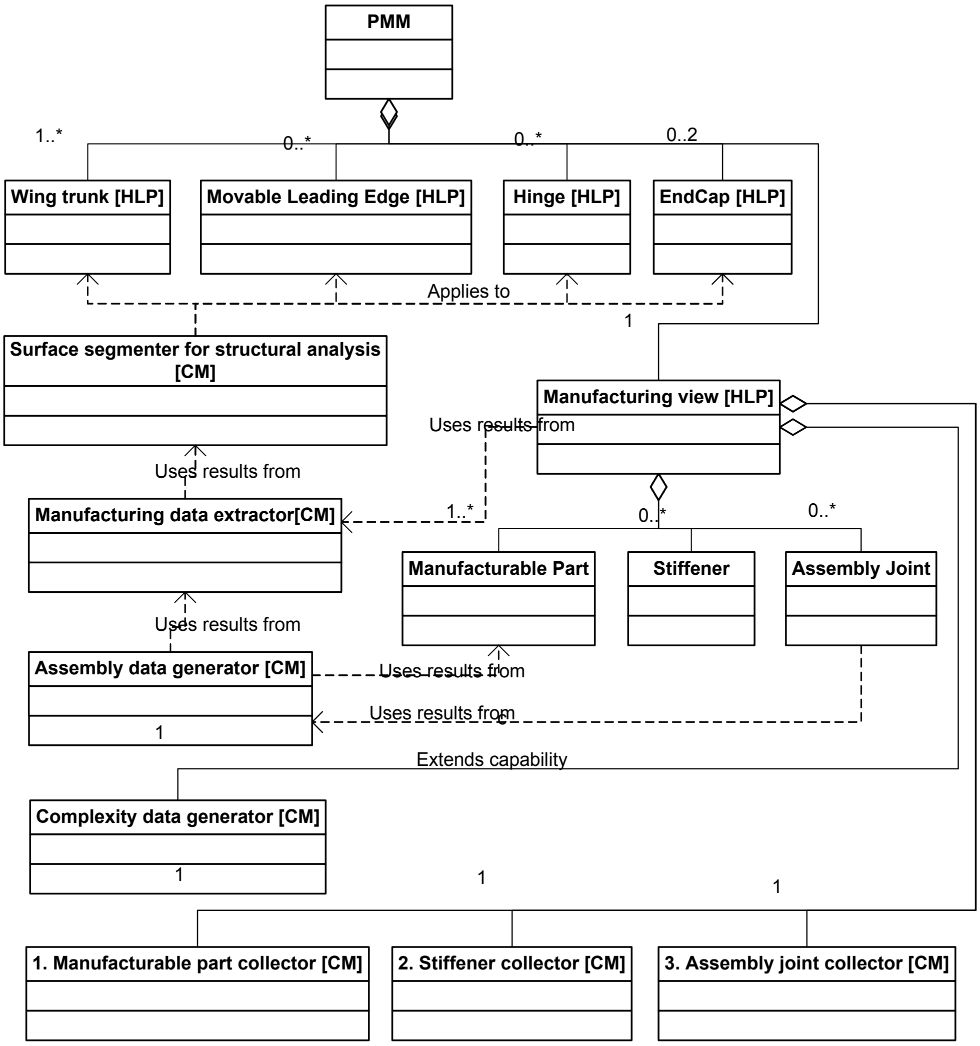


Figure 7-8 Schematic lay out of the PMM including the manufacturing data collectors

7.3.3 Collection storing manufacturable part data

In the “Collection storing manufacturable part data” (1) data is stored about the manufacturable parts. A manufacturable part is a part of the movable which is manufactured using one production method. A manufacturable part is used in an assembly process and is manufactured without using assembly processes, meaning that it is not a sub-assembly. It is specified in the PMM input data set and represented in the manufacturing view of the PMM discussed in chapter 5. In the collection each manufacturable part has an entry that consists of different sections. In Figure 7-9 all the manufacturable part attributes are shown.

Manufacturable parts data collection

1. General attributes
- Production group number
- Production group type

2. Geometric attributes
- Total area
- Total Volume
- Total outer boundary length
- Average maximum curvature from all surface segments
- Average minimum curvature from all surface segments

3. Manufacturing attributes
- Manufacturing process
- Manufacturing material
- Sub assembly number
- Sub assembly sequence number

4. Complexity attributes
- Maximum angle difference
- Flat surface area
- Normal curvature information content
- Normal curvature surface area
- Geodesic curvature information content
- Geodesic curvature surface area
- Induced geodesic curvature information content
- Flange flat area
- Flange normal curved area
- Flange single curved area
- Total flange area

5. Flange attributes (n times)
- ID number (n)
- Flange boundary angle
- Affected flange area
- Flange surface type
- Angle differences start and end of the flange
- Flange fill percentage

6. Layer attributes (i times)
- ID number (i)
- Layer thickness
- Layer orientation

7. Sub-surface attributes (k times)
- ID number (k)
- Maximum curvature
- Minimum curvature
- Sub-surface type
- Sub-surface area
- Sub-surface structural type

8. Assembly joint attributes (m times)
- ID number, not related to m but defined in the assembly joints data collection
- Connected production group number
- Assembly joint length
- Assembly joint type
- Assembly joint assembly method

Figure 7-9 The attributes stored in the "collection storing manufacturable part data" per manufacturable part

The sections represented in Figure 7-9 are:

1. *General attributes,* In these attributes general information about the manufacturable part is stored.
2. *Geometric attributes,* In these attributes geometric information about a manufacturable part is stored. This geometrical information is for instance the total outer boundary length. This is determined by collecting all the outside edges of a manufacturable part and summing the length of all these edges. How this is done is shown in Figure 7-10.

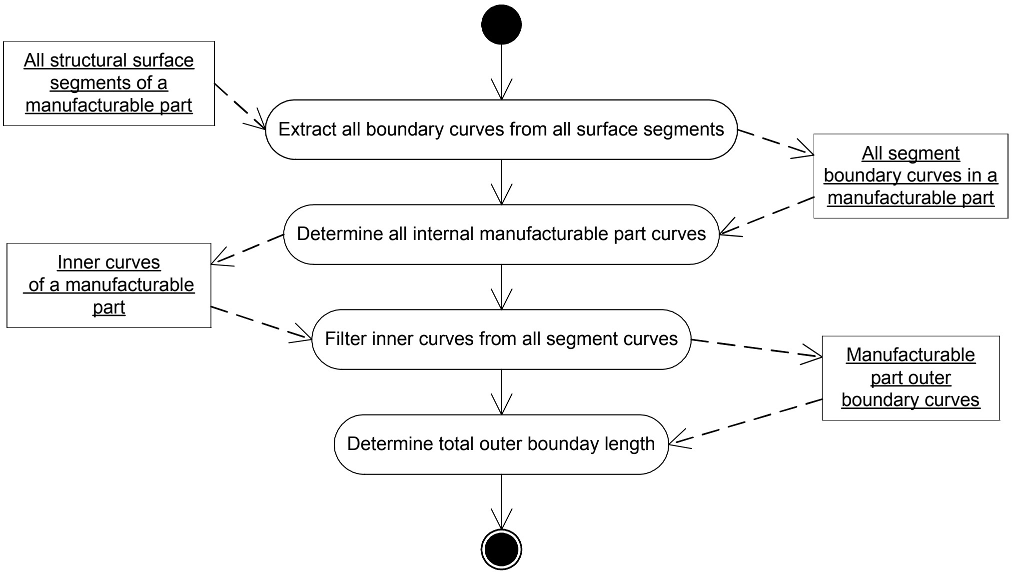


Figure 7-10 Activity diagram of the determination of the outer boundary length

3. *Manufacturing attributes,* The manufacturing attributes define how a manufacturable part is manufactured. This also includes the position of the part in the movable assembly sequence. Another attribute in this section is the material of which the part is constructed. This is considered constant for the whole part.
4. *Complexity attributes,* Complexity attributes are used when determining the manufacturing times for a particular manufacturing sub-process. They were discussed in the previous sections of this chapter. The complexity attributes are determined by the Complexity data generator CM shown in Figure 7-8.
5. *Flange attributes (n times),* The flange attributes are present for each flange. The number of flanges is dependent on the number of sub-surface edges that lie at the outer boundary of the manufacturable part. How the flange attributes are extracted from the PMM and what influence they have on the cost estimation is shown in Appendix C.
6. *Layer attributes (i times),* The layer attributes are present for each material layer. The number of which is defined in the manufacturing concept part of the input data set for the PMM.
7. *Sub-surface attributes (k times),* As was discussed before a manufacturable part is a collection of sub-surfaces created from the segmented structural model. For each of these sub-surfaces attributes are collected.
8. *Assembly joint attributes (m times),* For each connection of which the manufacturable part is a member attributes are stored. This data is linked to an entry in the collection storing assembly data.

7.3.4 Collection storing stiffener data

The collection storing the stiffener data stores the data extracted for all the stiffeners. Each stiffener has an entry. The attributes stored in the data collection can be divided into groups analogous to the collections storing the manufacturable parts data. All the attributes in the collection storing stiffener data can be seen in Figure 7-11.

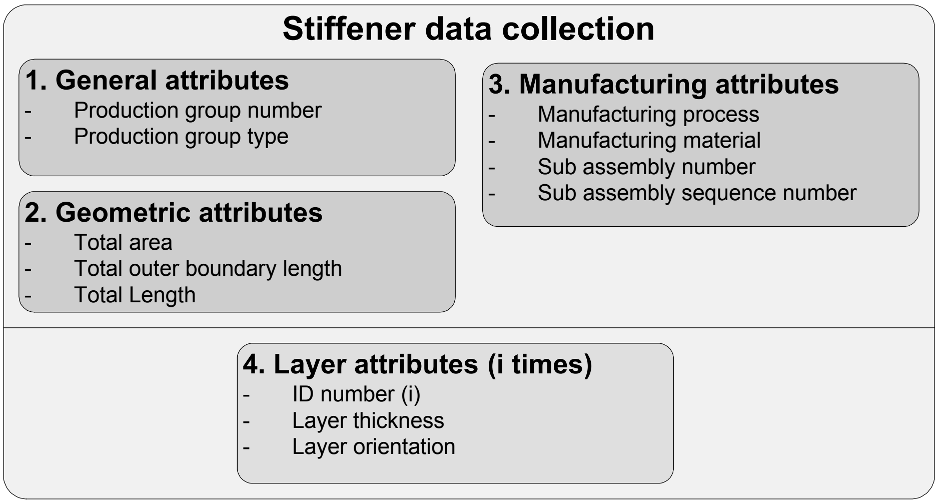


Figure 7-11 The attributes stored in the "collection storing stiffener data" per stiffener

7.3.5 Collection storing assembly data

In the assembly joint data collection the information about all the joints in the movable is stored. This information is generated in the manufacturing view of the PMM based on preferred assembly methods stored in the manufacturing database. What attributes are stored in the data collection can be seen in Figure 7-12. The sections in this data collection are analogous to those in the manufacturable part data collection.

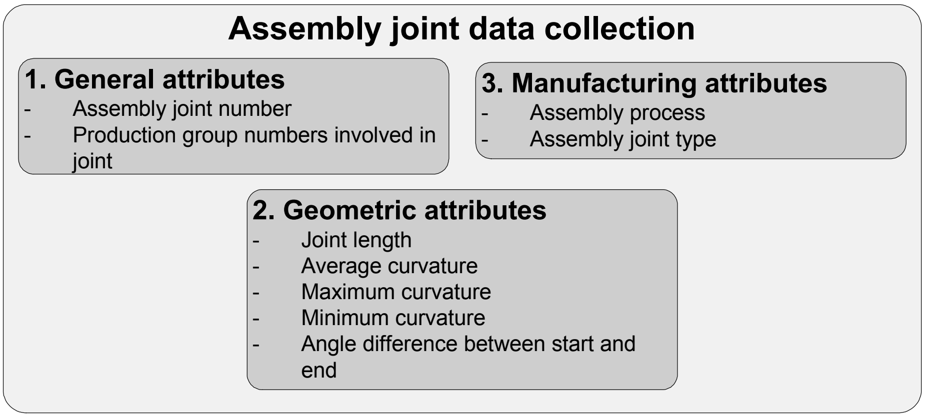


Figure 7-12 The attributes stored in the "collection storing assembly data" per assembly joint

7.3.6 Collection storing general manufacturing data

The collection storing general manufacturing data contains the general manufacturing information about the movable concept that is needed for the cost estimation of this concept. In this case the general information needed for the cost estimation consists of the manufacturing environment in which the cost estimation is to be performed. This manufacturing environment determines parameters such as material prices, labour rates and process characteristics. These parameters are stored in the manufacturing database. Which manufacturing environment should be used for the cost estimation itself is determined in the manufacturing concept part of the PMM input data set.

7.3.7 Data collection characteristics

As was mentioned earlier the four data collections needed by the cost estimation module are stored in the XML format. In this section the form and use of the data collections will be discussed, not the actual contents of the data collection which were discussed in the previous sections.

The XML file format has several characteristics that are advantageous when it is used to transport the information in the MDEE. These characteristics are:

- ***XML-files structure data into information using tags***. The numbers stored in XML files are always accompanied by a tag telling what the number means. In this way the files can be read and understood. This transforms the data, which are the numbers itself, into information because the context of the data is always supplied together with the number.
- ***XML-files can be parsed by many software tools***. Parsing in this case means that software tools can interpret the file and the data stored in the file according to the tools needs. This ensures that the structuring of the information remains intact when it is used by these software tools and that not only the numbers stored in the XML-file but also the structure of the XML-file itself can be used by the tool. Parsing also works the other way round, many software tools have the possibility to write data generated into a structured XML-file.
- ***XML-files can be represented in a structured way on most computers***. This in fact related to the previous issue. The internet browsers available on most computers parse or interpret the XML-file and show it in a structured way. An example of an XML-file represented in an internet browser can be seen in Figure 7-13.
- ***XML-files are basically plain text and can therefore be written by any text writer.*** The XML format is nothing more that formatting plain ASCII text in a smart way. Therefore it can be written by all software tools that have a text writing capability.

The characteristics described above make the XML-format well suited for the reports in the MDEE. XML also has disadvantages. For example if the amount of data is very large it is not very useful to use XML. Because each number in the data collection will also require a tag explaining what it means. This results in a big increase of the size of the data collection.

```
<ProdGroupInfo>
    <ProdgroupID type = "integer">0</ProdgroupID>
    <ProdgroupType type = "string">Part</ProdgroupType>
    <TotalAreaSurfs type = "double">15054.412083143116</TotalAreaSurfs>
    <TotalVolume type = "double">13548.970874828805</TotalVolume>
    <TotalOuterBoundLength type = "double">880.3753655126852</TotalOuterBoundLength>
    <Totalavgcurvmax type = "double">0.0</Totalavgcurvmax>
    <Totalavgcurvmin type = "double">0.0</Totalavgcurvmin>
    <Manufacturingprocess type = "string">RUBBER_FORMING_THERMOPLASTICS</Manufacturingprocess>
    <Material type = "string">CARBON_PEI</Material>
    <AngleDifference type = "double">9.80198522354923e-11</AngleDifference>
    <SurfFlatArea type = "double">15054.412083143116</SurfFlatArea>
    <SurfSingleCurveInfoContent type = "double">0.0</SurfSingleCurveInfoContent>
    <SurfSingleCurveArea type = "double">0</SurfSingleCurveArea>
    <SurfDoubleCurveInfoContent type = "double">0.0</SurfDoubleCurveInfoContent>
    <SurfDoubleCurveArea type = "double">0</SurfDoubleCurveArea>
    <BoundarySingleCurveInfoContent type = "double">0.0</BoundarySingleCurveInfoContent>
    <FlangeFlatArea type = "double">11885.067434421251</FlangeFlatArea>
    <FlangeSingleCurvedArea type = "double">0</FlangeSingleCurvedArea>
    <FlangeSingleCurveInfoContent type = "double">1244.6013513132364</FlangeSingleCurveInfoContent>
    <TotalFlangeArea type = "double">11885.067434421251</TotalFlangeArea>
    <FlangeSharpBoundaryInfo>
      <FlangeSharpBoundaryID>0</FlangeSharpBoundaryID>
      <FlangeBoundaryAngle type = "double">1.5707963267948966</FlangeBoundaryAngle>
      <FlangeAffectedSurfArea type = "double">3556.8618095665297</FlangeAffectedSurfArea>
      <FlangeAffectedSurfType type = "string">FLAT</FlangeAffectedSurfType>
      <FlangeConnectionAngleDiff type = "double">0</FlangeConnectionAngleDiff>
      <FlangePercentage type = "double">90</FlangePercentage>
    </FlangeSharpBoundaryInfo>
```

Figure 7-13 Example of an XML-file represented in a structured way by an internet browser. In this case part of the manufacturable parts file is represented.

7.3.8 The cost estimation module characteristics

The module that performs the actual cost estimation in the MDEE consists of several sub-modules. This modular build up is essential to keep the cost estimation efficient and maintainable. Maintainability is important because new manufacturing methods will have to be added to the cost estimation module to keep it up-to-date. In this section the different sub-modules that make up the cost estimation module will be discussed. What the cost estimation process looks like and how the different sub-modules fit in this process can be see in Figure 7-14.

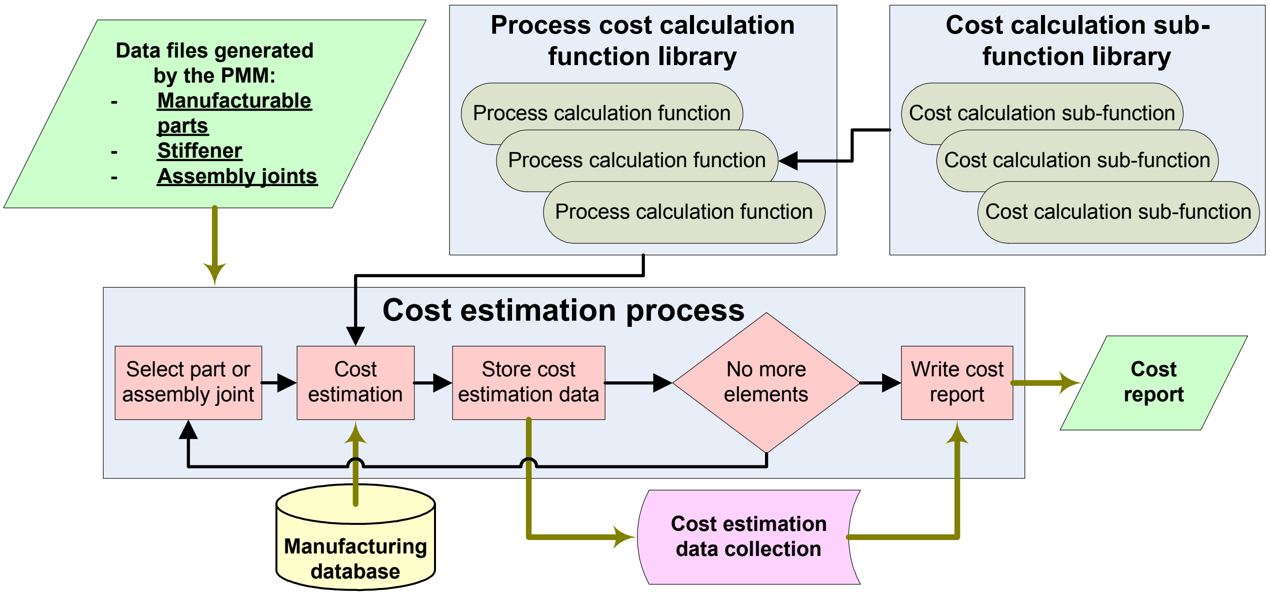


Figure 7-14 Diagram of the cost estimation process

Cost estimation core

The actual cost of a design concept is estimated in the cost estimation core. This core brings together the different other sub modules to perform the actual cost estimate. Figure 7-14 shows that the core of the cost estimation, called “Cost estimation process”, performs several tasks. Main task is to make sure that the data and calculation flow is performed correctly. The core of the cost estimation uses Matlab software. This software has the advantage that it is able to interpret the XML-reports, which can therefore easily be imported in the cost estimation module. Furthermore Matlab software provides all the calculation functionality needed by the core of the cost estimation. And finally the Matlab software provides a database interface so the manufacturing database can be accessed.

First task of the core of the cost estimation is the reading and preparation of the information provided through the four XML data collections that store the cost estimation information of the PMM. To do this the XML-code has to be interpreted with the functionality embedded in the software. During the interpretation of the information, the information structure is kept intact. Once the information has been interpreted the actual cost estimation can start.

In Figure 7-14 the cost estimation process is presented as one big loop. However in practice this proved un-practical and inefficient. Therefore the cost estimation is separated into several different loops. In each of these loops the cost is estimated of each manufacturability part or assembly joint manufactured with one production or assembly method. Grouping the cost estimation in this way ensures that the sub-module performing the cost estimation for one manufacturing method only has to be accessed once during the cost estimation process. The sub-module can then be executed several times until all the elements using the specific manufacturing method are handled. To ensure each manufacturing method can be handled separately the cost estimation data is split into different parts, each part representing a separate manufacturing method. Once the manufacturing data has been split, the actual cost estimation can be performed. Cost estimation in this case means estimating all the sub-process times and material costs. A detailed activity diagram of the cost estimation process implemented can be seen in appendix D. The actual cost estimation is performed by cost estimating functions and sub-functions that are stored in different modules. Once the process times and material costs have been determined they are again represented in a structured way. This means that each data entry in the results has an accompanying label that identifies the entry in such way that the cost estimation results can be read independently from input data or analysis software.

Process calculation functions and cost calculation sub-functions

With the entries in the “Process calculation functions library” and the “Calculation sub-function library” the actual cost of each sub-process used to manufacture the movable is estimated. Both the process calculation functions and the calculation sub-function library are implemented in the Matlab software to ensure good communication with the core of the cost estimation.

In the “Process cost calculation functions library” all manufacturing methods have an entry. When the cost of a manufacturing method has to be estimated, its library entry is accessed and the cost is estimated. The cost estimation of manufacturing process can be split in two parts:

- Preparing the data supplied for the cost estimation
- Performing the actual cost estimation

The first part is distinctly different for production methods and assembly methods. For production methods it consists mainly of determining geometric characteristics of the manufacturable part that is produced. This is done by using the basic geometric data supplied and some sub-functions. An example of this is the determining of the total thickness of a part based on material layer information. For assembly methods the first phase mainly consists of accessing the geometric information of the manufacturable parts involved in the joint. From these parts the geometric characteristics are needed in the rest of the cost estimation process are extracted.

The second part of the cost estimation of a manufacturing process is estimating the actual cost. For this estimation the actual manufacturing process is separated into several phases. In these phases the sub-processes where the manufacturing costs are incurred are positioned. In Figure 7-15 a schematic overview of the resistance welding assembly process can be seen including the different phases of the manufacturing process and the different sub-processes of these phases. For each sub-process a sub-function calculates the actual process time or material cost of this sub-process. Finally the cost estimates for all sub-process are combined into a cost estimate for each phase and a total cost estimate of the manufacturable part or assembly joint. This cost information is then supplied to the cost estimation core for further processing. What this process looks like in detail can be seen in appendix D. The functions for calculating the manufacturing times of each sub-process are stored in the “Cost calculation sub-function library”. One example of such a function is the hyperbolic cost estimating function described in the previous sections. The function to calculate material cost is also stored in this library. Both libraries discussed above have been implemented modularly. This enables the re-use of the entries in these libraries in other cost estimation modules.

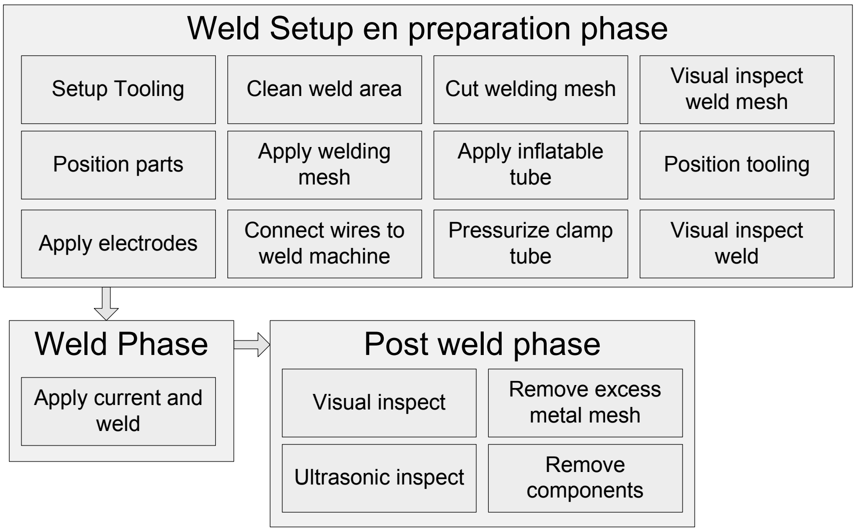


Figure 7-15 Schematic overview of the resistance welding assembly process including the different process phases and sub-processes

In the cost estimation each sub-process has two elements; a recurring part and a non-recurring part. The formulas discussed before were all used for estimating the process times of the recurring part of the sub-process. The non-recurring process time for a sub-process is a fixed time stored in the manufacturing database. The recurring part of a sub-process has to be run for every part or joint manufactured. The non-recurring part only has to be executed once every production batch. A production batch in this case is the number of same parts of joints that are manufactured in one go. The production batch size is an input for the cost estimation process stored in the manufacturing database. It is determined for all the manufacturing methods by the manufacturing experts. In the cost estimation process the non-recurring part of a sub-process for an individual part or joint is determined by dividing the estimated non-recurring process time by the batch size. Often a sub-process only has a recurring or a non-recurring part. For example setting up the lay-up tool in the hand lay-up production method only has a non-recurring part. In that same production method the ply lay-up sub-process only has a recurring part.

Data generated by the cost estimation module

The cost information calculated by the process calculations functions will have to be converted for better accessibility and has to be stored in a data collection. In this case the generation of this data collection is part of the cost estimation core. Before the cost data provided by the process cost calculation functions can be used some additional actions have to be performed. These actions involve reformatting and combining the cost calculation data and manufacturable part or assembly joint information. First action that is performed is combining the different cost estimates into totals. This determination of totals is done at different levels, so the cost data can be viewed at different levels. Also included in the data collection will be manufacturable part and assembly joint information. This information consists of some parameters describing the geometry of the part or joint and the some parameters describing the manufacturing methods used to produce them. The resulting data collection will be discussed in the “Data collections created by the cost estimation module” section.

Interaction with the manufacturing database

One element used in the cost estimations is the manufacturing database. In Figure 7-14 the manufacturing database interacts with the core of the cost estimation. The actual accessing of the data stored in the manufacturing database is usually performed by sub-functions. For example one of the inputs for the cost estimation function is the identification number of the sub-process of which the cost has to be estimated. This identification number is then used to extract the relevant data for this number from the “manufacturing sub-process attributes” table in the manufacturing database. Part of the process calculation functions also access the manufacturing database to find out which sub-processes should be include in the cost estimation. For each manufacturing process a table exists in the manufacturing database storing the sub-process data. Main parameter determining which sub-processes should be used is the manufacturing environment that is used for the cost estimation.

7.3.9 Data collections created by the cost estimation module

The data collection created by the cost estimation module consists of the cost estimated for the movable design concept handled. Like the data collections used to feed information to the cost estimation module this collection should be accessible and understandable. That’s why like, with the data collections feeding the cost estimation module, it is of the XML-file type. This offers all the advantages discussed previously, which are extra important to the cost results because the results will be used in judging the performance of a design concept. To make this judging possible the results must be accessed and must be understood. The XML results file can be accessed both manually, for a manual trade-off, or by other automated tools, for instance when the cost estimation module is used in an optimization loop.

The amount of information generated by the cost estimation module is large as each manufacturable part of assembly joint is manufactured using around 20 to 50 sub-processes. In the cost estimation module the process time for each of these sub-processes is determined. When one considers that, for example, a simple general aviation rudder has 12 different manufacturable parts and 41 different assembly joints the total amount of information generated becomes approximately 1600 sub-process times. To keep the information accessible it has to be represented at different levels. This means that every tool or person that wants to use the cost estimation results can view the results at the appropriate level. In case of the results data collection this multi-level approach means that cost results are grouped, so that for example the total process time of one manufacturable part can be viewed. The schematic overview of the process time results resulting from the cost estimation module can be seen in Figure 7-16. The same multi layer representation also applies to the material cost section of the cost estimation results file.

To keep the cost estimation report understandable some characteristics of the manufacturable parts and assembly joints for which the cost estimation is performed are also represented. These characteristics include the material and manufacturing method used to manufacture the manufacturable part or assembly joint. Other characteristics describe the geometry of the part such as total area and thickness for a manufacturable part or joint length for an assembly joint. In this way the reader of the cost estimation report can visualize the manufacturable part or assembly joint in question and can in this way check if the estimated results seem reasonable.

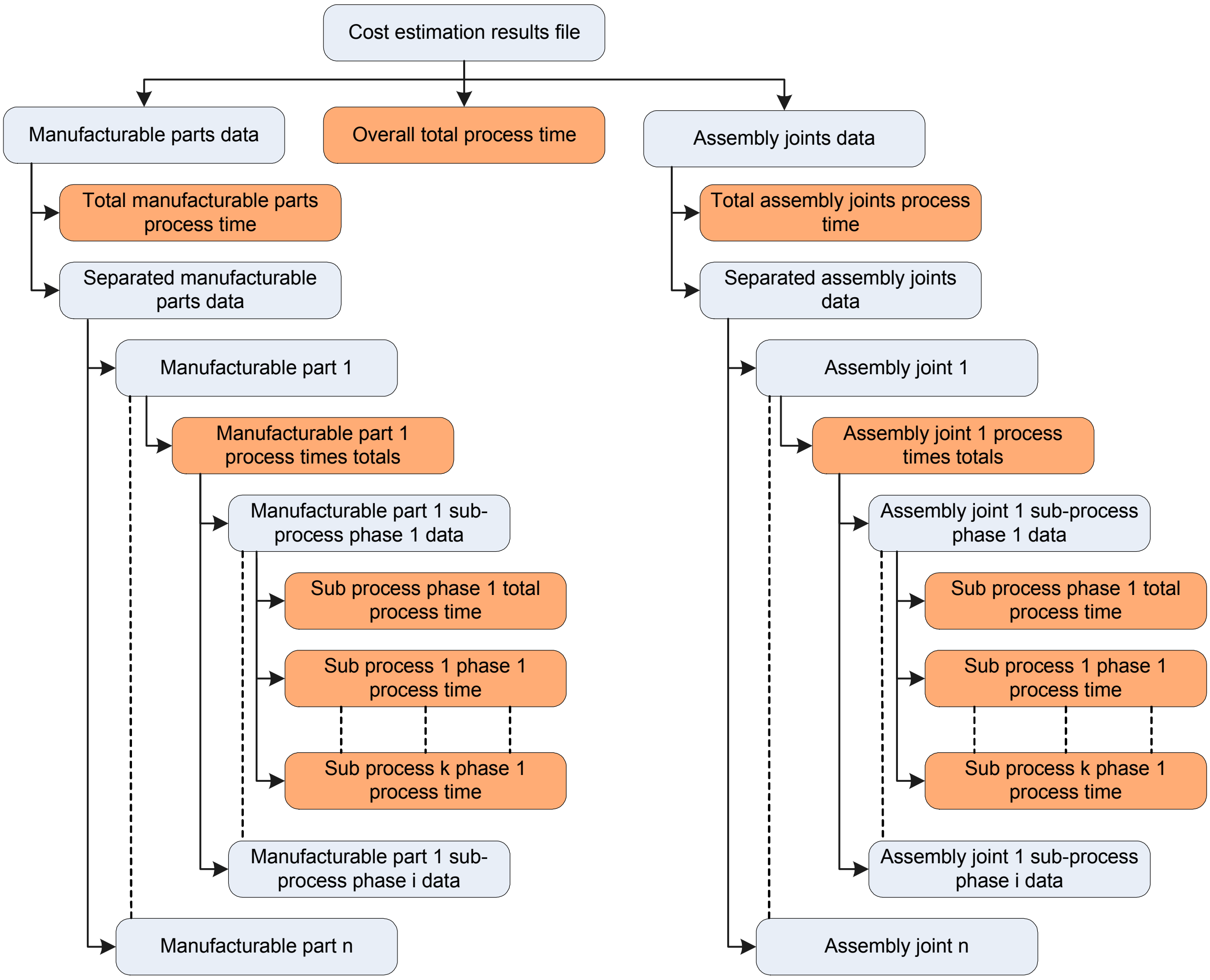


Figure 7-16 Schematic overview of the process time part of the cost estimation results file.

7.4 Future additions to the MDEE

To improve the cost estimation in the MDEE some elements of the it have to be developed further. First of all the interfaces between the different elements of the MDEE need to be automated. Secondly the actual cost estimation module has to be refined to process the estimated manufacturing process times into actual cost. Finally a results interpreter has to be developed that interprets the cost estimation results in such a way that they can be used in a multidisciplinary trade-off between movable design concepts.

Automating the interfaces between the different elements of the MDEE ensures that the tools developed can also be used in a fully automated MDEE. Until now some manual manipulations of interface files are sometimes required to let the MDEE run smoothly. This manual manipulation involves moving the in- and output data to and from the different tools. A simple solution to automate this process would be to store the interface files on a kind of server to which all cost estimation tools have access. Interface files would in this case be stored in standardized location and can therefore always be accessed by the different tools. Issue that has to be solved in this case is how to handle interface and results files from different movable design concepts or even from different movable design projects.

The actual cost estimation module has to be refined. For now process times and material cost are calculated. While the material cost can be used directly, the process times need another step to determining the actual manufacturing cost. This additional step involves using the process time to determine the total labour and machine hours for each sub-process. Labour and machine rates that will be stored in the manufacturing database can then be used to determine the actual manufacturing costs. To implement this additional step the biggest change or addition to the MDEE would be to expand the manufacturing database to include a section with characteristics of machines available in a manufacturing environment.

A probability layer has to be added to the cost estimation module of the MDEE. The values of many parameters used in the cost estimation process are uncertain, for instance steady state speed of a manufacturing process is uncertain and dependent on many factors. That is why, in the aircraft industry, the cost of a product is often accompanied by a figure indicating the probability that the estimated cost will be achieved. To take this uncertainty aspect into account a layer has to be added to the cost estimation module. This layer would have distributions for the parameters that are uncertain instead of fixed values. Using these distributions and commonly used statistical techniques, like Monte Carlo analysis, the cost estimation module would be able to create a cost distribution graph. Such a graph would link a cost estimate to the probability of achieving the estimated cost.

Final addition to the MDEE needed is the addition of a results interpreter. This results interpreter should interpret the cost estimation results into a financial feasibility score for each manufacturing concept. This financial feasibility score should be used together with the results from other analysis disciplines to determine the best movable concept. The results interpreter is closely related to the second improvement suggested, because when all cost estimation results are presented in the same format, in this case an amount of currency, the results interpretation could be relatively simple.

7.5 Cost estimation example

In this section an example will be given of the cost estimate of an aircraft movable using the tools discussed in this chapter. Purpose of this example is not to verify that the cost estimated by the tool is correct. The purpose is to verify that cost of a movable can be estimated with the developed tool. For the cost estimate produces by the tool to be valid in a real world environment the tool will have to be calibrated. When the tool is calibrated it will produce useful results as was shown in van der Laan et al. (2005).

The movable for which the cost estimate is made is the Eaglet rudder baseline, which was used in chapter 5 to discuss and illustrate the PMM. The Eaglet rudder baseline can be seen in Figure 7-17. In Appendix E the overall details of the cost estimate can be found. In Appendix F the full estimation details of one part, in this case a thermoplastic rib, can be found. For the cost estimation the following assumptions were made:

- Labour rate is 50 Euro/hour

- All manufacturing processes don't use machines and require only one labourer
- Batch size for all manufacturing parts and assembly connections is 20.
- Complex assembly connections, meaning connections involving more than 2 parts were not considered in the cost estimate.

A summary of the cost estimation results can be seen in Table 7-1. Final cost estimate for the eaglet rudder is 2024 Euro.

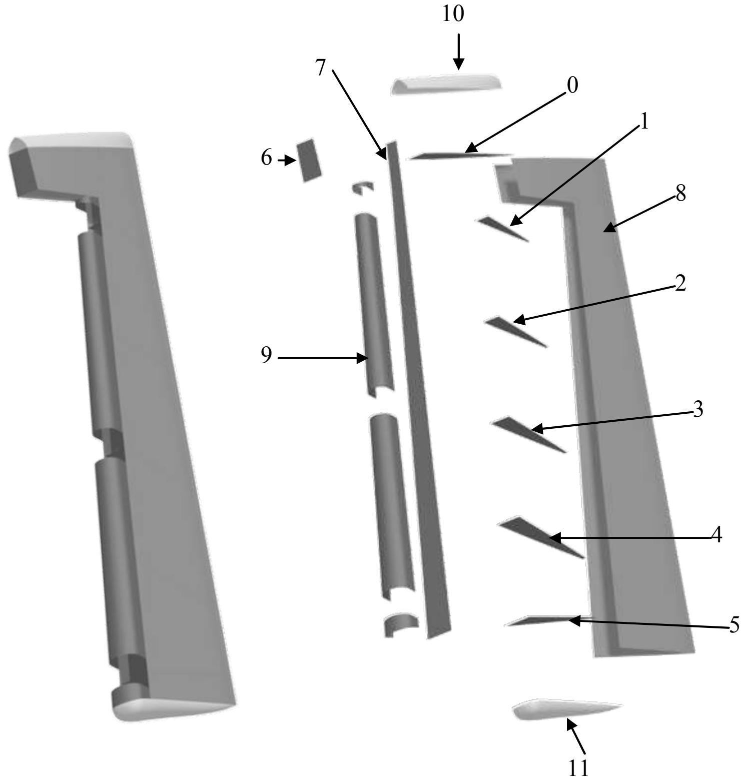


Figure 7-17 The Eaglet rudder manufacturing baseline with an exploded view

Table 7-1 Estimated cost of the eaglet rudder baseline

Manufacturable part ID	Part Name	Cost
0	Upper Closure Rib	€51
1	Hinge Rib 1	€31
2	Rib Between Hinge 1 and 2	€34
3	Hinge Rib 1	€39
4	Rib Between Hinge 2 and 3	€42
5	Hinge 3 / Lower closure rib	€44
6	Horn Spar	€33
7	Main Spar	€157
8	Skin Panels	€366
9	Leading Edge (complete)	€187
10	Upper Endcap	€114
11	Lower Endcap	€113
	Manufacturable Parts Total	€1,211
	Assembly connections	€813
	Overall Total	€2,024

7.6 Conclusions

In this chapter a cost estimation method has been implemented, which fits in the Movable Design and Engineering Engine (MDEE). To implement this cost estimation method several tools and modules have been added to the MDEE. The Cost Estimation Relations (CER's) used in the cost estimation modules simulate all production processes in the fabrication of an aircraft component. All estimations are based on geometric attributes defined in the Parametric Movable Model (PMM) and attributes describing the manufacturing processes. These attributes are stored in a manufacturing database. The use of a manufacturing database allows to store, and when necessary change, the manufacturing environment used for the cost estimation. To implement the cost estimation in the MDEE, data has to be transferred between the different modules in the MDEE. It is essential that the data collections used for these transfers are accessible and can be understood stand alone without any specialized software. Therefore the XML-data format has been used for most data transfers in the cost estimation process.

The cost estimation methods presented in this chapter enables quick and reliable cost estimations to be created of aircraft movable design concepts. These cost estimates relate manufacturing cost directly to movable sub-parts such as ribs and spars and the assembly joints between them. In this way the cost requirements of an aircraft movable can be checked and verified up to this detailed level. Because detailed requirements can be checked and verified this cost estimation method enables the “Design for Cost” part of the Systems Engineering methodology. The detail level of the cost estimate gives feedback to the aircraft movable designer, which enables him to modify existing design concepts, making them more cost effective, or to create new concepts that are more cost effective.

8 Implementation of structural analysis in the Movable Design and Engineering Engine (MDEE)

Design of an aircraft component can be seen as a trade of between cost and weight, with constraints on structural properties like strength and stiffness. For determining the weight of an aircraft component the different structural elements that are part of the component have to be sized, sizing in this case means determining the dimensions of the structural elements. When determining these dimensions the aircraft component developer has to make sure the component meets the structural constraints. To make sure of this the developer uses structural analysis tools that predict the structural behaviour of the aircraft component. It is important that these tools provide accurate and reliable results, because when the component does not meet the structural constraints during verification testing or in service an expensive re-design might be necessary. By developing Knowledge Based Engineering tools that can quickly verify the structural requirements the “Design for Strength and Stiffness” aspect of the Systems Engineering methodology can be enabled.

In the Movable Design and Engineering Engine (MDEE) structural analysis will form one of the analysis disciplines used to evaluate a design concept. Objective of the structural analysis is to determine if the design concept meets structural constraints. However it is also possible to use the structural analysis as a tool for the initial sizing of the aircraft components structural elements. With this sizing the dimensions and/or the material types of the different structural elements that form the aircraft component are determined. When used in this way the results of the structural analysis have a profound effect on other analyses such as the cost estimation, because parameters essential to the cost estimation such as material thickness and type are part of the results. This dependency between analyses disciplines underlines the need for a thorough and reliable structural analysis module in the MDEE.

In this chapter the aircraft movable will be used as an example of an aircraft component and the structural analysis tools developed will be used in the design process of such an aircraft movable. This chapter will focus on automating the repetitive time consuming part of the structural analysis process; the creation of a structural analysis model. This chapter will not discuss the results produces by analysis the structural model. In the first section of this chapter the selection of the structural analysis method most suited to the MDEE is discussed. Additionally the first section also identifies which elements should be added to the MDEE to implement this structural analysis method. The actual implementation of these elements is discussed in sections two and three. In the final two sections recommendations for improvements are made and conclusions are drawn.

8.1 Structural analysis method in the MDEE

Structural analysis forms an important part of the MDEE therefore the method that will be used in the MDEE will have to meet certain requirements. These requirements will be used as a guideline in the selection of the appropriate structural analysis method for the MDEE. The requirements the structural analyse method has to meet are:

- Use the data available from the Parametric Movable Model (PMM)
- Provide accurate, reliable and detailed results
- Provide transparent, accessible and understandable results

Structural analysis can contain many different elements and can for example be used to determining the stresses and strains in a structure. These stresses and strains can then be used to determine the dimensions of the structure. They can also be compared with the allowable stresses and strains of the materials used in the structure to determine if the structure will remain intact. For determining the strains and stresses, the external loads like pressures and forces exerted on the structural component or element must be translated to the resulting internal strains and stresses. For simple elements like beams and panels with simple external loads exerted on them the translation can be done using simple formulas. However aircraft components can be complex structures with many interactions between the structural elements. In this situation it is difficult to translate the exerted loads on the component into internal strains and stresses using simple formulas. In this case numerical methods can be used to determine the internal strains and stresses in the structure. An example of such a numerical method is a Finite Element (FE) method.

Using specialized FE software the loads exerted on the analyzed structure can be translated in internal strains and stresses. These strains and stresses are used to size the structural element or verify that the structural element will not fail during operation. In the FE method the structure of the analyzed object is represented by a discretized model consisting of a finite number of elements. The discretized models used in FE methods represent the analyzed object and resembles the geometrical lay-out of the object. The elements in the discretized model are usually smaller than the structural elements of the structure. In case of a model of an aircraft movable this for instance means that the ribs or spars consist of multiple elements. As a base for building the discretized model of an aircraft movable the structural view of the PMM can be used.

When used properly numerical structural analysis tools provide accurate and reliable results. The reliability of the results does depend on the level of detail of the discretized model that is used. Reliability is also dependent on the boundary conditions used in the structural analysis; they have to be defined properly. The result from a numerical structural analysis usually consists of a substantial amount of data. This data in itself is not very transparent or accessible. However they can be made more accessible by making use of additional tools that filter or process this data to only show the relevant information.

For the structural analysis in the MDEE the FE method will be used. With the selected structural analysis method in mind, the elements that are needed for implementation in the MDEE can be defined. In total 5 different elements have to be added to the MDEE, the position of these elements is shown in Figure 8-1. These 5 elements are:

1. Extra input parameters for the structural analysis.
2. Data collectors that collect the data needed for the structural analysis, extracted from the PMM.
3. The data collections containing the actual data for the structural analysis tools.
4. The structural analysis tools that perform the actual FE analysis.
5. Result interpreters that interpret the structural analysis results.

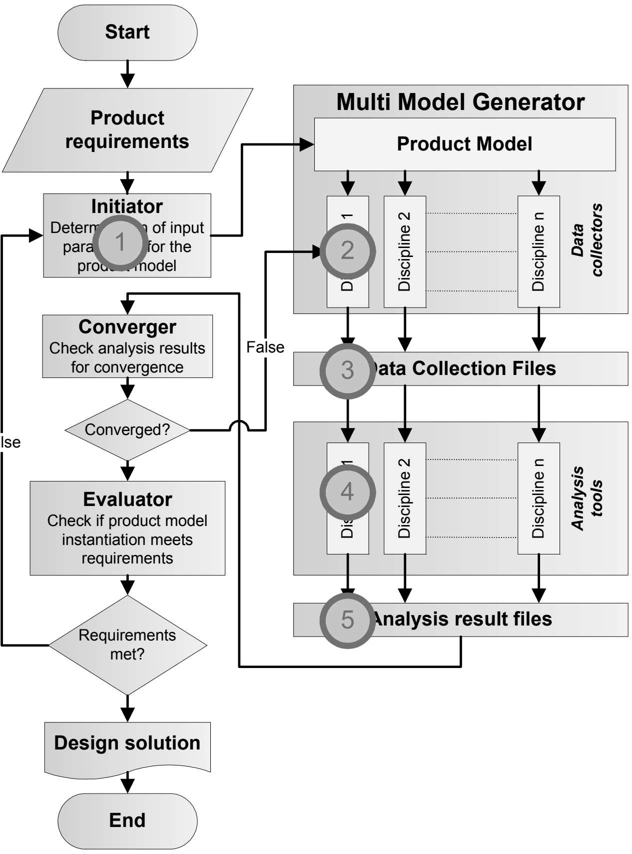


Figure 8-1 Position of structural analysis elements in the MDEE

8.1.1 Structural analysis input parameters (1)

The first element that has to be incorporated in the MDEE are the extra input parameters needed for the structural analysis. The extra input parameters will be positioned in the input data set used by the PMM to create the aircraft movable model. Many of the input parameters are geometrical inputs determining the actual geometry of the movable. How they are used is explained in chapter 4. One group of additional input parameters used for the structural analysis deals with the boundary conditions of the structural analysis. Boundary conditions in this case mean where the movable will be supported and how the loads used in the analysis are exerted on the movable. Another group of input parameters determine the properties of the structural elements for the structural analysis. These properties are comprised of the material types and, because the geometrical model created by the PMM is surface based, material thicknesses of the different structural elements. In fact these input parameters are also used for the manufacturing analyses of the aircraft movable. A schematic view visualizing the 3 different input groups can be seen in Figure 8-2.

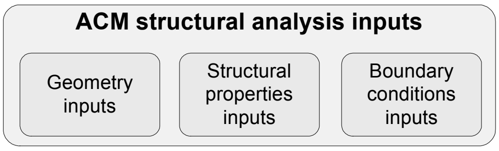


Figure 8-2 The three groups of inputs needed for the structural analysis

8.1.2 The structural analysis data collectors in the PMM and the produced data collections (2 & 3)

The structural analysis data collectors collect the data that is used by the structural analysis module to perform the structural analysis. The data that has to the transferred to this analysis module is collected in the PMM based on the generated movable model. This model is surface based. Therefore the data collected from it is also surface based. This has some consequences for the subsequent structural analyses performed. The data needed by the structural analysis module consists of three groups. First of these data groups is geometry data. Geometry data is needed for constructing the discretized FE model. The second group of data is data that determines the material properties of the structural elements; this group will be called the structural properties data. The third and final group of data are the boundary conditions that should be used for the structural analysis; this group will be called boundary conditions data.

The geometry data generated by the PMM should be formatted in such a way that it can be used in the structural analysis tool to create a discretized model. This imposes requirements on both the data format that can be used to transfer the data and also on the data itself. The data transfer format should be understandable by the structural analysis tool; this usually means that a standardized geometry transfer format such as IGES or STEP should be used. Using such a standardized data format has the added benefit that the geometry data can be accessed by independent CAD tools for checking and verification purposes. The data itself should ensure that the discretized model created in the structural analysis tool is useful and error free. How this is achieved is explained in the sections of this chapter that handle the actual implementation details of the structural analysis.

One element normally considered geometry data is the thickness of the different structural elements. However because the geometrical model created by the PMM is a surface model, the structural elements do not have a modelled thickness. The thickness of the structural element is added as an additional property linked to the surface representing the structural element. However this prevents the thickness of the structural elements to be stored in the geometry data files. The thickness data will therefore be part of the structural properties as is explained in the next paragraph.

The second type of data, the structural properties data, is closely related to the actual geometry entities. Each structural entity that is represented by the geometry also needs a property entry that determines the material composition. In case of monolithic structural elements like for example aluminium machined ribs the material composition consists of one entry defining the material type. However in case of composite structural elements the material composition consists of several layers, each with a different material type and orientation. In case of a composite material the layer thickness is also an important property. Therefore to properly describe the material properties of a structural entity the material type, orientation and thickness of each material layer present in the entities material composition should be stored. This automatically also stores the geometrical thickness of the structural entity. Note that for the structural analysis method described in this chapter the thickness of a structural entity is considered constant. The layer properties can be delivered to the structural analysis tool using text based data-files. The properties stored should be coupled in the structural analysis tool to the right structural entity.

The third and final data type, the boundary conditions data, can also be stored in data files. As was stated before the boundary conditions consist of the external loads exerted on the movable and the positions where the movable is supported. Normally this is in the hinges and actuators of the movable. The external loads on a movable consist of pressures exerted on the movable. However the external loads are dependent on the load conditions considered in the structural analysis.

8.1.3 Structural analysis tools and their results (4 & 5)

The structural analysis tools perform the actual structural analysis. In this case the FE method for structural analysis was chosen. Therefore the structural analysis tool performs a FE analysis. When selecting the FE analysis software that is going to be used there are two options: develop a new software tool or use existing FE analysis packages. Big advantage of the first option is that the software can be optimized for the needs of the MDEE. The second option of using existing FE software has several distinct advantages. First of all the users of the MDEE might be structural analysts that are familiar with FE software. Furthermore the existing knowledge of how to use such a FE tool can be used to speed up the development of the MDEE. Thirdly the available FE software usually has many different analysis options, such as buckling, stress and displacement analysis. Building an interface to such a tool can therefore make all these analyses methods available. Only drawback of using existing FE tools is that they will not fit seamlessly in the MDEE, interfaces will have to be developed. Because of the specified advantages existing FE software tools will be used in the MDEE. To solve the problem of fitting them in the MDEE, additional modules will be developed that handle the dataflow to and from the actual FE tool. The data handling and transfer tools form an important part of the structural analysis module.

The structural analysis module can produce many different results. It can perform different kinds of analysis as was specified before. Each of these analyses can be used to verify if the aircraft component meets the requirements or what the sizing of the aircraft component should be. Which analysis is used is dependent on the design stage in which the MDEE is used and also what the user of the MDEE expects. The results from the structural analysis can also be used in a trade-off between different design concepts.

8.2 Initial implementation of the structural analysis in the MDEE

The first method of implementing structural analysis in the MDEE is based on a previously developed method used for the automatic generation of structural models for whole aircraft (La Rocca, 2002). As a basis for the structural analysis the Parametric Movable Model (PMM), which is described in chapter 5, will be used. Because the PMM uses elements from the multi model generator of complete aircraft, the principles to prepare the geometrical entities for a structural analysis can be re-used. Re-using the work reduces the amount of work needed for developing the structural analysis elements of the PMM. It also ensures that the top level complete aircraft model and the PMM are closely related and can therefore be easily integrated.

In this implementation method the data preparation and data transportation modules are kept simple and specifically aimed at the MDEE. They are tailored in such a way that they can easily handle the data extracted from the PMM. This ensures that the modules work smoothly in the MDEE. It will however make it difficult to re-use these modules in other DEE's.

8.2.1 PMM Inputs (1)

The inputs of the PMM that are specifically needed for this implementation of the structural analysis consist of 2 groups. First group determines the material properties of the different structural elements. The second group is needed for determining the boundary conditions of the structural analysis. Both groups will be fed to the PMM as part of the input data set that defines the movable design concept. All other inputs used by the structural analysis are geometry inputs, which are discussed in chapter 4.

The first group of structural input parameters consist of material properties. In the structural view of the PMM the structural elements are divided into so-called structural groups. In these groups the elements with the same structural function are collected. A structural group is for example the ribs group, which contains all movable ribs. For each group the material properties are chosen from a fixed list of properties that are available in a material library. In this material library the total material composition of a material is stored, this consist of the material type, orientation and thickness for all layers in a material. There are a couple of problems with this way of determining the material properties of the structural elements:

- ***All structural entities of the same type have the same material properties***
  Because the material properties are specified per structural group all entities in this group have the same material properties. In case of, for instance, the ribs this can be problematic. The material properties of the ribs usually vary from rib to rib in an optimal movable design.
- ***Material properties can be inconsistent with other analyses***
  Because the material properties are specified per structural group they are not guaranteed to be consistent with the material properties specified for other analyses. For instance the material properties are specified separately for the manufacturing analyses. Because the 2 material specifications are separate they can easily be inconsistent, especially because for the manufacturing analyses the material properties are specified per manufacturable part.
- ***Material layer information cannot be specified***
  The specification of the structural material properties is limited to the selection of a material from the material properties library. The material specification and also the layer build up are specified in this property set. This means that there is no possibility to specify the characteristics of the different material layers using the input parameters.
- ***Only stiffener material can be adjusted***
  For stiffeners the material chosen from the material library is applied to a fixed stiffener geometry. Fixed geometry in this case means that the profile shape and

dimensions are fixed. Because the geometry is fixed the flexibility of the MDEE is limited in case of stiffeners.

The problems described above do not severely limit the possibilities of the structural analysis in the MDEE they do however show that when modules are combined into a DEE, consistency problems might occur and that it is therefore essential to identify and address these problems as soon as possible. Some of the problems described here are addressed in the second implementation method of structural analysis in the MDEE described in the “Improvements to the structural analysis process within the MDEE” section of this chapter.

The second group of input parameters are used to determine the boundary conditions for the structural analysis. De boundary conditions define the loading condition of the movable. In this case one loading condition has been implemented; that of a triangular pressure exerted on one side of the movable. This is the load specified by CS-23 appendix A23.11. In this condition the movable is supported at the hinge points, these point are determined using the geometry of the movable and do therefore not require any additional inputs. One of the support points will act as the actuator. The hinge that acts as actuator is defined by an additional input in the PMM input dataset. Because the shape of the pressure exerted on the movable is fixed this shape is hard coded in the PMM. The only input needed for this determination is the total force that will be exerted on the movable. This total force can usually be determined by looking at other parts of CS-23.

8.2.2 PMM data collectors and the produced data collections (2 & 3)

The input data files needed for the structural analysis are defined by data collectors in the PMM. These data collectors are added as Capability Modules (CM’s) to the PMM. These collectors base the data collections on the structural view of the PMM. In this view all the structural elements of a movable are represented according to their structural function. The data collectors in the PMM can be split in two groups. The first group collects the geometry data and creates the files containing this data. The second group collects the additional data needed for creating the structural model and stores this data in text data files. The CM’s added to the PMM for the structural analysis can be seen in Figure 8-3.

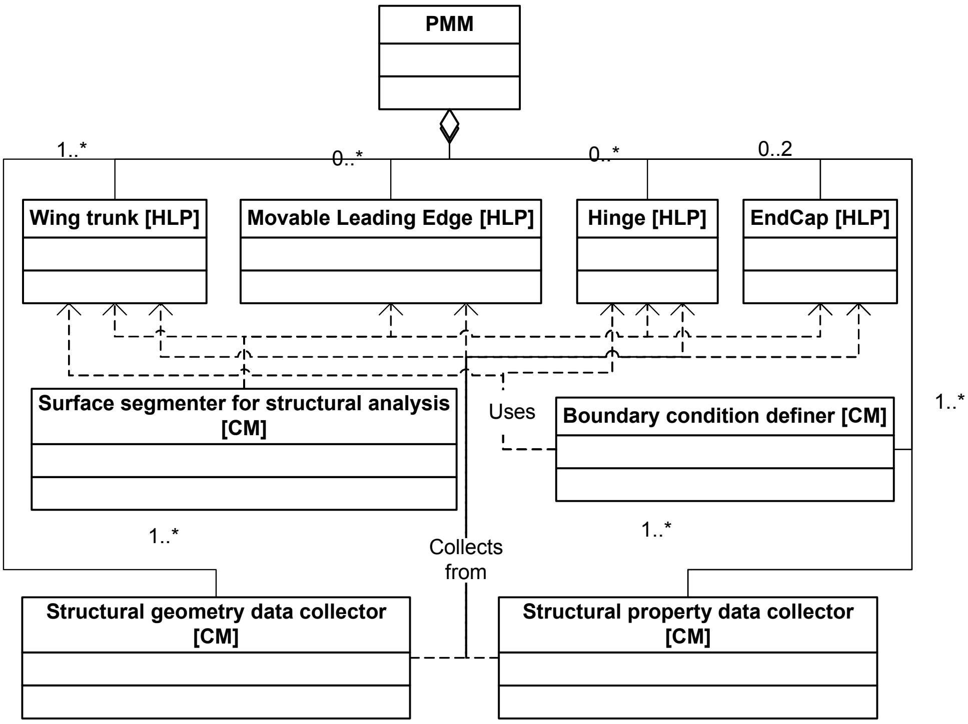


Figure 8-3 Schematic overview of the PMM including the CM's added for structural analysis

The geometry of each structural group will be represented by a separate geometry file. Therefore there are different geometry data collectors each collecting the geometry for one structural group. These data collectors are called "*Structural geometry data collector*". Before the structural entities can be stored in IGES files some processing is necessary. This processing involves cutting up the surfaces that make up the structural entities into smaller segments, the so-called segmentation process. This segmentation process is necessary to ensure that the movable model is easily mesh-able. Easily mesh-able means that only triangular and quadrangular surfaces exist and that these surfaces are only connected at their boundaries. This ensures that the mesh applied to the surfaces by the FE pre-processor has no inconsistencies.

The segmentation has been implemented by adding a CM to the PMM. This is the so-called "*Surface segmenter for structural analysis*" shown in Figure 8-3. This CM automatically splits all the structural surfaces (spars, ribs, skins) along their intersections. The CM was first developed to segment the surfaces of whole aircraft models (La Rocca, 2002) and later adjusted for the PMM. Using this CM spars are split along the intersection with all ribs; ribs are split along the intersection with all spars and skin panels are split in patches along the intersections both with the ribs and the spars. This segmentation is continued in all the other parts such as end-caps and leading edge. Virtual ribs and spars are also be specified in places where extra segmentation is needed, such as the leading edge slots. These virtual elements are not used in the actual structural analysis. A visualisation of the segmentation can be seen in Figure 8-4. Finally the surface segments are collected by a structural group's data collector, which creates an IGES file containing all the surface segments of the structural group in question.

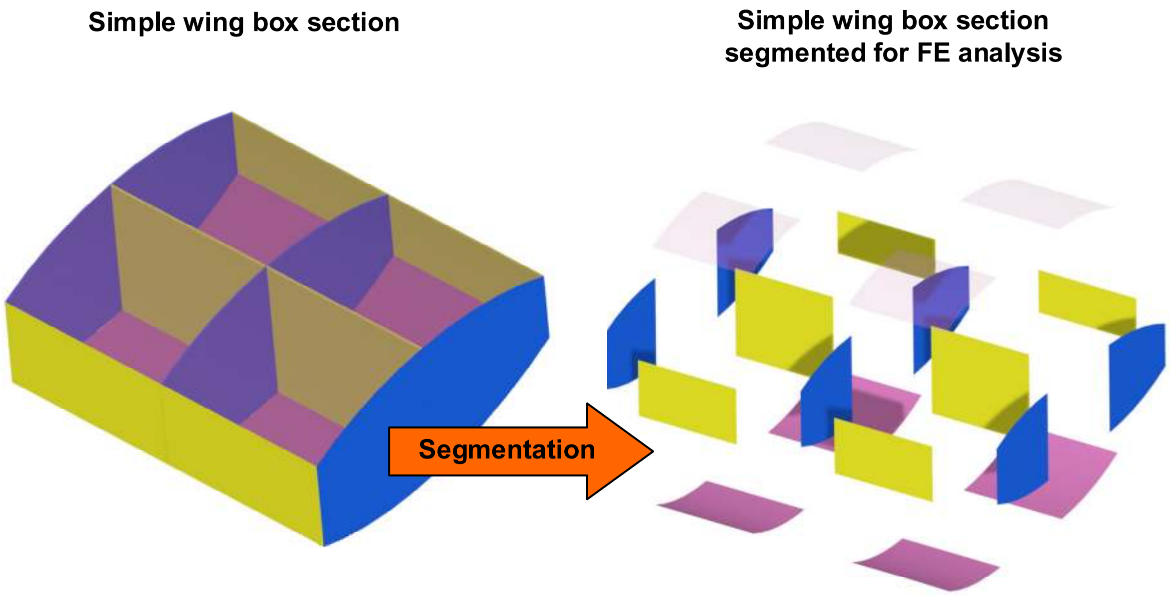


Figure 8-4 Visualization of the segmentation process of a simple wing-box example of 3 ribs, 3 spars and 2 skin panels. Segmentation results in 20 surface segments

The second group of data files, the additional information needed for creating the structural model, consists of two data files. The first file of this group is used to store the material properties associated to the different structural elements. This file is created by the "*Structural property data collector*". The second data file stores the information needed to specify the boundary conditions of the structural model in the structural analysis tool. This file is created by the "*Boundary condition definer*". To keep the interface between PMM and structural analysis tool simple, the file format used to store the material properties and the boundary conditions are specially adapted for the FE pre-processing software used.

The files containing the data defining the material properties of all the groups are not directly linked to the IGES files containing the actual geometry. To create a discretized model the information stored has to be "re"-linked to the geometry. To do this information must be stored in the material properties files that can be used in this "re"-linking process. In this case the start and end number of the surfaces that are members of the structural group to which the material properties must be applied are stored. These surface numbers can then be used to link the material properties to the surfaces in the FE pre-processing software. This process can however only work when the surfaces stored in the geometry IGES files are loaded in a controlled fashion in the FE pre-processing software. How this is enforced is explained in the "The structural analysis process (4 & 5)" section. Because the sequence of loading is known, the start and end surface numbers of the different structural groups can be determined. For this the number of surfaces in each group has to be determined, this is done by scanning the segmented movable model in the PMM. The principle of determining all the surface numbers can be seen in table 1.

Table 8-1 Parts surface numbers

Parts	Begin surface number	End surface number
1. Ribs	1	Number of rib surfaces
2. Spars	Number of last rib surface + 1	Number of spar surfaces + number of last rib surface
3. Covers-up	Number of last spar surface + 1	Number of cover-up surfaces + number of last spar surface
4. etc.	etc.	etc.

The curves used to generate stiffeners are handled in the same way; the start and end numbers of the curves used for creating the stiffeners are determined and using these numbers the proper material is awarded to the beams associated with these curves in the FE pre-processing software. In case of the stiffener curves the properties data file also determines the cross section of the stiffener.

The data file that determines the boundary conditions of the structural analysis first of all has to determine the pressure acting on the movable. In this case a pressure load distributed according to CS-23 is used. In the conceptual design phase this is useful and fast way to define a load case. In the later development stages pressure fields from aerodynamic tools or data from experiments can be used. The shape of the pressure field on the movable resembles a triangular pressure load with the maximum pressure at the hinge line of the movable and a pressure of zero at the trailing edge. The maximum total force that is exerted on the rudder is dependent on the configuration of the rest of the aircraft and should therefore be determined separately. The pressure is stored in the data file as four corner pressures. Position of the four corners can be seen in Figure 8-5. In the FE pre-processing software these corner pressures are used to define a pressure field using linear interpolation. How the pressures in the four corners are determined is explained in Appendix G.

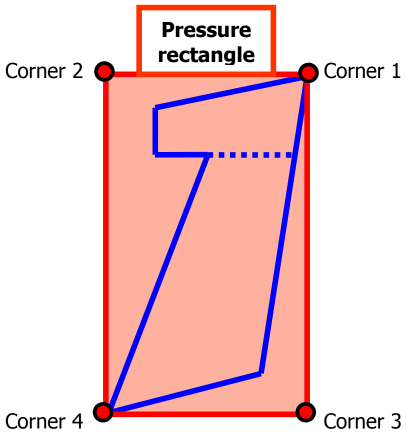


Figure 8-5 The pressure square defined in the PMM

The boundary conditions also consist of prohibiting movement of the model at the hinges. In the movable model the hinges are modelled as 4 lines running from the hinge point to the 4 corner points of the leading edge slot. The hinge point is the point where the hinge rib plane cuts the hinge line. In this point displacement in the three translation directions is prohibited. The hinge layout in can be seen in Figure 8-6. One of the hinges will also act as an actuator; this means that for this point rotation in any direction is prohibited.

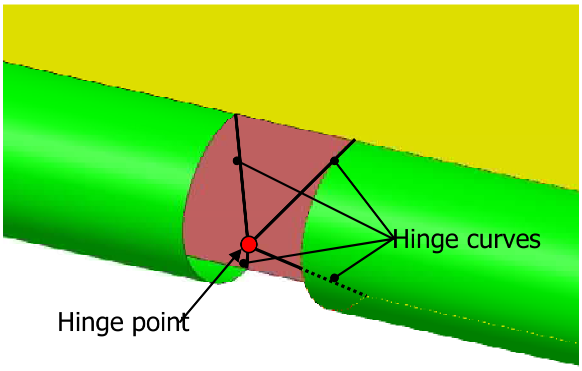


Figure 8-6 Hinge lay out

8.2.3 The structural analysis process (4 & 5)

In the aircraft industry the structural analysis itself is usually split it two separate tasks; creating the discretized model of the analyzed component and the structural analysis itself. Both tasks use different kinds of software. The first task of preparing the discretized model is usually performed using a so-called pre-processor. Such a pre-processor provides a graphical interface for building the model. The actual structural analysis, meaning determining the stresses and strains in the structure, is performed by structural analysis software. In this case Patran was used as a pre-processor and Nastran was used as the actual structural analysis software. What happens in the MDEE structural analysis module can be seen in Figure 8-7.

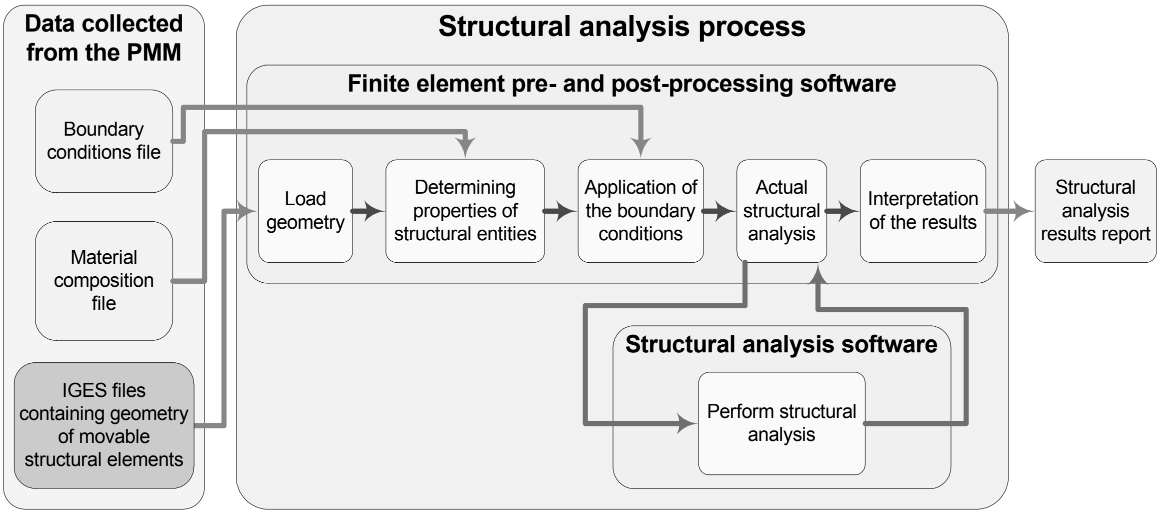


Figure 8-7 Schematic representation of the structural analysis process

In the structural analysis module all the activities for preparing discretized model are controlled by Patran session files. These session files specify commands to be executed by the Patran software. Two of these session files are created by the data collectors that are part of the PMM and are discussed in the previous section. The “Material composition file” is created directly by the “*Structural property data collector*”. The “Boundary conditions file” is created by the “*Boundary condition definer*”. Other session files are standardized and remain the same for all instantiations of the movable. Which session files play a role in the model preparation process and which role they play is shown in Figure 8-8.

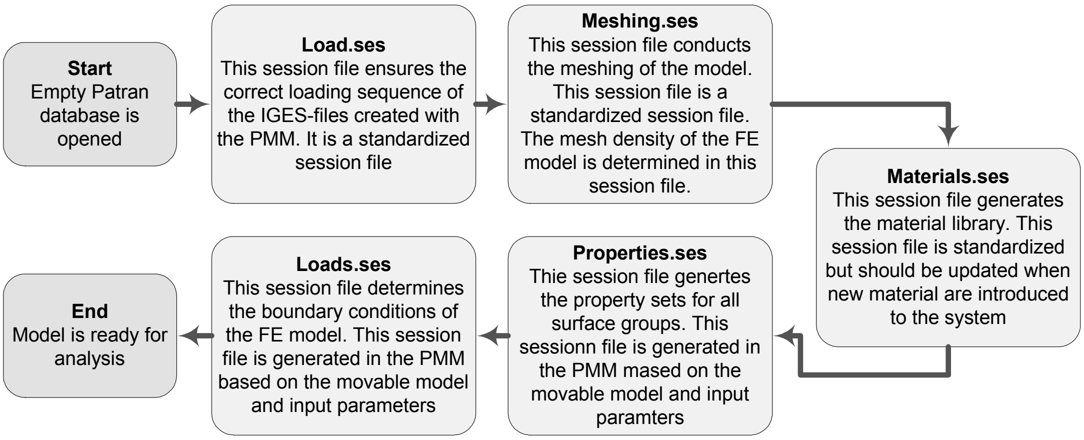


Figure 8-8 Overview of the Patran session files used to prepare the structural model for analysis

Once the model has been prepared the actual analysis can be executed. The actual execution of the analysis remains, for now, not automated. It is performed by Nastran however the results form the analysis can be interpreted and visualized by the FE post-processing software in this case again Patran. Finally a results file has to be written. For now this consist of the results report generated by Nastran.

FE results

The Natran results file that is the outcome of the FE analysis stores the structural analysis results. In this case the results consist of the internal strains and stresses in all the structural elements. Using the strains and stresses the structural performance of the design concept that is analysed can be determined. There is one drawback however and that is the amount of data can be big, especially for complicated movable models. Looking for specific results can therefore be time consuming. Therefore it is recommended to develop a results interpreter that can filter out the relevant FE results from the results file and write these results into a new report. This report should be formatted in such a way that it is better accessible and understandable.

8.2.4 The structural analysis script example

In this section the actual structural analysis of a movable using the method described in the previous sections will be shown. All steps needed for the structural analysis will be discussed briefly and illustrated. The structural analysis conducted in this example will be a displacement analysis. In Figure 8-9 the movable model is depicted after each step.

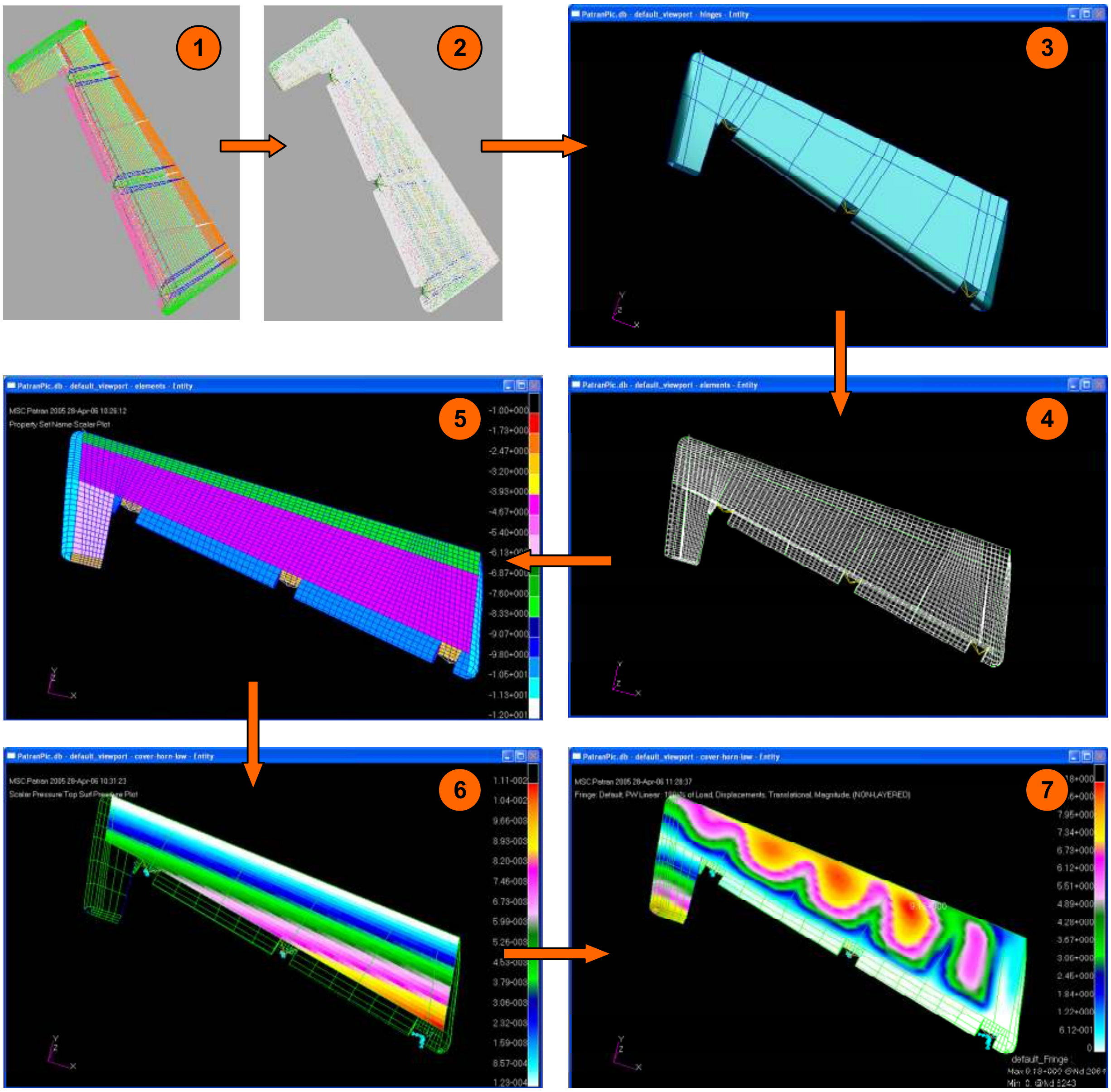


Figure 8-9 Script depicting all the steps of turning the structural view of the PMM into usable structural analysis results.

1. First step is generating the structural view of the PMM. The movable structure is created by the PMM based on its input data set, which defines the movable design concept. The PMM structural view consists of the structural elements of the movable such as spars, ribs and skins.
2. Second step is segmenting the structural elements that form the movable in the PMM using the "*Surface segmenter for structural analysis*" CM. Once split the surfaces segments are stored in several IGES files using the "*Structural geometry data collector*" CM. When the movable model is in the segmented state the property and boundary conditions session files are created using the "*Structural property data collector*" and "*Boundary condition definer*" CMs.
3. Third step is loading the IGES files containing surfaces segments created in the PMM into the Patran pre-processing software. Loading of the surfaces segments is

performed by the “load” session file. The result is a geometrical model of the movable in the Patran software.

4. The fourth step is meshing the geometrical model. To do this the “meshing” session file is run. In this meshing file the mesh coarseness is stored. The result of meshing the geometrical models is a discretized model of the movable consisting of quadrangular or triangular 3d elements and bar 2d elements.
5. The fifth step is awarding properties to the elements of the discretized model. To do this first the material library has to be loaded by running the “materials” session file. Once the materials are loaded the properties can be awarded using the “properties” session file generated by the “*Structural property data collector*” CM in the PMM. In this way the different surface groups are awarded their property. In step 5 of Figure 8-9 a plot can be seen where different colours are used to show the different properties.
6. The sixth step is applying the boundary conditions to the discretized model. This is done by running the “loads” session file generated by the “Boundary condition definer” CM of the PMM. The boundary conditions consist of two parts. In step 6 of Figure 8-9 the contour of the triangular pressure resulting from this session file can be seen. Once the boundary conditions are applied the model is ready for analysis.
7. The seventh and final step of the process is running the actual structural analysis. This has to be done manually in the Nastran software. Results from the structural analysis can be interpreted by the Patran software and plotted. In this case the displacement of the structural elements of the movable are plotted in step 7 of Figure 8-9.

8.2.5 Advantages and drawbacks of this implementation method

There are several advantages or strong points of this first method of implementing the structural analysis in the MDEE:

- COTS tools are used for the structural analysis. Using these commonly used software packages eases acceptation of the MDEE by structural analysts and simplifies the verification/certification of the analyses performed.
- Interface of the structural geometry is transparent and accessible through the use of the IGES files. The IGES files can be accessed by any commonly available CAD tool.
- The interface files between PMM and structural analysis tools are simple. Text files written by the PMM can be used directly by the FE pre-processing software and do not require any extra processing.

There are, however, also some disadvantages or weak points to this implementation of the structural analysis. These are:

- Text session files used to transfer data from the PMM to the structural analysis software are not accessible and transparent. The text files used to transfer the data are tailored for the FE pre-processing software and contain code and formatting specific for the chosen software package. This additional code and formatting obscures the actual information stored in the file.

- Human interaction in the FE pre-processing software is needed to run the different session files steering the structural analysis process. This human interaction requirement prohibits complete automation of the structural analysis.
- Results of the structural analysis are not processed but consist of the outputs of the structural analysis software. While this might be sufficient in the movable development process, these results can be difficult to handle in a trade-off of different movable design concepts.
- Material definition for the structural analysis is not the same as the material definition for the cost estimation. For the structural analysis materials are specified per structural group and not per production group as is the case for the cost estimation. Therefore the material definition can become inconsistent.

To overcome some of these disadvantages, especially in the area of data transparency, a second method of fitting structural analysis in the MDEE was devised. It is discussed in the next section.

8.3 Improvements to the structural analysis process within the MDEE

As was discussed in the previous section, there are some drawbacks to the implemented structural analysis method. To solve some of these drawbacks a new implementation of the structural analysis was defined. Main characteristics of this new implementation are:

- The interface between PMM and structural analysis tools is made more transparent.
- Manufacturing view material definition will be used for the structural model.
- Tools that are tried and tested will be used to facilitate the implementation.
- Level of automization is increased.

The new characteristics solve some but not all the problems and drawbacks stated in the previous section.

Because the improvements of the structural analysis implementation focus on improving the data transfer, the data collectors involved in this data transfer will be changed. The data collectors will be changed in such a way that the collections produced can be interpreted independently. The definition of the IGES-files representing the geometry of the movable will remain the same because they can be accessed with any common CAD tool. The collection containing the data about the movables properties will be changed however.

The structural analysis itself will be executed with the same combinations of FE pre- and post-processing software and structural analysis software tool as described in the previous sections. However these software tools will be “steered” in a different manner. Instead of using text files generated directly by the PMM to steer the FE pre-processing software directly, a layer will be put between the PMM and the structural analysis tools. This layer steers the FE pre-processing software. In this case the layer processes the data extracted from the PMM into Patran Command Language (PCL) code. PCL is a programming language that can be used to steer the FE pre processing software package Patran. The PCL-code is used to prepare the structural analysis model. The tools used in this layer have already been developed by Nawijn (2006). These tools will be considered black boxes and the actions performed in these tools will not be described in this thesis. The new structural analysis process with the added layer can be seen in Figure 8-10.

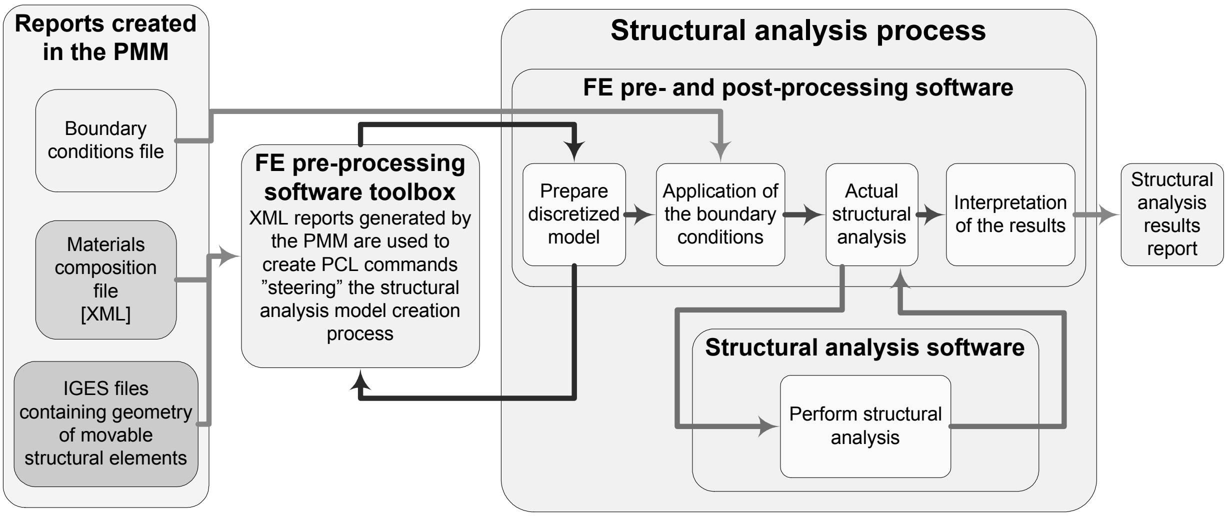


Figure 8-10 Schematics overview of the improved structural analysis process

8.3.1 The XML data files written by the PMM in the improved structural analysis process

Because of the advantages described in chapter 7, XML-files will be used to transfer data in the improved structural analysis process. The XML-files used in the new implementation of the structural analysis store all the data needed for the structural analysis plus additional data. The additional data can for instance be the identification number of the production group of which a surface is a member. Each structural group is represented by a separate XML-file. In the XML file all surface segments in the structural group get an entry in which their characteristics are stored. These characteristics consist of two groups; characteristics that determine the geometric position of the surface segment and characteristics that determined properties of the surface segment. Advantage of this approach is that the XML-data file can be extended to contain more or different data entries that might be required for other implementations of the structural analysis process. The extension of the data contained does not require a big change to the data collector infrastructure. In this way the MDEE becomes flexible and extendable.

The XML-files contain information about all surface segments in a structural group. This information has to be extracted from the structural view of the PMM. For each structural group the correct surface segments have to be selected and grouped. In the PMM each surface segment has additional information in the form of additional properties attached to it. One of the additional properties attached to a surface segment is to which manufacturing group it belongs. This information is used to get the appropriate material composition for each surface segment from the manufacturing concept definition stored in the PMM input data set. This information is stored in the XML-file storing the surface segment characteristics. A graphical representation of the process can be seen in Figure 8-11. By relating the material properties to the production groups and not to the structural groups, elements in the same structural group need not have the same material definition.

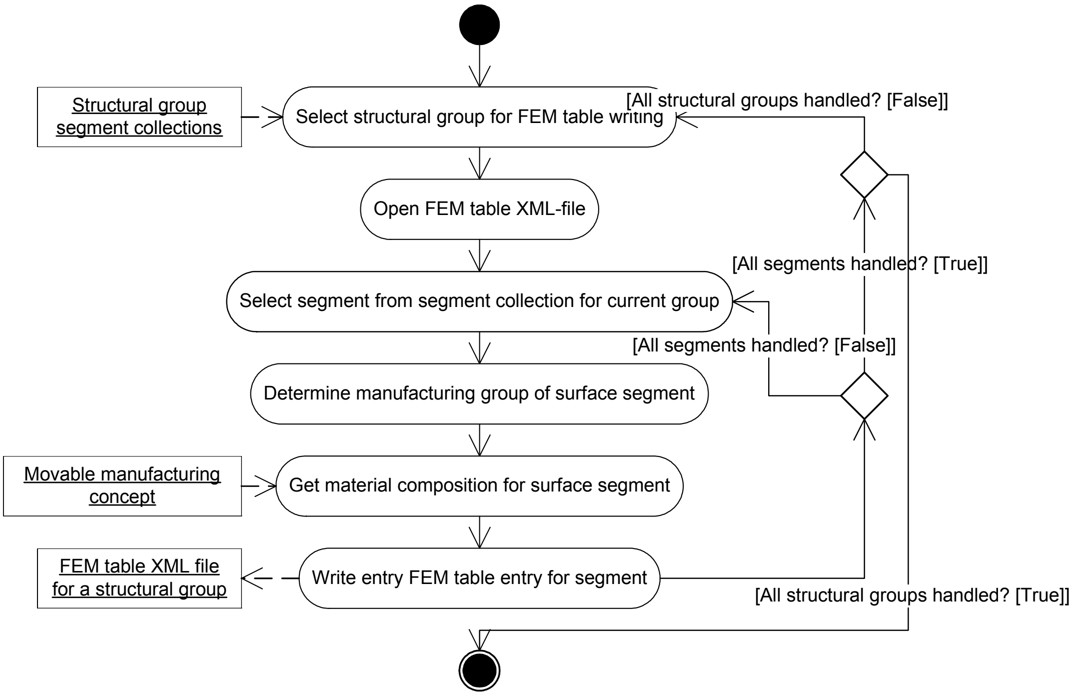


Figure 8-11 UML activity diagram visualizing the creation process of XML-files, in this case called FEM tables

Each surface segment has a separate entry in one of the XML files. Each entry consists of different sections containing different kinds of information. In Figure 8-12 an entry for a surface section can be seen. The first section of the entry contains the coordinates of the surface segments vertices. This information is used to map the information to the right surface in the FE pre-processing software. In the next section the function and other properties of the surfaces segment are described. These properties can for instance be used to identify which structural and or production group the surface segment belongs to. In the final element of the properties section the material properties of a surface segment are defined. In this element the material type, thickness and orientation of the material used in the surface segment are defined. It is possible to define several material layers, for each layer the thickness and orientation must be specified. The material type is constant for all the layers.

```
<SIA-DOC type = "Fem Table Movable" version = "0.1">
  <surface id = "7710000">
    <vertex id = "0">13.834980877646032 -183.99827264103547 15.888026361733038</vertex>
    <vertex id = "1">-24.414970989322953 -175.60215548626508 8.881784197001252e-16</vertex>
    <vertex id = "2">3.219814125670116 -448.50872850476406 0.0</vertex>
    <vertex id = "3">33.77976128552431 -449.25643837585415 25.034564679245083</vertex>
    <properties>
      <property type = "aircraft_part">not-known</property>
      <property type = "wing_part">not-known</property>
      <property type = "structure_part">END-CAP-SEGMENT</property>
      <property type = "isoparam_part">T</property>
      <property type = "ICAD_type">QUAD-BLEND-SURFACE</property>
      <property type = "design_variable_group">666</property>
      <property type = "disturbed_by_door_cutout">not checked</property>
      <property type = "attached_non_struct_masses">not checked</property>
      <property type = "number_of_nodes">4</property>
      <property type = "production_group">12</property>
      <materials>
        <material type = "Laminate">
          <layer id = "0" type = "materialtype">GLASS_PA6</layer>
          <layer id = "0" type = "thickness">0.25</layer>
          <layer id = "0" type = "orientation">0</layer>
          <layer id = "1" type = "materialtype">GLASS_PA6</layer>
          <layer id = "1" type = "thickness">0.25</layer>
          <layer id = "1" type = "orientation">45</layer>
          <layer id = "2" type = "materialtype">GLASS_PA6</layer>
          <layer id = "2" type = "thickness">0.25</layer>
          <layer id = "2" type = "orientation">90</layer>
        </material>
      </materials>
    </properties>
  </surface>
```

Figure 8-12 Surface section entry in an XML-file

8.3.2 Improvements over the original structural analysis process

Using robust and independent tools to facilitate the structural analysis process has improved the structural analysis process in several ways:

- ***The interface between PMM and structural analysis tools is made more transparent*.**
  Instead of writing files tailored to the chosen FE pre-processing software, XML files are used to transport the data between the PMM and the structural analysis module. These are accessible by common internet browsers and therefore accessible and, because they are readable, also transparent. The XML-files are interpreted by tools which prepare the FE pre-processing model. These tools are software package specific however they can be replaced by other tools as long as these tools understand the data stored in the XML files.
- ***Manufacturing view material definition will be used for the structural model.***
  In the original structural analysis implementation materials were defined for a structural group, meaning a group of surfaces with the same structural function like ribs. However for the manufacturing model materials were specified per production group. Therefore material specification could be inconsistent. Furthermore only material compositions stored in the material library could be used. For composites this means that only a limited number of pre-defined lay-ups could be chosen. In the new system the material specification of each surface segment is defined by looking at the production group of the surfaces

segment and finding the corresponding material definition. In this way the materials in the manufacturing and structural analysis are consistent. The materials can consist of multiple layers of different orientation and thicknesses. In this way composite materials can be modelled. The material type per production group can still only be chosen from the materials present in the materials database. Defining the material properties per production group also means that the different structural elements in a structural group can have different material definitions. Something that was not possible in the initial structural analysis implementation.

- ***Tools that are tried and tested will be used to facilitate the implementation.*** The new implementation uses tools that have used in previous projects and can be used in future projects. They are constantly updated. However the input format for these tools is fixed, so they will always be able to handle the data collections produced by the PMM. All developments of these tools can used to further up-date or up-rate the MDEE.
- ***Level of automation is increased.*** The level of automation is increased because the tools used automate the structural analysis process further than was achieved with the original implementation. For instance no interaction with the FE pre-processing software isneeded for creating the structural model. This automation will be improved further when the interface tools are improved.

The application of boundary conditions has not been addressed in the improved structural analysis process, for now the original loads session is run to create the boundary conditions and apply the pressure loads. In future this process could also be facilitated by the new interface tools. It will require the creation of an additional XML-file, which stores the boundary conditions and loads.

8.4 Recommendations for further improvement of the structural analysis process

Only the preparation of the structural analysis model is implemented, the structural analysis itself and the interpretation of the results still have to be done by hand. Automating these steps would automate the complete structural analysis process in the MDEE. This automation is essential if the structural analysis is to be used in optimization loops. For automating the structural analysis itself an analysis method should be chosen. What kind of analysis, for example linear or non linear, is required depends on the movable configuration and characteristics. Therefore knowledge rules have to be implemented for selecting the appropriate analysis method. The result from the numerical analysis consists of a substantial amount of data. To make this data accessible post processing will be required so the results can be interpreted quickly.

8.5 Conclusions

In this chapter the implementation of a structural analysis in the Movable Design and Engineering Engine (MDEE) is discussed. This implementation was achieved by adding several software modules to the MDEE. The structural analysis process of an aircraft movable is automated to a large extend. Because the data transformations in the analysis process are standardized using software modules, the structural analysis performed will create results of consistent quality. This makes sure that the analyses of different design concepts are comparable. Using the structural analysis module the movable designer quickly gets feedback on the structural performance of a design concept. The movable designer can use this feedback to adjust existing design concepts or create new design concepts that better meet the structural requirements. In this way the structural analysis supports the “Design for Strength and Stiffness” aspect of the Systems Engineering methodology.

9 Manufacturing feasibility Example: the preparation of DRAPE simulation models

Part of the manufacturing analysis is the feasibility analysis. Manufacturing feasibility in this case means the chance of successfully manufacturing a part or product. In case of aircraft components this feasibility is dependent on the physical appearance of the parts that form the component and on the production and assembly methods available to manufacture the component. The manufacturing feasibility of an aircraft component can therefore be determined by analysing the selected manufacturing methods. What analysis method is needed differs for each part or joint and is usually dependent on the manufacturing method used and the geometry of the part or joint. The analysis methods that can be used range from a manufacturing simulation to producing a prototype.

In this chapter a technical feasibility analysis for parts commonly encountered in aircraft movables is implemented. This will show how KBE tools can enable the “Design for Manufacturing” aspect of the Systems Engineering. The tools developed will enable this methodology for only one specific type of part. However the methodology used to develop the presented tools can be used to enable other manufacturing methods. In this chapter only the facilitation of the feasibility analysis is discussed and shown using existing analysis tools. The analysis itself falls outside of the scope of this chapter. Results from the analysis will be shown however. The parts for which the feasibility analysis is implemented are composite parts build using different forming techniques and fabric based materials. A commonly encountered problem with these parts is wrinkling of the material during the manufacturing process. This wrinkling is the result of deformation of the material imposed by the part geometry. When wrinkling occurs normally the parts requirements with regards to tolerances and structural properties cannot be met. This means that the part has to be re-designed. The wrinkling of parts can be predicted using simulation tools. These tools use mathematical algorithms to simulate the forming process. To enable this type of analysis a model of the analyzed part is required. In this chapter the preparation of such a model is described.

In the first section the theory and background of the feasibility analysis in the aircraft Movable Design and Engineering Engine (MDEE) is discussed. The second section discusses the actual implementation of the feasibility analysis in the DEE. Finally recommendations are made and conclusions are drawn.

9.1 Theory of adding feasibility analysis to the aircraft movable DEE

In this section the theory behind and the background of the feasibility analysis is discussed. From this theory the requirements for the actual implementation of the feasibility analysis can be extracted. The main issue that should be clear before developing the actual feasibility analysis is what the final outcome of such an analysis should be. In this case the outcome should be an estimation of the chance of successful production of a part. How this chance can be estimated is dependent on the parts analysed and the analysis tools that are used. Therefore the first issue that should be addressed are the characteristics of the analysed parts and the simulation tools used to analyse them. Using these characteristics the requirements for the other tools involved in the feasibility analysis can be determined. A large part of these characteristics is dependent on the position of the different tools in the MDEE. Finally the requirements of these tools need to be formalized so they can be used for the development of the actual feasibility tool.

In this chapter the drapability of composite part is used as an example of a feasibility analysis. However there are many more feasibility analyses for different manufacturing techniques. This can for instance be flow simulations for injection moulded parts. These different tools will need another implementation for use in the MDEE. However the principles shown in this chapter can be applied.

9.1.1 Characteristics of the composite forming feasibility analysis

Composite forming techniques can be used for many different parts. In this case the ribs of the aircraft movable model were chosen, an example of which can be seen in Figure 9-1. To reliably determine the feasibility of successful manufacture of such part, an accurate model of these parts should be available. In this case the level of geometric detail available in the PMM is not enough. Therefore a new model of these parts incorporating more details must be created.

Figure 9-1 Example of a rib analysed

For the composite forming feasibility analysis the DRAPE software developed at Delft University of Technology (Bergsma, 1995) will be used. This software simulates the lay up or forming process of fabrics based on mathematical algorithms. These fabrics are part of the composite material of which the parts consist. To perform the simulation a representation of the analysed part is required. The representation consists of a surface, which will be used as a basis to form the part in question. The DRAPE software simulates the forming process by looking for points on the surface where the nodes of a geodetically deformed fabric meet the product. Therefore the surface has to be represented in the form of points or a mesh. It is therefore not possible to use standard geometry files such as IGES or STEP files for supplying the geometry. The output of the DRAPE analysis is a plot of the deformed fabric. Deformation is this case is a change in angle between the fibres in the fabric. The deformations are in turn an indication of wrinkles that will be formed. When the angle between fibres becomes too small, wrinkling will occur. When wrinkles occur in areas where they are not allowed the chance of successfully manufacturing a part is zero.

9.1.2 Position of the feasibility analysis in the MDEE

As with the analysis tools discussed in the previous chapters, the elements used for the feasibility analysis can be found throughout the MDEE. However the feasibility analysis has an extra feature; the detail level of the model provided by the Parametric Movable Model (PMM) has to be increased significantly. To increase the level of detail, inputs or parameters are needed describing and configuring these details. Furthermore the details have to be generated in a new model generator. Therefore the element types in the DEE for a feasibility analysis differ somewhat from previous analyses. The position of the different elements in the DEE can be seen in Figure 9-2. These different elements are:

1. Input parameters for the PMM determining for which element a feasibility analysis should be performed.
2. Data collectors in the PMM.
3. Data collections in the form of files containing data about the manufacturable part of which a feasibility analysis will be performed.
4. Additional inputs to configure the details in the detailed product model generator.
5. Detailed product model generator which creates a detailed model and data for the actual analysis. In this case it is called the Rib Multi Model Generator (RMMG).
6. Data collected from the RMMG on which the actual analysis will be based.
7. The analysis tools performing the feasibility analysis.
8. Analysis result files containing the results from the feasibility analysis.

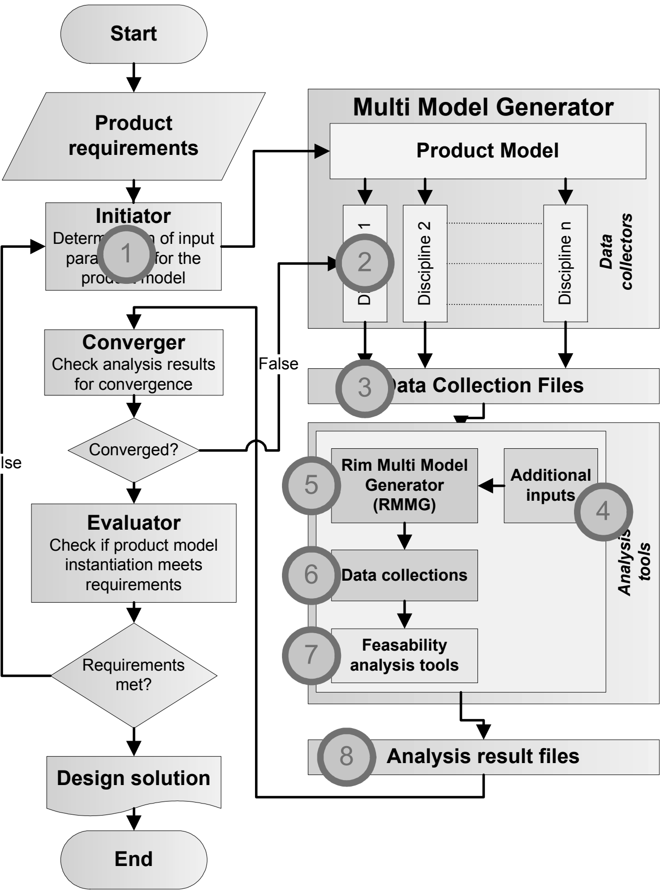


Figure 9-2 The adjusted DEE with the additional elements for creating a more detailed analysis model

The first element needed for the feasibility analysis in the MDEE are inputs for the PMM. With these inputs the part of which a feasibility analysis should be performed is determined. The second element are the data collectors in the PMM that collect the data required for the feasibility analysis. These data collectors extract data from the movable product model about the analysed part. In this case the information consists of geometrical information. This geometrical information is extracted from the aircraft component definition. Result of the data collectors is the third element, the data collections in which the geometry is stored. Like in previously discussed analyses these geometry files should be of standardized format.

The fourth and fifth element are needed to make a new, more detailed model of the part that is analysed. A new model is generated because more details are needed then can be supplied by the PMM. However this leads to a problem, namely that more inputs are required. These inputs could be made part of the PMM input data set. However this will result in a big increase in input parameters that are only needed for one part of the PMM. Furthermore if more parts of the PMM have to be analyzed the input parameter set would increase even further. Therefore it was decided to separate the inputs for the detailed part model. These inputs form the fourth element. This means that every analysed part has its own set of inputs. Therefore when analysing a complete movable, incorporating several parts that will be analysed for feasibility, several input files will be needed. These files have the same format but can be filled with different parameters. The input set for the rib feasibility tools are separate and unrelated to the PMM inputs, however in future a relationship between these inputs might be enforced. Why and how this can be done is explained in the next section.

The fifth element is the detailed product model, in this case called the RMMG. This is simply a new Multi-Model Generator (MMG) only in this case for detailed aircraft parts. This new MMG should also be capable of collecting the data needed for the actual drapability analysis. In the MDEE geometric data collections are fed from the PMM to the detailed part MMG. However because these geometry reports are of a standardized format they can also be supplied by other tools. The detailed MMG should therefore be considered as a stand alone tool that can fit to numerous DEE's and has its own set of inputs.

The sixth element of the MDEE is the data collected from the RMMG. This has to be interpreted by element seven, the feasibility analysis tool. This data should first of all store the geometry of the detailed part. This can again be done using standardized geometry file formats. Besides geometry other information is also needed to perform the feasibility analysis. What this additional data is dependents on the characteristics of the analysis itself. In this case the analysis tool needs a mesh. The mesh itself could be considered a geometric input. However the RMMG only deals with generating a geometrical model, not with the meshing of this model. Therefore the mesh has to be created by a meshing sub-module. Besides geometrical information this sub-module also requires information about the mesh density of the different geometrical elements that form the detailed part. This meshing information is therefore also required by the meshing sub module and has to be created by the RMMG.

The seventh element in the DEE is the actual analysis module. In this case the analysis module will perform a draping analysis. In the DRAPE analysis software the actual analysis is performed using the mesh created by the meshing sub module. The results from this analysis should be represented in the eight element of the MDEE the results file. This results file can be used to judge the chance of successful production of a part.

9.1.3 Hierarchical relationship of different level inputs in a Design and Engineering Engine

In a Design and Engineering Engine (DEE) different tools are linked together to develop or analyze a system or product. All these tools need inputs. Inputs needed by a tool can be distinguished in 2 groups: inputs supplied by other tools in the DEE and inputs supplied by the user of the DEE.

A DEE can consist of tools that operate on different scale levels. For instance the MDEE consists of tools to model and analyze the complete movable and of a tool to perform a detailed feasibility analysis of formed composite rib, discussed in this chapter. Because the detail level of the tools is different the detail level of the inputs needed for the tools is also different. This for instance means that the PMM only needs to know location and concept of the rib. A dedicated rib analysis tools also needs to know the detailed configuration of the rib to perform a sensible analysis. However this results in a problem because the detailed rib configuration has to be captured in input parameters for the detailed rib tool. This means that an input set has to be created for each rib that will be analyzed. This results in a substantial set of input parameters, which have to be provided by the MDEE user.

Previously inputs describing a design concept to be analysed by a DEE were kept in one input file. This guarantees that all tools used in the DEE use consistent inputs and that therefore the different analyses are comparable. However when tools of different scale levels are present in the DEE this results in input parameters sets of massive and unpredictable size. This could make them unworkable. Therefore it is advisable to keep the inputs for the tools operating on a scale levels requiring more details separate. These inputs will be called low level inputs while the initial inputs, for instance for the PMM, will be called high level inputs.

When the low level inputs are stored in separate input files without any connection to the high level inputs the total input parameter set for the DEE can become inconsistent. This is because there is a relationship between high level inputs and the low level inputs. For instance in the inputs for the PMM, the number of ribs and the manufacturing concept for the ribs are defined. This influences the number of times a detailed rib analysis has to be performed and therefore determines the number of low level input sets required. Furthermore the high level inputs define the input range for the lower level inputs. For instance the thickness of a rib defined in the high level inputs might influence the appropriate input range for a parameter like fillet radius in the lower level inputs. To keep the relationship between high and lower level inputs consistent rules that contain these relationships have to implemented and enforced within the DEE. In Figure 9-3 the relationship between the different input sets in the Movable DEE are depicted. For now the detailed rib analysis tool will work

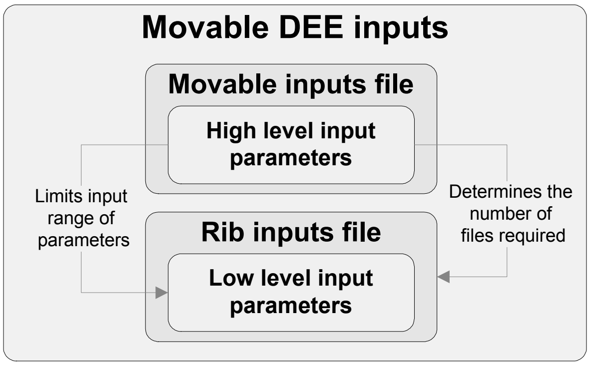


Figure 9-3 Input hierarchy of the different inputs files in the Movable DEE

as a separate entity without the PMM inputs having any influence on the input parameters, h in the future this issue has to be addressed to keep the MDEE consistent.

9.1.4 Requirements for the implementation of feasibility analysis in the MDEE

The characteristics described in the previous sections result in requirements for the actual implementation of the feasibility analysis in the MDEE. These implementation requirements are:

- **Files storing the data produced and/or transferred should be transparent and accessible**
  All the data collections used in the DEE should be transparent and accessible. This is only true for collections that transport data but do not fit a specialized tool. For instance the format for the Drape analysis tool is fixed and can therefore not be made transparent or accessible.
- **Detailed multi model generator should be a stand alone tool**
  The detailed multi model generator generates a representation of a part. It should be developed in such a way that it is a stand alone tool. In this way it not only fits in the MDEE but can also by used in other frameworks or operate as a separate tool.
- **Detailed multi model generator should incorporate all details that influence the manufacturing process**
  It is essential the detailed multi model generator captures all the details that influence the manufacturing process. What these details are is based on the knowledge of manufacturability experts. When not all key details are modelled the subsequent analyses that use the model become unreliable and are therefore not useful.
- **Inputs for the detailed multi model generator should be separated from the PMM input**
  Because the detailed multi model generator is a stand alone tool the inputs for this tool should be separated from the PMM inputs. This also prevents the excessive size increase of the PMM input dataset. When used in an automated system the inputs of the detailed analysis model can also be used to optimize the shape of the part.
- **Use COTS software where possible**
  To reduce development time and increase the chance of acceptance for the developed tools COTS software should be used as much as possible.

9.2 Implementation of the actual tool

The implementation of the feasibility analysis in the MDEE will be limited to the ribs of the movable. This part was chosen because in this part all the difficulties of composite forming techniques can be encountered. Furthermore experience exists in the actual forming process of these ribs.

9.2.1 Feasibility analysis in the PMM

The implementation of the feasibility analysis does not result in many changes or additions to the PMM. In fact the PMM only has to provide the contours of the rib that is analysed. Which rib is analysed is determined by additional PMM inputs. These inputs define the wing trunk and rib number of the analysed rib. When the rib is identified the data about this rib can be collected. The files storing the required data should store the shape of the upper and lower curve of the rib. Because the front and rear of the rib are always straight the upper and lower curve are enough to fully define the rib. The start of the rib is defined by the front spar, while the rear of the rib is defined by the last spar of the wing box. The geometry files storing the upper and lower curve are of the IGES format, providing the advantages discussed earlier.

9.2.2 Detailed description of the Rib Multi Model Generator (RMMG)

The detailed multi model generator that is used to generate detailed rib models is called the Rib Multi Model Generator (RMMG). The RMMG is developed as a stand alone tool this means that there is no interaction with any other tool during the process of generating a detailed rib model. The interaction the RMMG has with other tools occurs by in- and outputs. The input of the RMMG consists of the previously described geometrical inputs in the form of IGES files and inputs describing the details that are added in the RMMG. The outputs of the RMMG consist of data collections containing the geometry of the detailed rib and other information needed for the creation of the feasibility analysis model.

The RMMG in itself creates a model of a rib including all details that are essential for the draping analysis. The RMMG also prepares the model for data collection. Preparing for data collection is this case means segmenting the model so it can be easily meshed. This segmentation is analogous to the segmentation for structural analysis described in chapter 8 and consists of cutting up the rib surface into triangular and quadrangular surfaces. The segmentation of the model itself is not enough for the mesh generator to create an appropriate mesh for the DRAPE analysis software. This is where the additional information generated by the model is needed. This additional information defines the mesh density in certain areas of the rib. Mesh density in this case means how many nodes or mesh points have to be created.

The RMMG must be able to create a rib model similar is shown in Figure 9-4. The detail features shown here are the so called dents and a flange including the fillet to the main rib web. In the sections below the actual implementation of the models and how it is prepared for export to the DRAPE analysis module is discussed.

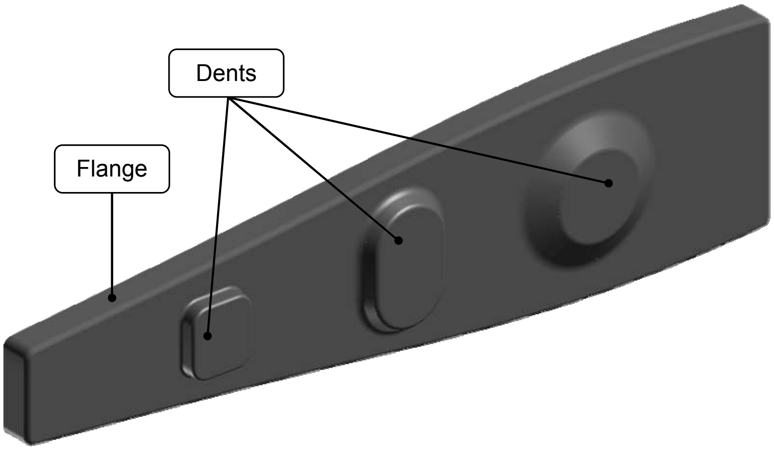


Figure 9-4 The rib that should be modelled by the RMMG showing the dent and flange details

The RMMG inputs

The inputs for the RMMG consist of several parts. The first part consists of the administrative inputs. These inputs are used by the RMMG to determine where the in- and output files used by the RMMG are stored. Besides the inputs referring to the files containing the rib contour curves, there is also an input referring to leading edge contour curves. This is an optional input that lets the RMMG create a model with a smooth leading edge. This leading edge cannot be provided by the PMM. However when used in different DEE's or as a standalone tool this additional input can be useful.

The second and largest group of inputs is the input group determining the characteristics of the detailed features that make up the rib model. These inputs can be further subdivided in several sub-groups:

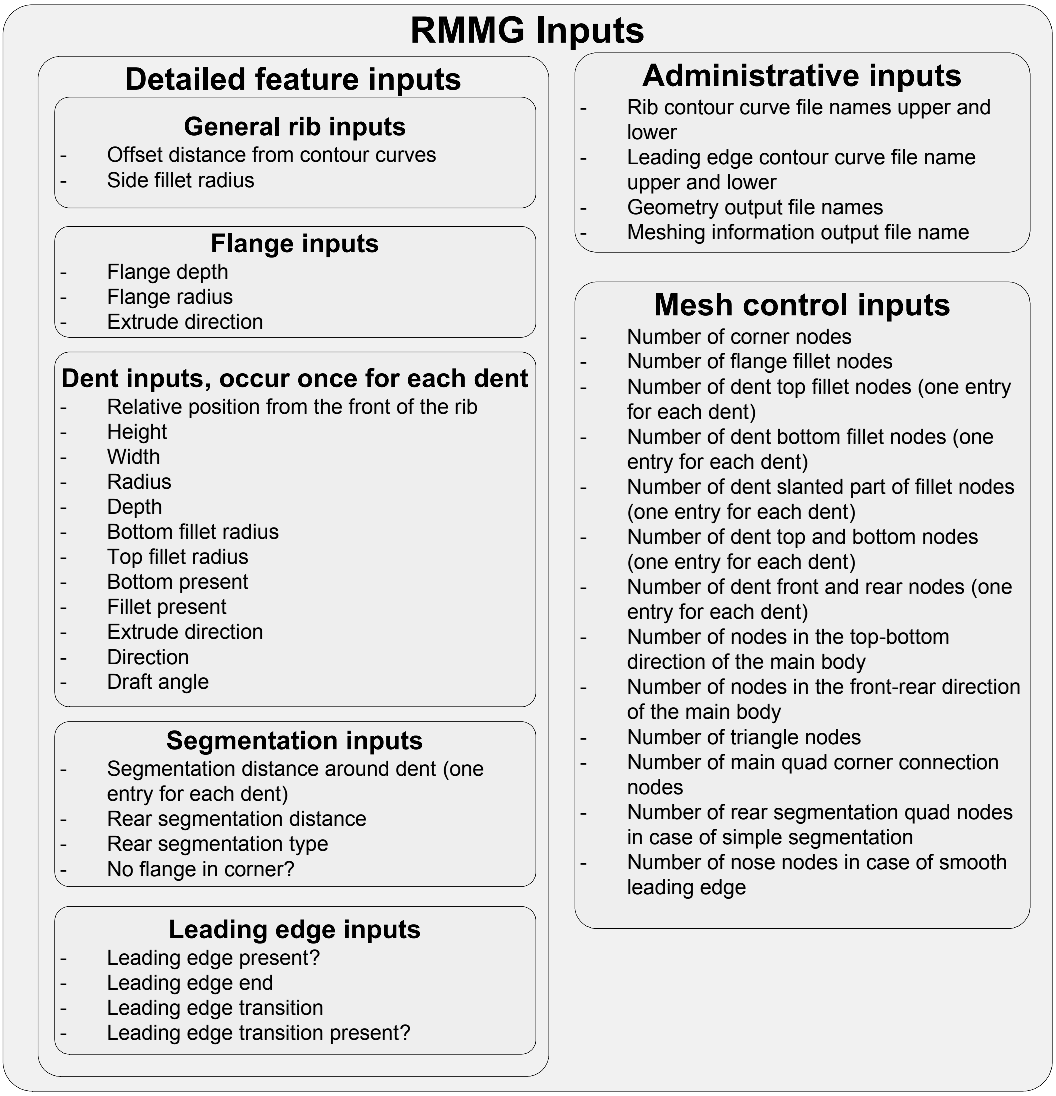
- *General rib inputs*. The general rib inputs determine the general shape of the rib models. An important input that is part of this group is the offset distance from the contour curves, which determines a shrink distance. The shrink distance is used to model the thickness of the material used in manufacturing.
- *Flange inputs.* The flange inputs determine the characteristics of the rib flange.
- *Dent inputs.* Dents are stiffening elements commonly encountered in composite ribs. Inputs in this group determine the shape and position of each dent. Multiple dents can exist in a rib model therefore all the inputs have the form of a list. From these lists each entry is linked to a dent. All inputs should be kept consistent meaning that all the input lists should have the same length.
- *Segmentation inputs.* Segmentation inputs determine what kind of segmentation is required and where segmentation is required. Segmentation prepares the model for meshing, which will be performed outside the RMMG. In this group of inputs entries exist that allow the user of the RMMG to delete some pieces of the geometry that could cause manufacturing difficulties and are not necessary to fulfil the ribs function.

- *Leading edge inputs.* Leading edge inputs determine whether or not a leading edge is present and when present what the configuration the leading edge should be.

With the detailed inputs the actual manufacturing concept of the rib is steered. When the RMMG is used in the rib design process or an optimization cycle these inputs can be used to change or optimize the design. Several detailed inputs have advanced input options allowing the user of the RMMG to use “smart” inputs analogous to the smart inputs of the PMM. These smart inputs can for instance mean that the position and dimensions of a dent are determined absolute or relative to another geometric feature such as the outer contour of the rib.

Final group of inputs are the mesh control inputs. These inputs control the required mesh density when the rib model is prepared for the drapability analysis. The mesh control inputs are used to determine the number of nodes in critical areas of the rib. In this way an appropriate mesh density can be assured in these areas. In other areas, for instance large flat area’s, a course mesh is allowed. This can also be achieved by specifying the number of nodes in certain areas. The number of nodes for each surface edge in the model is stored in the additional information file. This file, together with IGES files storing the geometry, is used by a specialized mesh generator to generate the mesh needed by the DRAPE analysis software.

An overview of the different input groups and all the inputs for the RMMG can be seen in Figure 9-5. As can be seen many inputs are needed. However several of these inputs can be kept the same for different rib concepts. This reduces the effort of coming up with inputs for each rib concept and also allows for re-using input values that work properly. This practice can for instance be used in the mesh control input group, where input changes are rarely required.



RMMG Inputs

Detailed feature inputs

General rib inputs
- Offset distance from contour curves
- Side fillet radius

Flange inputs
- Flange depth
- Flange radius
- Extrude direction

Dent inputs, occur once for each dent
- Relative position from the front of the rib
- Height
- Width
- Radius
- Depth
- Bottom fillet radius
- Top fillet radius
- Bottom present
- Fillet present
- Extrude direction
- Direction
- Draft angle

Segmentation inputs
- Segmentation distance around dent (one entry for each dent)
- Rear segmentation distance
- Rear segmentation type
- No flange in corner?

Leading edge inputs
- Leading edge present?
- Leading edge end
- Leading edge transition
- Leading edge transition present?

Administrative inputs
- Rib contour curve file names upper and lower
- Leading edge contour curve file name upper and lower
- Geometry output file names
- Meshing information output file name

Mesh control inputs
- Number of corner nodes
- Number of flange fillet nodes
- Number of dent top fillet nodes (one entry for each dent)
- Number of dent bottom fillet nodes (one entry for each dent)
- Number of dent slanted part of fillet nodes (one entry for each dent)
- Number of dent top and bottom nodes (one entry for each dent)
- Number of dent front and rear nodes (one entry for each dent)
- Number of nodes in the top-bottom direction of the main body
- Number of nodes in the front-rear direction of the main body
- Number of triangle nodes
- Number of main quad corner connection nodes
- Number of rear segmentation quad nodes in case of simple segmentation
- Number of nose nodes in case of smooth leading edge

Figure 9-5 Schematic overview of the RMMG inputs

Detailed description of the RMMG geometric model

The RMMG creates models of ribs. The most important part of the RMMG is its geometric modelling capability. The RMMG creates a geometric model of the rib by creating several geometrical entities. The different entities for the rib model are structured in a hierarchical fashion. Each geometrical element performs a specific function although not all elements need to be present in all rib models. The two main groups of geometrical elements can be seen in Figure 9-6, which is a UML representation showing the main functions and operations of the different entities. The elements of both the “flanges surfaces” and “main body surfaces” groups are shown in Figure 9-7 and Figure 9-8 respectively.

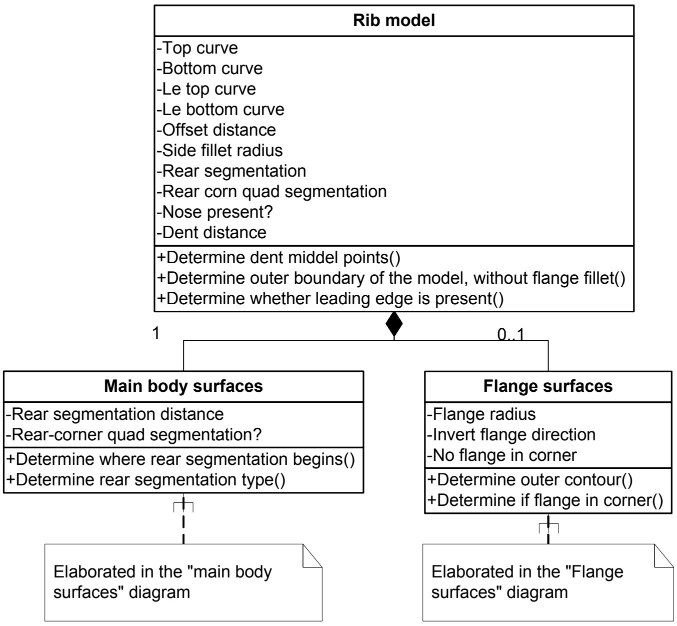


Figure 9-6 UML representation of the two main geometrical groups of the rib model.

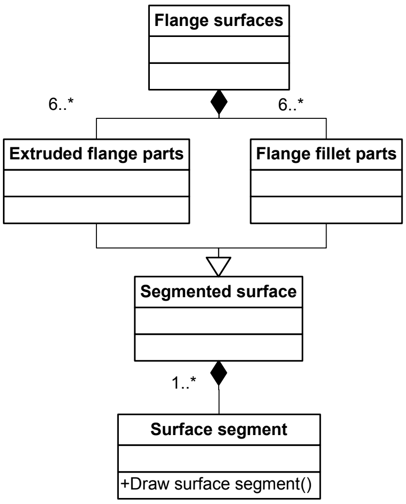


Figure 9-7 UML representation of the flanges surfaces group of geometrical entities from Figure 9-6

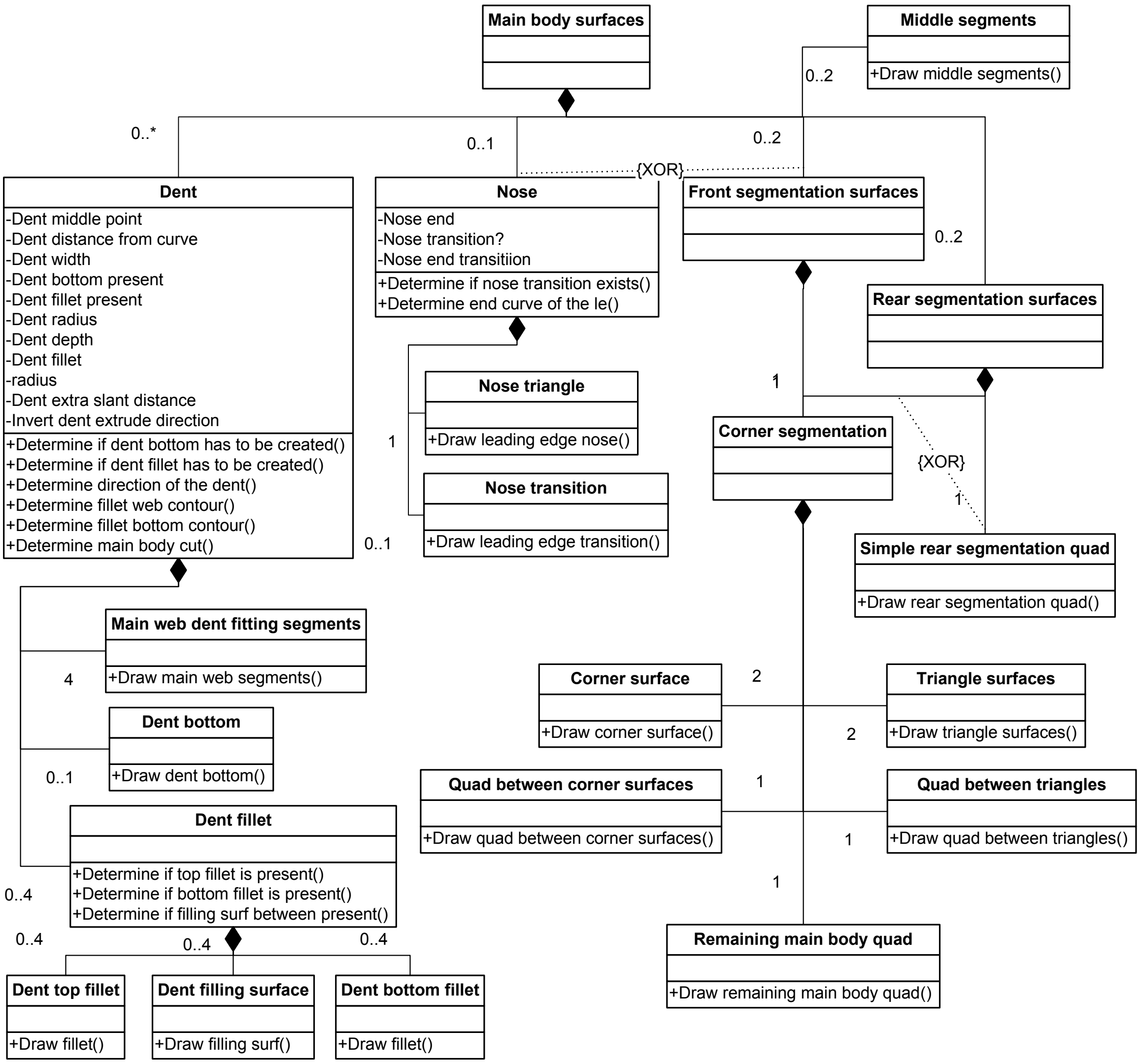


Figure 9-8 UML representation of the main body surfaces group of geometrical entities from Figure 9-6

The different geometric entities have to be modelled by a geometrical modelling engine. In this case the same ICAD software was used as for the PMM. The geometrical model makes use of the geometrical modelling engine incorporated in the software. The different geometrical elements that make up the RMMG are described in detail in Appendix H.

Examples

In Figure 9-9, Figure 9-10 and Figure 9-11 different instantiations of the RMMG are depicted showing different possible geometrical rib configurations. The only differences between the models are different input parameters and sometimes different input curves. These examples show the flexibility of the model and also show some of the potential configurations that can be generated with the model.

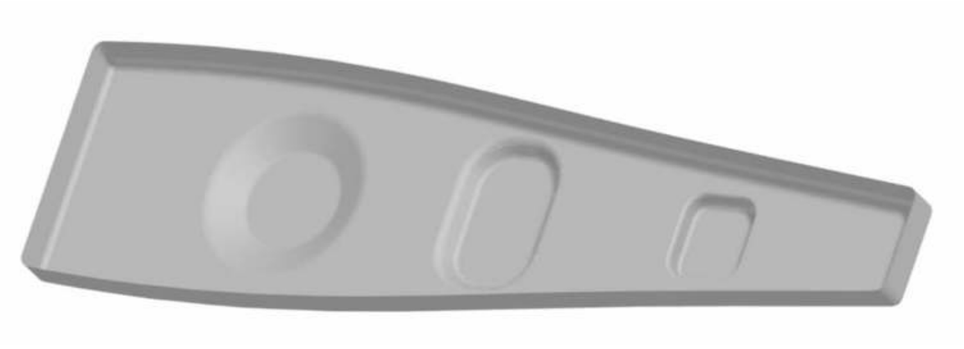


Figure 9-9 The standard rib example

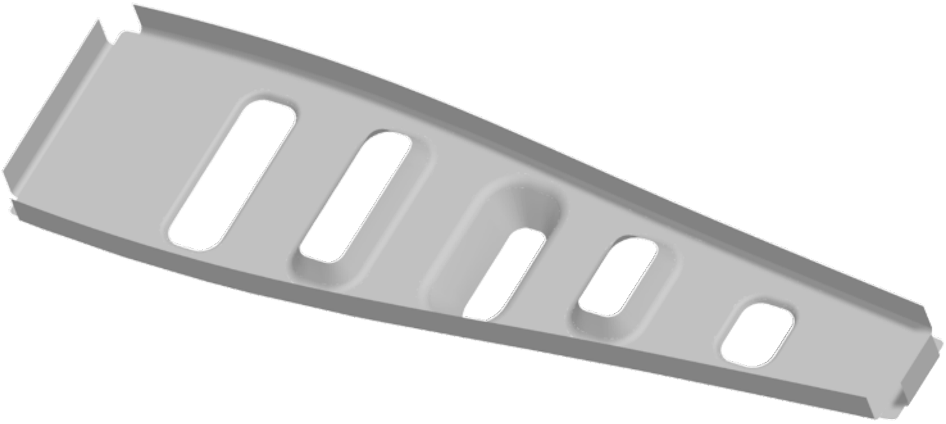


Figure 9-10 More intricate version of the standard example showing the possibility to remove elements such as dent bottoms and corner segmentations from the model

Figure 9-11 Model example showing the use of a nose or leading edge

The data collected from the RMMG

Two kinds of data are collected from the RMMG. The first kind is the geometry of the rib model. The second kind is the mesh density information. For storing the geometry data the IGES format is selected because it enables transparent and standardized storage of geometry data. The geometry that is stored consists of all the previously discussed surface segments. These surface segments result in a rib geometry that is easily mesh-able, meaning only three and four edged surface segments exists. In the next step the geometry will be used as a basis for the creation of the mesh needed for the DRAPE analysis.

For the creation of this mesh, the mesh density data should be stored so it can be transferred to the meshing module. The mesh density information consists of elements that have to be determined for each edge of each surface stored in the geometry file. The elements that have to be determined are:

- Number of nodes on the edge in question
- Mesh seeding type determining how the nodes are spread over the edge, can be uniform, one-way-bias or two-way-bias.
- Ratio that determines the form of the node spread in case of one-way-bias or two-way-bias seeding type.

These elements are determined for all the edges of all the surfaces in the RMMG input parameters. However in many areas mesh control is not required. Here the entry for the mesh seed is ‘nil’. This is interpreted by the mesh generation module and no mesh seed is applied to these edges. The number of nodes on these edges will be optimized by the mesh generation module itself.

Because the seeding information is basically text data and because of the advantages of the XML-format explained in chapter 7, the seeding data is stored as an XML-file. In the mesh density file the meshing information is stored per surface. Besides the mesh information the file also contains information about the geometric position of each surface in the form of the coordinates of its corner points. This information is needed to map the meshing information to the actual rib geometry in the mesh generation process. An example of the information stored about a surface can be seen in Figure 9-12.

```
<surface id = "1" nvertices = "4">
  <vertex type = "double" size = "1 3">71.07305272700945 -58.74360471225998 -2.418901185171012e-14</vertex>
  <vertex type = "double" size = "1 3">68.9128674363692 -56.583419322136216 2.999999999999976</vertex>
  <vertex type = "double" size = "1 3">69.37785075194637 -72.24360471225998 2.999999999999976</vertex>
  <vertex type = "double" size = "1 3">72.4110052469801 -72.24360471225998 -2.4188984149020598e-14</vertex>
  <MeshSeedInfo>
    <MeshSeed edge = "1" nel = "6" type = "UNIFORM" ratio = "NIL"/>
    <MeshSeed edge = "2" nel = "10" type = "UNIFORM" ratio = "NIL"/>
    <MeshSeed edge = "3" nel = "NIL" type = "NIL" ratio = "NIL"/>
    <MeshSeed edge = "4" nel = "NIL" type = "NIL" ratio = "NIL"/>
  </MeshSeedInfo>
</surface>
```

Figure 9-12 Example of an entry in the mesh information file for a surface. Edge “1” runs from vertex one to vertex two etc.

9.2.3 The Drape analysis tool preparation and execution

As was discussed before the DRAPE analysis tool needs a mesh as input. The mesh required by DRAPE can be supplied in different formats. The mesh that will be supplied to the tool has to be created using the data available from the RMMG; geometry information and mesh density information. For creating the actual mesh different tools can be used. Preferable a COTS tool should be used because this limits the development work of interfaces and is more likely to produce reliable results. In this case the Patran FE pre-processor will be used for generating the mesh. First of all because the meshes created by it are supported by DRAPE and secondly because toolboxes exist that aid the mesh creation process. Once the mesh has been created the execution of the draping analysis consists of loading the mesh in the DRAPE analysis tool, adding material layers, running the draping simulation and analysing the results. The DRAPE analysis itself will not be discussed however as it falls outside the scope of this chapter. Some analysis results will be shown at the end of this section.

Mesh generation process

As was discussed in the previous section for the creation of the actual mesh Patran will be used. One of the elements of Patran is the mesh generator, which can create a mesh based on geometry. This mesh capability will be used here to generate the mesh used by the DRAPE software. The most important issue is how Patran can be used in this mesh generation process. Usually when Patran is used interactively, geometry is loaded into its database and mesh seeds are applied to the surface edges after which the mesh is generated. For this process to fit in any DEE it has to be automated. The automation of this process depends on how the Patran software can be interfaced with the existing data or how the existing data can be reformatted to fit the Patran software. In this case tools were developed that interface the generated meshing information to it. The geometry data can be used “as is” because Patran has a build in IGES interface. The development of the interface tools will not be discussed in this section because they are developed externally (Nawijn, 2006). In this section merely the flow of data through the tool and the overall process will be discussed.

The actual process of creating the Patran mesh is relatively simple, geometry is read from the IGES file, mesh seeds are applied to the geometry surfaces and finally a mesh is created. However to run this process, several sub-steps have to be taken and tools have to be executed to take these sub-steps. Because the tools used in these sub-steps are developed externally these steps are not discussed in detail. The whole process and all the sub-steps can be seen in Figure 9-13.

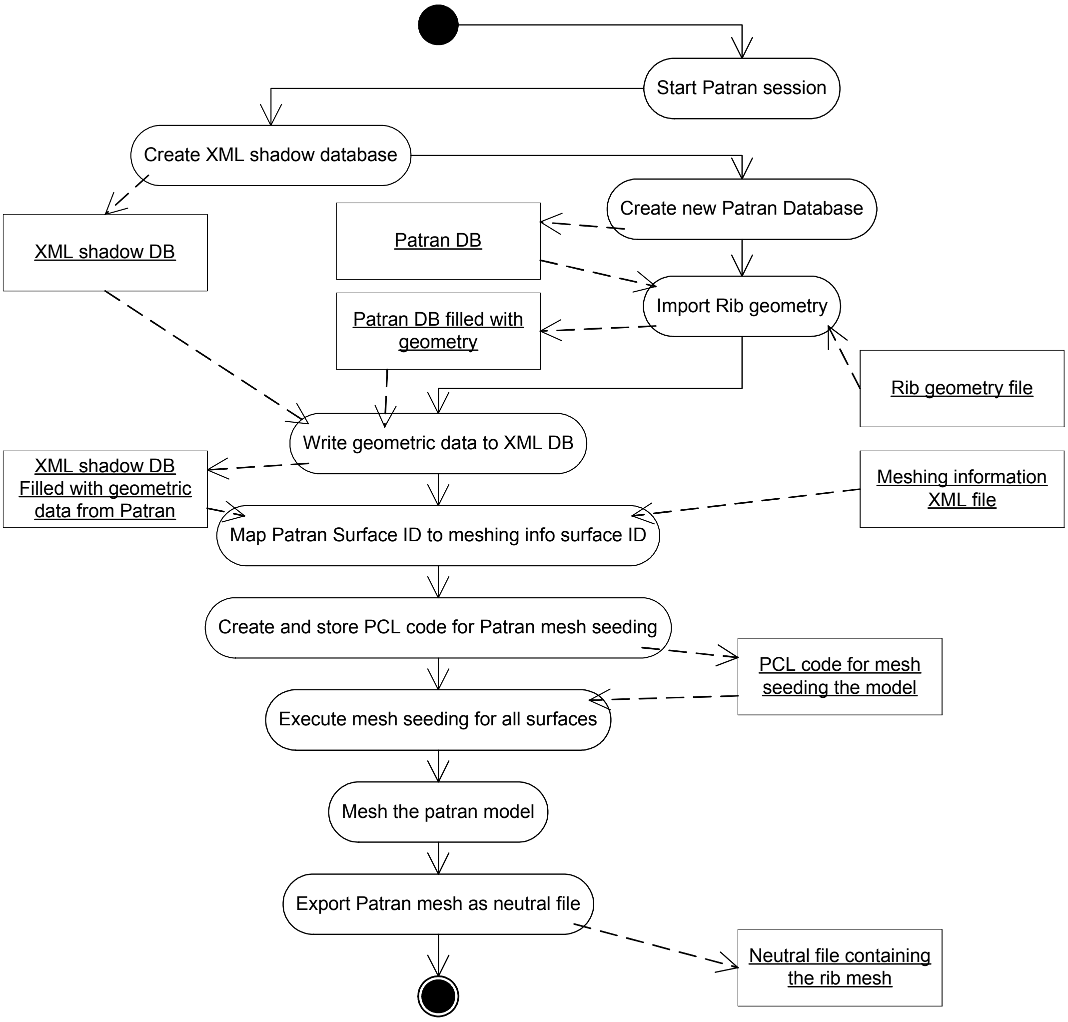


Figure 9-13 Meshing activity flow showing all activities performed during meshing. Data used and transferred is also depicted.

The final outcome of the mesh generation process is a mesh that can be used in the drapability analysis. This mesh has to be dense in certain areas where problems are to be expected and can be course in other areas. A dense mesh is for instance needed in the corners of the ribs and near dent fillets; here the rib is distinctly curved. A courser mesh is applied to large flat areas. The mesh is as course as possible to limit the number of nodes of the mesh. This minimizes the draping simulation time. The resulting mesh and some details can be seen in Figure 9-14to Figure 9-19.

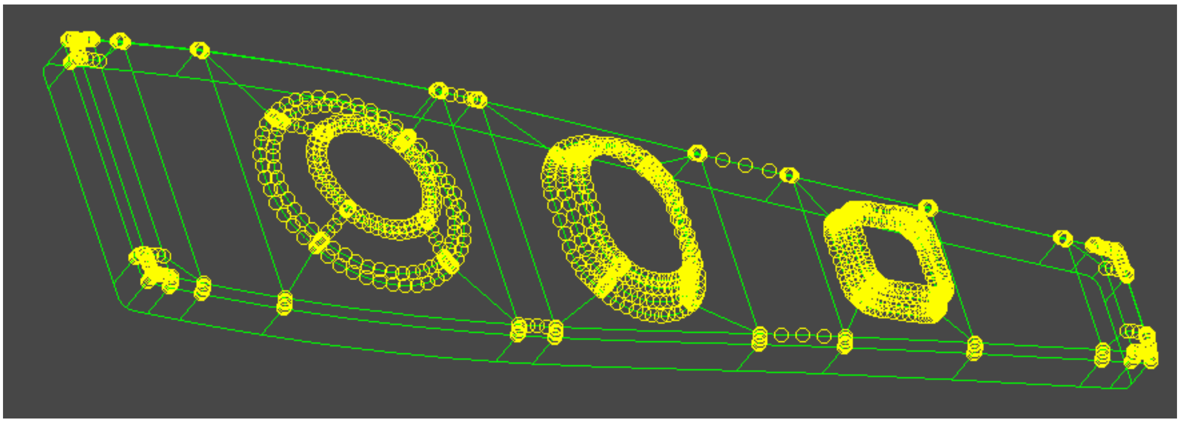


Figure 9-14 The rib model seeded in Patran using the seeding data generated in the RMMG

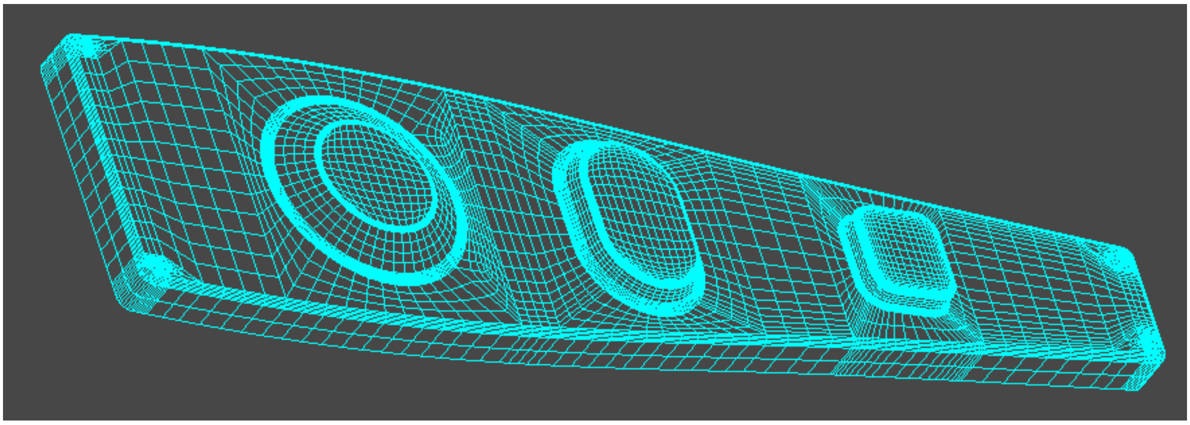


Figure 9-15 Meshed model in Patran

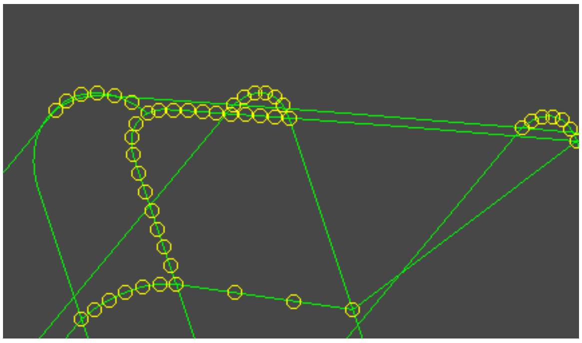


Figure 9-16 Seeded rib corner detail with increased segmentation

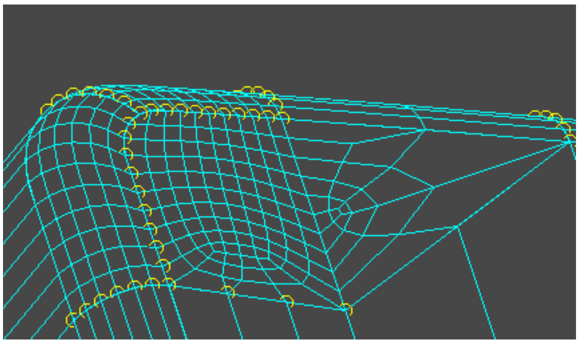


Figure 9-17 Resulting rib corner mesh detail

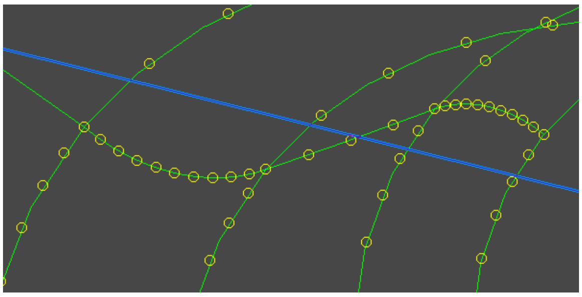


Figure 9-18 Seeded dent fillet detail

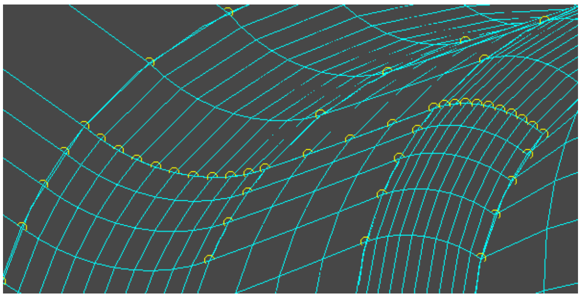


Figure 9-19 Resulting dent fillet mesh detail

Drape results

After the double nodes have been removed from the mesh in Patran using built in Patran functionality, the generated mesh is exported as a Patran neutral file and read by the

DRAPE analysis software. In fact DRAPE only uses the node data stored in this file to re-build the rib model. With the created model the composite lay-up process is simulated. From this lay-up simulation possible problem areas can be recognized and solutions for these problem areas can be devised or new rib geometries can be analyzed. For now the drape analysis and the interpretation of the results is a process that requires human input and interpretation. In Figure 9-20 the model as read by DRAPE from the Patran neutral file can be seen. The resulting analysis can be seen in Figure 9-21. As can bee seen excessive fabric deformations occur in the red areas. These deformations will result in wrinkling, which makes the analyzed design not feasible for the material lay up used.

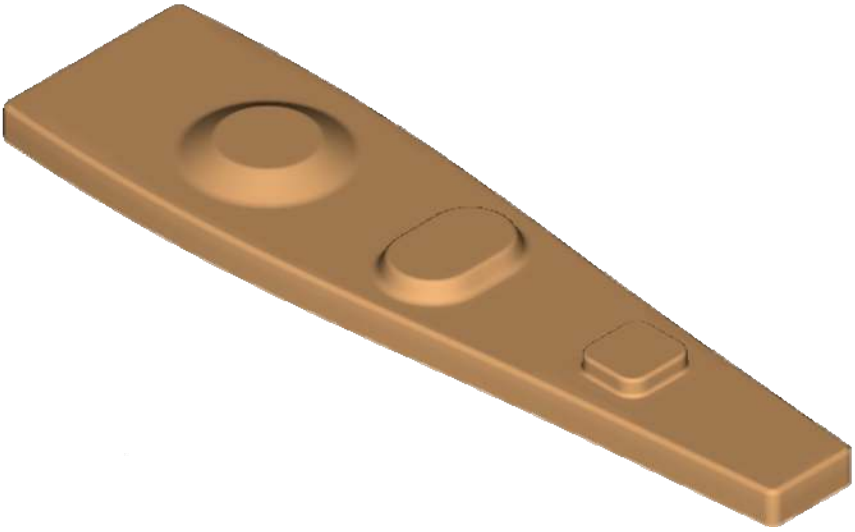


Figure 9-20 Drape model read from the Patran mesh

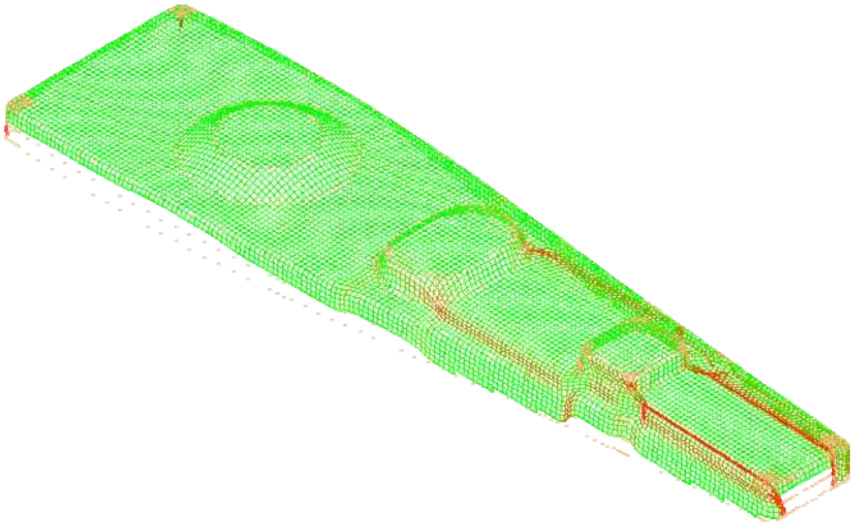


Figure 9-21 Rib model analyzed with DRAPE. The red areas clearly indicate fabric deformations around the rear dent. Note that the initial contact point is on the top of the front dent.

9.3 Recommendations

In the future the feasibility analysis tools could be improved first of all by automating the drapability analysis and by adding a results interpretation module. For now development of these elements is not possible as the DRAPE analysis tool is not robust enough to guarantee usable outputs in an automated process. The DRAPE tool needs manual tweaks and interaction to operate properly. When the knowledge about this interaction has reached a high enough level it can be used to increase the robustness of the drapability analysis, which would make automation possible.

Another element that can be improved is the actual RMMG. Improvement here means adding more manufacturing details and design options. Dent and flanges have been implemented however more design options are possible, like replacing the flat main web of the rib with a corrugated web.

Final improvement suggested would be to develop a module that generates the detailed RMMG inputs based on knowledge rules. This means that dent and flange configurations could be generated automatically or default inputs could be suggested to the user. This will improve the usability of the tool in an optimization framework and decrease the knowledge level needed to operate the tool. In case of the RMMG this could for instance mean that the PMM defines the space in which a rib lies and the material thickness. An optimization tool would then come up with a feasible rib configuration consisting of stiffening elements and flanges.

9.4 Conclusions

The developed model presented in this chapter shows how a drapability analysis for formed composite parts can be incorporated in the MDEE. Such a feasibility analysis can filter out un-feasible designs, which can obscure the design space of, in this case, an aircraft movable. By allowing the MDEE user to quickly analyse the manufacturing feasibility of a composite formed part, the “Design for Manufacturing” aspect of the Systems Engineering methodology is supported.

When to use the feasibility analysis should be carefully considered, because detailed feasibility analyses will require quite a detailed input level. When used too early in the design process the details needed for the analysis might not be known or fixed. Running a simulation then might give a false sense of security, because the analysis is only as reliable as the input parameters provided to it.

The developed model shows how data from high level modelling engines, in this case the Parametric Movable Model (PMM), can be used in lower level modelling engines, in this case the Rib Multi Model Generator (RMMG). Keeping the high and lower level modelling engines separate is essential to make sure that the low level modelling engine is widely applicable even when the high level modelling engine is not available. In this case PMM and RMMG are completely separate entities, interfaced using geometry stored in standardized in and output files.

10 Conclusions and Recommendations

In the introduction the thesis objective was defined, if and how this objective was achieved will be discussed in this chapter. Finally some recommendations for future research and improvements to the tools described in this thesis will be given.

Thesis objective:

Knowledge Based Engineering enables the application of the "Design for X" aspect of Systems Engineering for the aircraft component design process

10.1 Conclusions

In the aircraft component design process actors from disciplines like design, structural analysis and manufacturing engineering have to cooperate to define a design which meets the requirements. To enable the "Design for X" methodology the disciplines must be able to perform a detailed analysis in a limited amount of time. It has been shown throughout this thesis that KBE can automate time consuming non creative tasks in the design process, significantly reducing the time it takes to perform detailed analyses. For the "Design for X" methodology to function properly the results from the different analyses must be consistent. It has been shown throughout this thesis that KBE can ensure consistency by standardizing communications between the different analysis disciplines.

One of the main contributions of this thesis is to identify where the problem areas in the aircraft component design process lie and how they can be solved. Furthermore methodologies have been developed to use detailed analysis methods earlier in the aircraft component design process. The main contribution of the work in the industrial context is to show how KBE tools handling multiple design aspects can be implemented in the context of a Design and Engineering Engine and how this implementation can improve the aircraft component design process.

Because KBE is able to create detailed results quickly and able to keep analysis results from different disciplines consistent it enables the application of the "Design for X" aspect of the Systems Engineering methodology for the aircraft component design process.

In this thesis 4 application areas were identified to illustrate how KBE can improve the design process of aircraft components and enable the "Design for X" methodology. These areas are:

1. **Automating the model preparation and analysis for the structural analysis of an aircraft component.**
2. **Increasing the detail level of the manufacturability analysis of an aircraft component.**
3. **Automating the modelling of the aircraft component design itself.**
4. **Standardizing communication between the different analyses disciplines in the aircraft component design process.**

For the identified application areas methods were developed to improve the aircraft component design process. These methods were applied to KBE tools, which were developed. Below only a short conclusion about the methods and the accompanying tools is given, for a more thorough conclusion one is referred to the relevant chapters.

Creating generative aircraft component models. *(Chapter 5)*
Application area 3 is the automated modelling of an aircraft component design concept. The method identified to facilitate this is to develop a generative aircraft component model. Such a generative model creates the multiple design views of an aircraft component based on a single input data set. The generative model quickly generates a detailed basis for different analyses. These analyses can therefore also be detailed and reliable. Because the generative model is based on a single input set, it also ensures consistency of the different analyses. Both issues addressed above are important when enabling the “Design for X” methodology.

In chapter 5 a generative model, called the Parametric Movable Model (PMM), is implemented for an aircraft movable. This is capable of generating aircraft trailing edge movables in both structural and manufacturing design views quickly. Besides visualizing the concepts in their different views it is also capable of generating data for analysis based on these views. Contrary to existing research which usually focuses on simple products or do a not ctually implement the multi view approach, the multiple view approach has been implemented for a complex aircraft structures.

Automating the recurring cost estimation process and increasing the detail level of this cost estimation for aircraft components. *(Chapters 6 and 7)*
At the early stages of the aircraft component design process recurring cost estimation is usually not very detailed, for example cost is based on the expected weight of the component. However most recurring production cost is incurred in the early design phases. Therefore to enable the “Design for Cost” methodology a detailed cost analysis must be performed in the early design phases. This can be achieved by automating a detailed cost estimation method. This estimation method must provide cost data linked to the aircraft component structural elements, because this provides feedback to the component designer on how to create more cost effective design concepts. A cost estimation method suited for this is a cost estimation method based on process attributes which simulates the manufacturing process (Application area 2). This cost estimation method is also able to estimate the cost of part produced using new and innovative manufacturing methods.

Above described cost estimation method has been implemented in a cost estimation tool described in chapters 6 and 7. This tool is able to quickly generate detailed cost estimations of aircraft movables. The cost estimates are based on the manufacturing view of the PMM. The generated cost estimates provide the aircraft movable designer with valuable cost information early on in the design process. The novelty of this cost estimation system does not lie in the estimation methodology itself, but in the implementation of this methodology which shows that a detailed, process attribute based, cost estimation can be automated and applied early in the aircraft component design process. The novelty also lies in the fact that this cost estimation method has actually been applied to a complete complex aircraft structure, in this case a movable.

Automating the structural analysis model preparation of an aircraft component. *(Chapter 8)*

Preparing the structural analysis model is usually a time consuming step in the aircraft development process, because the structural analysis model has to be prepared by hand. This can result in out-dated structural models being used in the aircraft component development process or can increase the design lead time significantly. To enable the “Design for Strength and Stiffness” methodology the structural analysis process must be automated. The automated structural analysis must provide detailed results. Essential part of automating the structural process is automating the structural model preparation (Application area 1). Automation can be achieved by developing modules that automatically translate the aircraft component model, usually in CAD representation, into a structural analysis model.

In chapter 8 a tool is presented that automates the generation of an aircraft movable structural model based on the structural view of the PMM. Because of this automation detailed structural analysis can be performed quickly and reliable. This provides the designer with detailed structural analysis results early on in the design process.

Automating the preparation of models to analyse the chance of successful production of the aircraft component. *(Chapter 9)*

Analyzing if an aircraft component design concept can be produced successfully is important for determining if a design concept is feasible or not. However often determining if a concept can successfully be produced requires simulation software and detailed models not available at the early stages of the design process (Application area 2). Therefore to enable the “Design for Manufacturability” methodology detailed manufacturability models must be created and analysed quickly. This can be achieved by creating generative models that create detailed models of certain parts of the aircraft component. Creating more detailed models also requires the addition of more detailed information and therefore increases the dataset describing the aircraft component. This should be curtailed by limiting the analysis to the most critical parts identified in the aircraft component design concept.

A detailed formability analysis is enabled by a model preparation tool for drapability analysis of composite ribs, described in chapter 9. As a result of this tool detailed formability information about critical part in a movables construction will be available early in the design process. The novelty in the approach used to develop this tool lies in the fact that high level data, for instance from a movable model, can be used in more detailed analyses, in this case of a rib of this movable.

All communication inside and between the different KBE tools should use standardized and transparent data formats. In this way communication is standardized (application area 4). This is essential to enable the “Design for X” methodology, because not having standardized communication could result in inconsistent analyses results, effectively negating the advantages achieved by implementing this methodology. Standardizing communication in this case first of all means using standardized data formats that are accessible without any specialized software. Transparent data formats means that they can by understood stand alone without access to any other files.

In the tools discussed throughout this thesis the geometrical data transfer file format used has been the IGES format which is a commonly accepted format to store geometry. The IGES file format can be read by all common CAD tools. For storing other data the XML-file format is used as much as possible. This file format can be interpreted by many software packages simplifying the interfaces to these software packages. Furthermore they can be opened by any common internet browser.

All developed KBE tools should have clearly defined in- and outputs making them modular. Modularity of the tools is essential to make them re-usable in future projects and also to make maintaining them manageable. In future project different modules can be re-used to produce flexible automated design and analysis frameworks that can be used to explore the aircraft component design space.

All knowledge used to create KBE tools should be stored outside the KBE tools itself in a standardized modelling language. Besides improving the design process of aircraft component it is also important to store the knowledge about the component itself and the design process. It is important to not only store the knowledge in the developed tools but also to store the knowledge separately in documents and diagrams. Throughout this thesis Unified Modelling Language (UML) diagrams have been used to represent the aircraft component and design process knowledge. These diagrams can be used to re-create the KBE tools when, for instance, the initially used software becomes obsolete.

KBE tools can perform detailed analyses quickly. This can be used to reduce the aircraft component design lead time or to improve the quality of the resulting aircraft component design. Reducing design lead time would enable aircraft component suppliers using the KBE tools to quickly respond to demands and wishes of the aircraft integrator companies. Improving the aircraft component quality improves the aircraft component value for the customer.

10.2 Recommendations

With the analysis of the aircraft component design process and the subsequent development of KBE tools the objectives of this thesis have been met. However there is room for further or follow-on research and improvements to the developed methodologies and tools.

First of all the aircraft component process has been analysed using the authors experience. To verify the analysis of the aircraft component design process presented in this thesis such a design process should be analysed in the industry. This could for instance be done by documenting and analysing the development of an aircraft component from start to finish.

The different areas where methods have been suggested and tools have been developed can be improved in certain areas. For a more in dept discussion on these improvements one is referred to the chapters handling these tools.

Creating generative aircraft component models. *(Chapter 5)*
Generative models can be improved by extending the covered design space. Extending the design space can be achieved by increasing the design options implemented in the model. For example for the created aircraft movable model this could mean implementing the full depth honeycomb structural option.

Automating cost estimation process and increasing the detail level of this cost estimation for aircraft components. *(Chapters 6 and 7)*
The cost estimation tool used for estimating the cost of an aircraft component can be improved in different ways. Firstly the manufacturing options covered by the cost estimation models can be increased. To do this it important that the cost estimation models are modular, with clearly defined interfaces so the modules covering the new manufacturing methods can easily be plugged in. Another way the cost estimation model can be improved is by calibrating the cost estimation expressions. Final improvement suggested for the cost estimation process is to incorporate a results interpreter. Because the cost estimation is detailed the dataset containing the estimated cost is big. Extracting the essence of the cost estimation from this dataset improves the usefulness of the cost estimation model in the aircraft component design process.

Automating the structural analysis model preparation of an aircraft component. *(Chapter 8)*
Main improvement to the structural analysis process does not lie in the preparation process discussed in this thesis. The main improvement lies in extending the automation of the structural analysis process to the results creation and interpretation. Interpreting these results and representing them in a smart way would significantly improve the aircraft component design process, because it tackles a part of the aircraft component design process, which is time consuming.

Automating the preparation of models to analyse the chance of successful production of the aircraft component. *(Chapter 9)*
In this thesis the preparation of detailed models for manufacturing analysis is discussed. Analogous to the previous section the biggest improvement in this area would be to develop a results interpreter. Another improvement would be to develop an optimization tool which creates a low level detailed model which has a high chance of successful manufacture (determined by a simulation tool) and fits within boundary conditions put on it by a higher level generative model. In this way the detailed dataset does not have to be created by the tool user but is generated by the optimizer. This results in a decrease of inputs that have to be specified by the tool user, reducing his workload.

In this thesis all communication between software tools has been standardized as much as possible. However the aircraft component design process also involves a lot of human interaction and communication. To rule out any miscommunication it would be advisable to set op a human interaction communication protocol. Such a communication protocol would help eliminate human miscommunications and hereby improve the overall design process.

All the KBE tools developed are modular. This makes them suited for implementation in a Design and Engineering Engine (DEE). However the DEE itself has not been developed. Recommendation would therefore be to create a movable DEE using the tools developed. Such a DEE would automate the complete aircraft movable design process and could in turn be used in an optimization tool with cost and structural effectiveness as optimization objectives. For this optimization process to properly operate, the results used to judge if a design concept meets the requirements should be clear. Therefore result interpretation tools need to be developed. Optimization can only work properly if the design concept between optimization runs is changed in such a way that the results converge. In other words the changes to the design concept should result in a lighter and/or cheaper design. However the data set describing an aircraft can be big and quit complex, so choosing which parameter to change, for example adding a rib or a spar in case of a movable, can be difficult. Therefore the sensitivity of cost and weight of the component to the parameters should be analysed. Different optimization techniques exist to achieve the improvements discussed above, which one is most suited for operating in a DEE should be determined by optimization specialists.

References

Alhir, Sinan Si, “UML in a Nutshell: A Desktop Quick Reference”, O’Reilly, Beijing, 1998.

Asiedu Y. and Gu P., “Product life cycle cost analysis: state of the art review”, 1998, International Journal of Production Research, vol. 36, no. 4, pp. 883-908.

Aziz El-S., Chassapis C., "Knowledge-based Geometry Generation for Spur and Helical Gears", 2002, Concurrent Engineering: Research and Applications, vol. 10, no. 3, pp. 251-261.

Barlow D., Howe C., Clayton G., Brouwer S., “Preliminairy study on cost optimization of aircraft composite structures applicable to liquid moulding technologies”, Composite Structures, vol. 57, pp. 59-57

Bayandor J., Scott M.L., Thomson R.S., “Parametric optimization of composite shell structures for an aircraft Kruegerflap”, 2002, Composite Structures, No. 57, pp. 415-423.

Ben-Arieh D., "Cost estimation system for machined parts", 2000, International Journal of Production Research, vol. 38, no. 17, pp. 4481-4494.

Ben-Arieh D., Qian Li, “Activity-based cost management for design and development phase”, 2003, International Journal of Production Economics, vol. 83, pp. 169-183.

Bergsma, O, “Three Dimensional Simulation of Fabric Draping -Development & application-“,Delft University Press, Delft, 1995.

Bode J., Neural networks for cost estimation: simulations and pilot applications", 2000, International Journal for Production Research, vol. 38, no.6. pp. 1231-1254.

Boothroyd G., Dewhurst P., Knight W., Product Design for Manufacture and Assembly Second edition”, 2002, Marcel Dekker Inc., New York

Borg J.C., Yan X.F., Juster N.P., "Guiding component form design using decision consequence knowledge support", 1999, Artificial Intelligence for Engineering Design, Analysis and Manufacture, vol. 13, pp. 387-403.

Bright, C.D., “The Jet Makers; The Aerospace Industry from 1945 to 1972”, 1978, http://www.generalatomic.com/jetmakers/index.html [cited 20-01-06]

Castagne S., Curran R., Rothwell A., Price M., Benard E., Raghunathan S.,”A Generic Tool for Cost Estimating in Aircraft Design”, 2004, AIAA 4th Aviation Technology, Integration and Operations (ATIO) Forum; Chicago, USA.

Cavalieri S., Maccarrone P., Pinto R., "Parametric vs. neural network models for the estimation of production costs: A case study in the automotive industry", 2004, International Journal of Production Economics, vol. 91, no. 2, pp.165-177.0

Chapman C.B., Pinfold M., "The application of a knowledge based engineering approach to the rapid design and analysis of an automotive structure", 2001, Advances in Engineering Software, vol. 32, pp. 903-912.

Collopy P.D., Eames D.J.H., "Aerospace Manufacturing Cost Prediction from a Measure of Part Definition Information", 2001, SAE Publications, http://www.dfmconsulting.com/cost.pdf[Cited 30 August 2005].

Crosby S., Kundu A.K., Curran R., Raghunathan S., “Fabrication and assembly cost drivers for aircraft manufacturing”, 2003, AIAA's 3rd Annual Aviation Technology, Integration, and Operations (ATIO) Forum, Denver, AIAA2003-6827.

Curran R., Kundu A., Raghunathan S., Eakin D., McFadden R., “Influence of manufacturing tolerance on aircraft direct operating cost (DOC)”, 2003, Journal of Materials Processing Technology, vol. 138, pp. 208-213.

Curran R., Raghunathan S., Price M.,“Review of aerospace engineering cost modelling: The genetic causal approach”, 2004 B, Progress in Aerospace Sciences, vol. 40, pp. 287-534.

Curran R., Raghunathan S., Price M.,Kundu A., Benard E., Castagne S., Mawhinney P., Crosby S., Early J., “A Methodology for Integrated Cost Engineered Systems within Aerospace”, 2004C, AIAA 4th Aviation Technology, Integration and Operations (ATIO) Forum; Chicago, USA.

Curran R., Rothwell A., Castagne S., “A numerical method for Cost-Weight optimisation of Stringer-Skin Panels”, 2004 A, Proceedings of the 45th AIAA Structures, Structural Dynamics and Materials Conferences, Palm Springs, AIAA2004-2018.

Cuthosky M.R., Engelmore R.S., Fikes R.E, Genesereth M.R., Gruber T.R., Mark W.S., Tenenboum J.M., Weber J.C., “PACT: An Experiment in Integrating Concurrent Engineering Systems”, 1993, Computer, vol. 26, no. 1 pp. 28-37.

Duverlie P., Castelain J.M., “Cost Estimation During Design Step: Parametric Method versus Case Based Reasoning Method”, 1999, International Journal of Advanced Manufacturing Technology, vol. 15, pp. 895-906.

Eaglesham M.A., “A Decision Support System for Advanced Composites Manufacturing Cost Estimation”, 1998, Virginia Polytechnic Institute and State University.

Engels H., Becker W., Morris A., “Implementation of a multi-level optimization methodology within the e-design of a blended wing body”, 2004, Aerospace Science and Technology, vol. 8, pp. 145-153.

European Aviation Safety Agency (EASA), certification specifications, including airworthiness codes and acceptable means of compliance for normal, utility, aerobatic and commuter category aeroplanes (« CS-23 »)

Gantois K., Morris A.J., “Incorperation of manufacturing information into an MDO environment”, 1999, The Aeronautical Journal, paper no. 2444.

Gern F.H., Ko A., Sulaeman E., Gundlach J.F., Kapania R.K., “Multidisciplinary Design Optimization of a Transonic Commercial Transport with Strut-Braced Wing”, 2001, Journal of Aircraft, vol. 38, no. 6, pp. 1006-1014.

Haffner S.M., “Cost Modeling and Design for Manufacturing Guidelines for Advanced Composite Fabrication”, 2002, PhD. Thesis, Massachusetts Institute of Technology.

Herencia, J.E., “The GW Designer, an ICAD application for the Cranfield generative wing design tool (CGWDT)”, 2000, Cranfield University, MSc. Thesis.

Hinte, Ed van, Tooren, Michel van (ed.), "First Read This, Systems Engineering in Practice", 010 Publishers, Rotterdam, The Netherlands, ISBN 978 90 6450 643 7, 2008 (to be published).

Ilcewicz L.B., Mabson G.E., Metschan S.L., Swanson G.D., Proctor M.R., Tervo D.K., Fredrikson H.G., Gutowski T.G., Neoh E.T., Polgar K.C., “Cost Optimization Software for Transport Aircraft Design Evaluation (COSTADE), Desing Cost Methods”, 1996, NASA Contractor Report 4737.

International Society of Parametric Analysts, “Parametric Estimating Handbook”, 3rd ed.”, 2003, http://www.ispa-cost.org/PEIWeb/Third_edition/ newbook.htm [cited 23 August 2005]

Kassapoglou C., “Minimum cost and weight design of fuselage frames Part A: design constraints and manufacturing process characteristics”, 1999A, Composites: Part A, No. 30, pp. 887-894.

Kassapoglou C., ”Minimum cost and weight design of fuselage frames Part B: cost considerations, optimization and results”, 1999B, Composites: Part A, No. 30, pp. 895-904.

Kim E., “Composites cost modelling: complexity”, section 3.2.1, pp. 31, 1993, Master Thesis, Massachusetts Institute of Technology.

Komarov V.A., Weisshaar T.A., “New Approach to Improving the Aircraft Structural Design Process”, 2002, Journal of Aircraft, Vol. 39, No. 2, pp. 227-233.

Koonce D., Judd R., Sormaz D., Masel D.T., “A hierarchical cost estimation tool”, 2003, vol. 50, pp. 293-302.

Krakers L.A., Tooren M.J.L. van, Beukers A., La Rocca G., Lisandrin P., "A design & engineering engine to investigate acoustics in preliminairy fuselage design", 2003, 9th AIAAI CEAS Aeroacoustics Conference and Exhibit, Hilton Head, AIAA 2003-3162.

Kulkarni U.A., Bao H.P." “Close-Loop Cost Equation for Objects Manufactured by Milling”, 2003, Journal of Manufacturing Science and Engineering, vol. 125, pp.436-448.

Kumar J., Kendall E., “Complexity Based Cost Estimation Model for Composite Aerospace Structures”, 1999, Cooperative Research Centre for Advanced Composite Structures internal report, CRC-ACS CP 99004

La Rocca G., “Knowledge Based Engineering Techniques to support Aircraft Multi Disciplinary Design and Optimization”, PhD. thesis, to be published, 2008.

La Rocca G., Krakers L.A., Tooren M.J.L. van, “Development of an ICAD generative model for blended wing body aircraft design”, 9th AIAA/ISSMO Symposium on Multidisciplinary Analysis and Optimisation, Atlanta, GA, USA, 2002, AIAA 2002 5447.

La Rocca G., Toren, M.J.L. van, “Development of Knowledge-Based Engineering Techniques to Support Aircraft Design and Multidisciplinary Analysis and Optimization”, To be published, 2007

Laan A.H. van der, Curran R., Ritchie C., Tooren M.J.L. van, "Fitting friction stir welding into a cost estimation framework", 2005, International Conference on Innovation and Integration in Aerospace Sciences, Belfast, CEIAT 2005-0075.

Laan T. van der, Weteringe B., Tooren M. van, "Automatic generation of rib mould for rubber forming of thermoplastic composites, using knowledge based engineering", 2004, 11 th European Conference on Composite Materials, Rhodes

Leake D.B., Birnbaum L., Hammond K., Marlow C., Yang H., "Integrating diverse information resources in a case based design environment", 1999, Engineering Applications of Artificial Intelligence, vol. 12, pp. 705-716.

Lee R.-S., Chen Y.-M., Cheng H.Y., Kuo M.-D.,"A framework of a concurrent process planning system for mold manufacturing", 1998, Computer Integrated Manufacturing Systems, vol. 11, no. 3, pp. 171-190.

Lisandrin, P., Tooren M.J.L. van, “Generic Volume Element Meshing for optimization applications”, 9th AIAA/ISSMO Symposium on Multidisciplinary Analysis and Optimisation; Atlanta, 2002, AIAA-2002-5647.

Ma Y.-S., Tong T., "Associative feature modeling for concurrent engineering integration", 2003, Computers in Industry, vol. 51, pp. 51-71.

Madhusudan T., “An agent-based approach for coordinating product design workflows”, 2005, Computers and Industry, vol. 56, pp. 235-259.

Meijer P.B., "Parametric modeling of an Airbus aircraft family for dynamic response simulations in the preliminary design phase", 2003, MSc. Thesis Delft University of Technology, Faculty of Aerospace Engineering.

MOKA consortium, “Managing engineering knowledge”, Professional Engineering Publishing Limited, London, 2001

Morris, A.J., “MOB, A European Distributed Multi-Disciplinary Design and Optimisation Project,” *9th AIAA/ISSMO Symposium on Multidisciplinary Analysis and Optimisation*, Atlanta, Georgia, Sep. 4-6, 2002.

Nawijn, M., Tooren, M.J.L. van, Berends J.P.T.J., “Automated Finite Element Analysis in a Knowledge Based Engineering Environment”, 2006, 44th AIAA Aerospace Sciences Meeting and Exhibit, Reno, USA.

Neoh, E.T., “Adaptive framework for estimating fabrication time”, 1995, PhD. Thesis, Massachusetts Institute of Technology.

Rais-Rohani M., Dean E.B., “Towards manufacturing and cost considerations in multidisciplinairy aircraft desing”, 1996, AIAA Paper 96-1620, AIAA Meeting Papers on Disc, pp. 2602-2612.

Rais-Rohani M., Xie Q., “Probabilistic Structural Optimization Under Reliability, Manufacturability, and Cost Constraints”, 2005, AIAA Journal ,vol.43, no. 4, pp. 864-873.

Rehman S., Guenov M.D., “A methodology for modelling manufacturing costs at conceptual design”, 1998, Computers & Industrial Engineering, Volume 35, Issues 3-4, pp. 623-626.

Roozenburg, N.F.M., Eekels, J., “Productontwerpen, structuur en methoden”, 1998, Lemma, Utrecht

Rush C., Roy R., “Analysis of cost estimating processes used within a concurrent engineering environment throughout a product life cyle”, 2000, 7th ISPE International Conference on Concurrent Engineering: Research and Applications, Lyon pp. 58-67.

Rush C., Roy R., “Capturing Quantitive & Qualiative Knowledge for Cost Modelling within a CE environment”, 2001, ISPE International Conference on Concurrent Engineering: Research and Applications, Anaheim, , pp. 209-218.

Scanlan J., Hill T., Marsh R., Bru C., Dunkley M., Cleevely P., ”Cost modelling for aircraft design optimization”, 2002, Journal of Engineering Design, vol. 12, no. 3, pp. 261-269.

Shehab E.M., Abdalla H.S., "A design to cost system for innovative product development", 2002, Proceedings of the I MECH E Part B Journal of Engineering Manufacture, vol. 216, pp.999-1019.

Simonson G.R.,”The history of the American aircraft industry”, 1968, The MIT press, Cambridge, Massachusetts, USA.

Smith A.E., Mason A.K., "Cost Estimation Predictive Modeling: Regression versus Neural Network", 1997, Engineering Economist, vol. 42, no. 2, pp 137-162.

Stockton D.J., Forster R., Messner B., “ Development time estimating models for advanced composite manufacturing processes“, 1998, Aircraft Engineering and Aerospace Technology, vol. 70, no. 6, pp. 445-450.

Sues R.H., Cesare M.A., Pageau S.S., Wu J.Y.T.,”Reliability-Based Optimization Considering Manufacturing and Operational Uncertainties”, 2001, Journal of Aerospace Engineering, Vol. 14, No. 4, pp. 166-174.

Sun J., Zhang Y.F., Nee A.Y.C., “A distributed multi-agent environment for product design and manufacturing planning”, 2001, International Journal of Production Research, vol. 39, no. 4, pp. 625-645.

Tang D., Eversheim W., Schuh G., Chin K-S., "Concurrent metal stamping part and die development", 2003, Proceedings of the I MECH E Part B Journal of Engineering Manufacture, vol. 217, pp. 805-825.

Tomiyama T., Kiriyama T., Hidaeki T., Xue D., Yoshikawa H., “Metamodel: a Key to Intelligent CAD Systems”, 1989, Research in Engineering Design, vol 1

Tooren M.J.L. van, La Rocca G., Krakers L.A., Beukers A. , “Design and Technology in Aerospace: Parametric Modelling of Complex Structure Systems”, The 14th International Conference on Composite Materials (ICCM-14), San Diego, 2003.

Tooren M.J.L. van, Nawijn M., Berends J.P.T.J., Schut E.J., “Aircraft Desing Support using Knowledge Engineering and Optimisation Techniques”, 2005, 46th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Austin, AIAA-2005-2205

Tse M., “Design cost model for advanced composite structures”, 1992, Master Thesis, Massachusetts Institute of Technology.

Zweber J.V., Blair M., Kamhawi H., Bharatram G., Hartong A., “Structural and manufacturing analysis of a wing using adaptive modeling language”, 1998, AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference and Exhibit, 39th, and AIAA/ASME/AHS Adaptive Structures Forum, Long Beach, AIAA-1998-1758

Appendix A Inputs for the Parametric Movable Model

Variable name	Description	Example input
General		
:test?	Determines whether the movable is “left” or “right”, ‘t is “left”, ‘nil is “right”	t
:segmentation	Determines whether or not the model should be segmented. Segmented meaning all the cut up structural elements created. If a manufacturing view is required segmentation must be true. Options are ‘t or ‘nil.	T
:reference	The position of the reference coordinate axis. 0 is the tip of the leading edge of the original airfoil and 1 is the tip of the trailing edge of the original airfoil.	1
:twist-angle	List of twist angles beginning with the root twist angle and ending with the tip twist angle, angles in-between are the transition points between the different wing-trunks. Length of the list should be the number of wing-trunks plus 1.	(list (degree 0) (degree 0) (degree 0)(degree 0))
:sweep-angle	Sweep angle of the product	(degree 0)
:dihedral-angle	Dihedral angle of the product.	(degree 0)
:span-pos-list	Position at which the trunk transitions are located plus the root and tip positions. Length of the list should be the number of wing-trunks plus 1.	(list 0 200 1300 1700)
:c-list	Coord length at the trunk transition points. ‘sm means a smooth transition based on the tip and root cords**.**	(list 500 'sm 'sm 1000)
:no-of-seg-between-2-spars	Number of segments between two spars, should be kept at 1 if possible. Used for segmentation	1
:mov-l-edge-present?	Determines whether a leading edge is present for each wing trunk. Length of the list should be the same as the number of wing trunks.	(list nil t t)
:first-endcap-present?	Is there an end-cap present at the root?	t
:last-endcap-present?	Is there an end-cap present at the tip?	nil
:trailing-edge-present?	Determines whether a trailing edge is present for each wing trunk. Length of the list should be the same as the number of wing trunks.	(list t t nil)
:mov-l-edge-height-factor-list-0	Shape of the different leading edges, 0 denotes the shape ate the beginning of the wing trunk. Points are determined by this list in height direction. Points are moved from the top point on the leading edge spar in downward direction. The distance moved in height direction is the value contained in the list times the local spar height. Length should be a list of lists, number of lists should be the number of wing trunks. Length of the lists for the different wing trunks should be the same as the same as the list length in “:mov-l-edge-offset-factor-list-0”.	(list (list 0.0 0.15 0.5 0.85 1.0) (list 0.0 0.15 0.5 0.85 1.0) (list 0.0 0.15 0.5 0.85 1.0))
:mov-l-edge-offset-factor-list-0	Shape of the different leading edges, 0 denotes the shape ate the beginning of the wing trunk. Points are determined by this list in length direction. Points are moved from the top point on the leading edge spar to the front. The distance moved in length direction is the value contained in the list times the local spar height. Length should be a list of lists, number of lists should be the number of wing trunks. Length of the lists for the different wing trunks should be the same as the same as the list length in “:mov-l-edge-offset-factor-list-0”.	(list (list 0.0 0.35 0.5 0.35 0.0) (list 0.0 0.35 0.5 0.35 0.0) (list 0.0 0.35 0.5 0.35 0.0))
:mov-l-edge-height-factor-list-1	Analogous to “:mov-l-edge-height-factor-list-0”, except that points are used for a curve at the end of the wing trunk, size should be the same as “:mov-l-edge-offset-factor-list-1”	(list (list 0.0 0.15 0.5 0.85 1.0) (list 0.0 0.15 0.5 0.85 1.0) (list 0.0 0.15 0.5 0.85 1.0))
:mov-l-edge-offset-factor-list-1	Analogous to “:mov-l-edge-offset-factor-list-0”, except that points are used for a curve at the end of the wing trunk, size should be the same as “:mov-l-edge-height-factor-list-1”	(list (list 0.0 0.35 0.5 0.35 0.0) (list 0.0 0.35 0.5 0.35 0.0) (list 0.0 0.35 0.5 0.35 0.0))
:hinge-line-offset-factor-list-0	This variable determines part of the position of the start point of the hinge line. It determines the length the hinge-line pint is offset from the first spar to the front. Length with which the point is offset is the factor times the local first spar height. Length of the list should be the same as the number of wing trunks.	(list 0.5 0.5 0.5)
:hinge-line-height-factor-list-0	This variable determines part of the position of the start point of the hinge line. It determines the height the hinge-line pint is offset from the top of the front spar in downward. Length with which the point is offset is the factor times the local first spar height. Length of the list should be the same as the number of	(list 0.5 0.5 0.5)

	wing trunks.	
:hinge-line-offset-factor-list-1	Analogous to ":hinge-line-offset-factor-list-0", except this is the end point of the hinge line	(list 0.5 0.5 0.5)
:hinge-line-height-factor-list-1	Analogous to ":hinge-line-offset-factor-list-1", except this is the end point of the hinge line	(list 0.5 0.5 0.5)
:mov-l-edge-hinge-present?	This variable determined if hinge line and hinges must be drawn for the appropriate wing trunk. Length of the list should be the same as the number of wing trunks. Inputs can be t or nil.	(list 'nil 't ‘t)
Airfoils		
:offset-list	This variable determines the position of the different airfoils. Variable should be a list of lists with a length the same as the number of wing trunks. Size should be the sama as the other airfoil variables.	(list (list 0.0 1.0) (list 0.0 1.0) (list 0.0 1.0))
:airfoil-list	This variable determines which airfoil should be used for wing generation. Variable should be a list of lists with a length the same as the number of wing trunks. Size should be the sama as the other airfoil variables.	(list (list 'Airfoil-1 'Airfoil-1) (list 'Airfoil-1 'Airfoil-1) (list 'Airfoil-1 'Airfoil-1))
:airfoil-thickness-list	This variable determines the relative airfoil thickness. Variable should be a list of lists with a length the same as the number of wing trunks. Size should be the sama as the other airfoil variables.	(list (list 1.0 1.0) (list 1.0 1.0) (list 1.0 1.0))
:airfoil-angle-list	This list determines the angle the airfoil makes this the flight direction. Variable should be a list of lists with a length the same as the number of wing trunks. Size should be the same as the other airfoil variables.	(list (list (degree 5) 0.0) (list 0.0 (degree 7)) (list (degree 7) 0.0))
Production-groups		
:manufacturing-view?	Whether or not the manufacturing view should be created	't
:cost?	??????	‘t
:manufacturing environment	The manufacturing environment determines which values are used from the manufacturing database for the manufacturing analysis. A manufacturing environment is a collection of manufacturing variables. For one only one manufacturing environment exists which is 1.	1
:production-group-up-skin	Production group numbers of the upper skin are determined. List should be as long as the number of wing trunks in the model.	(list 5 5 5)
production-group-low-skin	Production group numbers of the lower skin are determined. List should be as long as the number of wing trunks in the model.	(list 5 5 5)
:production-group-up-te	Production group numbers of the upper trailing edge are determined. List should be as long as the number of wing trunks in the model.	(list 5 5 5)
:production-group-low-te	Production group numbers of the lower trailing edge are determined. List should be as long as the number of wing trunks in the model.	(list 5 5 5)
:production-group-le	Production group numbers of the leading edge. List should be as long as the number of wing trunks in the model.	(list 6 6 6)
:production-group-first-endcap	Production group of the first endcap	nil
:production-group-last-endcap	Production group of the last endcap	nil
production-squence	This variable represents the assembly sequence of the different production groups. It has the form of a list of lists, each sub-list representing a subassembly	(list (list 4 5 2 0 3 7) (list 1 6 8 9 10 11 12 13 14))
:rubber-forming-tp-prod-group-list	This variable contains a list of production groups that are going to be built using the rubber forming thermoplastic components manufacturing technique. All production groups should come back in on of the manufacturing methods lists otherwise they are not considered for the manufacturability analyses. Form of the variable is a list of numbers that can be empty.	(list 0 1 2 3 4 5 6 8 11)
:cutting-prod-group-list	This variable contains a list of production groups that are going to be built using the cutting manufacturing technique. All production groups should come back in one of the manufacturing methods lists otherwise they are not considered for the manufacturability analyses. Form of the variable is a list of numbers that can be empty.	(list)
:folding-prod-group-list	This variable contains a list of production groups that are going to be built using the folding manufacturing technique. All production groups should come back in one of the	(list 7)

	manufacturing methods lists otherwise they are not considered for the manufacturability analyses that can be empty.	
:vacuum-inf-prod-group-list	This variable contains a list of production groups that are going to be built using the vacuum infusion manufacturing technique. All production groups should come back in one of the manufacturing methods lists otherwise they are not considered for the manufacturability analyses. Form of the variable is a list of numbers that can be empty.	(list 9 10)
:atp-prod-group-list	This variable contains a list of production groups that are going to be built using the automated tape laying of composite pre-pregs manufacturing technique. All production groups should come back in one of the manufacturing methods lists otherwise they are not considered for the manufacturability analyses. Form of the variable is a list of numbers that can be empty.	(list)
:rtm-prod-group-list	This variable contains a list of production groups that are going to be built using the resin transfer moulding manufacturing technique. All production groups should come back in one of the manufacturing methods lists otherwise they are not considered for the manufacturability analyses. Form of the variable is a list of numbers that can be empty.	(list)
:hand-lay-up-prod-group-list	This variable contains a list of production groups that are going to be built using the hand lay-up manufacturing technique. All production groups should come back in one of the manufacturing methods lists otherwise they are not considered for the manufacturability analyses. Form of the variable is a list of numbers that can be empty.	(list)
:Carbon_PEI-mat-list	This variable contains a list of production groups that are going to be built from Carbon PEI laminate. All production groups should come back in one of the materials lists otherwise errors are created in the manufacturability analyses. Form of the variable is a list of numbers that can be empty.	(list 0 1 2 3 4 5 6 7 8 11)
:Glass_PA6-mat-list	This variable contains a list of production groups that are going to be built from Glass PA6 material. All production groups should come back in one of the materials lists otherwise errors are created in the manufacturability analyses. Form of the variable is a list of numbers that can be empty.	(list 9 10)
:Aluminum_2024-mat-list	This variable contains a list of production groups that are going to be built from Aluminium 2024 material. All production groups should come back in one of the materials lists otherwise errors are created in the manufacturability analyses. Form of the variable is a list of numbers that can be empty.	(list)
:Carbon_Epoxy-mat-list	This variable contains a list of production groups that are going to be built from Carbon Epoxy material. All production groups should come back in one of the materials lists otherwise errors are created in the manufacturability analyses. Form of the variable is a list of numbers that can be empty.	(list)
:material-thickness-input-list	A list containing the material thickness for each production group. Form of the variable is a list of lists. Each sub-list containing the data for one production group. First entry of the sub list should be the production group number; second entry is a list of lists. Each of the sub-sub-lists defines a layer of the material the first entry of the sub-sub-list defines the thickness of the material while the second entry defines the orientation of the material.	(list (list 0 (list (list 0.9 0))) (list 1 (list (list 0.9 0))) (list 2 (list (list 0.9 0))) (list 3 (list 0.25 0) (list 0.25 45) (list 0.25 90))) etc.
:flange-information	A list containing the flange information for each production group. Form of the variable is a list of lists. Each sub-list containing the data for one production group. First entry of the sub list should be the production group number. Second entry is the angle between product and flange. Third entry is the with of the flange in mm. The fourth entry is the percentage of the production group boundary that has a flange.	(list (list 0 (degree 90) 15 90) (list 1 (degree 90) 15 90) (list 2 (degree 90) 15 90) (list 3 (degree 90) 15 90) etc.
:connection-material-or-process?	Whether material or production process should determine the assembly method of the different production groups. Inputs can be ‘material or ‘process	‘process
:connection-visulization	What should be shown in the manufacturing view representation, type of assembly or the connection type? Inputs can be ‘asm or ‘type-con.	‘asm
:file-name-assembly	The file name where the text report for creating a test file containing data for the assembly cost should be written	"d:/icad/movable/seer-files/assembly-cost.txt"

:file-name-XML-assembly-joints	The file name where the XML report containing data about the assembly joints should be written	"d:/icad/movable/seer-files/XML-assembly-joints.xml"
:file-name-XML-parts-data	The file name where the XML report containing data about the different parts should be written	"d:/icad/movable/seer-files/XML-parts-data.xml"
:file-name-XML-stringer-data	The file name where the XML report containing data about the stringers should be written	"d:/icad/movable/seer-files/XML-stringer-data.xml"
:file-name-XML-manuf-general	The file name where the XML report containing the general manufacturing data should be written	"PMM:output;manufacturing-files;Manufacturing-general.xml"
End Caps		
:first-endcap-airfoil-name	This variable contains the name of the airfoil that determines the shape of the first endcap. The airfoil determines the shape of the tip curve.	'top-cap
:last-endcap-airfoil-name	This variable contains the name of the airfoil that determines the shape of the last endcap. The airfoil determines the shape of the tip curve.	'bottom-cap
:first-rat-fac-1-1	This variable contains the first value of a formula, which determines the extent in which the tangent vector influences the shape of the endcap. Form of the formula is: Value (X (= length of the curve))= first-rat-fac-1-1 * X +:first-rat-fac-1-2 (X runs from 0 to 1) So the first variable determines the extent in which the influence of the tangency changes over the curve. This specific variable determines the values of the first curve, which is the tip curve, of the first endcap.	0.33
:first-rat-fac-1-2	This variable contains the first value of a formula, which determines the extent in which the tangent vector influences the shape of the first endcap. Form of the formula is: Value (X (= length of the curve))= first-rat-fac-1-1 * X + first-rat-fac-1-2 (X runs from 0 to 1) So the second variable determines the general influence of the tangency. This specific variable determines the values of the first curve, which is the tip curve, of the first endcap.	0.35
:first-rat-fac-2-1	This variable contains the first value of a formula, which determines the extent in which the tangent vector influences the shape of the endcap. Form of the formula is: Value (X (= length of the curve))= first-rat-fac-2-1 * X + first-rat-fac-2-2 (X runs from 0 to 1) So the first variable determines the extent in which the influence of the tangency changes over the curve. This specific variable determines the values of the second curve, which is the end of the wing trunk, of the first endcap.	0.1
:first-rat-fac-2-2	This variable contains the first value of a formula, which determines the extent in which the tangent vector influences the shape of the endcap. Form of the formula is: Value (X (= length of the curve))= first-rat-fac-2-1 * X + first-rat-fac-2-2 (X runs from 0 to 1) So the second variable determines the general influence of the tangency. This specific variable determines the values of the second curve, which is the end of the wing trunk, of the first endcap.	0.1
:last-rat-fac-1-1	This variable contains the first value of a formula, which determines the extent in which the tangent vector influences the shape of the endcap. Form of the formula is: Value (X (= length of the curve))= last-rat-fac-1-1 * X + last-rat-fac-1-2 (X runs from 0 to 1) So the first variable determines the extent in which the influence of the tangency changes over the curve. This specific variable determines the values of the first curve, which is the tip curve, of the last endcap.	0.33
:last-rat-fac-1-2	This variable contains the first value of a formula, which determines the extent in which the tangent vector influences the shape of the first endcap. Form of the formula is: Value (X (= length of the curve))= last -rat-fac-1-1 * X + last-rat-fac-1-2 (X runs from 0 to 1) So the second variable determines the general influence of the tangency. This specific variable determines the values of the first curve, which is the tip curve, of the last endcap.	0.35
:last-rat-fac-2-1	This variable contains the first value of a formula, which determines the extent in which the tangent vector influences the shape of the endcap. Form of the formula is: Value (X (= length of the curve))= last-rat-fac-2-1 * X + last-rat-fac-2-2 (X runs from 0 to 1) So the first variable determines the extent in which the	0.1

	influence of the tangency changes over the curve. This specific variable determines the values of the second curve, which is the end of the wing trunk, of the last endcap.	
:last-rat-fac-2-2	This variable contains the first value of a formula, which determines the extent in which the tangent vector influences the shape of the endcap. Form of the formula is: Value (X (= length of the curve))= last-rat-fac-2-1 * X + last-rat-fac-2-2 (X runs from 0 to 1) So the second variable determines the general influence of the tangency. This specific variable determines the values of the second curve, which is the end of the wing trunk, of the last endcap.	0.1
:first-front-vector-angle	This variable determines how the endcap airfoil fits to the wing trunk leading edge. The leading edge vector is turned the amount indicated by the variable in the clockwise direction. The vector resulting from this is used as input to draw the first endcap airfoil.	(degree 0)
:first-rear-vector-angle	This variable determines how the endcap airfoil fits to the wing trunk trailing edge. The trailing edge vector is turned the amount indicated by the variable in the clockwise direction. The vector resulting from this is used as input to draw the first endcap airfoil.	(degree 0)
:last-front-vector-angle	This variable determines how the endcap airfoil fits to the wing trunk leading edge. The leading edge vector is turned the amount indicated by the variable in the clockwise direction. The vector resulting from this is used as input to draw the last endcap airfoil.	(degree 0)
:last-rear-vector-angle	This variable determines how the endcap airfoil fits to the wing trunk leading edge. The trailing edge vector is turned the amount indicated by the variable in the clockwise direction. The vector resulting from this is used as input to draw the last endcap airfoil.	(degree 72)
Loads		
:total-force	Variable determining the total force exerted on the movable by the pressure determined by the loads session file. Should be the total force in Newton.	1400
actuator-hinge-number	This variable determined the hinge that is going to used as the actuator in the structural analysis.	2
:hinge-side-displacement	With this variable the side displacement of the hinges in the FE analysis is determined. Input is a list of numbers each number representing the side displacement in mm of one hinge. The length of the list should be the same as the number of hinge ribs.	(list 0 0 0)
Stringer-input		
:stringer-type	This variable determines the stringer type of all the stringers present in the model. Options are for now a T or a Z stringer, these require ‘t and ‘z as inputs respectively. Stringer inputs are only used in the manufacturing view, not in the structural view.	'z
:stringer-height	This variable determines the stringer height. Input should be a number which determines the height of all the stringers present in the model in mm. Stringer inputs are only used in the manufacturing view, not in the structural view.	20
:stringer-upper-flange-total-width	This variable determines the stringer upper flange width. Input should be a number which determines the upper flange width of all the stringers present in the model in mm. Stringer inputs are only used in the manufacturing view, not in the structural view.	10
:stringer-lower-flange-total-width	This variable determines the stringer lower flange width. Input should be a number which determines the lower flange width of all the stringers present in the model in mm. Stringer inputs are only used in the manufacturing view, not in the structural view.	10
:stringer-radius	This variable determines the stringer radius. Input should be a number which determines the radii of all the stringers present in the model in mm. Stringer inputs are only used in the manufacturing view, not in the structural view.	2
FE-materials		
:FE-rib-mat	This variable determines the property set for the old style FEM analysis. In this case the materials for the ribs are	'4_layer_Carbon_PEI

	determined. All elements in the group have the same property set.	
:FE-LE-riblet-mat		'4_layer_Carbon_PEI
:FE-spar-mat		'4_layer_Carbon_PEI
:FE-skin-up-mat		'3_layer_Carbon_PEI
:FE-skin-low-mat		'3_layer_Carbon_PEI
:FE-horn-skin-up-mat		'3_layer_Carbon_PEI
:FE-horn-skin-low-mat		'3_layer_Carbon_PEI
:FE-sandwich-skin-up-mat		'3_layer_Carbon_PEI
:FE-sandwich-skin-low-mat		'3_layer_Carbon_PEI
:FE-TE-up-mat		'3_layer_Carbon_PEI
FE-TE-low-mat		'3_layer_Carbon_PEI
:FE-LE-mat		'3_layer_Carbon_PEI
:FE-cap-mat		'3_layer_Carbon_PEI
:FE-stringer-mat		'carbon_PEI_090
External-data		
:use-wingtrunk-and-hinges-from-file?	This variable determines whether or not to use external files to build the movable. For instance when files are delivered from the conventional aircraft model (ACPAM). Input can be t or nil, hen it is ‘t external files are used.	‘nil
:file-name-wing-trunk-iges	This input determines the place of one of the files that is loaded when external files are used for creating the movable. In this case the iges file of the external shape of the wing part in which the movable should fit	"D:/icad/brp/acpam_final/reports/wing-trunk-for-movable.igs"
:file-name-hinge-line-iges	This input determines the place of one of the files that is loaded when external files are used for creating the movable. In this case the iges file of the hinge line of the movable.	"D:/icad/brp/acpam_final/reports/hinge-line.igs"
:file-name-hinge-points-iges	This input determines the place of one of the files that is loaded when external files are used for creating the movable. In this case the iges file of the hinge points where the movable connects to the rest of the aircraft.	"D:/icad/brp/acpam_final/reports/hinge-points.igs"
:hinge-cut-rel-hinge-pos-hinge	Data from this list will be added to the corresponding list for input ribs. The length of the list should be as long as the number of hinges that are imported. Input options are the same as the corresponding list for input ribs	(list 0.5 0.5 0.5)
:hinge-cut-width-hinge	Data from this list will be added to the corresponding list for input ribs. The length of the list should be as long as the number of hinges that are imported. Input options are the same as the corresponding list for input ribs	(list 70 70 70)
:rib-orienting-referred-to-spar-hinge	Data from this list will be added to the corresponding list for input ribs. The length of the list should be as long as the number of hinges that are imported. Input options are the same as the corresponding list for input ribs	(list 'hl 'hl 'hl)
:rib-orienting-angles-list-hinge	Data from this list will be added to the corresponding list for input ribs. The length of the list should be as long as the number of hinges that are imported. Input options are the same as the corresponding list for input ribs	(list 90 90 90)
:le-riblet?-hinge	Data from this list will be added to the corresponding list for input ribs. The length of the list should be as long as the number of hinges that are imported. Input options are the same as the corresponding list for input ribs	(list t t t)
:te-riblet?-hinge	Data from this list will be added to the corresponding list for input ribs. The length of the list should be as long as the number of hinges that are imported. Input options are the same as the corresponding list for input ribs	(list t t t)
:le-riblet-angles-list-hinge	Data from this list will be added to the corresponding list for input ribs. The length of the list should be as long as the number of hinges that are imported. Input options are the same as the corresponding list for input ribs	(list 0 0 0)
:hinge-middle-or-side-hinge	Data from this list will be added to the corresponding list for input ribs. The length of the list should be as long as the number of hinges that are imported. Input options are the same as the corresponding list for input ribs	(list 's 's 's);
:hinge-side-displacement-hinge	Data from this list will be added to the corresponding list for input ribs. The length of the list should be as long as the number of hinges that are imported. Input options are the same as the corresponding list for input ribs	(list 0 0 0)
:production-group-ribs-hinge	Data from this list will be added to the corresponding list for input ribs. The length of the list should be as long as the number of hinges that are imported. Input options are the same as the corresponding list for input ribs	(list nil nil nil)
:production-group-le-riblet-	Data from this list will be added to the corresponding list for	(list nil nil nil)

hinge	input leading edge riblets. The length of the list should be as long as the number of hinges that are imported. Input options are the same as the corresponding list for input leading edge riblets.	
:hinge-slot-closed?-hinge	Data from this list will be added to the corresponding list for input ribs. The length of the list should be as long as the number of hinges that are imported. Input options are the same as the corresponding list for input ribs	(list nil nil nil)
:type-of-rib-te-ns-hinge	Data from this list will be added to the corresponding list for trailing edge ribs. The length of the list should be as long as the number of hinges that are imported. Input options are the same as the corresponding list for input trailing edge ribs.	(list 'v 'v 'v)
Wing trunk structure		
Spars, Wing trunk Leading Edge		
:type-of-spar-le-ns	This input is related to leading edge spars of the wing trunk. In the movable model the original wing trunk leading edge is not used so the input should stay empty	(list (list)
:spar-position-list-root-le-ns	This input is related to leading edge spars of the wing trunk. In the movable model the original wing trunk leading edge is not used so the input should stay empty	(list (list)
:spar-position-list-tip-le-ns	This input is related to leading edge spars of the wing trunk. In the movable model the original wing trunk leading edge is not used so the input should stay empty	(list (list)
Spars, Wing trunk wing box		
:type-of-spar-wb-ns	List of lists containing the type of the different spars in the corresponding wing trunk. Types can be: ‘r real spar, normal spar. ‘st stringer, stringer curves are created on the upper and lower skin, no spar web. ‘st-u stringer, stringer curves are created on the upper, no spar web. ‘st-l stringer, stringer curves are created on the lower, no spar web. ‘v virtual spar, spar is only used for segmentation and is not a physical entity. ‘h horn spar, normal spar in the horn, this spar is used to define the horn area. ‘san sandwich spar, this spar forms the edge of a sandwich area and is not a physical entity Number of lists should be the same as the number of wing trunk. Size should be the same as the other spar inputs.	(list (list 'r 'st 'st-u 'v))
:spar-position-list-root-wb-ns	List of lists containing the root position of the different spars in the corresponding wing trunk. Number of lists should be the same as the number of wing trunk. Size should be the same as the other spar inputs.	(list (list 0.6916 0.72 0.9 0.93))
:spar-position-list-tip-wb-ns	List of lists containing the tip position of the different spars in the corresponding wing trunk. Number of lists should be the same as the number of wing trunk. Size should be the same as the other spar inputs.	(list (list 0.6916 0.72 0.9 0.93))
:cap-sparlet?-wb-ns	Variable determines if a cap sparlet should be created. Number of lists should be the same as the number of wing trunk. Size should be the same as the other spar inputs.	(list (list 't nil nil nil))
:production-group-spars-wb-ns	This variable determined the production group number of the specific spar. Production group number determines where the part is positioned in the assembly sequence and which parts are combined into a single manufacturing part. Number of lists should be the same as the number of wing trunk. Size should be the same as the other spar inputs.	(list (list 3 8 9 nil))
Spars, Wing trunk trailing edge		
:type-of-spar-te-ns	Analogous with :type-of-spar-wb-ns, only tested with one virtual spar. Number of lists should be the same as the number of wing-trunks. Length of each list should correspond with the rest of the trailing edge spar inputs	(list (list 'v))
:spar-position-list-root-te-ns	Analogous with :spar-position-list-root-wb-ns, only tested with one virtual spar. Number of lists should be the same as the number of wing-trunks. Length of each list should correspond with the rest of the trailing edge spar inputs	(list (list 0.93))
:spar-position-list-tip-te-ns	Analogous with :spar-position-list-tip-wb-ns, only tested with one virtual spar. Number of lists should be the same as the number of wing-trunks. Length of each list should correspond with the rest of the trailing edge spar inputs	(list (list 0.93))

:cap-sparlet?-te-ns	Variable determines if a cap sparlet should be created. Number of lists should be the same as the number of wing trunk. Size should be the same as the other spar inputs.	(list (list ‘nil))
:production-group-spars-te-ns	This variable determined the production group number of the specific spar. Production group number determines where the part is positioned in the assembly sequence and which parts are combined into a single manufacturing part. Number of lists should be the same as the number of wing trunk. Size should be the same as the other spar inputs.	(list (list ‘nil))
Rib inputs, general		
:type-of-rib-le-ns	This variable determines the leading edge rib type. Inputs are analogous with the “:type-of-rib-ns” inputs	(list (list 'l 'v 'v 'v))
:rib-orienting-referred-to-spar-ns	This variable determines with respect to which rib a leading edge rib is oriented. Inputs are analogous with the “:rib-positioning-referred-to-spar-ns” inputs	(list (list ‘le 1 1 1))
:rib-le-orienting-angles-list-ns	This variable determines the orientation angle of a leading edge rib is oriented. Inputs are analogous with the :rib-orienting-angles-list-ns” inputs	(list (list 90 90 90 90))
:type-of-rib-ns	This list determines the type of rib. Options can be : ‘l light-rib, the standard rib ‘h hinge rib, a hinge an the leading edge slot will be created ‘v virtual rib, rib is only used for segmentation and not a physical entity ‘san sandwich rib, this rib forms the edge of a sandwich area and is not a physical entity	(list (list 'l 'san 'h 'r))
:rib-positioning-referred-to-spar-ns	List of lists containing the number of the spar to which the positioning of the rib is referenced. Other options are: ‘le rib is positioned relative to the leading edge ‘te rib is positioned relative to the trailing edge ‘hl rib is positioned relative to the hinge line Number of lists should be the same as the number of wing trunk. Size should be the same as the other rib inputs.	(list (list 1 1 1 1))
:rib-orienting-referred-to-spar-ns	List of lists containing the number of the spar to which the orienting of the rib is referenced. Other options are: ‘le rib is oriented relative to the leading edge ‘te rib is oriented relative to the trailing edge ‘hl rib is oriented relative to the hinge line ‘fd rib is oriented in flight direction Number of lists should be the same as the number of wing trunk. Size should be the same as the other rib inputs.	(list (list 1 1 1 1))
:rib-positioning-offset-list-ns	List of lists containing the offset values of the different ribs. Offset distance is the value in the list times spar length to which the rib is referenced, 0.0 being the root and 1.0 the tip. Number of lists should be the same as the number of wing trunk. Size should be the same as the other rib inputs.	(list (list 0.2 0.3 0.5 0.8))
:rib-orienting-angles-list-ns	List of lists containing the orienting angle values of the different ribs. Orienting angle is the angle the rib makes with the spar referenced in “:rib-orienting-referred-to-spar” in degrees. When the value in “:rib-orienting-referred-to-spar” is ‘fd the value in this list has no meaning. When input is lower than 1.0 a point is created on the spar specified “:rib-orienting-referred-to-spar-ns”, which is used together with the other positioning point to draw a rib between. Number of lists should be the same as the number of wing trunk. Size	(list (list 90 90 90 90))
:type-of-rib-te-ns	This variable determines the trailing edge rib type. Inputs are analogous with the “:type-of-rib-ns” inputs	(list (list 'l 'v 'v 'v))
:rib-te-orienting-referred-to-spar-ns	This variable determines with respect to which rib a trailing edge rib is oriented. Inputs are analogous with the “:rib-positioning-referred-to-spar-ns” inputs	(list (list ‘le 1 1 1))
:rib-te-orienting-angles-list-ns	This variable determines the orientation angle of a trailing edge rib is oriented. Inputs are analogous with the :rib-orienting-angles-list-ns” inputs	(list (list 90 90 90 90))
Rib inputs, movable specific		
:hinge-cut-rel-hinge-pos-ns	List of lists containing the position of the hinge rib in the hinge hole. Position is measured from the root, so at 0.0 the rib is positioned in the hole corner closest to the root, 0.5 means the rib is positioned in the middle and 1.0 means the rib is positioned in the hole corner closest to the tip. Only the values in the position of hinge ribs, as determined by “type-of-rib”, will be read. Number of lists should be the same as the	(list (list 0.5 0.5 0.5 0.5))

	number of wing trunk. Size should be the same as the other rib inputs.	
:hinge-cut-width-ns	List of list containing the width of the hinge hole width is measured parallel to the first spar. Only the values in the position of hinge ribs, as determined by "type-of-rib", will be used. Number of lists should be the same as the number of wing trunk. Size should be the same as the other rib inputs.	(list (list 70 70 70 70))
:hinge-middle-or-side-ns	List of lists determining if, in case of a hinge rib, the rib should be placed in the middle of the slot or that 2 ribs must be created coinciding with the edges of the slot. Only the values in the position of hinge ribs, as determined by "type-of-rib", will be read. Options are: ‘ m rib in the middle of the hinge slot, ' s hinge ribs on the side of the hinge slot, 'v no real ribs, 'v- san no real ribs but all sandwich ribs Number of lists should be the same as the number of wing trunk. Size should be the same as the other rib inputs.	(list (list 'm 'm 'm 'm))
:le-riblet?-ns	List of lists determining if a leading edge riblet should be created. When the value is true for a hinge rib, riblets will be created on both sides of the leading edge slot. Number of lists should be the same as the number of wing trunk. Size should be the same as the other rib inputs.	(list (list t t t t))
:te-riblet?-ns	List of lists determining if a training edge riblet should be created. Number of lists should be the same as the number of wing trunk. Size should be the same as the other rib inputs.	(list (list t t t t))
:le-riblet-angles-list-ns	List of lists determining the angle the leading edge riblet makes with the rib it is attached to. Number of lists should be the same as the number of wing trunk. Size should be the same as the other rib inputs.	(list (list 0 0 0 0))
:production-group-ribs-ns	With this variable the manufacturable part to which the rib belongs is determined. Number of lists should be the same as the number of wing trunk. Size should be the same as the other rib inputs.	(list (list 0 nil 1 2))
:production-group-le-riblet-ns	With this variable the manufacturable part to which the leading edge riblet belongs is determined. In case of a hinge rib and this 2 riblets the input should not be a number but a list of 2 numbers. Number of lists should be the same as the number of wing trunk. Size should be the same as the other rib inputs.	(list (list 5 nil nil nil))
:hinge-slot-closed?-ns	This variable determines whether or not the hinge slot should be closed. In this way the leading edge can be made continuous when necessary. Variable is only meaningful when rib is a hinge rib. Number of lists should be the same as the number of wing trunk. Size should be the same as the other rib inputs.	(list (list nil nil nil nil))
FEM Table file locations		
:mov-spars-fem-table-name	This variable defines where the FEM tables created for a FE analysis are stored. Each structural group has its own FEM table.	PMM:output;FEM-tables;FEM-table-mov-spars.xml
:mov-ribs-fem-table-name		PMM:output;FEM-tables;FEM-table-mov-ribs.xml
:mov-upper-cover-fem-table-name		PMM:output;FEM-tables;FEM-table-mov-upper-cover.xml
:mov-lower-cover-fem-table-name		PMM:output;FEM-tables;FEM-table-mov-lower-cover.xml
:mov-upper-cover-horn-fem-table-name		PMM:output;FEM-tables;FEM-table-mov-upper-cover-horn.xml
:mov-spars-fem-table-name		PMM:output;FEM-tables;FEM-table-mov-spars.xml
:mov-lower-cover-horn-fem-table-name		PMM:output;FEM-tables;FEM-table-mov-lower-cover-horn.xml
:mov-upper-cover-sandwich-fem-table-name		PMM:output;FEM-tables;FEM-table-mov-upper-cover-sandwich.xml
:mov-lower-cover-sandwich-fem-table-name		PMM:output;FEM-tables;FEM-table-mov-lower-cover-sandwich.xml
:mov-upper-trailing-edge-fem-table-name		PMM:output;FEM-tables;FEM-table-mov-upper-trailing-edge.xml
:mov-lower-trailing-edge-fem-table-name		PMM:output;FEM-tables;FEM-table-mov-lower-trailing-

		edge.xml
:mov-upper-movable-leading-edge-fem-table-name		PMM:output;FEM-tables;FEM-table-mov-upper-movable-leading-edge.xml
:mov-lower-movable-leading-edge-fem-table-name		PMM:output;FEM-tables;FEM-table-mov-lower-movable-leading-edge.xml
:mov-upper-first-endcap-fem-table-name		PMM:output;FEM-tables;FEM-table-mov-upper-first-endcap.xml
:mov-lower-first-endcap-fem-table-name		PMM:output;FEM-tables;FEM-table-mov-lower-first-endcap.xml
:mov-upper-last-endcap-fem-table-name		PMM:output;FEM-tables;FEM-table-mov-upper-last-endcap.xml
:mov-lower-last-endcap-fem-table-name		PMM:output;FEM-tables;FEM-table-mov-lower-last-endcap.xml
:mov-movable-leading-edge-riblets-fem-table-name		PMM:output;FEM-tables;FEM-table-mov-movable-leading-edge-riblets.xml
Input for a rib feasibility analysis		
:wing-trunk-nr	This variable defines from which wing trunk the rib exported for drapability analysis is taken.	0
:rib-nr	This variable defines which rib is exported for drapability analysis is taken.	0
:rib-lower-curve-file-name	This variable defines where the lower rib curve used in a drapability analysis is stored	PMM:output;manufacturing-files;rib-lower-curve.igs
:rib-upper-curve-file-name	This variable defines where the upper rib curve used in a drapability analysis is stored	PMM:output;manufacturing-files;rib-upper-curve.igs

Appendix B Integrating part complexity of composite parts into a cost estimation

When estimating the cost of a product using the actual physics of the manufacturing process it is important to address and incorporate all physical aspects that influence the manufacturing process. One such aspect is the complexity of the part. Complexity defines how difficult a part is to manufacture and is dependent first of all on the geometry of the part. For instance a part with a lot of sharp angles and double curved surfaces is difficult to manufacture and therefore has a high complexity. On the other hand a flat part is easy to manufacture and therefore has a low complexity. Complexity is to an extent subjective and therefore difficult to quantify. Complexity is also dependent on the physics and characteristics of the manufacturing methods themselves. Describing these characteristics usually requires a lot of data, not available at an early phase of the design process. However methods have been developed to quantify complexity using limited part geometry information. The applied method should fit in the Movable Design Engineering Engine (MDEE) and use the data supplied by the Parametric Movable Model (PMM) and will be used as an extension of the existing cost estimation module.

The complexity influences the manufacturing times of a part and will therefore be used in the determination of these manufacturing times. To do this existing cost estimation module has to be adjusted to incorporate the use of the complexity data. Furthermore the complexity data has to be transferred from the product model to the cost estimation module.

In the first section of this appendix the method that is used for determining complexity is described and its different elements are discussed. This will result in expressions dealing with several aspects of complexity. In the second section the use of the complexities in the actual cost estimation formulas is discussed. The third section deals with the actual implementation details in the cost estimation software. The fourth section shows the cost estimation of complex structures applied to an example, giving quantified results. Finally conclusions will be drawn.

B.1 Definition of complexity and methods of extraction from a product model

Several theories have been developed on how to quantify the complexity of a part. Most of these theories are very much related to the manufacturing processes and materials they handle. In dealing with complexity 2 groups of methods exist.

First group is the statistical method. This method uses data from existing parts and regression techniques to formulate relations between features that increase the complexity of a part and the manufacturing time or cost of such a part. Examples of these methods can be found in Kumar(1999) and Kim(1993). In this way complexity can also be incorporated in parametric cost estimation models. Complexity for cost estimation methods in this group is usually quantified using part features. Such a feature can for instance be a flange with a certain characteristics. These characteristics can then be used to quantify the complexity of a part. Advantage of this method is the resulting formulas are easy to use and the relation between complexity adding features and the complexity content of a part is clear. Disadvantage of this method is the shape of the features adding complexity is usually simple, for example flanges or single curved surfaces with a fixed radius. Therefore determining the complexity of integrate curved parts can be difficult. For the cost estimation of complex parts this first method will not be used. First of all because information about the cost of previously produced complex parts is needed, this information can be difficult to obtain or to develop. Second and most important reason for not choosing this method is that it doesn't fit the models created by the PMM.

The second group of methods uses mathematical relations to determine the complexity of a part. These methods differ per manufacturing method. In this chapter composite manufacturing methods and more specifically the hand lay up of laminates used analysed. In case of composite materials the behaviour of the individual fibres determines the complexity of a part. The more a fibre has to bend or shear during the forming of the product, the more difficult the forming will be and therefore the more complex the product is for production. Several theories have been developed in this area. The theory used and described in this chapter is developed by Tse(1992) and considers the fibre to be a information storage device, storing information about the bending of the fibre. The amount of information stored in a fibre is measured in bits. More information on this theory can also be found in Haffner(2002) and Neoh(1995). A basic summary of the theory will be given below.

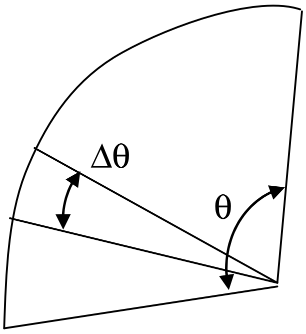


Figure B-1 Discretization of a curved fibre (Haffner(2002))

Consider a sensor running along a fibre detecting angles with an accuracy of $\Delta\theta$ running along a fibre as shown in Figure B-1. Every time the angle $\Delta\theta$ is detected a bit of information is added so:

$$I = \frac{\theta}{\Delta\theta} \rightarrow I \text{ is proportional to } \theta \qquad (1)$$

Because the information content is proportional to θ, θ can by used to measure the information content of the fibre. The angle θ has a relation with the curvature of the curve or fibre. The curvature of a curve or fibre at a point can be described by a curvature vector pointing along the direction of the fibre. When a curve is positioned on a surface the curvature can be divided in 2 curvatures one normal (out of plane) to the surface and one in plane to the surface or geodesic. This can be written as:

$$\kappa = \kappa_n + \kappa_g \qquad (2)$$

In this formula κ_n represents the single curvature of the surface and κ_g represents the double curvature. When integrating along the fibre these curvatures can in turn be used to determine the enclosed angles of the fibre on the surface:

$$\theta_n = \int \kappa_n ds \text{ and } \theta_g = \int \kappa_g ds \qquad (3)$$

The cost estimation method that has already been implemented is based on the hyperbolic cost expression to estimate the cost and is largely based on the method presented in Haffner(2002). In this reference also adjustments are made to the hyperbolic functions to accommodate for complexity of a part. These adjustments use the information content of a part to impose penalties on the standard hyperbolic functions. Information content can be split in three different elements:

1. Complexity due to continuous curvature of surfaces in the single or normal curved and double or geodesic curved directions.
2. Complexity due to discontinuous connections between surfaces.
3. Complexity due to deformation imposed by angled discontinuous connections between surfaces

Each of these complexities can be expressed as an information content, how this can be done is explained in the next three paragraphs. The different information contents must be kept separate because they have different physical implications on the manufacturing process and therefore impose different penalties on the cost estimation. This is expressed in how the information contents are used in the actual cost estimation formulas.

B.1.1 Complexity due to continuous curvature

The information content of the surfaces in question is determined using the previously explained theory on information content of a fibre. However in Haffner (2002) only simple surfaces such as circular curved and flanged parts are handled. This is not very convenient for the automated systems as it is unlikely that an aircraft part is build up of only these simple elements. Therefore a new method of determining the information content was devised using the capabilities of the existing product model and the software it is implemented in. This method produces results analogous to the information content definition used in Haffner (2002), so the cost estimation factors that have already been determined can also be applied using the information content determined by the new method. The new method of determining the information content is described below:

In the original complexity model information content (I_n), in this case in the normal direction (Figure B-2), is defined as:

$$I_n = \theta_n \cdot L \qquad (4)$$

I_n = Information content of a surface

θ_n = Change of normal angle in the surface

L = Length over which the angle change takes place

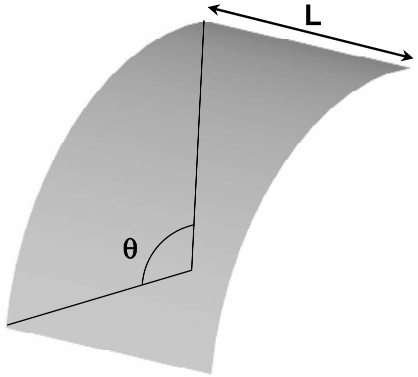


Figure B-2 Dimensions for information content according to Haffner(2002)

For infinitely small surface elements of size *du* and *dv* (Figure B-3) this can be rewritten as:

$$dI_n = d\theta \cdot du \qquad (5)$$

dI_n = Information content of the element

$d\theta_n$ = Angle change in the element

du = Size of the element in the u direction, perpendicular to the curvature

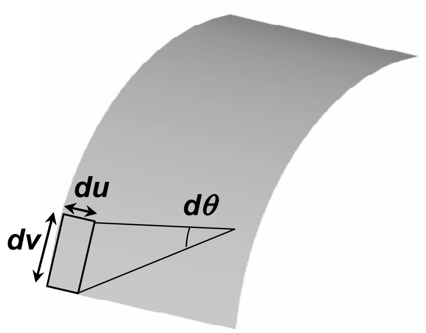


Figure B-3 Element definition

Because information can be summed the total information of a surface is:

$$I = \sum_{elements} dI \qquad (6)$$

The angle change can also be rewritten to involve the curvature

$$\theta_{n/g} = \int \kappa_{n/g} ds \qquad (7)$$

We can also write this formula for the normal angle of an infinitely small element (Figure B-4):

$$d\theta_n = \kappa_n \cdot (dv + \varepsilon) \qquad (8)$$

dv = Size of the element parallel to the curvature

ε = Error or difference in length between dv and the true curvature

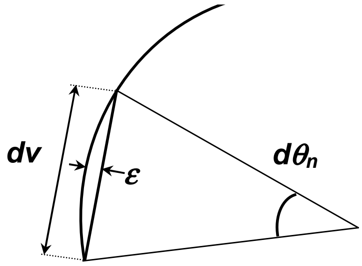


Figure B-4 Definitions in a element of a fibre

Using previous formulas the information content of a small element can be rewritten as:

$$dI_n = \kappa_n \cdot dv \cdot du \qquad (9)$$

The Information content of a surface built from these elements is now:

$$I_n = \sum_{1}^{u\text{-}elements} \sum_{1}^{v\text{-}elements} \kappa_n \cdot du \cdot dv \qquad (10)$$

In fact for the determination of the information content the orientation of the elements is not important as long as then whole surface is handled. This can be seen when imagining an surface segment that does not have edges perpendicular or parallel to the curvature. This element can be filled with infinitely small strips that are perpendicular to the curvature. The area weighted average curvature in these elements is the same as the average curvature of the surface segment. Therefore when adding all the “area times curvature” values of the elements, the outcome is the same as just multiplying the surface segment area times the average curvature.

Therefore the information content of a surface is:

$$I_n = \iint_{surface} \kappa_n dS \qquad (11)$$

This theory is also applicable to the curvature in the geodesic direction:

$$I_g = \iint\limits_{surface} \kappa_g dS \qquad (12)$$

B.1.2 Complexity due to discontinuous connections

Second element of complexity is expressed in the information content due to discontinuous connection between surfaces. These connections between the different surfaces are sharp. This means that there is an angular direction change between the surfaces involved in the connection. The information content of these sharp connections can be determined in a manner analogous to the determination of information content of surface.

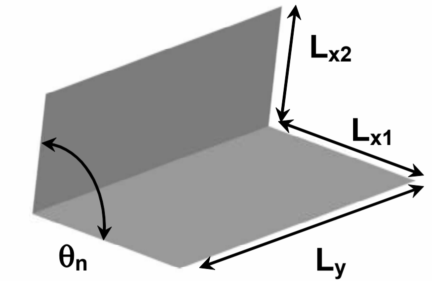


Figure B-5 Sharp angle definition (Haffner(2002))

In Figure B-5 the definition of a sharp connection from the original complexity model can be seen. Here the total sharp edge information content is:

$$I_{sharp} = \left|\pi - \theta_{sharp}\right| \cdot L_y \qquad (13)$$

This formula is only valid for simple straight connections, unfortunately curved connections are also present in aircraft parts however and here a more general formula applies, definitions shown in Figure B-6:

$$I_{sharp} = \int\limits_{connection} \left|\pi - \theta_{sharp}(s)\right| ds \qquad (14)$$

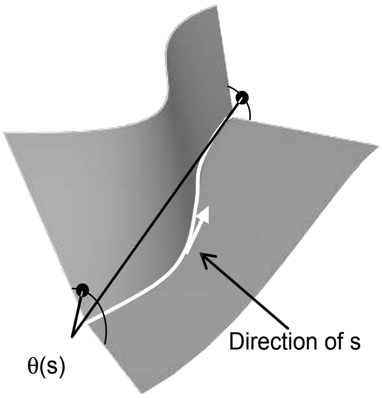


Figure B-6 Definitions for a complex connection

One simplification will be introduced for determining the sharp information content in the product model. When a sharp connection exist in the model usually the angle difference between the connecting surfaces is constant so the expression for the information content becomes:

$$I_{sharp} = \int\limits_{connection} \left|\pi - \theta_{sharp}(s)\right| ds \rightarrow I_{sharp} = \left|\pi - \theta_{sharp}\right| \cdot L_{curve} \qquad (15)$$

L_{curve} = Total connection length

B.1.3 Complexity due to deformations imposed by discontinuous connections

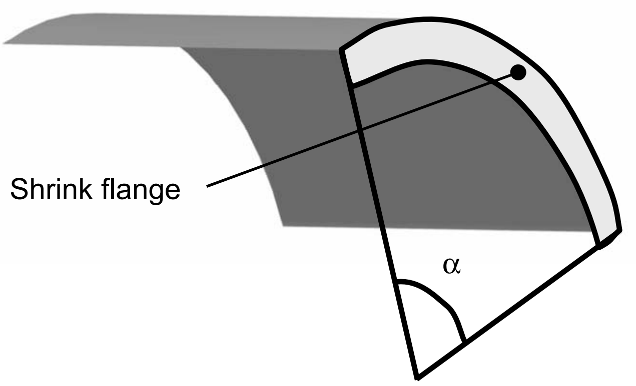


Figure B-7Shrink flange example

Final element of complexity is the complexity due to the deformation of surfaces imposed by discontinuous connections. Examples of this deformation can be found in stretch and shrink flanges. In these flanges the composite material, for example a fabric will wrinkle or has to be sheared to prevent wrinkling to occur. In Figure B-7 an example of a shrink flange can be seen. In the original model an addition to the hyperbolic function has been made to incorporate the added complexity of these area's. In the cost estimation module another implementation is used that is explained in the "Cost estimating function incorporating complexity" section. However the definition of information content remains the same as for the original model. The information content is specified as the geodetic curvature of the fibres that lie on the stretch flange. This geodetic curvature is not only dependent on the surface the material lays on but also on the initial orientation of the material itself. In Ilcewicz(1996) as rule of thumb the maximum possible geodetic curvature is used. For stretch and shrink flanges this geodetic curvature is given as:

$$\theta_d = \frac{\alpha}{2} \qquad (16)$$

θ_d = Geodetic angle due to discontinuous curved connections

α = Angle difference of the connection curve

This geodetic curvature can be used in the cost estimation module. Because the geodetic curve of a stretch or shrink flange is very much dependent on the orientation of the material, the results of the part of the information content determination can be unreliable. This is extra true for the information extracted from product model because the parts in this model are more complex that the simple shrink flange shown here. An extra issue to consider is that in case of a simple shrink or stretch flange the assumption is made the connection curve is constantly perpendicular to the material orientation. However in more complex connections the angle of the connection with the material is not constant over the whole connection. This introduces other issues that are not dealt with in this definition of information content. However to address all these issues properly a lay up simulation of the part in question is needed, which can be expensive in terms of time and money. The proposed information content definition is therefore by no means perfect but it provides some means of quantifying the complexity as a result of curved discontinues surface connections in a part.

B.1.4 Summary of the calculated complexities

In total 4 different kinds of complexities have been determined. These will be used in combination with data about the areas they apply to in the cost estimation module that will be discussed in the next section. A summary of information content formulas can be seen below in equation 17-20.

Single curved-information content of smooth surfaces:

$$I_n = \iint\limits_{surface} \kappa_n dS \qquad (17)$$

Double curved-information content of smooth surfaces:

$$I_g = \iint\limits_{surface} \kappa_g dS \qquad (18)$$

Information content of sharp connections

$$I_{sharp} = \left|\pi - \theta_{sharp}\right| \cdot L_{curve} \qquad (19)$$

Angle difference in curved connections inducing double curvature:

$$\theta_d = \frac{\alpha}{2} \qquad (20)$$

B.2 Cost estimating function incorporating complexity

The cost estimation method implemented in the cost estimation module uses formulas to simulate the cost estimation process. These formulas are based on the ones presented in Neoh(1995) and Haffner(2002). The expression that lies at the hart of the cost estimation is the hyperbolic expression that can be seen below:

$$t = t_{delay} + \tau_0 \sqrt{\left(\frac{x}{\nu_0 \cdot \tau_0} + 1\right)^2 - 1} \qquad (21)$$

t_{delay} = Delay time in the manufacturing operation

ν_0 = Steady state speed of the manufacturing process

τ_0 = Time it takes to reach 63% of the steady state speed

x = Variable on which the cost estimation is based, for instance area or length

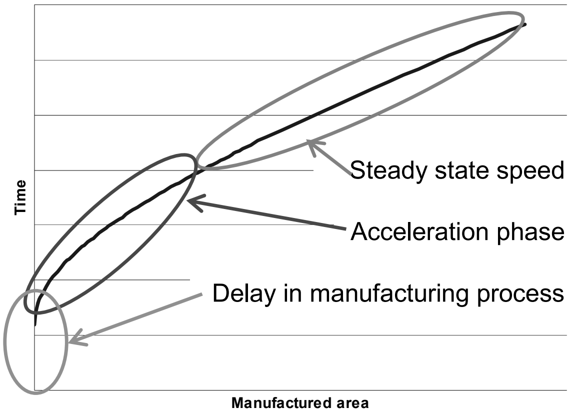


Figure B-8 Hyperbolic manufacturing speed

In Figure B-8 an example can be seen of the hyperbolic function. The three factors describing the manufacturing process all act in their own part of the diagram. The delay time determines the initial delay. The acceleration factor determines the length and speed of the first phase of the manufacturing process. Finally the steady state speed determines the manufacturing speed in the later phases of the manufacturing process.

In Haffner(2002) the hyperbolic function is expanded to incorporate complexity data. The resulting expression is applicable for the lay-up of composite plies in the hand lay up manufacturing process. In the expression the delay time is not incorporated because complexity has no influence on this time. This is the resulting expression:

$$t = \left(\tau_{single} \cdot \sqrt{\left(\frac{A_{single}}{\nu_{single} \cdot \tau_{single}} + 1\right)^2 - 1}\right) + \left(\tau_0 \cdot \sqrt{\left(\frac{A_{double}}{\nu_{double} \cdot \tau_0} + 1\right)^2 - 1}\right) \qquad (22)$$

Where:

$$\tau_{single} = \tau_0 + b_n \cdot I_{sharp} \qquad (23)$$

b_n = Factor determining the influence of sharp edges on the acceleration phase

$$v_{single} = \frac{v_0}{1 + \left({v_0}/{c_n} \right) \cdot I_n} \qquad (24)$$

c_n = Factor determining the influence of normal curvature on the steady state speed

$$v_{double} = \frac{v_0}{1 + \left({v_0}/{c_g} \right) \cdot \theta_d} \qquad (25)$$

c_g = Factor determining the influence of geodesic curvature imposed by discontinuous connections on the steady state speed

What can be seen from this expression is that the single curved part and the double curved part are completely separated and the double curved part of the expression only handles double curvature as a result of sharp connections. The separation of single and double curvature in the expression means that for the double curved part a new acceleration phase exists, as if one was starting with a new product. This seems quit odd because when encountering a sharp edge only a penalty to the acceleration phase is incurred. A remark that should be made here is that the model not only considers sharp edges between surfaces as sharp, but also all smooth single curvatures with a radius of below 12 inch. Another drawback of this expression is that double curved smooth surfaces are not handled, while these will impose a serious penalty on manufacturing time.

Because the existing expression doesn't handle all the complexity elements and has some odd features it was decided to generate a new expression for incorporating complexity in the cost estimation process. The new expression will be based on the existing one in order to guarantee that the information content definition does not change. This means that the factors describing the manufacturing processes determined for the original model can be used.

The new expression is based on the hyperbolic function. In the new expression the complexity issues are incorporated by using different acceleration and steady state factors. In these factors the issues of complexity are handled. The new expression is:

$$t = \tau_{overall} \cdot \sqrt{\left(\frac{A_{total}}{v_{overall} \cdot \tau_{overall}} + 1 \right)^2 - 1} \qquad (26)$$

A_{Total} = Total area of the manufacturable part

$\tau_{overall}$ = Acceleration factor including complexity issues

$v_{overall}$ = Steady state speed factor including complexity issues

Of the complexity issues that are dealt with the acceleration factor handles the sharp edges. This includes all discontinuous surface connections in the part, so curved connections, dealt previously only by adding a double curved surface, are also included. Contrary to the previous model smooth surfaces with a small radius are not included in the acceleration factor. How this affects the actual cost estimation has to be evaluated. The expression for the combined acceleration factor looks like this:

$$\tau_{overall} = \tau_0 + b_n \cdot \sum_{n}^{NoOfShrpConnections} I_{sharp} \qquad (27)$$

As can be seen the expression is very similar to the expression of the acceleration factor for single curved surfaces in the original model. This also means that the same factor for determining the influence of the complexity (b_n) can be used.

The expression for the new overall steady state speed is somewhat more complex. It basically represents a weighted average of the steady state speed for singe curved surfaces, double curved surfaces and double curved surfaces due to curved connections.

$$v_{overall} = \frac{v_0 \cdot A_{flat} + v_{single} \cdot \left(A_{single} + A_{double}\right) + v_{double} \cdot A_{double} + V_d}{\left(A_{flat} + A_{single} + 2 \cdot A_{double} + \sum_{n}^{NoOfCurvedConnections} A_n\right)} \qquad (28)$$

Where:

$$v_{single} = \frac{v_0}{1 + \left(v_0 / c_n\right) \cdot \sum_{i}^{NoOfSurfaces} I_{n_i}} \qquad (29)$$

$$v_{double} = \frac{v_0}{1 + \left(v_0 / c_d\right) \cdot \sum_{i}^{NoOfSurfaces} I_{g_i}} \qquad (30)$$

c_d = Factor determining the influence of smooth geodesic curvature on the steady state speed

$$V_d = \sum_{n=1}^{NoOfCurvedConnections} \frac{v_0 \cdot A_n}{1 + \left(v_0 / c_g\right) \cdot \theta_{d_n}} \qquad (31)$$

The expressions for the different elements resemble the definition from Haffner(2002) therefore existing factors that determine the influence of the complexity (C_n, C_g) can be used. The only new factor compared to equations 22-25, is the factor determining the influence of the double curved smooth complexity (C_d). This factor has to be determined for the relevant manufacturing processes.

The resulting cost estimating expression has the form of the hyperbolic function and therefore only has one acceleration phase, which resembles the actual physics of the production process. Sharp edges influence the acceleration phase while single and double curvature of any radius influence the steady state speed of the manufacturing process. The factors that determine the influence of the different complexities were copied from the original model. However because the new cost estimation expression has a different form validity of using these factors has to be evaluated. This is especially true where sharp edges are involved because the changes in this area are significant. Furthermore the new expression can be applied to very complex models as long as it can be generated by the PMM. The old expression was only tested and validated for relatively simple shapes and forms of constant radii and angles.

B.3 Implementation details

The new expressions for cost estimation will be implemented in the cost estimation module. To do this the appropriate data will have to be extracted from the PMM. In this section the implementation details of integrating the cost estimating expression and the extraction of the complexity data from the product model are described. The transfer of the complexity data from the PMM to the cost estimation module is also described.

B.3.1 Extracting the data from the PMM product model

The information content needed for the cost estimation has to be extracted from the product model in the PMM. In this section where and how this is done is handled. Each information kind is dealt with in a different paragraph.

Smooth surface information content

According to equations 17 and 18 the information content of smooth surfaces can be determined by integrating the curvature in normal or geodetic direction over the surface. This integration will be performed numerically in the PMM because here the definitions of the surfaces are available in form of the geometrical representation of the aircraft part. In the PMM the integration is facilitated by the coding language behind the product model that provides integration and other useful functions.

The actual integration of the curvatures is implemented in the following manner. The principle curvatures at any point on a surface can be determined by simple command available in the software of the product model. As was shown previously in formulas 5 to 10, a discritized representation, or mesh, of the surface has to be formulated to calculate the total information content of a surface. This consists of discrete elements that resemble the surface as much as possible. Of these elements the curvature will be determined.

The definition of the elements on a surface is largely dependent on the kind of surface. Flat surface only need a course mesh, while integrate curved surfaces need a dense mesh to cancel out the discretization error. Therefore before the real calculation of the information content of a surface starts, the surface is first sampled with a course mesh to determine the surface type. Once this is determined the real calculation starts using the appropriate mesh density. To form the actual mesh, u- and v-parameters are used; these parameters can be used to define a position on a surface. The u and v parameters are distributed in a particular order along an edge of a surface. This distribution does not have to be uniform, that’s why a grid created with constant values for u and v parameters can look somewhat distorted. An example of such a grid can be seen in Figure B-9. When the distorted mesh affects the results of the analysis the mesh density can be increased. In the code checks are performed to ensure the mesh density is appropriate.

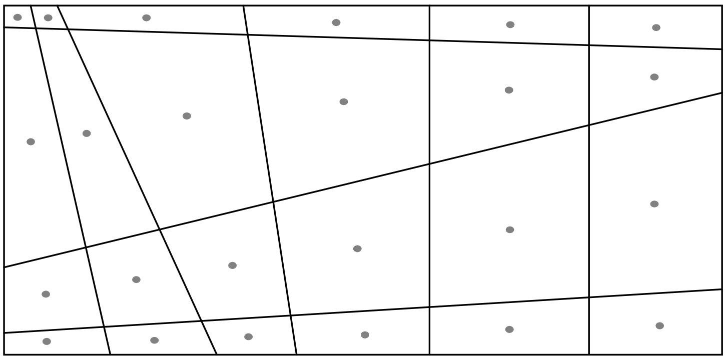


Figure B-9 Grid according evenly distributed u and v parameters

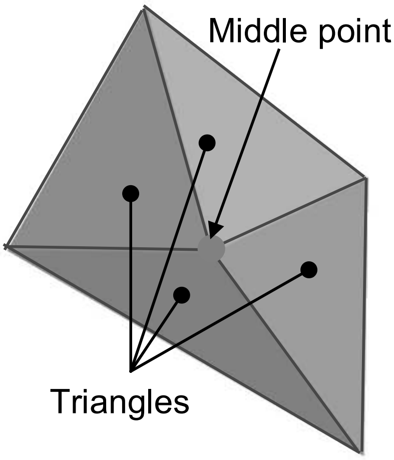


Figure B-10 Division of a Quadrangle in triangles

The elements in the grid are used to estimate the actual information content of the surface. To do this the curvature of each element is determined in both normal and geodetic direction. The determination of the curvature is done in the middle of a grid quadrangle, the dots in the Figure B-9. Next step is multiplying the curvature with the area of the element resulting in the information content of each element. Determination of the area of each element is done by splitting each element into 4 triangles. The area of such a triangle can be determined using the distances between middle and corner points and Heron's Formula. Splitting the elements into 4 triangles allows for a more accurate area determination because some 3d effects are taken into account in the calculation. How the grid quadrangle is divided can be seen in Figure B-10. Finally an error estimation is made based on the total area of the surface and the sum of all element areas. Using this error estimation the appropriateness of the generated mesh can be judged and changes to the mesh can be made when needed.

The resulting information contents I_n and I_g of each surface are not only used to determine whether a surface is flat single curved or double curved. This information is in turn used to determine the flat, single curved and double curved areas of a part. This area information is needed to calculate $\nu_{overall}$ in equation 28. The actual procedures of determining what kind of surfaces is handled and how the information content is determined can be seen in Figure B-11and Figure B-12

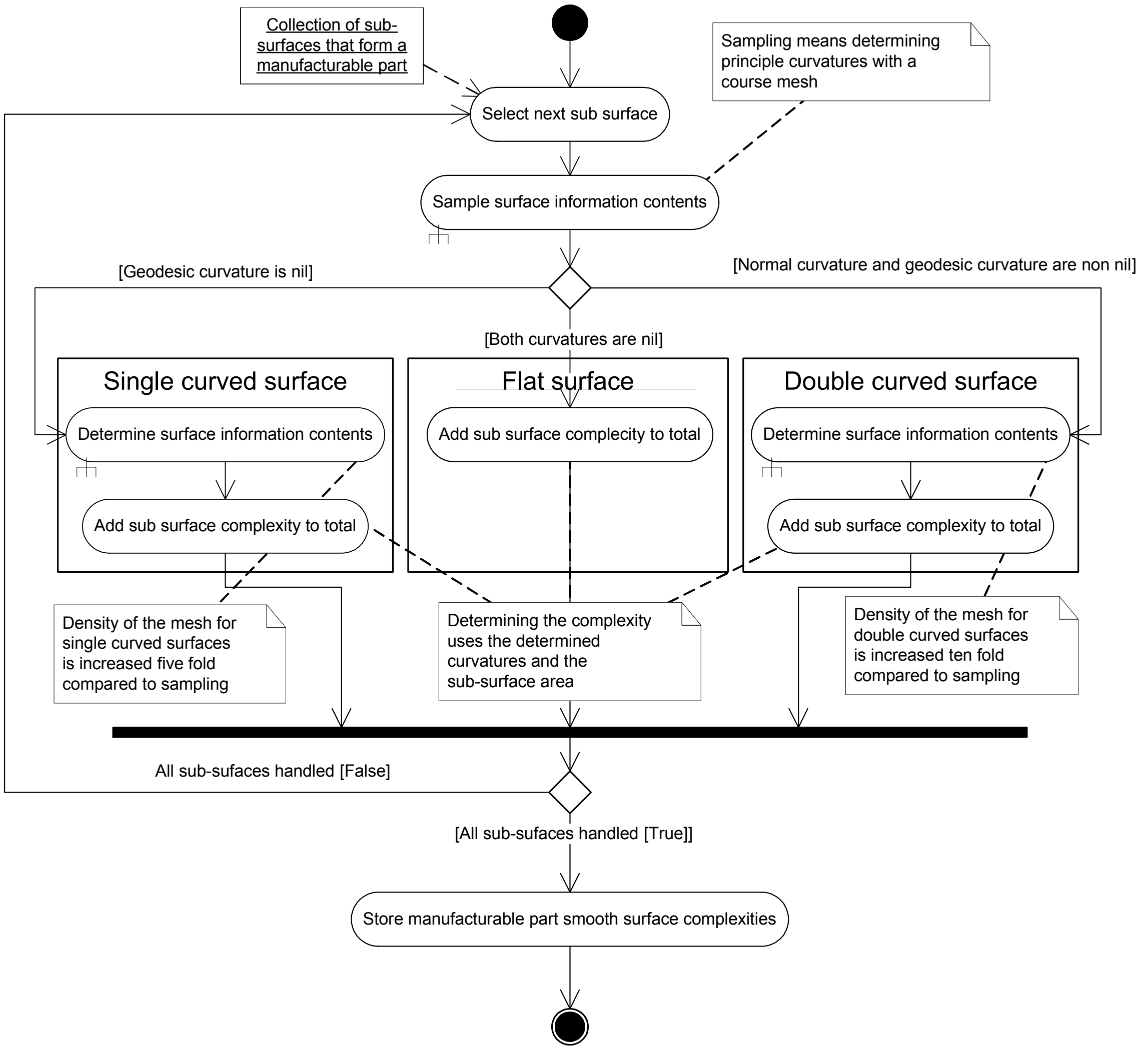


Figure B-11 The process of determining the information content of a continuous surface. The actual information content determination is depicted in Figure B-12

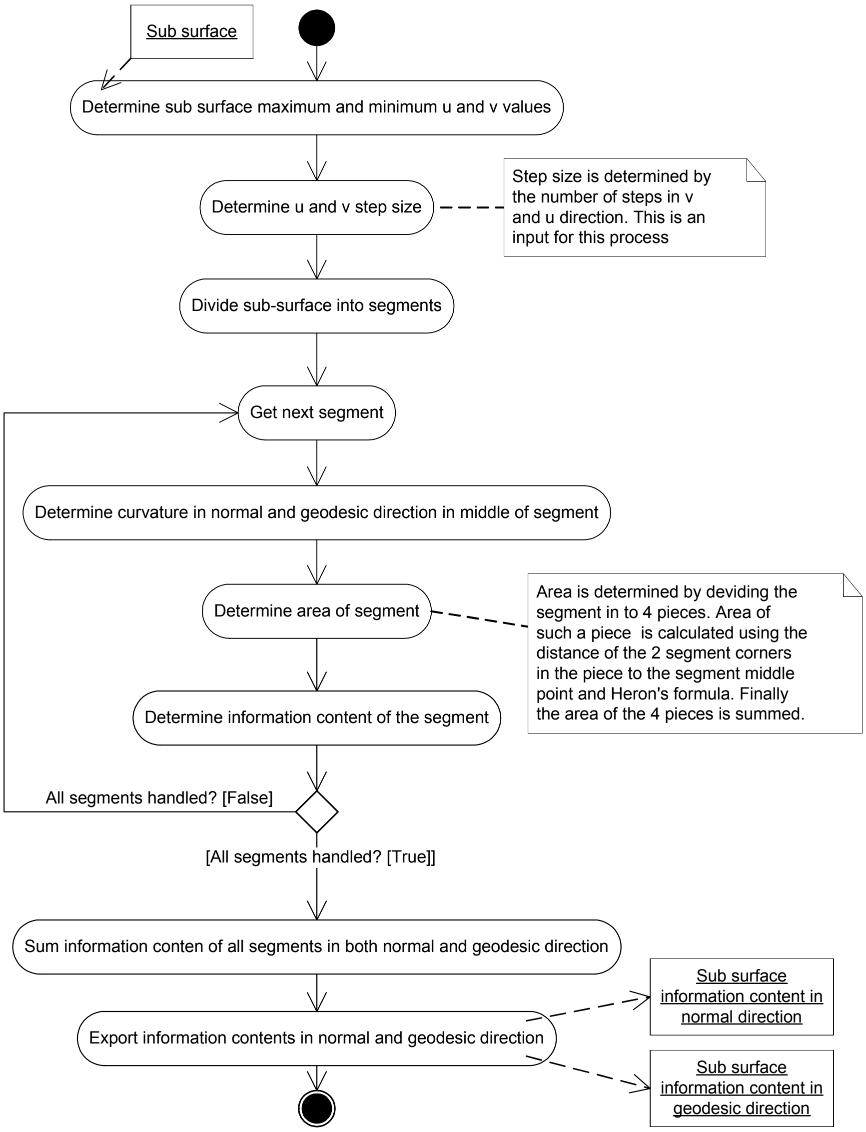


Figure B-12 The actual information content determination

Sharp surface connections information content

According to equation 19 the information content of sharp connections between surfaces within a part is calculated by multiplying the angle between the surfaces with the connection length. The angle during the connection does not have to be constant over the whole connection. However in practice it turns out that most angle differences of internal surfaces of parts are constant or almost constant. Therefore for simplification purposes the angle is considered constant over the whole connection length.

The product model runs in software that supports a lot of vector manipulation and calculations. One option available is determining the surface normal at any position of the surface. This option is used in calculating the minimum angle between two surfaces. The practical implementation entails sampling both surfaces and recording the surface normal at certain places. In this case the surface normals at the four corner points and at the middle point are recorded. Lists containing the normals from both surfaces involved in a connection are compared resulting in a minimum angle between arbitrary normals from both lists. This normal is then used as the constant normal for the whole connection. There are some pitfalls in this approach however. Main one is the in the case of curved surfaces the estimated angle can be rather different than the connection angle. Therefore further work in this area might be needed.

Once the angle between surfaces involved in a connection is known the information content can be determined. In doing this there is also the possibility to set a sharp angle lower boundary, meaning that angles below this boundary are considered smooth, in the case of the PMM a boundary of 15^o was chosen. Using this boundary all smooth connections are filtered out and thrown away because they don't add to the information content of sharp edged connections. For the remaining connections the connection length is multiplied with the angle resulting in information content. A summation of the information contents of all the connections results in the total sharp connection information content of the manufacturable part.

Geodetic curvature due to sharp edges information content

In equation 31 it can be seen that the information content of geodetic curvature due to curved discontinuous connections is defined by the directional difference of the connection. This difference can be easily determined by determining the angle between the tangent vectors in the start and end points of the connection curve. The angle between these vectors is used in the cost estimation module.

Because the sharp surface connection information content and the induced geodesic curvature are both the result of sharp connections, they are determined simultaneously. What the actual procedure looks like can be seen in Figure B-13.

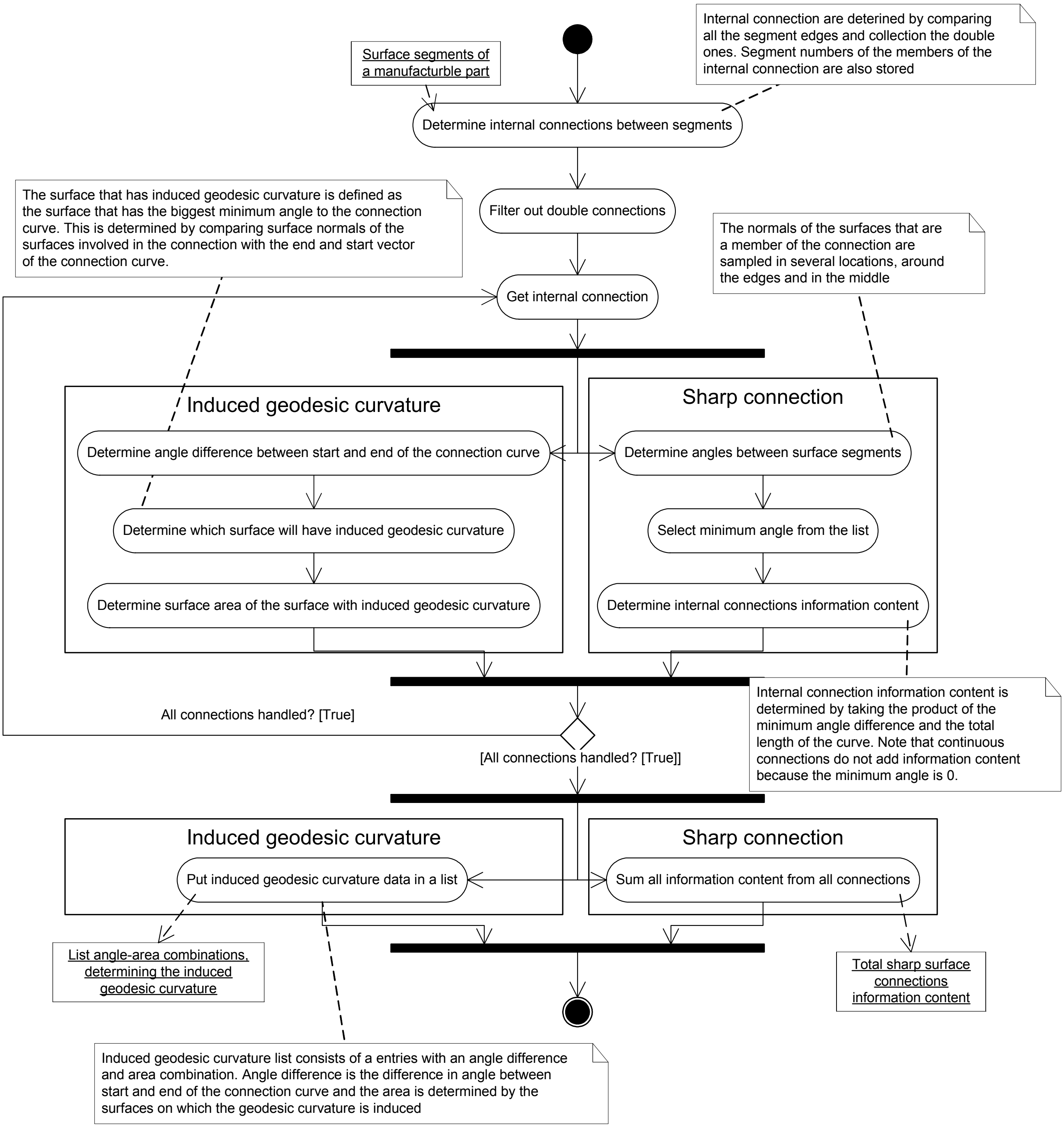


Figure B-13 Determination of the sharp connection information content and induced geodesic curvature

B.3.2 Transferring the data to the cost estimation module

The PMM and cost estimation module are part of the MDEE. This will be used to automate much of the design process. Determining the manufacturing cost of part is only one piece of this framework. Because the framework will provide a highly automated design environment, the transfer of data between the different elements of the framework, in this case the PMM and the cost estimation module, should be fast, robust and accessible. This can be achieved by using standardized data structures and files in the data transfer. In this case the data will be transferred using files of the XML format.

The actual data file that is used to transfer the complexity data is in fact the same file that was already used for the transfer of other data needed for the cost estimation process. An addition is made to this file in which the information about complexity is contained. In this way all cost estimation data for each manufacturable part is concentrated and easily accessible without the need of opening an searching multiple files.

B.3.3 Use of the complexity data in the cost estimation module

The use of the complexity data in the cost estimation module consists of implementing equations 27-31 for the appropriate manufacturing method in this case the hand lay up manufacturing method. The resulting expressions for the acceleration factor (τ) and the steady state speed factor (ν) replace the existing factors τ_0 and ν_0. This results in adjusted manufacturing times for the lay up part of the hand lay up manufacturing method. In the *Examples* section a description is shown of how this works in practice.

B.3.4 Problems and pitfalls in the implementation

The theory and implementation details shown in this apendix enable a quantification of complexity that can be used to make a better cost estimation for certain manufacturing methods. However during the process of implementing the theory many simplification assumptions are made. These assumptions can limit the applicability and accuracy of the method. This should be taken into consideration when assessing and analyzing the results from this method of complexity implementation. Below the biggest problems and pitfalls are summarized:

- Curvature and angle changes of a part are inherently dependent on material orientation and thus the “start point” of the material. This is not addressed in the model. Merely rules of thumb or best practices are implemented.
- The methods used for defining complexity and the factors used by these methods have been validated for simple constructions. However in the model they are also applied to much more complex geometries where applicability might be questionable.
- Many simplifications are implemented, some of which are known to be untrue. For instance, according to the model the influence of complexity on manufacturing time is the same both stretch and shrink flanges while it is known that, in practice, this is not actually true.
- Changes have been made to the original cost estimation formula (equation 22). While these changes are supported by the theory behind the cost estimation, they are not validated and might therefore deteriorate results.
- The data is extracted from the product model using certain algorithms embedded in the software package. These algorithms are not always very accurate, and therefore the results for the data extraction might be flawed.

B.4 Examples

In this section an example will be shown of an imaginary aircraft movable. Using this example the actual occurrences of complexity in a real product will be shown and the results of the complexities will be quantified. The aircraft movable that is analyzed is a simple imaginary instantiation of the movable product model built from 6 separate parts and includes all forms of complexity. All part will be manufactured using the hand lay up techniques and are 8 layers thick. The structural lay-out of the movable is simple with the outer skins supported by ribs and spars. The movable can be seen in Figure B-14. All manufacturing times shown are the times from the hand lay up sub process, other sub processes are not considered, because here complexity is not an issue.

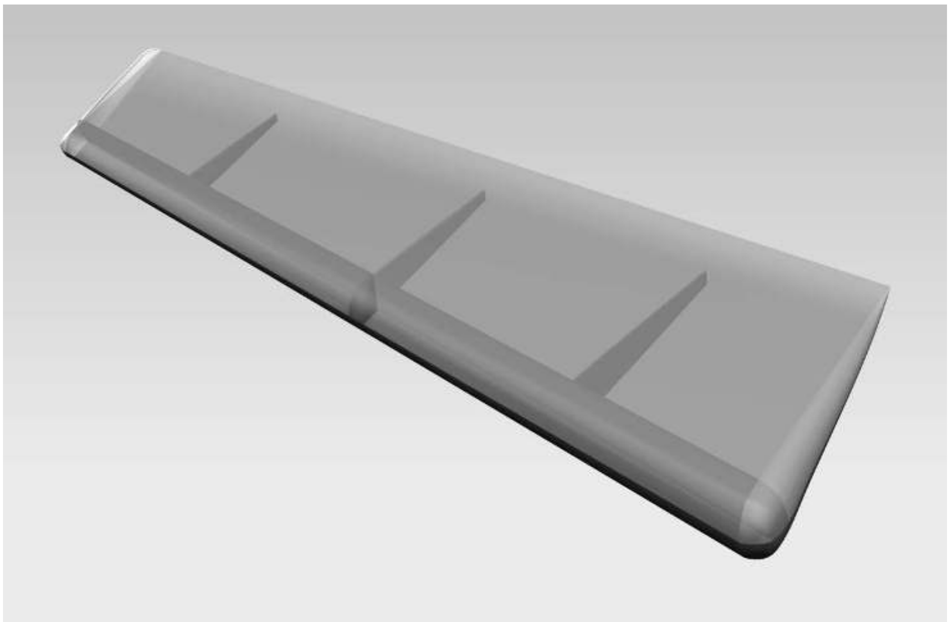


Figure B-14 Movable example

B.4.1 Description of complexity in the different parts

Part 1 *Spar and ribs combination*

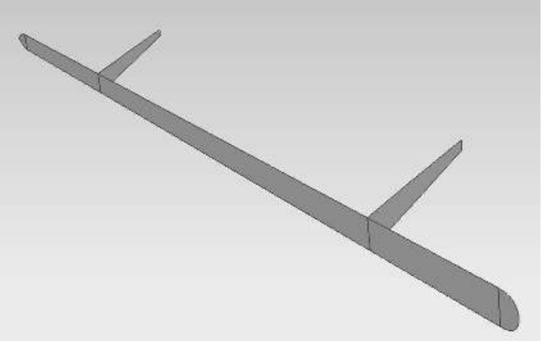


Figure B-15 Part 1, spars and ribs

Part 1 (Figure B-15) consists of the main spar and 2 ribs. This part is an example of a simple integrated product. It integrates a spar and 2 ribs. All surfaces in this part are flat. The complexity in this part lies in the connections of the ribs to the spar, which is a sharp connection. However the influence of the connections will be small because the connection length is only small. This can be seen in the manufacturing times estimated by the cost estimation module. In the Table B-1 the manufacturing time of this part calculated using the module where complexity is included is compared to the original calculated manufacturing time where no complexity issues are considered.

Table B-1 Manufacturing times comparison part 1

Manufacturing time complexity not considered	607.2s
Manufacturing time complexity considered	609.5s
Increase in percentage	0.4%

As can be seen from the table there is only a marginal difference in manufacturing time. This is caused mainly because the sharp connections are very short and therefore add little to the sharp connections information content.

Part 2 *Flat rib*

Part 2 (Figure B-16) is a flat rib. Because it is flat and has no complexity adding features the estimated manufacturing time of this part is the same in the estimations considering or not considering complexity. This can be seen in Table B-2.

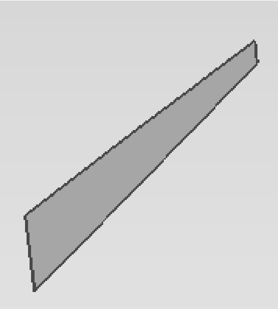


Figure B-16 Part 2, rib

Table B-2 Manufacturing times comparison part 2

Manufacturing time complexity not considered	186.6s
Manufacturing time complexity considered	186.6s
Increase in percentage	0.0%

Part 3 *Skin Panels*

Part 3 (Figure B-17) consists of skin panels. This part is an example of a part with a long sharp connection and for the rest almost flat surfaces. The complexity in this part is the long sharp connection. This long sharp connection will have a significant effect on the acceleration factor. The resulting manufacturing times can be seen in Table B-3.

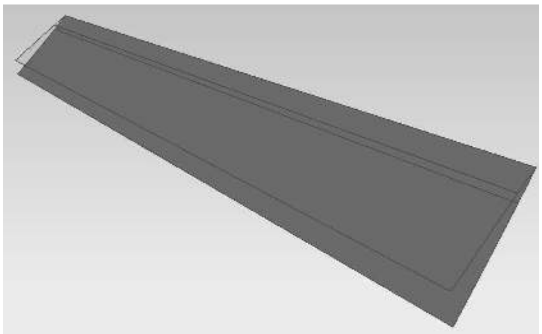


Figure B-17 Part 3, skin panels

Table B-3 Manufacturing times comparison part 3

Manufacturing time complexity not considered	1742.0s
Manufacturing time complexity considered	1818.7s
Increase in percentage	4.4%

As can be seen for this part the added complexity has a significant effect increasing the manufacturing time by 4.4% due to the increased acceleration time. Note that accessibility issues are not handled by this model they could otherwise play a major part in the manufacturing of this part.

Part 4 *Leading with integrated nose rib*

Part 4 (Figure B-18) consists of the leading edge of the movable including an integrated nose rib. This part is an example of an integrated part including single curvature, sharp edges and geodetic curvature of the fibres due to the curved sharp connection. One would expect a big difference in the manufacturing times. However this is not apparent in the difference in the manufacturing time estimations seen in Table B-4.

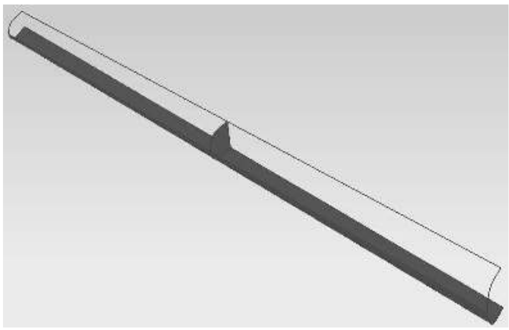


Figure B-18 Part 4, leading edge with nose rib

Table B-4 Manufacturing times comparison part 4

Manufacturing time complexity not considered	843.1s
Manufacturing time complexity considered	879.9s
Increase in percentage	4.4%

There are a few reasons why the difference in estimated manufacturing time is so low. First of all single curvature in the hand lay-up process does not slow the process very much. Furthermore the factors determining the slowing down have been determined using large diameter test articles, while in this case the radius is relatively small. It should be noted that the factors that were used are applicable on large diameter parts according to Haffner(2002). Therefore it might be useful to see if another implementation for small diameter single curvature is needed. The second complexity issue that should cause the manufacturing to slow down is the nose rib, which has geodetic curvature due to a curved sharp edge. However the area of the nose rib is relatively small and the therefore the influence of the nose rib on the overall steady state speed (equation 28) is also small.

Part 5 *Upper endcap*

Part 5 (Figure B-19) consists of the upper endcap. This is an example of a highly double curved part. The upper endcap is a aerodynamic fairing and is highly double curved. This double curvature should add significantly to the manufacturing time that is estimated. The time estimation results for part 5 can be seen in Table B-5.

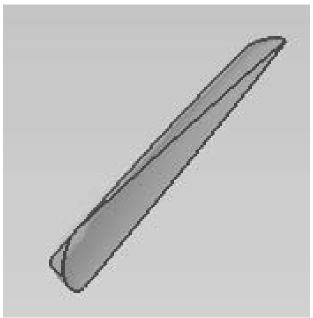


Figure B-19 Part 5, upper endcap

Table B-5 Manufacturing times comparison part 5

Manufacturing time complexity not considered	213.2s
Manufacturing time complexity considered	276.0s
Increase in percentage	29.5%

As can be seen there is a significant increase in the estimated manufacturing time. There is however one important issue to consider here, because the factor determining the influence of double curvature on manufacturing time has been estimated without relevant test data it is not very reliable. Besides this issue the increased time shows that the new cost estimation includes the double curvature in the manufacturing time estimation.

Part 6 *Lower endcap*

Part 5 (Figure B-20) consists of the upper endcap. It is very similar to the lower endcap in that it is highly double curved. One would therefore expect a resulting time increase similar to part 5. The results from the time estimation can be seen in Table B-6.

Table B-6 Manufacturing times comparison part 6

Manufacturing time complexity not considered	400.5s
Manufacturing time complexity considered	541.0s
Increase in percentage	35.1%

As can be seen the results from part 6 are in the same order as for part 5. The remarks for part 5 are also valid for part 6.

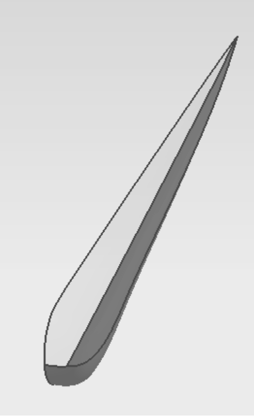


Figure B-20 Part 6, lower endcap

B.5 Conclusions

An addition to the cost estimation module to include complexity in the cost estimation has been proposed and implemented. The method used includes complexity uses elements for the method presented in Haffner (2002). The elements have been re-ordered or used in a different method. A term has been added for complexity as a result of geodesic curved surfaces. Finally the method of including complexity in the cost estimation process has been implemented in the existing cost estimation module. Compared to the old cost estimation module the results from the new cost estimation calculations including complexity show that for certain geometries complexity adds a significant manufacturing time increase. Some complexity elements and their implementation might have to be re-evaluated. This is true for the normal curvature especially of small radii, which uses factors that might not be suited for this configuration. Another issue is that the factors determining the influence of smooth geodesic curved surfaces is a rough estimation and has to be verified by test data.

The addition of an implementation of complexity issues to the cost estimation module increases the accuracy of the cost estimation module. The implementation of the data extraction to feed the cost estimation module has increased the data extraction capability of the PMM product model. With the increased accuracy and information density the cost estimation module and product model are an important addition to the Movable Design and Engineering Engine.

Appendix C Implementation of flanges in the manufacturing view of the PMM

Because the Parametric Movable Model (PMM) provides a simplified model of a movable for the early phases of the design process, flanges have not been implemented in the model. However when assessing the manufacturing cost of a movable these flanges have a big impact. For instance they add complex corners and fillets to otherwise flat surfaces. The incorporation of these flanges in the cost estimation will therefore improve the accuracy and applicability it. Incorporating them means, however, that they have to be modelled. Modelling the flanges directly in the PMM is an option. It will however lead to much more complicated model and will take a lot of time to implement. Other more simplified methods of modelling them also exist, however before deciding how to model them first the main requirement for the flanges has to be understood. This is the requirement is that the modelled flanged should provide data for the cost estimation module. The data required for this cost estimation consists of geometrical data, such as flange area, and complexity data such as the increase in information content. The data required for the cost estimation consists of:

- *Length of the flange*
- *Area of the flange*
- *Angle of the flange*
- *Curvature of the flange*

These four elements can be determined by combining new input information about the flange and information about the contour onto which the flange will fit. The information about the shape and configuration of the flange will be added to the PMM input data set and will for each manufacturable part consist off:

- *Flange width.* The width of the flange, it is considered constant for the whole flange.
- *Flange angle.* The angle the flange is turned with respect to the mother part.
- *Flange filling percentage.* The percentage of the outer boundary of the part that has a flange attached to it.

Combining the new inputs and the geometric boundary information from the PMM, the required data for the affordability analysis can be generated. In this way the flanges will not require any new geometrical modelling, which keeps the PMM simple. The data extracted from the PMM to be transferred to the cost estimation module consists of:

- *Total flange area*
  This area will be added to the product area for determining the manufacturing time, it is dependent on the outer boundary length extracted from the PMM, the flange width, and the flange filling percentage.
- *Flange flat area*
  This is the part of the flange area that is flat; this information is needed in determining the complexity penalties.
- *Flange single curved area*

This is the part of the flange area that is single curved; this information is needed in determining the complexity penalties.

- *Flange single curved information content*
  This information content determines the acceleration penalty due to the sharp corners between main part and the flanges. The information content is determined using the outer boundary length extracted from the PMM, the flange angle and the flange filling percentage.

Besides the previous elements of flange information that were determined for the whole flange of a part also information is generated for each separate boundary section. This information consists of:

- *Flange surf type.*
  This surf type can be flat or single curved depending on the curvature of the local boundary segment. This information is needed to determine if and where a complexity penalty should be added to the manufacturing time of the part. This element is determined by looking at the curvature of the local boundary segment extracted from the PMM.
- *Flange affected area.*
  This is the area of the flange for the local boundary segment, determined in the same way as for the whole flange area. This flange affected area is used to determine the impact of the complexity of the flange section on the overall manufacturing time.
- *Flange connection angle difference.*
  This is the angle difference between the start and end point of the boundary section. This connection angle difference is used to determine the measure of complexity of the particular piece of flange.

The above described data elements are transferred to the cost estimation module as an addition to the existing XML-file used. This file is read by the cost estimation module.

The data from the flanges is treated in the cost analysis module in the same way as other complexity information. The flanges add two main elements to the actual manufacturing time of a part. First of all the overall area of the part is increased. This results in an increase in manufacturing time for all manufacturing methods. Secondly the complexity of the part is increased. This results in increases in manufacturing time for certain manufacturing methods, such as hand lay up of composites. In an example below the influence of incorporating flanges on parts manufactured using hand lay up of composites will be shown.

C.1 Example

The example used for investigating the effect of the incorporation of the flanges in the model is that of a simple movable built from hand laid up parts. The movable is approximately 1 meter in length and the material used for all parts is an 8 layered composite. The flanges added to the parts have width of 20mm and the angle is 90 degrees. The filling percentage for all parts is the same at 80 %. This means that the flange will fill 80% of the outside boundary of each part. Not all parts will be discussed as only the effect of incorporating the flanges on different kinds of parts is investigated. The results of the affordability analysis will be presented in the form of manufacturing times.

For each part a table with these manufacturing times is generated. The manufacturing times are split into different categories to show the difference between the original and the flanged parts and the difference when complexity is incorporated in the cost estimation. Factors used for determining the manufacturing times were taken standard from Haffner(2002), except for the factor determining the influence of smooth double curved surfaces on steady state speed, here and estimation was used.

Part 1 Spar

The first part (Figure C-1) consists of a spar. Although it is a relatively simple part the flanges include some complexity, not only because of the sharp part-flange connection, but also because the curved ends of the spar result in induced double curvature on the flanges in these areas. The results of the cost estimation for part 1 are presented in Table C-1. Because of the slender nature of the part, the influence of adding flanges is quit big on the total area of the part, resulting in a 61% increase. This area increase results in a quite significant manufacturing time increase. This is even more apparent when looking the estimated lay up times of the part. Incorporating the complexity increases the estimated manufacturing time even more.

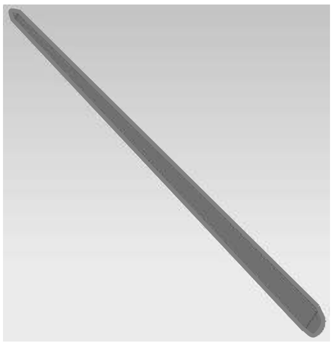


Figure C-1 Part 1 spar including the flange boundaries

Table C-1 Manufacturing times for part 1

Area original	60601 mm^2	Area inc flange	97601 mm^2	
Area percentage increase	61.06%			
	Total recurring		Lay up recurring	
	absolute	percentage	absolute	percentage
Original	9329 s		542 s	
Original inc complexity	9329 s	0.00%	542 s	0.00%
Inc flange	9662 s	3.57%	690 s	27.31%
Inc flange and complexity	9713 s	4.12%	741 s	36.72%

Part 2 Skin panels

The second part (Figure C-2) consists of skin panels. This part represents a relatively large part in which the addition of flanges should have a smaller impact. This can be seen in Table C-2. The area only increases by 9.2%. Manufacturing times differences are all small except for the one in which all the complexities and flanges are incorporated. This might seem odd but the flanges increase the overall complexity of parts significantly. This is

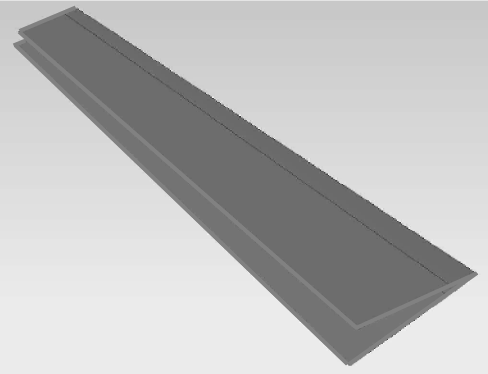


Figure C-2 Part 2 skin panels including the flange boundaries

due to the fact that the outer boundary is long and the filling rate of this boundary is 80%. This added complexity slows the acceleration of manufacturing speed, increasing the overall manufacturing time.

Table C-2 Manufacturing times for part 2

Area original	569130 mm^2	Area new	621550 mm^2	
Area percentage increase	9.21%			
	Total recurring		Lay up recurring	
	absolute	percentage	absolute	percentage
Original	13807 s		1724 s	
Original inc complexity	13902 s	0.69%	1819 s	5.51%
Inc flange	14076 s	1.95%	1808 s	4.87%
Inc flange and complexity	14307 s	3.62%	2040 s	18.33%

Part 3 Endcap

The third part (Figure C-3) consists of an endcap. This part is a relatively small part with a complex double curved geometry. On such a small part the added flange should have a big impact on the total area of the part. In Table C-3 the results for this part can be seen. The area increase is relatively big at 45.8%. This also results in a big increase in manufacturing times. For these complex parts it is essential to incorporate complexity in the estimation as can be seen in the differences between complex and non- complex estimations. Surprisingly when incorporating the flanges the relative influence of the complexity decreases. This is because simple curved surfaces are added to a part consisting otherwise of double curved surfaces.

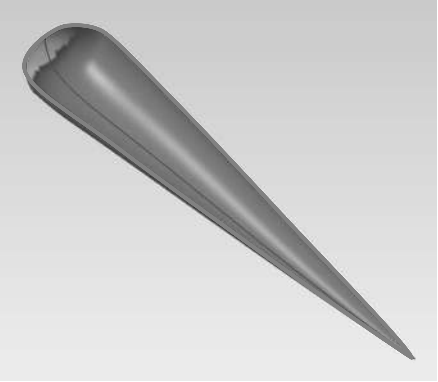


Figure C-3 Part 3 endcap including the flange boundaries

Table C-3 Manufacturing times for part 3

Area original	33239 mm^2	Area new	48448 mm^2	
Area percentage increase	45.76%			
	Total recurring		Lay up recurring	
	Absolute	percentage	absolute	percentage
Original	7137 s		400 s	
Original inc complexity	7277 s	1.96%	541 s	35.25%
Inc flange	7312 s	2.45%	484 s	21.00%
Inc flange and complexity	7450 s	4.39%	622 s	55.50%

C.2 Conclusions

It was shown that flanges can be incorporated in the affordability analysis using relatively simple means and without changing the modelling engine of the PMM. The implementation requires a few extra inputs. It was also shown that these flanges have a significant effect on the manufacturing times of the parts. This is especially true when the parts are relatively small and the manufacturing methods are slowed by complexity features such as the sharp edges between flange and part surfaces.

Appendix D Cost estimation process activity diagrams

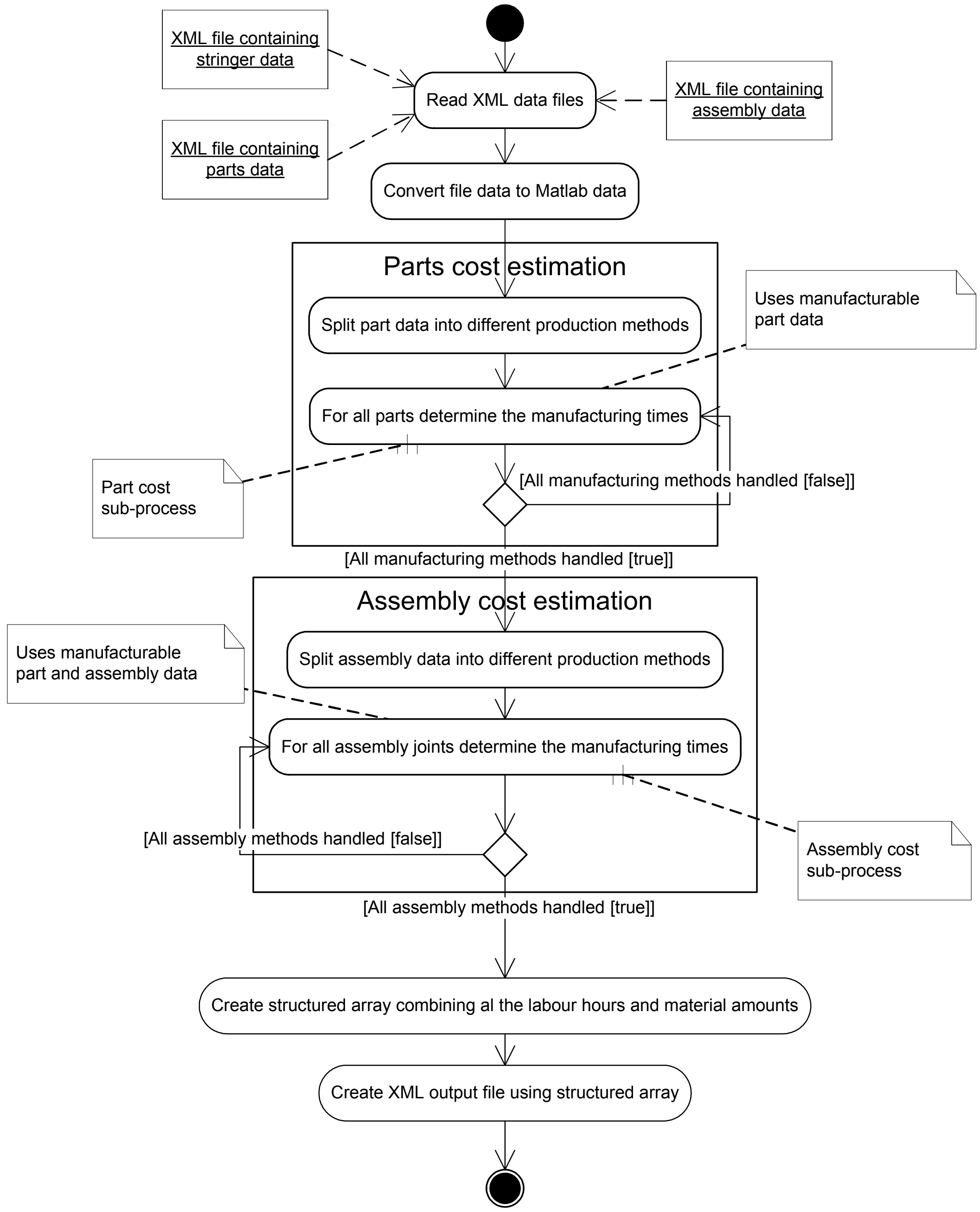


Figure D-1 The cost estimation process activity diagram

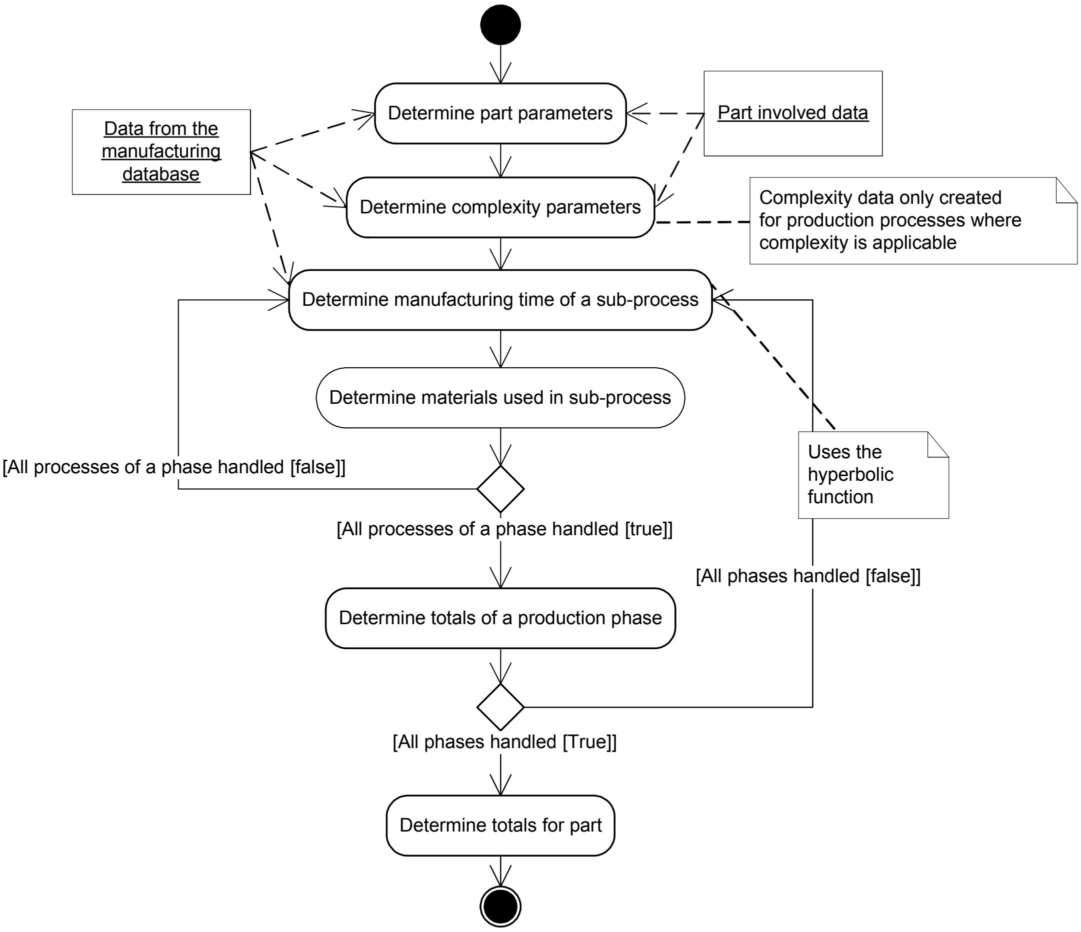


Figure D-2 The part cost sub-process

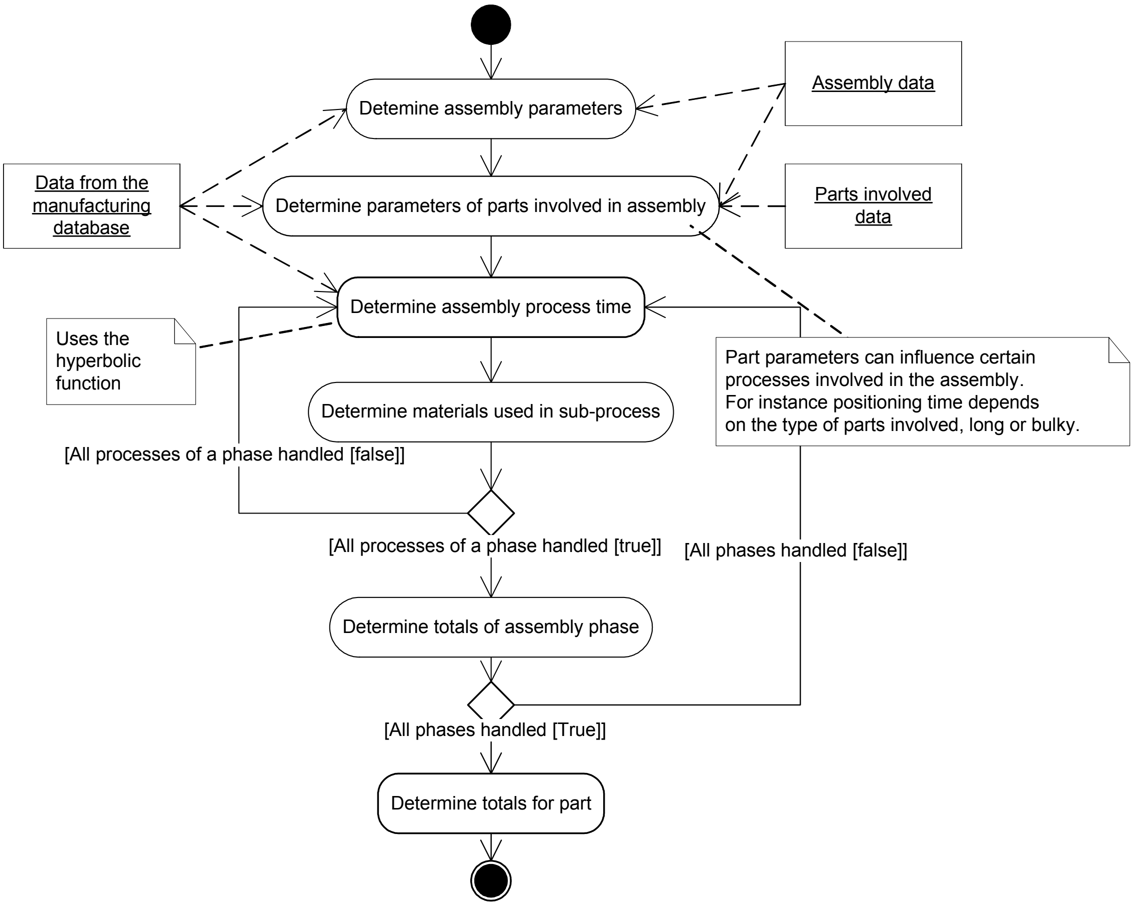


Figure D-3 The assembly cost sub-process

Appendix E Cost estimation results for the eaglet rudder baseline

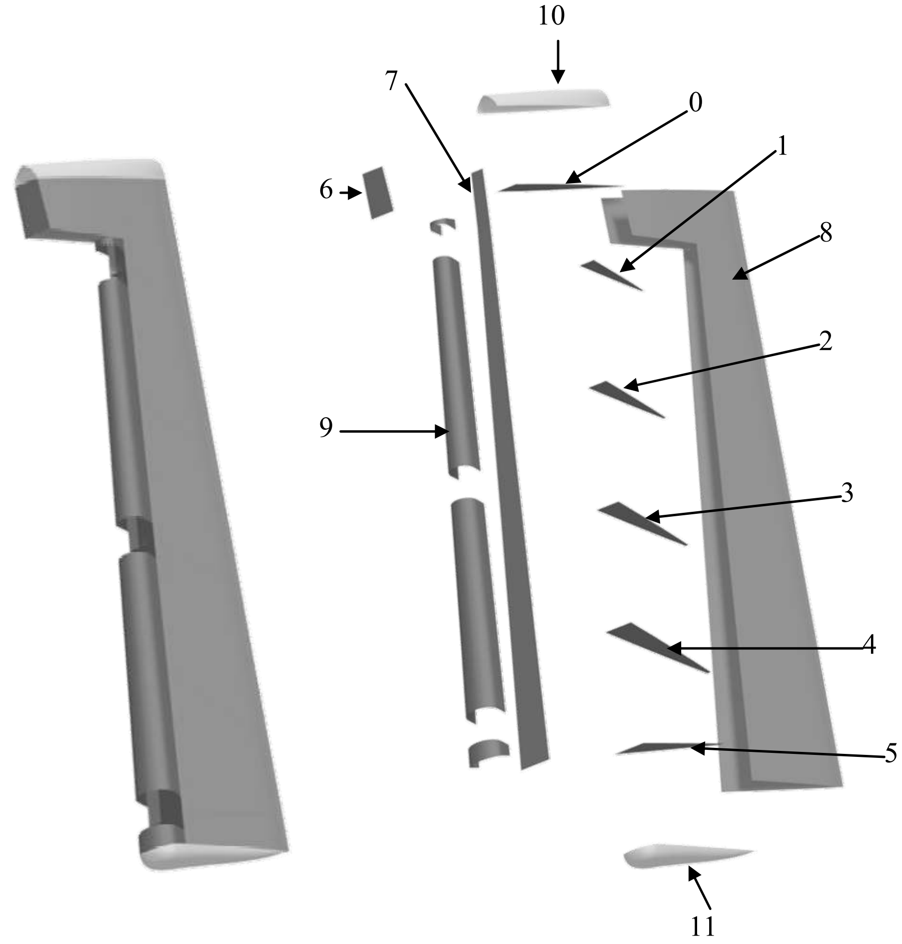


Figure E-1 Eaglet rudder manufacturing baseline including an exploded view showing all manufacturable parts

Table E-1 Names connected to the ID numbers of Figure E-1

Manufacturable part ID	Part Name
0	Upper Closure Rib
1	Hinge Rib 1
2	Rib Between Hinge 1 and 2
3	Hinge Rib 1
4	Rib Between Hinge 2 and 3
5	Hinge 3 / Lower closure rib
6	Horn Spar
7	Main Spar
8	Skin Panels
9	Leading Edge (complete)
10	Upper Endcap
11	Lower Endcap

Table E-2 Estimated cost of the Upper Closure Rib

Manufacturing Part ID	0		
Part Name	Upper Closure Rib		
Manufacturing method	Thermoplastic Rubber Forming		
Manufacturing sub-group	Recurring Time [min]	Non-Recurring Time [min]	Material Cost
ToolSetUp	3	233	€10
MaterialSetUp	13	11	€0
Forming	3	7	€0
Demoulding	1	0	€0
Inspect	15	26	€0
Overall	35	277	€10
Overall Batch size 20	35	14	€10
Total cost	€51		

Table E-3 Estimated cost of the Hinge Rib 1

Manufacturing Part ID	1		
Part Name	Hinge Rib 1		
Manufacturing method	Thermoplastic Rubber Forming		
Manufacturing sub-group	Recurring Time [min]	Non-Recurring Time [min]	Material Cost
ToolSetUp	2	129	€3
MaterialSetUp	10	11	€0
Forming	3	7	€0
Demoulding	1	0	€0
Inspect	10	26	€0
Overall	25	172	€3
Overall Batch size 20	25	9	€3
Total cost [Euro]	€31		

Table E-4 Estimated cost of the Rib Between Hinge 1 and 2

Manufacturing Part ID	2		
Part Name	Rib Between Hinge 1 and 2		
Manufacturing method	Thermoplastic Rubber Forming		
Manufacturing sub-group	Recurring Time [min]	Non-Recurring Time [min]	Material Cost
ToolSetUp	2	146	€4
MaterialSetUp	10	11	€0
Forming	3	7	€0
Demoulding	1	0	€0
Inspect	11	26	€0
Overall	27	190	€4
Overall Batch size 20	27	9	€4
Total cost [Euro]	34		

Table E-5 Estimated cost of the Hinge Rib 2

Manufacturing Part ID	3		
Part Name	Hinge Rib 2		
Manufacturing method	Thermoplastic Rubber Forming		
Manufacturing sub-group	Recurring Time [min]	Non-Recurring Time [min]	Material Cost
ToolSetUp	2	166	€6
MaterialSetUp	11	11	€0
Forming	3	7	€0
Demoulding	1	0	€0
Inspect	11	26	€0
Overall	29	210	€6
Overall Batch size 20	29	10	€6
Total cost [Euro]	39		

Table E-6 Estimated cost of the Rib Between Hinge 2 and 3

Manufacturing Part ID	4		
Part Name	Rib Between Hinge 2 and 3		
Manufacturing method	Thermoplastic Rubber Forming		
Manufacturing sub-group	Recurring Time [min]	Non-Recurring Time [min]	Material Cost
ToolSetUp	2	189	€7
MaterialSetUp	11	11	€0
Forming	3	7	€0
Demoulding	1	0	€0
Inspect	13	26	€0
Overall	31	232	€7
Overall Batch size 20	31	12	€7
Total cost [Euro]	42		

Table E-7 Estimated cost of the Hinge 3 / Lower closure rib

Manufacturing Part ID	5		
Part Name	Hinge 3 / Lower closure rib		
Manufacturing method	Thermoplastic Rubber Forming		
Manufacturing sub-group	Recurring Time [min]	Non-Recurring Time [min]	Material Cost
ToolSetUp	2	189	€9
MaterialSetUp	11	11	€0
Forming	3	7	€0
Demoulding	1	0	€0
Inspect	13	26	€0
Overall	31	232	€9
Overall Batch size 20	31	12	€9
Total cost [Euro]	44		

Table E-8 Estimated cost of the Horn Spar

Manufacturing Part ID	6		
Part Name	Horn Spar		
Manufacturing method	Thermoplastic Rubber Forming		
Manufacturing sub-group	Recurring Time [min]	Non-Recurring Time [min]	Material Cost
ToolSetUp	2	139	€4
MaterialSetUp	10	11	€0
Forming	3	7	€0
Demoulding	1	0	€0
Inspect	10	26	€0
Overall	26	182	€4
Overall Batch size 20	26	9	€4
Total cost [Euro]	33		

Table E-9 Estimated cost of the Main Spar

Manufacturing Part ID	7		
Part Name	Main Spar		
Manufacturing method	Thermoplastic Rubber Forming		
Manufacturing sub-group	Recurring Time [min]	Non-Recurring Time [min]	Material Cost
ToolSetUp	7	905	€54
MaterialSetUp	23	11	€0
Forming	3	7	€0
Demoulding	1	0	€0
Inspect	43	26	€0
Overall	76	948	€54
Overall Batch size 20	76	47	€54
Total cost [Euro]	157		

Table E-10 Estimated cost of the Skin Panels

Manufacturing Part ID	8		
Part Name	Skin Panels		
Manufacturing method	Thermoplastic Folding		
Manufacturing sub-group	Recurring Time [min]	Non-Recurring Time [min]	Material Cost
SetUp	0	4	
MatLoad	7	2	
Cutting	31	0	€326
Finnishing	3	6	
Folding	6	13	
Overall	46	25	€326
Overall Batch size 20	46	1	€326
Total cost [Euro]	366		

Table E-11 Estimated cost of the Leading Edge

Manufacturing Part ID	9		
Part Name	Leading Edge		
Manufacturing method	Thermoplastic Rubber Forming		
Manufacturing sub-group	Recurring Time [min]	Non-Recurring Time [min]	Material Cost
ToolSetUp	7	1107	€67
MaterialSetUp	25	11	€0
Forming	3	7	€0
Demoulding	1	0	€0
Inspect	51	26	€0
Overall	87	1150	€67
Overall Batch size 20	87	58	€67
Total cost [Euro]	187		

Table E-12 Estimated cost of the Upper Endcap

Manufacturing Part ID	10		
Part Name	Upper Endcap		
Manufacturing method	Vacuum infusion		
Manufacturing sub-group	Recurring Time [min]	Non-Recurring Time [min]	Material Cost
ToolSetUp	5	44	€20
MaterialSetUp	22	24	€0
LayUp	3	0	€0
DeBulk	0	0	€0
VacuumBagging	19	20	€6
InfAndCure	25	287	€0
Finishing	12	26	€0
Overall	85	400	€26
Overall Batch size 20	85	20	€26
Total cost [Euro]	114		

Table E-13 Estimated cost of the Lower Endcap

Manufacturing Part ID	11		
Part Name	Lower Endcap		
Manufacturing method	Vacuum infusion		
Manufacturing sub-group	Recurring Time [min]	Non-Recurring Time [min]	Material Cost
ToolSetUp	4	44	€20
MaterialSetUp	22	24	€0
LayUp	3	0	€0
DeBulk	0	0	€0
VacuumBagging	19	20	€6
InfAndCure	24	287	€0
Finishing	12	26	€0
Overall	84	400	€26
Overall Batch size 20	84	20	€26
Total cost [Euro]	113		

Table E-14 Estimated cost of the connection joints

Connection ID	Product ID First Element involved	Product ID Second Element involved	Recurring Time [min]	Non Recurring Time [min]	Total cost
0	0	6	21	4	€21
1	1	8	25	4	€24
2	1	8	24	4	€23
3	1	7	25	4	€24
4	2	8	25	4	€24
5	2	8	25	4	€24
6	2	7	21	4	€20
7	3	8	25	4	€24
8	3	8	25	4	€24
9	3	7	21	4	€21
10	4	8	26	4	€25
11	4	8	26	4	€25
12	4	7	21	4	€21
13	5	8	26	4	€25
14	5	8	26	4	€25
15	5	7	22	4	€21
20	0	8	28	4	€26
21	0	8	28	4	€26
22	0	7	21	4	€20
23	6	8	23	4	€22
24	6	8	23	4	€22
25	6	10	22	4	€21
26	7	8	23	4	€23
27	7	8	23	4	€23
28	7	8	22	4	€22
29	7	8	22	4	€22
32	7	8	22	4	€22
33	7	8	22	4	€22
36	7	8	22	4	€22
37	7	8	22	4	€22
38	8	11	28	4	€26
39	8	11	28	4	€26
40	9	11	23	4	€23
41	8	10	29	4	€27
42	8	10	29	4	€27
		Totals:	846	130	€813

Table E-15 Cost estimation results for the Eaglet rudder baseline

Manufacturable Part ID=0	€51
Manufacturable Part ID=1	€31
Manufacturable Part ID=2	€34
Manufacturable Part ID=3	€39
Manufacturable Part ID=4	€42
Manufacturable Part ID=5	€44
Manufacturable Part ID=6	€33
Manufacturable Part ID=7	€157
Manufacturable Part ID=8	€366
Manufacturable Part ID=9	€187
Manufacturable Part ID=10	€114
Manufacturable Part ID=11	€113
Manufacturable Parts Total	€1,211
Assembly connections	€813
Overall Total	€2,024

Appendix F Cost estimation details

In this appendix a table is represented with the details of the cost estimation of part 0, the Upper Closure Rib, in appendix E.

Table F-1 Cost estimation details of part 0, the Upper Closure Rib, from appendix E

Part Area	26939	mm^2
PartBoundaryLength	880	mm
Tool Area	29633	mm^2
Blank Area	28286	mm^2
Blank Boundary	924	mm
Material thickness	0.9	mm

		Recurring [s]	Non-Recurring [s]	Material cost [Euro]
ToolSetUp				
	CleanMetalTool	69	180	
	CleanRubberTool	97	300	
	SetupMetalTool	0	1500	
	SetupRubberTool	0	1200	
	SetupClamps	0	900	
	SetupHeaters	0	600	
	HeatMould	0	9319	
	Totals	166	13999	
MaterialSetUp				
	CutBlank	252	360	10
	CleanBlank	100	154	
	ClampBlank	432	120	
Totals		785	634	10
Forming				
	DetMachPress	0	300	
	SetUpMachine	60	120	
	HeatMaterial	106	0	
	Forming	30	0	
Totals		196	420	
Demoulding				
	Coolmaterial	30	0	
	DemouldProduct	30	0	
Totals		60	0	
Inspect				
	VisualInspProduct	152	0	
	VisualInspRubMould	124	0	
	TrimPart	249	360	
	UltrasonicInspect	371	1200	
Totals		896	1560	
TotalRecurringTime	Overall Totals	2103	16613	10

$$\text{Recurring} = \text{Delay} + \text{Tau1}\sqrt{\left(\frac{x}{\text{Vo1}\cdot\text{Tau1}}+1\right)^2-1}$$

$$\text{Non-Recurring} = \text{SetUp}$$

Process Code	Type			Setup [s]	Delay [s]	Vo1 [mm^2/s] or [mm/s]	Tau1 [s]
240	Area	Tool Area		180.00	0.00	530472.06	426.29
270	Area	Tool Area		300.00	0.00	3763.43	596.75
7090	Area	Tool Area		1500.00	0.00	0.00	0.00
7100	Area	Tool Area		1200.00	0.00	0.00	0.00
7110	Area	Tool Area		900.00	0.00	0.00	0.00
7120	Area	Tool Area		600.00	0.00	0.00	0.00
NA							
7130	Length	BlankBoundary		360.00	60.00	8.47	120.00
NA							
180	Area	BlankArea		153.60	30.00	5340.53	466.20
7140	Length	BlankBoundary		120.00	240.00	8.47	120.00
7150	Area		0	300.00	0.00	0.00	0.00
7160	Area		0	120.00	60.00	0.00	0.00
7170	Length	MatThickness		0.00	0.00	0.01	0.00
7180	Area		0	0.00	30.00	0.00	0.00
7190	Area		0	0.00	30.00	0.00	0.00
7200	Area		0	0.00	30.00	0.00	0.00
7210	Area	PartArea		0.00	60.00	21.17	60.00
7220	Area	ToolArea		0.00	60.00	42.33	60.00
7130	Length	PartBoundaryLength		360.00	60.00	8.47	120.00
7230	Area	PartArea		1200.00	120.00	4.23	0.00

Appendix G Triangular pressure field calculation according to CS-23

According to CS-23 appendix A23.11 the load on a movable must be represented as a pressure load. The shape of the pressure load on the movable (rudder or elevator) resembles a triangular pressure load with the maximum pressure at the hinge line of the movable and a zero pressure at the trailing edge. The pressure field must apply the force determined by the loads analysis. In the FE pre-processing software pressures applied are often rectangular pressure fields where the pressure magnitudes in the four corner points are linearly interpolated. To apply the triangular pressure load it has to be translated in a rectangular pressure field with the right corner magnitudes so the total force exerted on the movable matches the calculated total force. The rectangular pressure field overlapping the movable can be seen in Figure G-1. Definitions used in this figure will be used throughout this appendix.

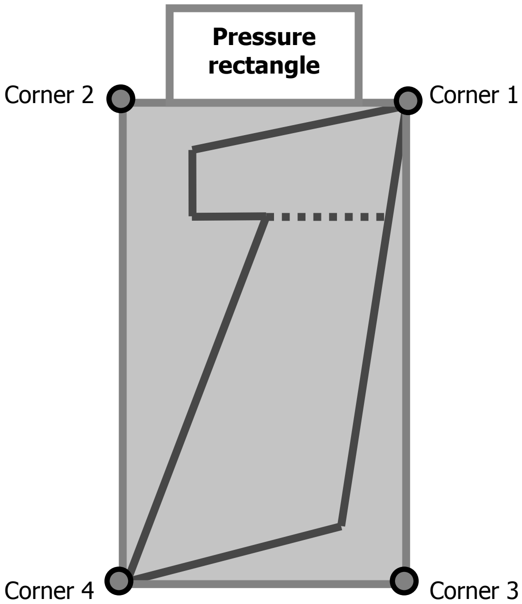


Figure G-1 Pressure rectangular used to apply the triangular pressure

G.1 Calculation of the pressure factor q_x

To apply the right pressure to the movable the magnitudes of the pressure in the four corner points has to be determined. First step taken is to calculate a pressure factor that is used to define the four corner point pressure magnitudes and makes sure the triangular pressure exerts the specified total force on the movable. Here it has to be taken into consideration that the movable can be build up of multiple sections the so called wing trunks.

The pressure anywhere in the movable is defined as being:

$$P = q_x \cdot x \qquad (1)$$

P = Pressure
q_x = Pressure factor
x = Distance on the movable from the trailing edge, measured in flight direction

The average pressure on a section is then:

$$P_{avg} = \tfrac{1}{2} \cdot q_x \left(\frac{x_{root} + x_{tip}}{2} \right) \qquad (2)$$

P_{avg} = Average pressure on a wing trunk section
x_{root} = Root coord of the wing trunk section
x_{tip} = Tip coord of the wing trunk section

Area of a section can be calculated as:

$$A = \frac{x_{root} + x_{tip}}{2} S \qquad (3)$$

A = Area of the wing trunk section

S = Span of the wing trunk section

The total force calculated over all wing trunk sections then becomes:

$$F = \sum_{1}^{n} P_{avg_n} \cdot A_n \quad \Rightarrow \quad F = \sum_{1}^{n} \tfrac{1}{2} \cdot q_x \cdot S_n \left(\frac{x_{root} + x_{tip_n}}{2} \right)^2 \qquad (4)$$

F = Total force on movable

n = Number of wing trunk sections, also denotes the relevant wing trunk section

Because the total force exerted on the movable is a given value the pressure factor can be calculated according to:

$$q_x = \frac{2 \cdot F}{S_n \left(\frac{x_{root_n} + x_{tip_n}}{2} \right)^2} \qquad (5)$$

With the pressure factor calculated pressure magnitudes in the four corners of the pressure rectangle can be determined. For each corner they are determined as follows:

Corner 1 pressure $=$ 0

Corner 2 pressure $= q_{x_{tot}} \cdot$ pressure rectange width

Corner 3 pressure $= q_{x_{tot}} \cdot \tan($sweep angle$) \cdot$ movable span

Corner 4 pressure $=$ Corner 2 pressure $+$ Corner 3 pressure

An example of a resulting pressure field can be seen in Figure G-2.

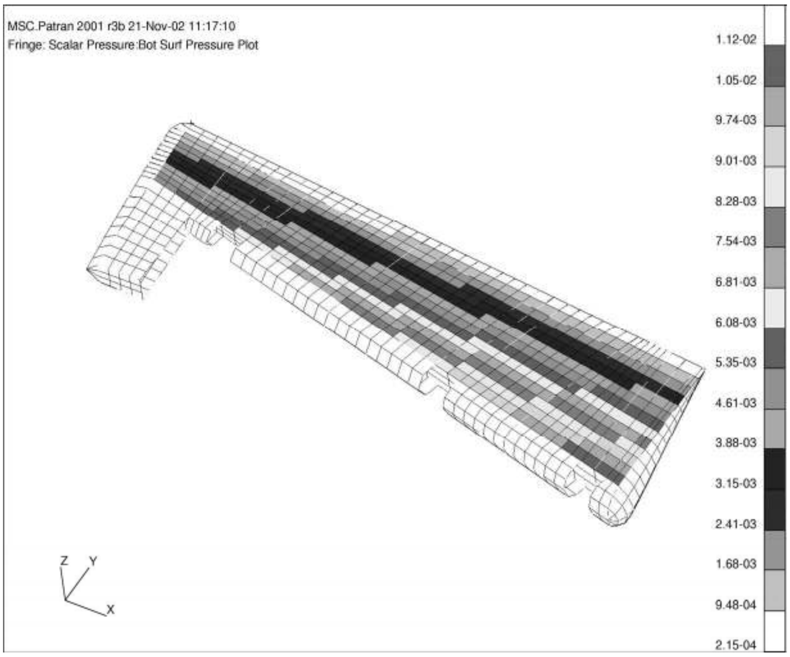


Figure G-2 CS-23 appendix A23.11 Pressure contour in Patran

Appendix H Detailed description of the Rib Multi Model Generator geometrical elements

This appendix describes the geometrical elements of the Rib Multi Model Generator (RMMG). These elements are divided into two parts: the main body surfaces and the flanges.

H.1 Main body surfaces

The geometrical entities making up the main body can be divided into two main groups; the dents and the surfaces that fill the rest of the main body. The dents are stiffening elements that are commonly encountered in composite ribs. The rest of the main body surfaces are shaped in such a way that the mesh for the DRAPE analysis can be easily generated.

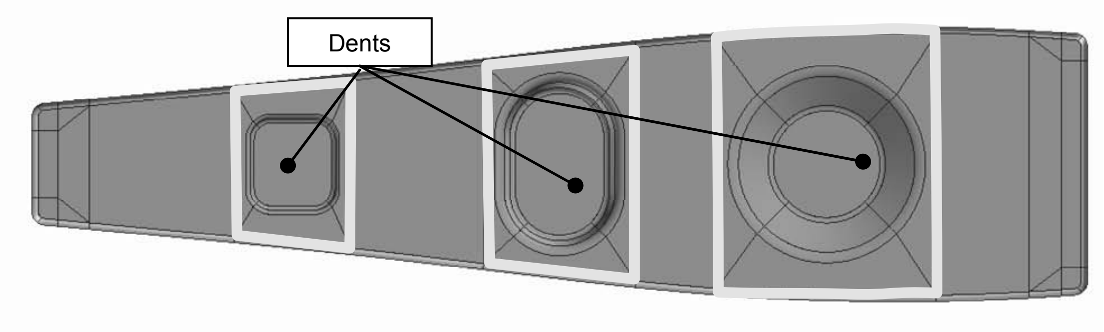


Figure H-1 Dent surfaces in the RMMG model

The dents are bulges in the ribs web; they are represented by the surfaces that can be seen in Figure H-1. The dents provide stiffness to the rib and can often be found in composite ribs for movables. Dents can have a lot of different shapes, each of which has a different effect on the drapability of a rib. Position and size of the dents is also important because interference between the different dents can hamper manufacturability of the rib. Because the dents have such a profound effect on the manufacturability their shape, size and position has to be carefully selected. In the RMMG different shaped dents are possible; they are all based on a rectangular dent with filleted corners. Clever options have been implemented to create a circular dent and a dent with a smooth top and bottom. Because the user has control over which elements of the dent to use and which to discard the dent can also be used to represent a lightening hole. In this case the dents middle surface and, optionally, the fillets to this surface are discarded.

As discussed earlier the rib geometry will be segmented in triangular and quadrangular surfaces to accommodate meshing. To do this the dent is divided in different surface groups:

- Surfaces around the dent, these surfaces fit the dent to the rest of the model and appear to be part of the rib main body
- The fillet surfaces, these surfaces represent the smooth filleted sides of the dent.
- Dent bottom, this surface represents the surface at the middle of the dent.

The surface groups are defined in such a way that they consist of easily mesh-able surfaces. This is done by segmenting the mother surfaces with planes originating from the dents corners. For instance the dent bottom fillet surface is cut into 4 pieces that have 4 edges. The fillet surface is special in this sense because it is built up of 3 mother surfaces: the bottom fillet, the top fillet and the surface filling the gap between these fillets. All these three surfaces are segmented. The different surfaces that make up a dent can be seen in Figure H-2. The three different surface groups in the dent fillet can be seen in Figure H-3.

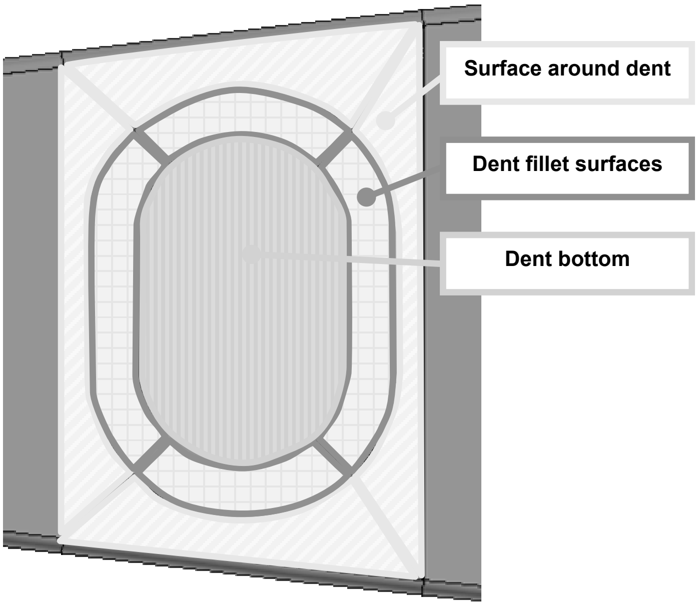


Figure H-2 Dent surfaces and segmentation

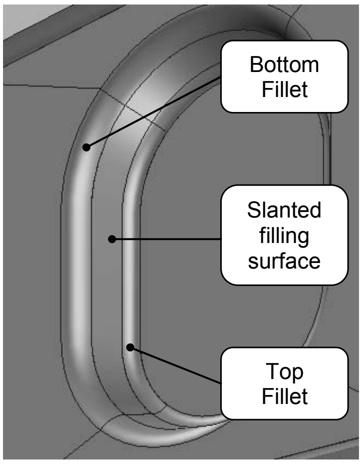


Figure H-3 Dent fillet details showing the three different surface groups

The surfaces that make up the rest of the main body surfaces are called the body surfaces. These body surfaces fill the gaps between the different dents and make sure the main body surfaces fit smoothly to the flange. In Figure H-4 the body surfaces can be seen in a standard rib configuration without a leading edge.

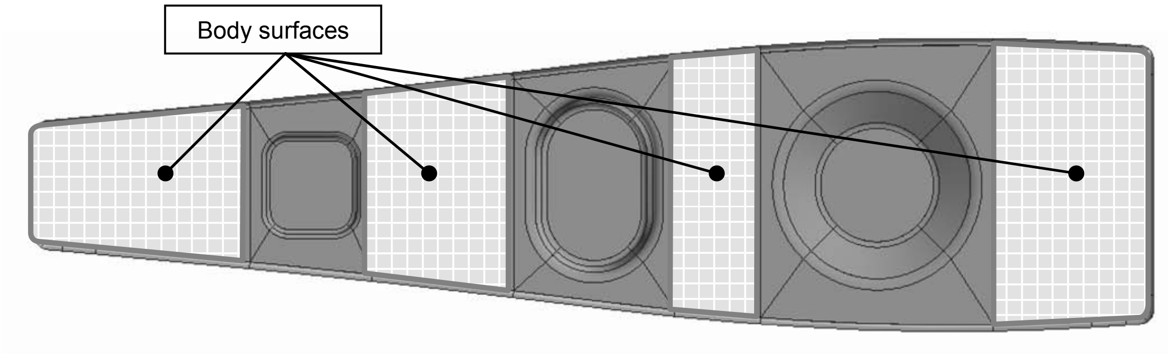


Figure H-4 Main body surfaces in the RMMG model

The body surfaces are defined in such a way they are easily mesh-able and that therefore the surfaces are only allowed to be triangular or quadrangular. The different body surfaces are defined in such a way that they improve the controllability of the mesh density. This means that in areas where a high degree of control is needed extra surfaces are created. By defining the mesh densities in these surfaces using the mesh control inputs, the resulting mesh will be efficient. Dense meshes are required where the curvatures of the model are large. This for instance happens in the corners of the main body. Therefore extra surfaces are created in these corners, the so-called segmentation surfaces. The different corner surfaces can be seen in Figure H-5. The corner segmentation consists of:

1. One quadrangular surface per corner in the corner where mesh control is needed
2. One triangular surface per corner of consistent aspect ratio so the mesh created in it is acceptable.
3. One quadrangular surface filling the gap between the corner rectangles
4. One quadrangular surface filling the gap between the triangles
5. One quadrangular surface making up the rest of the main body of the rib

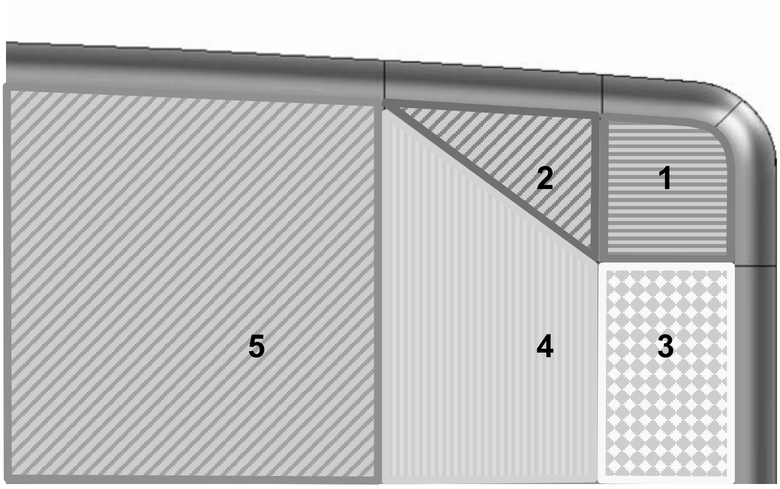


Figure H-5 Corner surface segmentation

There are several options to change the standard configuration of the main body one of them is to simplify the segmentation of the rear edge. This results in a simplified model. This option can for instance be used when the rear height is small or when there is no flange at the rear edge. An example of the rear edge without corner segmentation can be seen in Figure H-6. Another option changing the standard configuration is to add a leading edge. This leading edge requires that two curves are given as input to the RMMG. These curves must be closed at the front tip and be connected to the rib upper and lower input curves. The adding of the leading edge also requires a different segmentation strategy, no corner segmentation is needed. An example of a leading edge and the part of the mould body can be seen in Figure H-7.

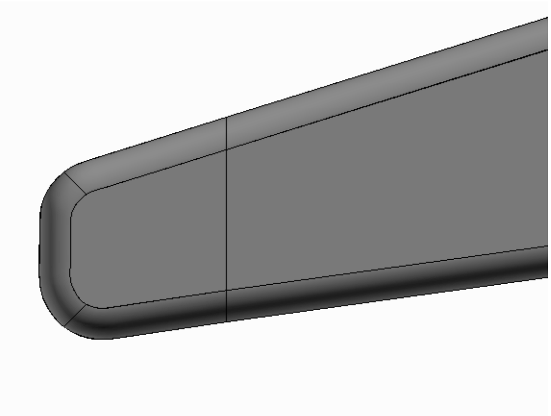


Figure H-6 Simplified rear edge segmentation

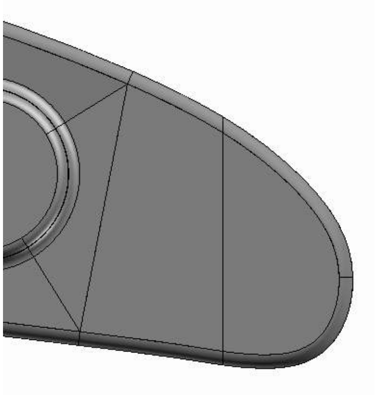


Figure H-7 Example of a loading edge

H.2 Flanges

The geometrical entities making up the flange surfaces can also be divided in two main groups; the flange surfaces and the flange fillet surfaces. The flange surfaces extend all along the edge of the main body. During the assembly process of the aircraft component this flange is used to connect the rib to other parts of the component like skin panels. The flange fillet surfaces make up the fillet between the flange and the main body.

The flange is an extrusion of the edge of the un-filleted body of the model. It is segmented to fit to the segmentation of the body. Therefore is has increased segmentation in the corners. These corners usually form a problem when using composites because wrinkling can occur in these areas. Therefore the increased number of segments in this area is very useful. There is also an option to eliminate the flanges in these corners. This is a common way of avoiding wrinkling. The presence of the flange in the corners is determined by an input parameter. When the flange is not present in the corner the flange fillet is also deleted from the corner. The position of the flange in the model can be seen in Figure H-8.

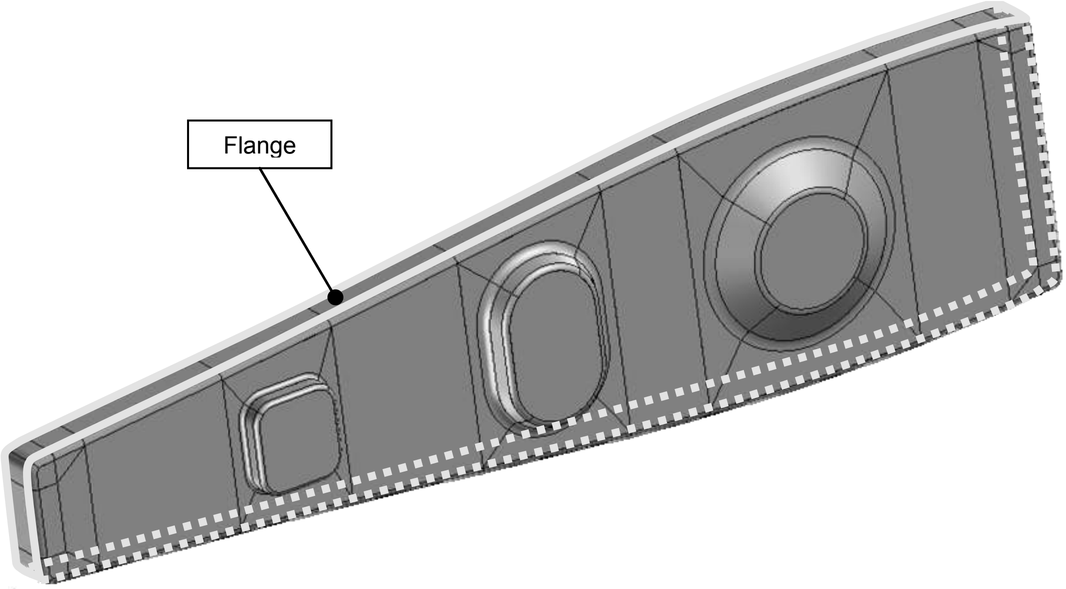


Figure H-8 Rib flange

The flange fillet is the part that makes sure that there is a smooth connection between the body of the rib, including the dents, and the flange of the rib. The flange fillet consists of a fillet, which is cut up into different surface segments to fit of the segmentation of the main body. The radius of the fillet is determined by an input parameter. The position of the flange fillet within the model can be seen in Figure H-9.

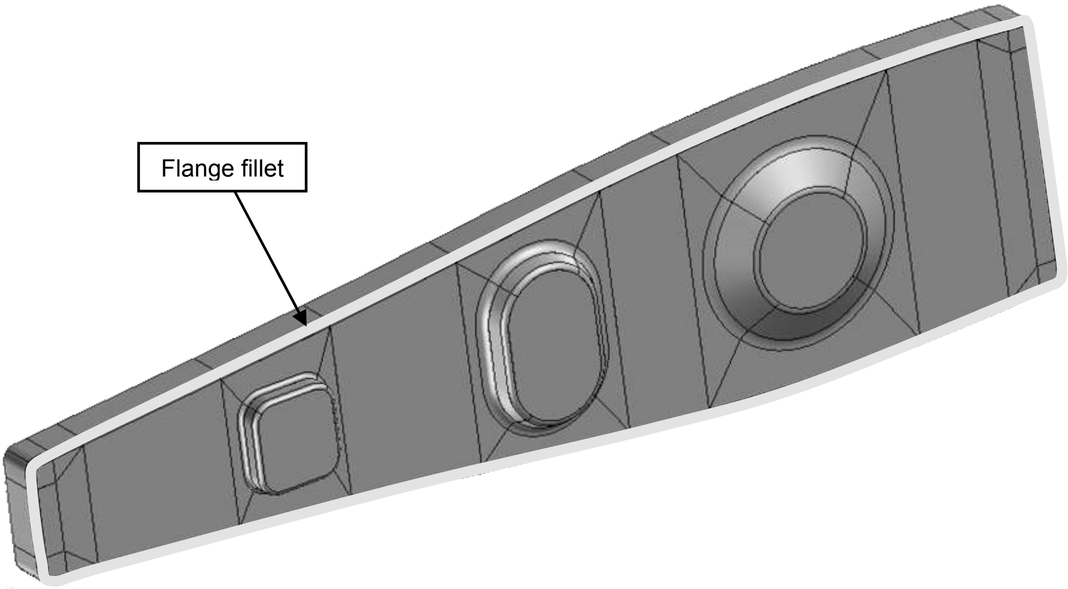


Figure H-9 Rib flange fillet

Samenvatting

Tegenwoordig zijn de verbeteringen van de vliegtuigindustrie zelden gebaseerd op configuratieveranderingen van de vliegtuigen zelf. In plaats daarvan is het huidige evolutieve proces in de vliegtuigindustrie gebaseerd op de ononderbroken innovatie en de verbeteringen van de vliegtuigencomponenten die in het vliegtuigen productieproces worden gebruikt. Deze vliegtuigencomponenten worden vaak niet ontworpen en geproduceerd en door de vliegtuigenfabrikant zelf. Het ontwerp en de vervaardiging van de componenten worden uitbesteed aan leveranciers. De mate van uitbesteding stijgt, omdat vliegtuigenfabrikanten zich en meer die meer concentreren op de integratie van de verschillende componenten en op het managen van de toeleveringsketen. Om concurerend te blijven en aan de eisen van de vliegtuigfabrikanten tegemoet te komen worden de leveranciers van de vliegtuigencomponenten gedwongen om ontwerp- en productiekosten en doorlooptijden te reduceren. Om deze verminderingen van kosten en doorlooptijden te realiseren moeten de leveranciers van de vliegtuigencomponenten hun ontwikkelingsproces verbeteren. Eén methode om het ontwikkelingsproces te verbeteren is het gebruik van de Systems Engineering methodiek in het ontwerp van nieuwe vliegtuigencomponenten.De Systems Engineering methodiek bestaat uit een inzameling van gereedschappen en technieken het ontwerpproces kunnen verbeteren. Een deel van de Systems Engineering methodiek is duidelijk het bepalen van wat de eisen ten aanzien van een systeem zijn en controleren tot welke graad aan deze vereisten worden voldaan aan. Dit maakt deel uit van de zogenaamd “Design for X” methodologie, waar X de subset van vereisten bepaalt die zal worden gecontroleerd. De “Design for X” methodologie kan worden gebruikt om het het ontwerpproces van de vliegtuigencomponent te verbeteren. De “Design for X” methodologie kan echter erg tijds intensief zijn.. Dit kan worden overwonnen door hulpmiddelen te creëren die een deel van de methodologie automatiseren. Één van deze automatiseringstechnieken is Knowledge Based Engineering (KBE). Daarom is de doelstelling van dit proefschrift is het volgende te bewijzen: “Knowledge Based Engineering” maakt het mogelijk het “Design for X” aspect van de Systems Engineering methodiek te gebruiken in het vlegtuigcomponentenontwerpprocess.

Het ontwerpproces van een vliegtuigencomponent bestaat uit een cyclus van het produceren van ontwerpconcepten, deze concepten analyseren en, gebruik makend van de analyseresultaten, het kiezen van het beste concept, waarna het gehele proces wordt herhaald op een volgende detailniveau. In dit ontwerpproces spelen drie actoren een belangrijke rol, dit zijn de ontwerper, de structurel ingenieur en de productie ingenieur. Deze verschillende actoren hebben elk een verschillende kijk op het ontworpen component. Dit kan tot inconsistenties tussen de analyses van de verschillende actoren leiden. Deze inconsistenties kunnen ertoe leiden dan analyseses opnieuw gedaan moeten worden of dat fouten worden gemaakt wanner het beste ontwerpconcept moet worden gekozen. Een andere kwestie in het ontwerpproces is dat de belangrijkste besluiten vroeg in het ontwerpproces moeten worden genomen. Alleen is in deze fase de informatie waarop de besluiten te baseren kunnen worden niet erg gedetailleerd. Dit kan tot gevolg hebben dat verkeerde besluiten worden genomen, die rampzalige gevolgen voor het project hebben. Naast de eerder besproken kwesties kan het analyseren van een ontwerpconcept zo tijdrovend zijn dat niet de gehele mogelijke ontwerpruimte kan worden onderzocht.

Het toepassen van de "Design for X" methodologie impliceert het vroeg in het ontwerpprocess uitvoeren van gedetailleerde analyses op specifieke analysesgebieden. In dit proefschrift worden de KBE gereedschappen gepresenteerd die kunnen worden gebruikt om een deel van het gedetailleerde analyseproces te automatiseren. Het meeste potentieel voor het verbeteren van het vliegtuigencomponentontwerpproces met KBE gereedschappen is geidentifiseerd als zijnde:

- **Het automatiseren van de modelvoorbereiding voor de structurele analyze van een vliegtuigcomponent en het automatiseren van de analyze zelf.**
- **Het verhogen van het detailniveau van de produceerbaarheidsanalyse een vliegtuigcomponent.**
- **Het automatiseren van de modellering van het vliegtuicomponentontwerp zelf.**
- **Het standaardiseren van communicatie tussen de verschillende analysesdisciplines in het vliegtuigcomponentontwerpproces.**

Voor de eerste drie gebieden werden de KBE gereedschappen ontwikkeld. De ontwikkelde gereedschappen worden geplaatst in een ontwerpkader, een een zogenaamde Design and Engineering Engine (DEE). Gebied vier wordt behandeld door de communicatie binnen deze DEE te standaardiseren gebruikmakend van algemeen gebruikte en toegankelijke dossiertypes.

Het automatiseren van de modellering van het vliegtuicomponentontwerp zelf.

Een generatieve modelleringsmotor voor de beweegbare onderdelen op de achterranden van vliegtuigvleugels en staarten is ontwikkeld. Deze modelleringsmotor kan geometrische modellen van de beweegbare onderdelen produceren op basis van een reeks inputparameters. De modelleringsmotor kan zowel een structurele kijk als een productie kijk genereren. In de structurele kijk worden de geometrische elementen waarut de beweegbare onderdelen bestaan volgens structurele functie gerepresenteerd. In de productie kijk worden de geometrische elementen gerepresenteerd volgens de manier waatop het beweegende deel wordt vervaardigd. Naast geometry produceert de modelleringsmotor ook data die nodig is voor zowel structurele als productieanalyses.

Het verhogen van het detailniveau van de produceerbaarheidsanalyse een vliegtuigcomponent.

Een kostenschahttingsgereedschap gereedschap is ontwikkeld dat kan worden gebruikt om de productiekosten van de beweegbare onderdelen op de achterranden van vliegtuigvleugels en staarten te schatten. In het kostenschattingsprocess worden de kenmerken van de onderdelen gerelateerd aan de middelen die nodig zijn om het onderdeel te procuderen. Er zijn vele verschillende manieren om deze relatie te bepalen.

Het identificeren hoe deze relatie is bepaald kan echter moeilijk zijn omdat er geen standaardmanier is om de kostenschattingsmethodes te classificeren. Daarom is er een nieuwe methode om de kostenschatting methodes te classificeren bedacht. In deze classificatiemethode worden de kenmerken van een kostenschattingsmethode expliciet duidelijk gemaakt. In het ontwikkelde kostenschattingsgereedschap worden de productiekostendetails van een beweegbaar onderdeel geschat gebasserd op een model gegenereerd door de generatieve modelleringsmotor voor de beweegbare onderdelen op de achterranden van vliegtuigvleugels en staarten. Het kostenschattingsgereedschap relateerd geometrische kenmerken, zoals een oppervlakte of volume, met productietijden. Deze productietijden worden bepaald voor alle stappen in het productieproces. Het kostenschattingsgereedschap leidt tot gedetailleerde kostenramingen, die in de “Design for Cost” methodologie passen.

Er is een gereedschap ontwikkeld om de drapeerbaarheid van een rib in een beweegbaar onderdeel te analyseren. Drapeerbaarheid wordt hier gebruikt als een indicator voor de kans van succesvolle vervaardiging van een dergelijke rib. Dit gereedschap illustreert hoe de kans van succesvolle vervaardiging vroeg in het ontwerpproces kan worden bepaald gebruikend verfijnde simulatiehulpmiddelen. Door deze kans vroeg in het ontwerp process te bepalen wordt de “Design for manufacturability” methodologie ondersteund.

Het automatiseren van de modelvoorbereiding voor de structurele analyze van een vliegtuigcomponent en het automatiseren van de analyze zelf.

Voor het automatiseren van het structurele analyseproces is een gereedschap ontwikkeld dat automatisch het eindige elemented model van een beweegbare onderdelen produceert. Dit hulpmiddel gebruikt het model van het beweegbare onderdeel dat door de generatieve modelleringsmotor wordt geproduceerd. Dit gereedschap kan een gedetailleerd structureel analysemodel genereren. Het gebruiken van een dergelijk gedetailleerd model past in de "Design for Strength and Stiffness" methodologie. Omdat de structurele analyse op de generatieve modelleringsmotor gebaseerd is zijn zijn resultaten consistent met de resultaten van het kostenschattinggereedschap.

Het standaardiseren van communicatie tussen de verschillende analysesdisciplines in het vliegtuigcomponentontwerpproces.

Al communicatie binnen en tussen het verschillende ontwikkelde KBE gereedschappen gebeurt door middel van gestandaardiseerde en transparante bestandsformaten. Op deze manier wordt de datatransfer gestandaardiseerd. Gestandarizeerde bestandsformaten wil zeggen dat de bestanden kunnen worden geopend zonder gebruik te maken van specialistische software. Transparante bestandsformaten betekend dat de bestanden op zich zelf staand kunnen worden begrepen zonder toegang te hebben tot andere data..

In het vliegtuigencomponentontwerpprocess moeten verschillende disciplines, zoals ontwerp, structurele analyse en productietechniek, samenwerken om een ontwerp te genereren dat aan de vereisten voldoet. Om de “Design for X” methodologie mogelijk temaken moeten de disciplines een gedetailleerde analyse in een beperkte hoeveelheid tijd kunnen uitvoeren. Het werk gepresenteerd in dit proefschrift heeft aangetoond KBE tijdrovende niet creatieve taken in het ontwerpproces kan automatiseren. Hierdoor duurt het korter om gedetailleerde analyses uit te voeren. De “Design for X” methodologie kan alleen gebruit worden als the resultaten van de verschillende analyses consistent zijn.

KBE kan deze consistentie verzekeren door communicatie tussen de verschillende analysedisciplines te standaardiseren.

Één van de belangrijkste bijdragen van het werk gepresenteerd in dit proefschrift is dat de probleemgebieden binnen het vliegtuigencomponentontwerpproces zijn geidentificeerd en dat oplossings methoden voor deze problemen zijn gevonden . Verder zijn methodologieën ontwikkeld om gedetailleerde analysemethodes vroeg in het vliegtuigencomponentontwerpproces te gebruiken. De belangrijkste bijdrage van het werk in de industriële context is dat is aangetoond hoe KBE gereedschappen die verschillende analyse disciplines behandelen, kunnen worden geimplementeerd in de context van een zogenaamde Design and Engineering Engine en hoe deze implementatie het vliegtuigencomponentontwerpproces kan verbeteren.

Omdat KBE snel tot gedetailleerde resultaten kan leiden en ook in staat is de verschillende analyses consistent te houden maakt KBE het gebruik van het “Design for X” aspect van de Systems Engineering methodiek mogelijk in het vliegtuigcomponentontwerpprocess.

About the Author

Ton van der Laan
Born 22th of February 1977 in Wanroij, The Netherlands

1989-1995	VWO (pre-university education) at the Elzendaal College in Boxmeer.
1995-2001	Aerospace Engineering at Delft University of Technology. Master project at the Production Technology chair concerning the conceptual structural design of a four-sear general aviation amphibious aircrafts fuselage.
2001-2003	Design of a thermoplastic composite general aviation rudder at the Production Technology chair of the faculty of Aerospace Engineering at Delft University of Technology. Design included the development of Knowledge Base Engineering tools used in the design process.
2003-2006	PhD research at Delft University of Technology, under the supervision of prof. dr. ir. M.J.L. van Tooren. This research resulted in several Knowledge Based Engineering tools that can be used in the design process of aircraft movables.
2006-current	Knowledge engineer at Stork Fokker AESP.

List of publications

Laan T. van der, Tooren M. van, “Incorporating cost analysis in a multi disciplinary design environment for aircraft movables”, 13th ISPE International Conference on Concurrent Engineering: Research and Applications, 2006, Antibes, France. (Winner of the best paper in conference award)

Laan T. van der, Tooren M. van, ”Integrating resistance welding cost modelling into a multi-disciplinary framework”, 2006, SAMPE EUROPE 27th International Conference, Paris.

Laan, A.H. van der,, Curran, R., Tooren, M.J.L. van, C. Ritchie, “Integration of Friction Stir Welding into a Multidisciplinary Aerospace Design Framework”, Aeronautical Journal, Vol. 110, Issue 1113, pp. 759-766, 2006.

Laan A.H. van der, Curran R., Ritchie C., Tooren M.J.L. van, "Fitting friction stir welding into a cost estimation framework", 2005, International Conference on Innovation and Integration in Aerospace Sciences, Belfast, CEIAT 2005-0075.

Laan A.H. van der, Tooren M.J.L. van, “Manufacturability analysis of aircraft movables in a multi disciplinary design environment", 2005, International Conference on Innovation and Integration in Aerospace Sciences, Belfast, CEIAT 2005-0076.

Laan, A.H. van der, Tooren, M.J.L. van, “Parametric modeling of movables for structural analysis”, 2005, Journal of aircraft, vol. 42, no. 6, pp 1606-1614.

Laan T. van der, Weteringe B., Tooren M. van, "Automatic generation of rib mould for rubber forming of thermoplastic composites, using knowledge based engineering", 2004, 11th European Conference on Composite Materials, Rhodes