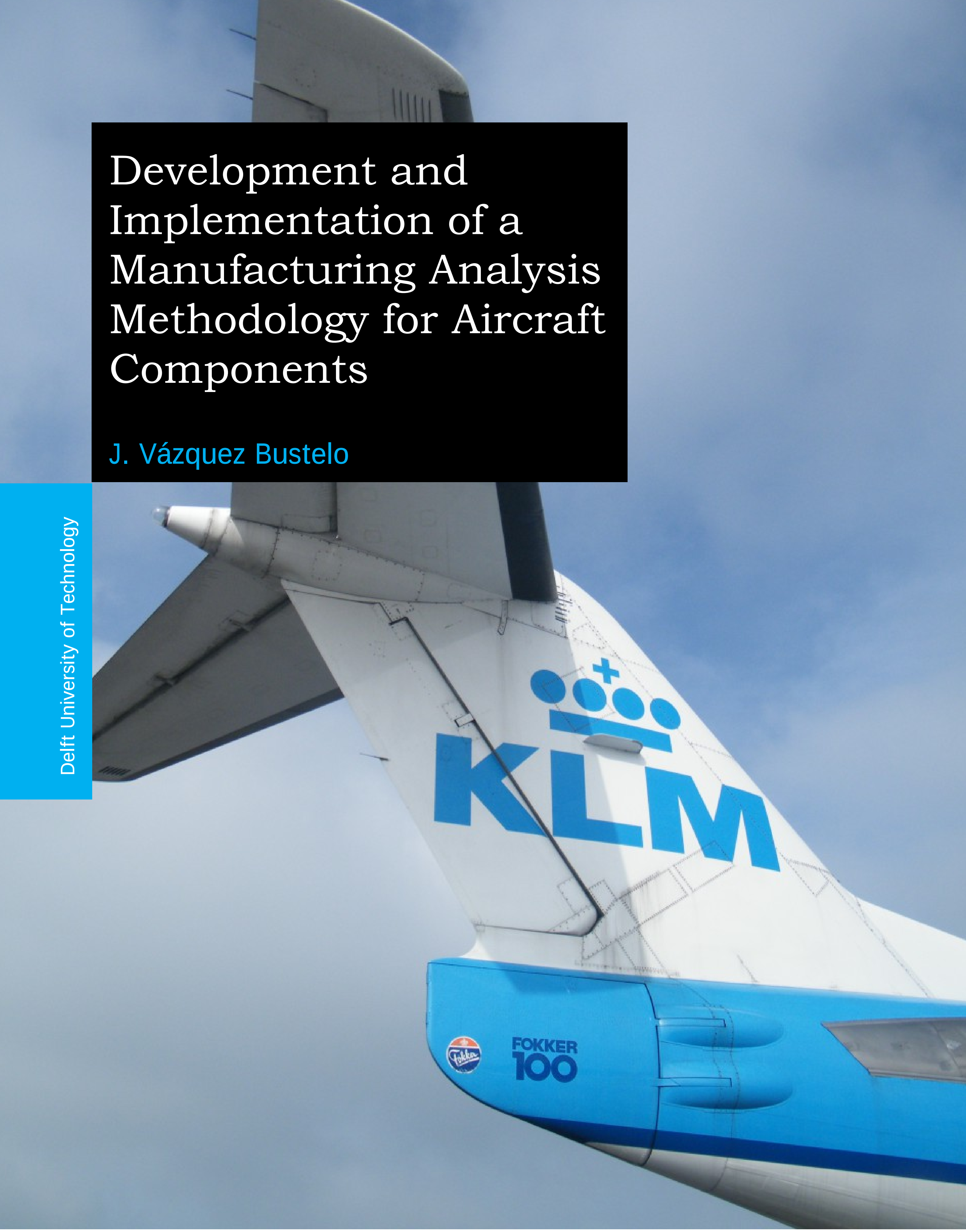

Development and Implementation of a Manufacturing Analysis Methodology for Aircraft Components

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Challenge the future

Development and Implementation of a Manufacturing Analysis Methodology for Aircraft Components

By

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J. Vázquez Bustelo

Delft, January 2018

“It’s.”

– Michael Palin, *Monty Python’s Flying Circus*

Summary

In the last ten years, the airlines are demanding lower aircraft prices and fuel consumption. Aircraft manufacturers as well as component and sub-assembly manufacturers are adapting to this situation by optimizing existing aircraft configurations. Traditional design processes, due to their inability to capture multidisciplinarity at the early stages of design and to the amount of manual work, do not allow component optimization in the typical time frames of the aircraft industry. Fokker Aerostructures is developing an automated rudder design program, the Rudder Generator, to tackle the limitations of the traditional design method. To effectively capture the multidisciplinarity of aircraft component design, the knowledge of each expertise involved in the design process must be included in the program at the same level of detail. The manufacturing analysis capabilities of the Rudder Generator are significantly lower than the ones of other expertise such as stress, weight or cost.

This thesis focuses on developing a valid methodology to include manufacturing analyses in the rudder conceptual design stage. The developed methodology is created to expand the Rudder Generator capabilities as well as to support the traditional design process. A Knowledge Based Engineering (KBE) application, WelToGen, which generates thermoplastic welding tooling for a given rudder geometry is created. The program runs feasibility checks on the tooling models based on the process requirements and then ensures through design changes the fulfillment of those requirements. The application also measures the manufacturing performance by estimating the tooling cost.

The tool is both integrated in the RG and used as a standalone tool to perform design studies. With WelToGen's automation it is possible generate a tooling conceptual design, analyze its feasibility and estimate its cost in minutes. The traditional method requires detailed tooling design for the analysis, taking up to weeks to perform the same tasks. Rudder geometries for which tooling has been manufactured at Fokker have been given to WelToGen, which has found new tooling designs that, while also being feasible, are between 3 and 5% cheaper than Fokker's original tooling designs. Also, parametrical studies on the effect on manufacturing feasibility and performance are executed. WelToGen's results show influences of rudder and tooling design parameters that were unknown to Fokker engineers before. Additionally, it is found to be feasible to create tooling for rudder configurations which manufacturing had not been considered at Fokker before due to the resources limitations of the traditional design methods. Based on the results, rudder and tooling design recommendations are made.

The implementation of the methodology proves to be effective in improving the conceptual design phase. The developed methodology, compared to the traditional method, has obtained improved rudder and tooling designs, taken a shorter lead-time and led to less risk and missed opportunities. The RG team will integrate the tool and plans on creating new modules adapting the same methodology to other rudder manufacturing and assembly processes, expanding the program's manufacturing analysis capabilities. Fokker's tooling engineer will use WelToGen to support the conceptual design stage of tooling design projects currently ongoing at Fokker.

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Nomenclature

List of Abbreviations

ATA	Abbreviation
BJ	Business Jet
CAD	Computer Assisted Design
CBS	Contour-Block Structure
CBSM	Contour-Block Structure Module
CE	Concurrent Engineering
CM	Cost Module
DfMA	Design for Manufacturing and Assembly
DRG	Dummy Rudder Generator
FEMM	Finite Element Model Module
FL	Front Loading
FM	Frame Module
GAS	Generative Assembly Structural analysis
IGES	Initial Graphics Exchange Specification
IW	Induction Welding
KBE	Knowledge Based Engineering
LA	Light Aircraft
MDO	Multidisciplinary Design Optimization
NBA	Narrow Body Aircraft
OML	Outer Mold Line
PIM	Plastic Injection Mold
RG	Rudder Generator
TP	Thermoplastic
UML	Unified Modelling Language
WelToGen	Welding Tooling Generator
WL	Welding Line

List of Symbols

A	Area
C	Cost
d	Distance or Displacement
E	Young’s Modulus
h	Beam Section Height
I	Moment of Inertia
l	Length
L	Beam Length
M	Moment
σ	Stress
t	Thickness
w	Line Load

1

Introduction

Nowadays, almost 50% of an airline's total operating costs are due to fuel and to aircraft finance and maintenance [1]. Airlines are demanding aircraft with reduced both fuel consumption and acquisition price, while not being interested in new aircraft configurations [2]. Aircraft manufacturers have been forced in the past decade to adapt to the new market situation by shifting to optimize existing aircraft configurations instead of creating new ones [1]. Boeing's B787 and Airbus' A350 were the last new configurations two companies created, both initiated at the beginning of the century. Since then, the aviation manufacturers are allocating their resources into improved versions of previous aircraft with reduced operating costs (e.g. A320neo or B737 MAX). The optimization process consists in optimizing independently the sub-components of the already existing aircraft. The airlines obtain the benefit of having the same configurations which operating know-how they already have, yet in variants with lower consumption and aircraft-price-dependent costs.

In the new market situation aircraft manufacturers changed their roles towards integrators of the aircraft components and sub-assemblies, which are sub-contracted to tier 1 suppliers [3]. Manufacturers can then share risks with the part suppliers in the increased competition of the aircraft market [4, 5]. The supplier's size and technological capacity are the two main factors that help them become the integrator's partner [6]. Fokker Aerostructures, now part of GKN Aerospace, is one of the part and subassemblies manufacturers competing in the new market. Fokker is developing new design methods focusing on three main points to make parts more attractive to OEMs. First, weight reduction as weight is one of the main objective functions of aircraft design. Second, reduce costs to allow price reduction for the OEMs and increase Fokker's profit. Third, reducing lead-time since OEMs pay attention to product availability when awarding contract.

The past and present of the design process in the aerospace industry will be explained in this chapter to further understand the limitations of the traditional design methods to adapt to the new market situation and the new methodologies being developed to overcome these limitations.

1.1. Concurrent Engineering's Limitations

Approximately 80% of the aircraft's total life-cycle cost is determined at the earlier stages of design, while these stages account for a 10% of the cost [7-9]. However, at the first stages little information about the design is known, thus the difficulty of making early design choices. Additional difficulty in the design process arises from the amount of disciplines involved in aircraft design and their interactions [10]. The methodology currently used in aircraft and aircraft component design is called concurrent engineering (CE) [11]. CE is a design methodology that improves lead-time compared to sequential engineering by parallelizing design tasks. By performing the stress, weight, manufacturing and other analyses at the same time, the time to market is reduced.

Despite CE improving sequential engineering’s time, it is not an optimal solution, presenting a main drawback. Due to the parallelization of tasks, some disciplines’ analyses work with pre-frozen data from other disciplines. Any time a change is made in the design, analyses might have to be repeated due to the change of inputs. CE fails to capture the multidisciplinarity of the aircraft design problem leading to sub-optimal designs [12]. In addition to CE’s limitations, the design tools currently used add further drawbacks:

- Inconsistencies are yielded by the diverse views of different experts on the product and the tools and models they use for their analyses [13].
- More attention is put into some disciplines such as structures or weight compared to others like cost or manufacturing [8]. The preference for certain expertise when analyzing designs, biases the design outcome towards the favored disciplines.
- Traditional design methods require abundant manual and repetitive tasks. Putting aside creative and engaging design tasks to perform the manual ones may lead to engineers’ frustration and errors, which might hamper the design results [14].

Each analysis iteration required in CE due to design changes increases the probability of the previous disadvantages affecting the design process and its outcome. Furthermore, CE’s necessity of analyses repetition, allows to create few feasible fully-analyzed designs in the time frame desired by the OEM. The number of concepts created which are compliant with the set requirements determines the probability of one of those being an optimal design [15]. The time shortage for design analysis when using CE significantly limits the amount of design exploration that can be done. The time limitations lead Fokker to create designs which are close to existing concepts, which could imply missing opportunities of more optimal designs.

CE’s inefficiency to obtain optimal designs calls for new design methodologies in the aforementioned market situation in which optimization of existing designs is needed. The new methodologies should properly capture multidisciplinarity from the early stages to achieve optimal designs [16].

1.2. Front Loading and its limitations

A possible substitute of CE is front loading (FL). FL is a design principle based on identifying the problems and solving them even before the start of a design process [17]. FL aims at shifting the availability of information about the design problem solving to the earliest phase as possible, which ultimately is before the design problem starts. Consequently, at the early stages of design, design choices are made with a high amount of information about the design and with highly detailed analysis tools. For applying FL, knowledge and methodologies must be prepared beforehand, allowing for quick design creation and analyses once a project starts. FL can effectively tackle the current design method’s limitations, yet it needs to be supported with proper tools and methods [18]. The selected technologies by Fokker to support FL are Multidisciplinary Design Optimization (MDO) and Knowledge Based Engineering (KBE). With KBE and MDO, a front loaded process that solves the current design limitations can be achieved [13].

KBE is defined as “*a technology based on dedicated software tools called KBE systems, that are able to capture and reuse product and process engineering knowledge*” in [19, p.57]. KBE effectively reduces time and cost compared to traditional design methods through the automation of manual tasks [20]. The automated design tools, called KBE applications, are created modularly with the knowledge rules used in traditional design methodologies. Engineers using the applications are then more productive and able to focus on creative and value adding activities. The design iterations’ time reduction allows to analyze more design cases than in CE within the same time frame. Additionally, all modules of the KBE application use the same product definition to feed each expertise's analyses, ensuring multidisciplinary consistency within all involved expertise [14].

MDO is a technology which automatically searches optimal design solutions according to one or more specified objective functions. The search is performed using the KBE application to obtain design solutions when introducing varying inputs. The multidisciplinarity is accounted for by using each expertise's KBE modules, thus obtaining designs which have been analyzed for all involved disciplines. MDO is used to perform automatic design space exploration. The use of MDO increases the engineers' design space knowledge, enabling them to make more informed design choices. Also, MDO allows to find optimal designs in a fast manner compared to CE's method.

However, FL has a main pitfall which can counterbalance the aforementioned advantages. As explained, KBE's and MDO's multidisciplinarity capturing abilities depend on having properly captured the knowledge of each expertise that plays a role in the design. For performing rigorous multidisciplinary design analyses, it is crucial to include the knowledge from all expertise. Apart from knowledge from all expertise being included, this knowledge must be equal in level of detail for each expertise. Differences in detail level lead to unbalanced design analyses, being biased towards the disciplines which included knowledge is deeper. The solutions selected with unbalanced knowledge might not be optima, or even not feasible if analyzed with the lacking expertise's knowledge. A FL method must therefore be made with all the involved knowledge captured at the same level of detail in the KBE application.

Fokker is currently developing new design methodologies based on FL principles. The company collaborates in international projects which aim to create new methods, such as ITEA 3's IDEaliSM. Fokker contributes in this project by developing a front loaded rudder multidisciplinary design and optimization platform called Rudder Generator (RG). The RG project is currently in development, with certain disciplines' KBE modules at different levels of development or even missing. Specifically, manufacturing analysis' detail is lagging behind the other expertise such as stress, weight or cost.

This MSc thesis is framed in the RG project, focusing specifically on manufacturing analyses. The methodology developed in this thesis will be applied to rudders, since Fokker's application is oriented to these specific structures. However, the used method can be extrapolated to other aircraft control surfaces or flaps due to the similarities in design between these aircraft components.

1.3. Manufacturing Knowledge

Manufacturing and assembly represent 60% of aircraft production cost [3]. Manufacturability performance is one of the main drivers of the profitability of a project in the aerospace industry [21]. The importance of manufacturing on the design outcome calls for early manufacturability and cost assessment and considerations [22]. However, the RG only accounts for manufacturability with basic manufacturability rules such as which materials can be used for manufacturing specific components. On the other hand, other disciplines are accounted for much more rigorously, e.g. stress or weight. A methodology has to be found to effectively and objectively include manufacturing knowledge in a front loaded design process.

In the aircraft design industry, the Design for Manufacturing and Assembly (DfMA) methodology is widely used to account for manufacturing in traditional design processes. DfMA is a design method based on considering the product requirements and goals at the same time as the manufacturing constraints [23]. The main attempts to include DfMA's principles in the CE design process are systems based on scoring design choices according to a list of manufacturing aspects. The designers are handed guides with descriptions of various core aspects of manufacturability to look after when designing. Examples of the manufacturing aspects described in these guides to analyze each design configuration are: compatibilities (material-process, material-configuration, etc.), complexity (accessibility, symmetry, uniformity, etc.), or efficiency (part count, manufacturing operation count, etc.) [24]. Designers score their designs on each of these manufacturing aspects, according to their subjective interpretation of the definitions. Adding up every aspect's score, the design with the highest overall score is selected. The scoring methodology is not suitable due to the inconsistencies that subjectivity imply. Each engineer would give different scores due to the subjectivity of this methodology (different interpretation of the definitions or different criteria on the importance of each manufacturing aspect when adding up scores).

There have been attempts to eliminate subjectivity from the scoring methodology by creating a systematic scoring method [23, 25]. These approaches are based on establishing scales for each manufacturing aspect, each scale being a function of one or more design features. The designs are systematically placed on these scales according to their configuration. An example of a scale for a specific manufacturing aspect is given in Table 1, where the part count score would depend on the number of parts of the design configuration. The score for each manufacturing aspect described in the guide is obtained and then added up to obtain an overall manufacturability score.

Table 1: Example of scoring table for a DfMA design scoring methodology.

PART COUNT SCORE					
Score	1	2	3	4	5
No. of Parts	1-5	6-10	11-20	21-50	>50

Authors tried to apply these scoring methods in front loaded processes by automating the scoring [26-28], yet with unsuccessful results due to the subjectivity of the scores. Creating an objective automated scoring method is not possible since the scales and their relation to design features are subjective. Additionally, to add up the scores of each manufacturing aspect to obtain an overall design score, it is necessary to establish importance weights to each aspect, which are also subjective. It is necessary to find an objective measure of manufacturability to be able to include manufacturing with the same level of detail and objectivity as the other expertise.

One successful example of an automated design process which accounts for manufacturing can be found in [29]. In the study by van Dijk et al., an automated plastic injection mold (PIM) part design method which accounts for manufacturing was created. PIM part design has to comply with strict requirements that come from the manufacturing method. There are two main concerns when designing PIM: cooling time and final part warpage. Minimizing the cooling time and warpage are the objective functions of the design method proposed in the study. Design scoring is done based on quantifiable manufacturing aspects (cooling time and warpage simulations). The same methodology can be followed by adapting the constraints and objective functions to rudder design. The constraints will be the specific constraints that the manufacturing processes involved in rudder manufacturing have. However, the objective function cannot be specific to manufacturing, since the results of the manufacturing analysis have to be weighed with the results from all other expertise involved in rudder design. Therefore, it is necessary to find a quantifiable manufacturing performance factor that can be summed objectively with the performance values of the other expertise.

The definition of manufacturability is analyzed to understand what a manufacturing analysis tool needs to include. Manufacturability is "*the ability to manufacture a product for established levels of quality and rate of production while minimizing cost*" [30]. To incorporate the definition in a methodology, two main elements of the definition are important. First, the design process should include constraints and requirements coming from the manufacturing and assembly processes. Second, the method should use cost as the objective manufacturing performance assessment, which can be introduced in the product’s overall cost analysis to allow a balanced multidisciplinary design analysis.

For RG, a cost estimation method was created which includes partial manufacturing knowledge in the form of manufacturing processes’ rules and constraints [31]. However, the manufacturing knowledge that the cost estimation provides has a lower level of detail than the other disciplines’ analyses, leaving RG unbalanced. The manufacturing constraints which the cost estimation includes are limited to selecting from a few manufacturing processes and the allowable limits of the manufacturing parameters in each process. Another limitation is the lack of non-recurring costs in this estimation. Higher level of detail in manufacturing analyses is needed for the RG to be balanced.

Therefore, a manufacturing analysis methodology is needed, based on constraining the design and measuring the manufacturing performance in terms of cost. There are many manufacturing and assembling processes for which a rudder design needs to be analyzed in detail. It is not possible within the scope of this thesis to create a manufacturing analysis tool for all the manufacturing processes involved in rudder production. Instead, it is decided to create a manufacturing analysis tool for the thermoplastic welding process, for the reasons which will be next explained.

1.3.1. Thermoplastic welding

Thermoplastic (TP) welding is a bonding process in which two thermoplastic parts are united by applying to them heat and pressure at the same time, bonding the matrices of the two parts together. At Fokker, a specific type of TP welding called induction welding is used for assembling the rudder’s structural box. It is performed in an automatic fashion with a robotic arm. The specifics of the method will be explained in chapter 2.

TP welding is usually traded off against mechanical fastening regarding structural joining options. The main advantages of welding over fastening are lower joint weight (no material is added) and lower recurring costs (fast automated process). The main drawback is that the process requires expensive and complex tooling for the bonding process. The complexity comes from the requirements that the tooling must fulfill for a correct welding process to take place. The requirements are: to allow application of heat and pressure while keeping dimensions of the manufactured rudder within specified tolerances. In order to know if a tooling design fulfills the requirements, detailed design analyses are needed. These analyses need to be fed with detailed information about the tooling design which might not be known at the early stages or might take a long engineering time to obtain (e.g. create detailed geometry models). Additional complexity comes from the fact that the tooling design and the rudder design are interdependent, affecting each other with their requirements and constraints. The interdependencies will be thoroughly explained chapter 2.

At Fokker, according to CE principles for reducing lead-time, the tooling design is started when the rudder design is not finished. Designing the tooling with non-frozen rudder geometry inputs is not efficient as it has been explained in the limitations of CE. Moreover, the manufacturing of the tooling might start without the rudder design finished to avoid rudder delivery delays due to the lengthy tooling manufacturing. Once the tooling is ordered, the rudder design flexibility is reduced significantly since rudder changes are constrained by the tooling design, which is fixed.

If only the joint properties are looked at, omitting the assembly process characteristics, TP welding is a significantly superior bonding solution over fastening. However, the disadvantages coming from higher non-recurring costs, the tooling effect on the rudder’s lead-time and on rudder design flexibility make TP welding not so attractive. As a conclusion, potential is seen at Fokker in improving the tooling design process to eliminate or at least minimize the TP welding disadvantages. With a manufacturing analysis tool focused on TP welding tooling design, the tooling design process will be supported. The tool will:

- Automate the process of creating the input information needed for performing feasibility assessments and automating the feasibility assessments themselves. This will accelerate significantly the tooling design process. Moreover, it will enable automated tooling design space exploration, increasing the probabilities of finding optimum designs.
- Automate the process of creating feedback information for the rudder design. The generation of more detailed and earlier information for the rudder design will enhance the rudder design process and reduce the negative effects of the tooling-rudder design dependencies.

Provide detailed knowledge about tooling design which can lead to tooling design with lower cost, thus lowering the rudder non-recurring costs.

1.4. Research Objectives & Research Questions

The objectives of the thesis are to develop a methodology to include manufacturing in a multidisciplinary front loaded rudder design environment and to assess the impact of performing this inclusion. The research will apply the methodology to a specific manufacturing process, establishing a base for later expanding the capabilities until all the manufacturing processes are included. Hence, several hypotheses are presented:

1. **Higher rudder quality.** Including detailed and objective manufacturability assessments will equalize the manufacturing knowledge level of detail to the other rudder design expertise. This will enable better informed rudder design choices.
2. **Higher tooling quality.** Being able to perform quick automated tooling design analyses will increase the tooling knowledge, hence enabling better tooling design choices.
3. **Shorter design time.** The automation of the tooling design knowledge will shorten the tooling design process.
4. **Less risks and missed opportunities.** The manufacturing analyses will give detailed information about the tooling early in the rudder design process. Making informed design choices will avoid generating rudder designs that are found later in the design process to be unfeasible. This implies less work redone due to late design changes. The risks will be significantly reduced for Fokker and their competitiveness increased. On the other hand, design information in the first design stages will enable designers to not miss opportunities that might be unknown with traditional design methods.

The thesis will search for the answers to the following research questions:

- How to include manufacturing analyses in a front loaded automated rudder design process?
- How does adding manufacturing analyses affect the rudder and tooling designs on product performance and the design process itself in terms of lead-time?

1.5. Report Outline

This report will describe the process that has been followed to answer the research questions. First, in chapter 2, the thermoplastic welding tooling and its design process will be explained in detail. Then, the developed methodology will be illustrated in chapter 3, explaining the KBE application created for the project and its development process. Next, the experimental setups created to test the application and the results obtained are shown in chapter 4. Finally, in chapter 5 the results will be related to the research objectives and questions, giving a series of conclusions. Also, recommendations for future work will be given.

2

Thermoplastic Welding Tooling

2.1. Induction Thermoplastic Welding

Fokker uses a type of thermoplastic (TP) welding called induction welding (IW). IW is based on inducing localized magnetic fields that generate eddy currents in the electrically conductive carbon fibers inside the TP laminate. The fibers then heat the laminate from the inside, making the matrix melt. IW can only be used on carbon fiber reinforced plastics since the fiber needs to be electrically conductive. The process starts by loading the TP components into tooling which applies localized pressure to the joints (a sketch of the assembly is shown in Figure 1). Then, one automated robot arm with an induction coil proceeds to create the currents in the fibers which melt the matrix and the parts get fused together[1]. The robotic arm moves, along the lines that need to be welded, the so called Welding Lines (WLs), one by one, from start to end. The head of the torch must be almost in contact[2] with the rudder to perform the welding as will be shown in Figure 4.

2.2. Tooling Description

The tooling is a key element in the welding process. The tooling is composed of steel and aluminum parts for structural integrity and a non-electromagnetic-reactive composite material parts. The latter parts are intended to hold the rudder in the area where the torch will be during the welding process, yet not reacting to the electromagnetic field. It is a structure that presents gaps for the robotic arm to be able to reach the rudder and weld the skin to the spars and the ribs along the spars' and ribs' flanges.

The tooling is divided in several main parts which can be seen in Figure 1:

- Frame. The frame gives the structural integrity to the tooling, withstanding the pressure applied on the WLs. It is composed by the frame box and the frame closing structure. The frame box is hollow with an internal grid of structural elements acting as beams, which are seen in Figure 2. The frame box has gaps for allowing the welding. The closing structure consists of a middle beam which runs along the symmetry plane and of beams that are clamped to the frame box in several points. The closing structure is lifted with a crane to allow the introduction of the rudder components before welding and to take out the welded rudder once the process is finished.

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[1] This information is publicly available at:
http://www.tencate.com/emea/Images/Seattle%2010-Development%20of%20the%20Gulfstream_tcm28-27304.pdf
https://www.compositesworld.com/articles/fokker-aerostructures-hoogeveen-the-netherlands
Accessed on: 5 December 2017

[2] The distance between rudder and the coil is in the order of millimeters.

- Contour-block structure (CBS). Compound of machined composite material blocks which holds the rudder skin. They have to main requirements. First, adapt the curved rudder geometry to the planar frame geometry. Second, not react to the torch magnetic field which occurs around the WLs, thus they are made of non-electromagnetic-reactive material. The structure must also include the welding gaps to allow welding. Additionally, the CBS must transmit to the frame the loads of the pressure applied inside the rudder components.
- Rudder component holders. Parts which hold the spar and ribs while the welding is taking place in addition to apply the pressure on the flanges from the inside.
- Support. Structure that supports all the other tooling parts and fixes them to the ground.
- Pneumatics and electronics. Devices to apply, control and measure pressure on the welding spots.

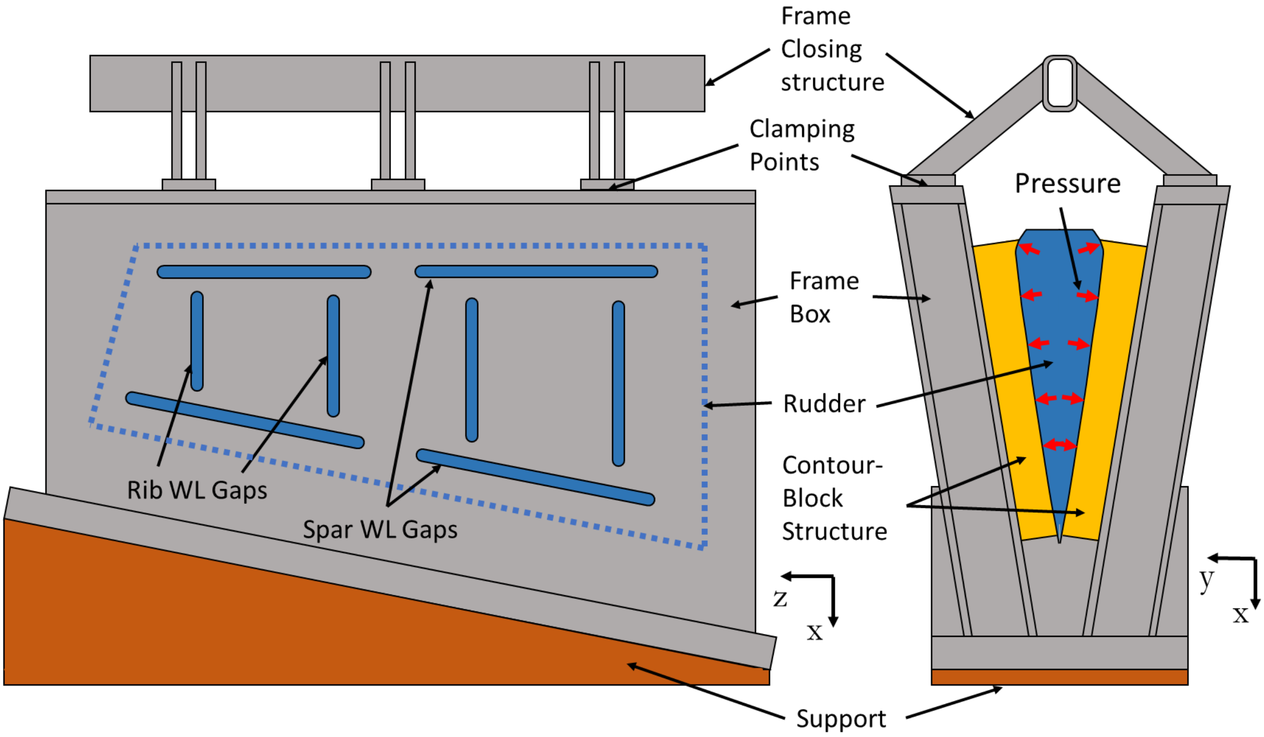


Figure 1: Schematic representation of the tooling parts holding the rudder with the pressure application.

The welding is done along the spar and rib flanges, hence the pressure application is done solely on the flanges from the inside of the rudder, as seen in Figure 1 and Figure 4. The frame and contour-block structure hold in place the skin on the other side. A more detailed sketch of the welding will be shown later in, when further explaining the welding process.

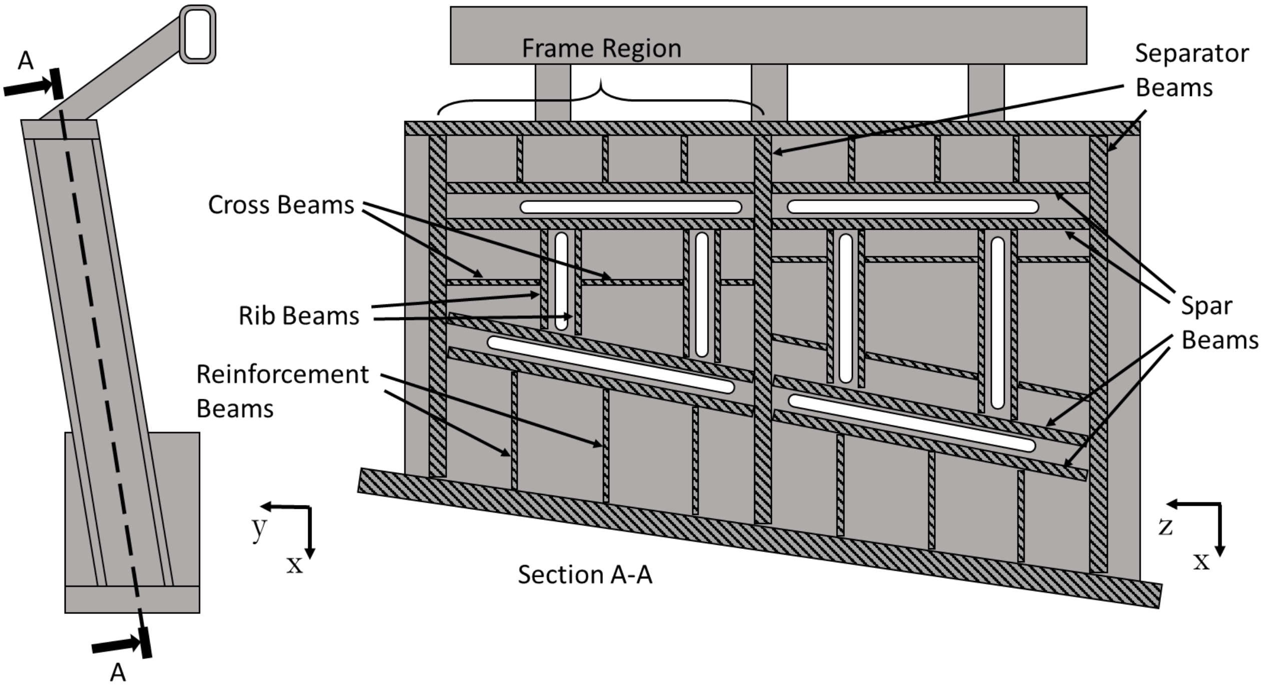


Figure 2: Frame box sectioning and inner elements designation.

The welding process imposes strict requirements on the tooling. First, the tooling is required to be stiff enough to keep the manufactured part within specified tolerances during the manufacturing process. The pressure applied is withstood by the frame structure, which displacement will have a specific maximum allowable to keep the rudder within geometrical specifications. Second, the tooling must include gaps to allow the torch to move along the WLs when welding. The two requirements are coupled since the gaps affect the tooling stiffness by breaking possible load transmission paths in the tooling structure.

The design of all parts of the tooling depend on the rudder geometry and the aforementioned tooling requirements imposed by the welding process. However, only the frame design and the CBS design can compromise the fulfillment of the requirements. In other words, once the frame and CBS fulfill the requirements, the design of all the other tooling parts will not affect the requirement fulfillment of the entire tooling. Therefore, only the frame and CBS designs will be automated and included in the manufacturing analysis. All the other tooling parts are considered detailed design and not needed in feasibility assessments.

In the majority of the cases, the rudder is symmetrical with respect to the X-Z plane, and therefore the tooling will be symmetrical too. The cases treated in this project are all symmetrical, so only half of the tooling is modeled to save computational time. In the event of a non-symmetrical rudder design, the program could be quickly modified to also create the other half of the tooling, since the same knowledge is used to design the second half.

The tooling can significantly affect the overall rudder lead-time and cost. The tooling design process, as it will be explained next, is complex and takes long engineering time. Also, the tooling manufacturing time is lengthy. Regarding cost, the tooling is considerably expensive due to the large amount of manufacturing time and the expensive pneumatics and electronics. The tooling cost is non-recurring; thus it is important to consider the shipset size when analyzing the rudder design.

2.3. Tooling Design Process

The tooling design process starts by taking part of the rudder geometry as input. The specific rudder geometry elements (seen in Figure 3) needed for designing the tooling are:

- Outer mold line (OML). Outer surface of the rudder. It is defined by the OEM.
- Welding lines (WL). The WLs are the curves where the welding will take place to unite the inner components to the skin. The ribs and spars are joint to the skin along their flanges. The WLs will then be on the OML surface where the projection of the middle of the flanges is, as shown in Figure 4. The breaks on the forward spar WLs are due to the existence of other components inside the rudder such as brackets and hinges that break the continuity of the spar flanges; without flanges, welding cannot occur in those zones. The breaks in the aft spar WLs are placed where the forward breaks are for tooling feasibility, as it will be explained next.
- Reference planes to define tooling geometry (e.g. dimensions and orientations): front and aft spar planes, rib orientation planes (only one rib plane shown on Figure 3), and rudder's root and tip planes.

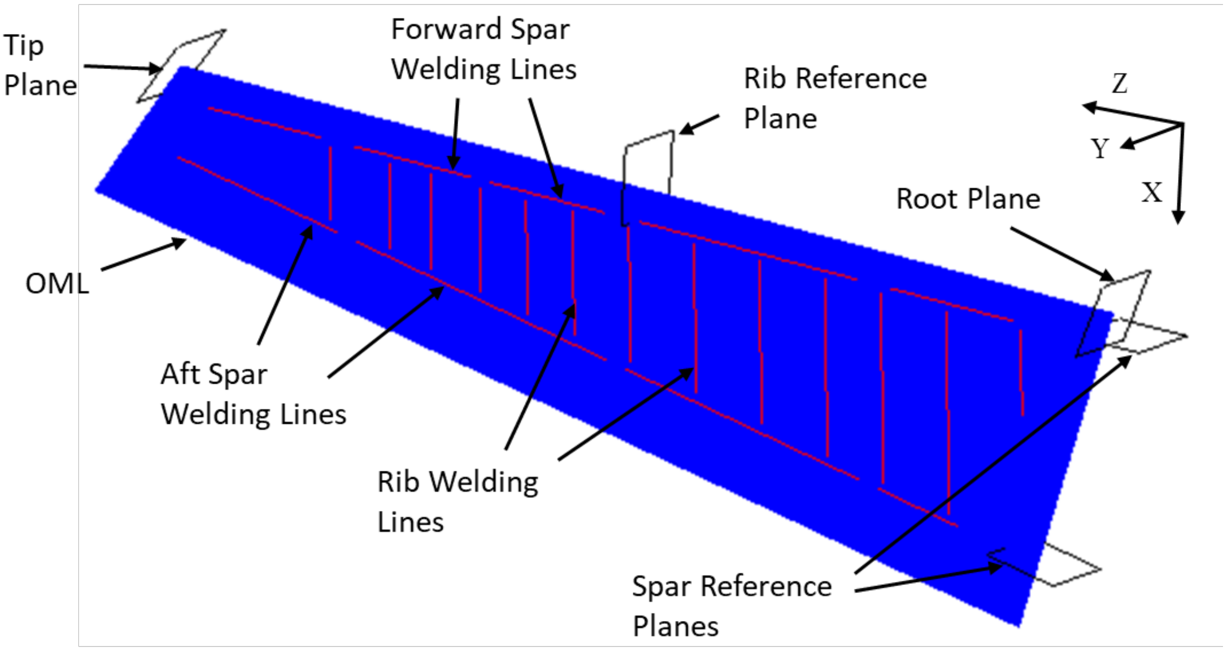


Figure 3: Right hand side rudder input geometry for tooling creation.

The WLs' definition is affected by many factors:

1. The welding is used to bond together the skin and the flanges of the ribs and spars, as it was aforementioned. Consequently, the WLs' number and position depend on the number and position of ribs and spars.
2. The torch angle with which the spars are welded (welding angle) might need to be modified to avoid intersection between spar gaps and rib gaps in the tooling as shown in Figure 5. Ideally, the welding would occur perpendicular to the skin (null welding angle), since this weld gives the best joint properties. The ideal welding angle is represented by the red color. By increasing the spar welding angle, the spar gaps are moved away from the rib gaps, ensuring material between gaps for the tooling's structural integrity. The correct welding angle is represented with green.

3. The welding process defines the length of the WLs (e.g. welding technology requirements force to weld up to certain lengths from the flange's end).
4. The WL breaks are used for placing structural elements inside the tooling frame, profiting the inexistence of gaps in the frame in those zones. If the WL breaks are few or far away from each other, the stiffness of the tooling could be compromised. If the tooling is not sufficiently stiff, more WL breaks might need to be proposed to allow putting extra structural elements. The WL segments between breaks must be shorter than a specific length which is set according to limitations on the pressure application system.

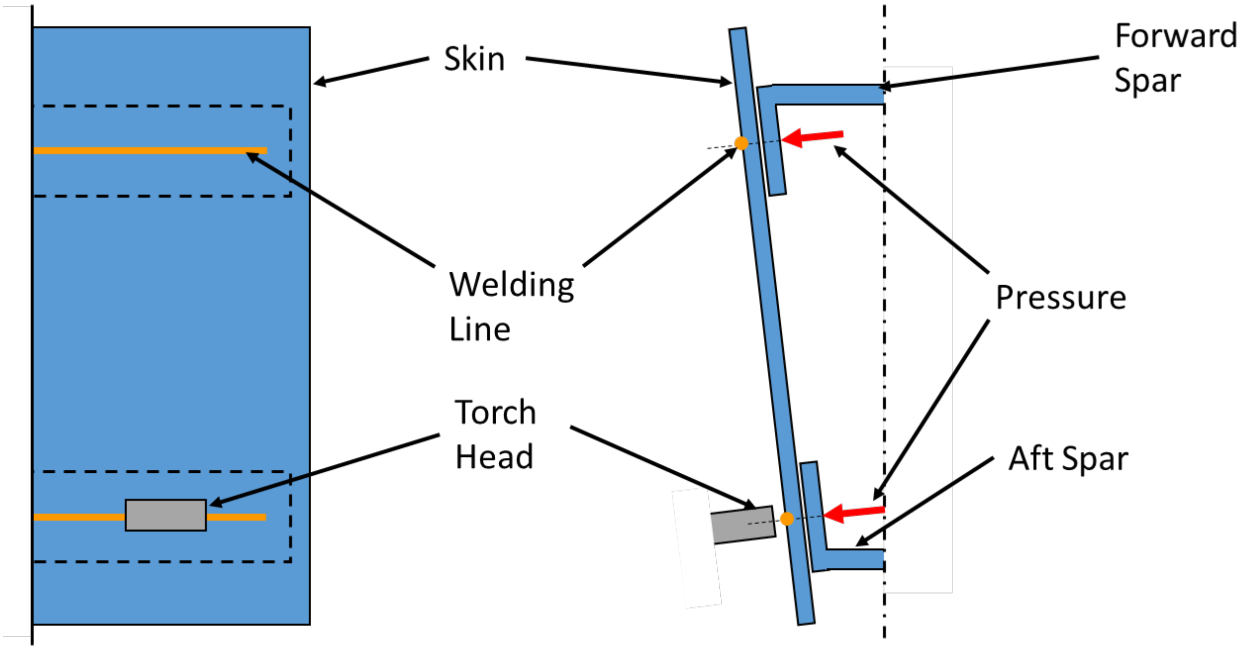

Skin
Forward Spar
Welding Line
Pressure
Torch Head
Aft Spar

Figure 4: WL position with respect to the rudder inner components' flanges.

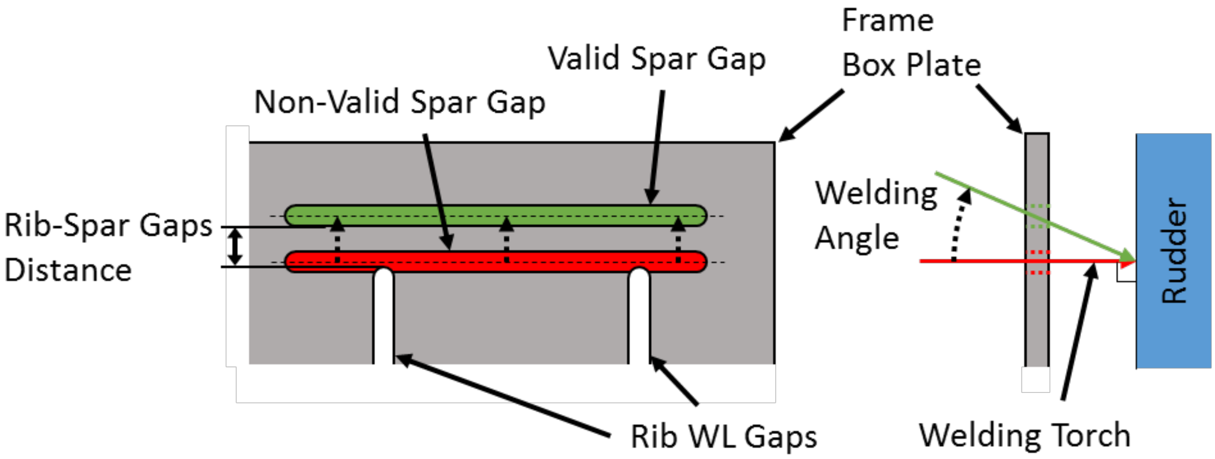

Frame Box Plate
Valid Spar Gap
Non-Valid Spar Gap
Rib-Spar Gaps Distance
Welding Angle
Rudder
Rib WL Gaps
Welding Torch

Figure 5: Schematic representation of the welding angle and the effect on the spar gap position on one of the frame plates.

The coupling between tooling design and rudder design comes from the WLs. On the one hand, the WLs define the tooling design. Also, the tooling dimensions and overall shape will depend on the rudder's OML. Consequently, the tooling depends on the rudder design. On the other hand, if the WLs are broken due to tooling, the rudder joint characteristics might change, thus changing the rudder's stress behavior. Additionally, the welding angle, which might be modified in tooling design, also changes the welding characteristics (larger welding angle implies weaker joint). Rudder’s joint characteristics play an important role in the rudder’s performance (e.g. stress, weight or cost). Hence, the rudder design also depends on the tooling design. The interdependence between tooling design and rudder design, which can be seen in Figure 6, is what makes the design process of the tooling and rudder complex.

The current tooling design process can be seen in Figure 6. The process starts when the rudder design is mature enough as to have the WLs defined, yet the rudder design is not frozen. During rudder design, manufacturing considerations in the WL definition are taken into account with the manufacturing analyses that a manufacturing engineer provides. These manufacturing analysis are of significant lower detail than other rudder design analyses, such as stress or weight. Therefore, the WLs are defined according mostly to rudder stress and weight in detriment of rudder manufacturability. The result is that during the tooling design process, as the level of manufacturing analysis increases, manufacturing inefficiencies or infeasibilities for the rudder design might be found. This generates feedback loops between the tooling design team and the rudder design team.

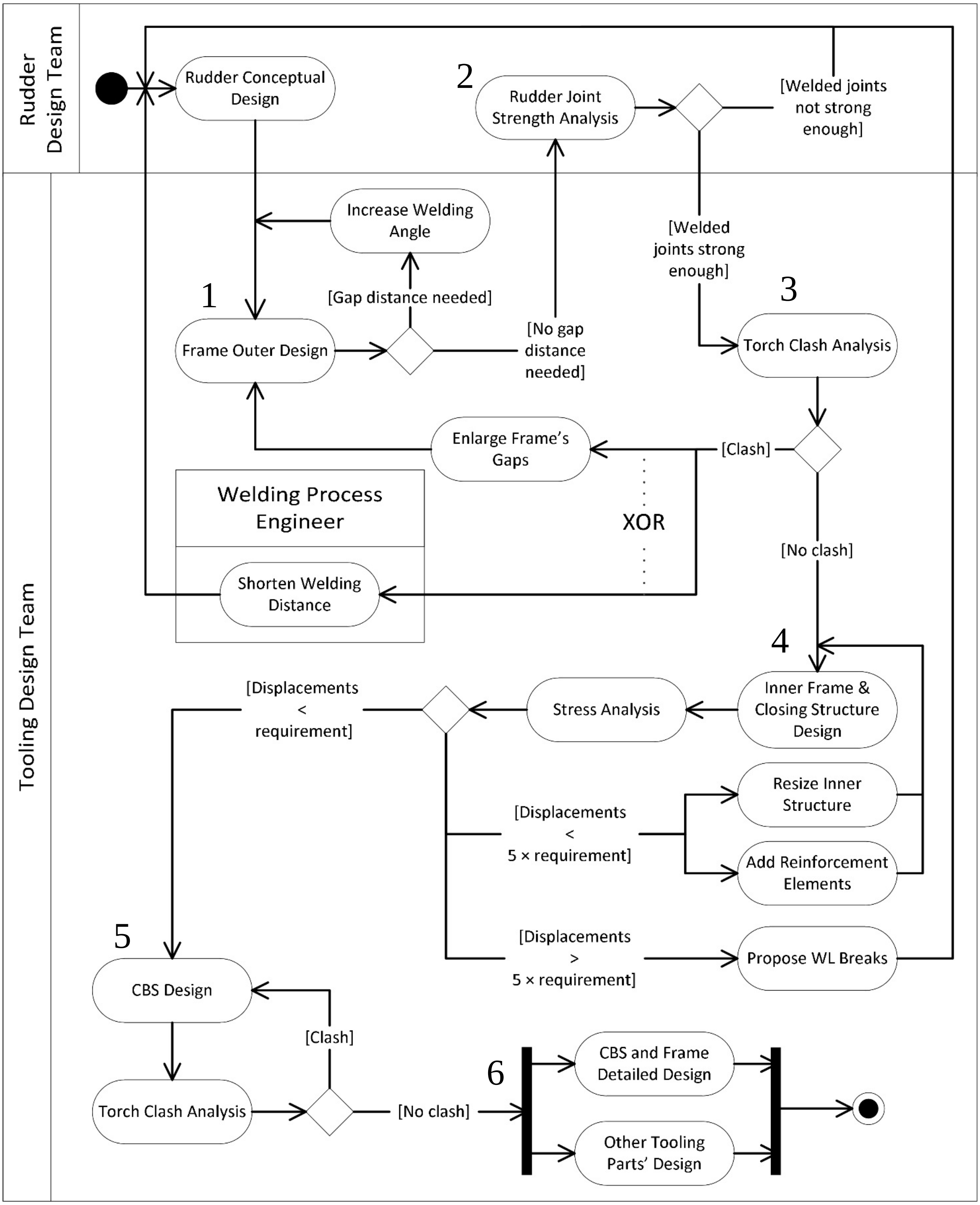

Rudder Design Team
Tooling Design Team
Rudder Conceptual Design
2
Rudder Joint Strength Analysis
[Welded joints not strong enough]
[Welded joints strong enough]
Increase Welding Angle
[Gap distance needed]
1
Frame Outer Design
[No gap distance needed]
3
Torch Clash Analysis
Enlarge Frame's Gaps
[Clash]
Welding Process Engineer
XOR
[No clash]
Shorten Welding Distance
4
Inner Frame & Closing Structure Design
Stress Analysis
[Displacements < requirement]
[Displacements < 5 × requirement]
Resize Inner Structure
Add Reinforcement Elements
[Displacements > 5 × requirement]
Propose WL Breaks
5
CBS Design
[Clash]
Torch Clash Analysis
[No clash]
6
CBS and Frame Detailed Design
Other Tooling Parts' Design

Figure 6: Activity diagram of the current tooling design process at Fokker

1. The tooling design is started by designing the tooling frame's outer structure. The frame's outer structure has gaps to allow the torch to reach the rudder through the frame. The gaps must be at a certain distance from each other to allow for frame material in between them as was shown in Figure 5. If the gaps are connected, the frame cannot keep structural integrity. The spars welding angles are increased starting at null value until the spar gaps in the frame are at a user specified

distance from the rib gaps. There is a single welding angle value for each spar applied to all the gaps belonging to the spar; the position of all the gaps belonging to one of the spars depend on the same angle.

2. Then, the rudder design team checks if the joints are strong enough with a weld at that specific angle. If the joints do not meet stress requirements, the rudder design might need to be changed. If the rudder design changes affect the tooling input geometry, the tooling design process has to be restarted.
3. The torch clash feasibility check is done. Clashes between the tooling frame and the welding torch are searched for in the torch positions throughout the welding process. Clashes might occur at the start or end of the WLs since these are the positions in which the torches are closer to the gaps' borders. In case of clash, first the torch movement along the WL is shortened (i.e. the welding starts or ends with an offset from the WL's start or end) by the welding process engineer. It is necessary to check with the rudder design team what the maximum offset allowed is to keep rudder joint properties. If clashes still occur at the maximum allowed, the design the gaps can be expanded in length only if this expansion does not make two gaps be two close to each other, breaking a load path along the frame.
4. Afterwards, the tooling frame's inner beam layout, as seen in Figure 2, is designed. The beams are placed where there are no gaps. The second feasibility check is done: a stress analysis to determine the tooling displacements during the welding process. A stress analysis of a 3D finite element model of the tooling frame geometry is run. If the displacement at any point of the tooling is larger than the allowable maximum to ensure a correct welding process, two options can happen. If the displacement is over the limit, the tooling inner design is redone to increase stiffness (e.g. adding reinforcement beams or increasing existing beams' thicknesses). However, if the maximum displacement is more than five times of the maximum allowable, requirement fulfillment cannot be accomplished by inner structure redesign. Therefore, a break has to be made to one of the WLs in order to include more frame structural elements. The breaks are proposed to the rudder design team and the process restarts from the rudder conceptual design.
5. Next, the CBS is designed to fit in between the rudder exterior surface and the already designed frame. The CBS has gaps at the same locations as the frame to allow the torch to reach the rudder. Another torch clash check is run for the CBS, which allows to modify the CBS gap geometry in case the welding would not be possible.
6. Finally, the rest of the parts of the tooling are designed. Also, the detail design of the frame and CBS is performed (i.e. finish the design aspects which were not affected by the requirements and thus not necessary for the analysis of the conceptual designs).

To minimize the effect of the tooling on the rudder lead-time, it is important to start the tooling manufacturing as soon as possible. However, starting the tooling production when the rudder design is not finished might lead to restricting design changes in the rudder. Moreover, the tooling design is not fully performed by Fokker; a company manufactures the tooling and supports Fokker with the design. The tooling design is performed jointly by Fokker's tooling engineers and the outsource company's engineers. Fokker's engineers have more influence at the early stages of tooling design due to their experience with tooling design and theirs link with the rudder design team. The outsource engineers have more influence over the detailed design since they know in detail the tooling manufacture capabilities at their company. The shift in design responsibilities is gradual and varying from project to project. The outsourcing implies multiplying the communication loops between Fokker and the outsource company, with many tooling design iterations needing to be performed until the design is finished. In Figure 6, the tooling design team activities gathers both the activities performed by the outsource engineers and Fokker's engineers. Having automated highly detailed manufacturing analyses will enable Fokker to perform tooling conceptual design significantly quicker and easier, leading to tooling and rudder designs made with more knowledge about the design space.

3

Followed Methodology

The limitations of the current rudder front loaded design process, RG, have been presented. In order to improve the existing method, this thesis will develop a manufacturability analysis tool which will be added to the rudder design program. The tool will perform the conceptual design of rudder welding tooling, with capabilities for feasibility analyses and manufacturing performance measurement.

The tool will be made to be integrated in the RG to tackle the lack of manufacturing knowledge in the process' current development state. The tool will perform rudder welding feasibility analyses of the RG's rudder designs. Also, in case a design is unfeasible, it will give detailed information on the broken constraints, how they are violated and on how to achieve constraint fulfillment. Based on the feedback data from the analyses, the rudder application can automatically modify rudder design parameters to search for a feasible design. Additionally, the tool will estimate the tooling cost so the rudder design program can include it in the rudder's cost performance measurement. The RG cost estimation includes the recurring costs of the bonding process (both fastening and thermoplastic welding process). However, the method lacks the non-recurring costs that the tooling implies, which could be considerable depending on the shipset size.

The welding tooling design tool will also work as standalone to support traditional tooling design. The program will support the tooling engineer by performing automated generation and analysis of conceptual tooling. With the program, the early stages of design will be shorter and with more available design information. Also, the conceptual design given to the outsourcing company can be more complete and have been more analyzed, reducing the number of iterations between Fokker and this company to complete the tooling.

3.1. Front Loading and its Support Tools

Fokker's new rudder design method, RG, is based on front loading. The manufacturability analysis tool will help front loading the design. KBE, a technology proven to support FL, will be used to develop the manufacturing tool. KBE offers three main advantages which the manufacturing tool needs in order to fit RG: modularity, easy integration and support for multidisciplinary optimization. Modularity and easy integration will enable the manufacturability analysis module to be easily included into the RG while working also as standalone. Enabling optimization is important in order to be useful for the RG, since the RG project aims at performing rudder multidisciplinary optimization.

A modular program is developed, coded in the language *python* using an extension called *ParaPy*. ParaPy is a KBE system, which are platforms used to create KBE applications. ParaPy is a compendium of python libraries of pre-coded functions which capabilities enhance modular coding, facilitating the achievement of a powerful KBE system.

3.2. KBE Application Creation Process

A KBE application (also referred to as app or program) is packaged knowledge which can automatically perform tasks based on the included knowledge. The automation of the thermoplastic welding tooling design knowledge will allow to systematically deliver the needed elements for a rudder manufacturing analysis. The development of a KBE app presents several main phases: identifying and capturing the knowledge, formalizing and packaging the knowledge and configuring and activating the application.

The tooling design knowledge exists at Fokker solely in the form of tooling engineers' experience. Only three tooling models have been designed and manufactured at Fokker; the tooling design knowledge is still not formalized in documents. The thesis project was based on personal interviews with tooling engineers. The difficulties of interviewing experts to obtain tacit knowledge are numerous. The interviewees often might not be able to express in a systematic manner their knowledge, might omit knowledge or might expand on non-relevant information. The interviewer faces the task of understanding the experts' explanations to follow and guide the interview while capturing the knowledge in an organized manner. However, the disadvantages are avoided by applying knowledge acquisition techniques as found in [8, 32].

The first phase of the program creation comprised the identification and capture of the TP welding tooling knowledge. This phase consisted on analyzing the tooling's function and components, analyzing the rudder and tooling design processes and pinpointing the dependencies between the rudder design and the tooling design. The formalizing phase happens at the same time as the identified knowledge is documented. The results of identifying, capturing and formalizing are documents such as chapter 2 with the formalized knowledge about tooling components, their design and the interrelations with the rudder design. Then, the knowledge is packaged into the KBE application, translating the logic of the knowledge into design rules in the program.

The phase of the program activation can also occur while the other phases are happening. The modularity of the system allows for activation of small packages as they are being created. Package activation is a key phase in app creation since it starts the iterative process of verification. By using the package, missing knowledge rules or errors in the code can be found. This step will be further explained at the end of this chapter.

3.3. KBE Application Description

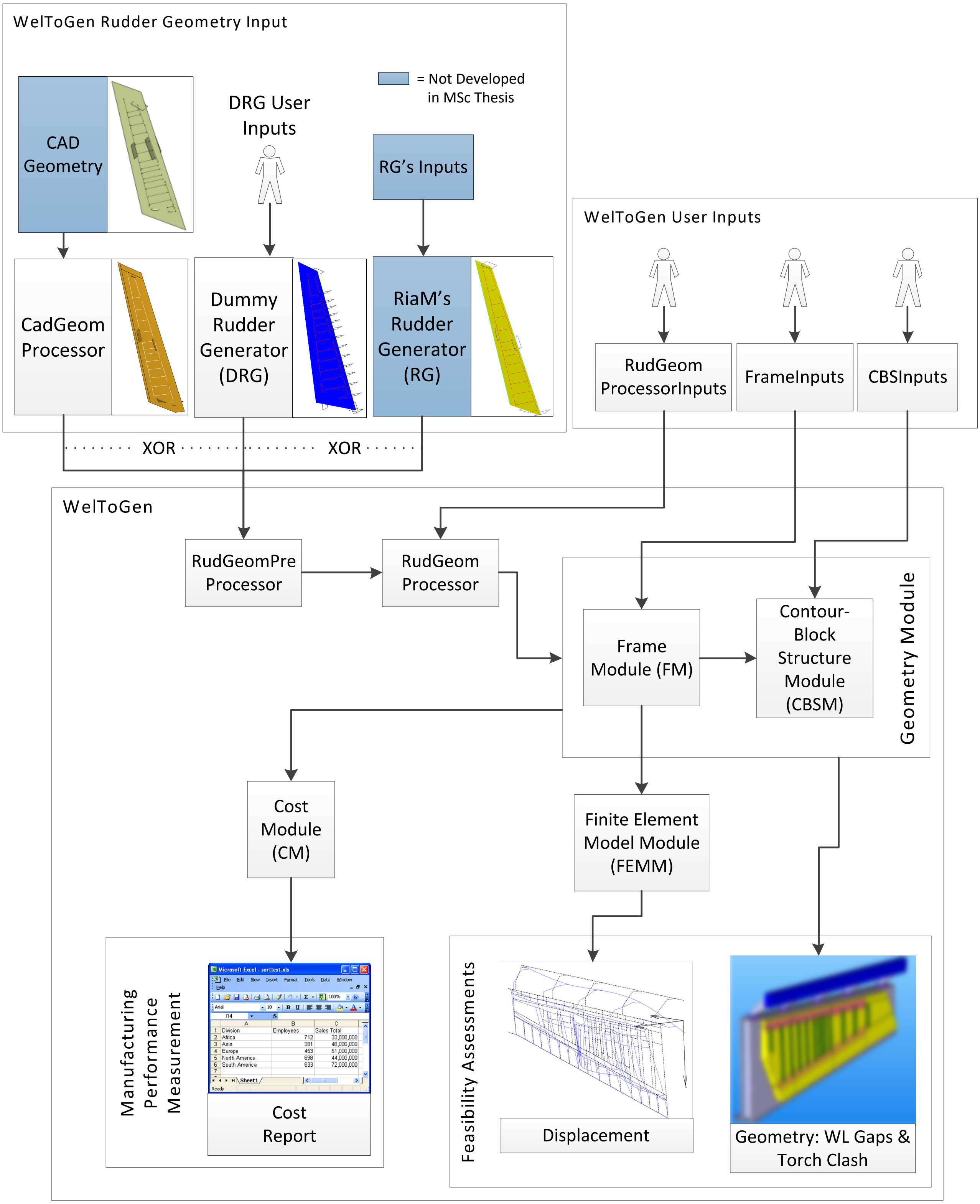
The developed KBE application is called Welding Tooling Generator (WelToGen). WelToGen was coded following the coding standards used in the Rudder Generator to facilitate integration. WelToGen is also a standalone welding tooling analysis module for several types of input geometries, as it will be further explained.

The WelToGen is an application which contains the knowledge rules to: design welding tooling for a specific rudder geometry input, ensure its feasibility and estimate the cost of manufacturing and assembling that tooling. WelToGen allows for parametric modeling and its modules create dedicated tooling model abstractions specific to each module's analysis (e.g. geometry model or finite element model). First, there is an input geometry processor to standardize the inputs for WelToGen.

Afterwards, a geometry module creates the frame and CBS geometries, accounting for the gap and torch clash requirements. Then, a module performs the stress analysis on the frame to obtain displacement and check with the requirements. Finally, the cost module calculates the cost for manufacturing each tooling part and for assembling the entire tooling together. In Figure 7 a general diagram of WelToGen's modules and their interactions can be seen. The Unified Modelling Language (UML) class diagram is seen in Figure 8. In the following sub-sections each module will be furtherly explained.

The KBE application will fulfill the objectives of the research in two main aspects. First, it will generate a conceptual tooling model based on a rudder design and ensure its feasibility. Secondly, the cost of the tooling model will be estimated. The tooling cost can be included in the rudder's total cost estimation, which currently lacks non-recurring costs such as tooling. In this way, the performance of the rudder's manufacturing can be objectively analyzed: through weight (affected by the joint properties) and cost (affected by the bonding process cost, including tooling). Note that the weight refers to rudder weight; the weight of the tooling is not a performance parameter since tooling has virtually no restrictions.

WelToGen is intended to support the tooling conceptual design stage. WelToGen will allow to front load the design process by enabling conceptual design analyses early in the design process. Since the analyses are automated, they are performed significantly quicker than the traditional manual methods. The quickness is a crucial capability at the early design stages, when changes to the design are done frequently.


WelToGen Rudder Geometry Input
= Not Developed in MSc Thesis
CAD Geometry
DRG User Inputs
RG's Inputs
CadGeom Processor
Dummy Rudder Generator (DRG)
RiaM's Rudder Generator (RG)
XOR
XOR
WelToGen User Inputs
RudGeom ProcessorInputs
FrameInputs
CBSInputs
WelToGen
RudGeomPre Processor
RudGeom Processor
Frame Module (FM)
Contour-Block Structure Module (CBSM)
Geometry Module
Cost Module (CM)
Finite Element Model Module (FEMM)
Manufacturing Performance Measurement
Microsoft Excel - sorttest.xls
File Edit View Insert Format Tools Data Window Help
Arial
10
100%
I14
Sheet1
Ready
Cost Report
Feasibility Assessments
Displacement
Geometry: WL Gaps & Torch Clash

	A	B	C
1	Division	Employees	Sales Total
2	Africa	712	33,000,000
3	Asia	381	48,000,000
4	Europe	453	51,000,000
5	North America	698	44,000,000
6	South America	833	72,000,000
7			

Figure 7: Welding Tooling Generator's modules and structure

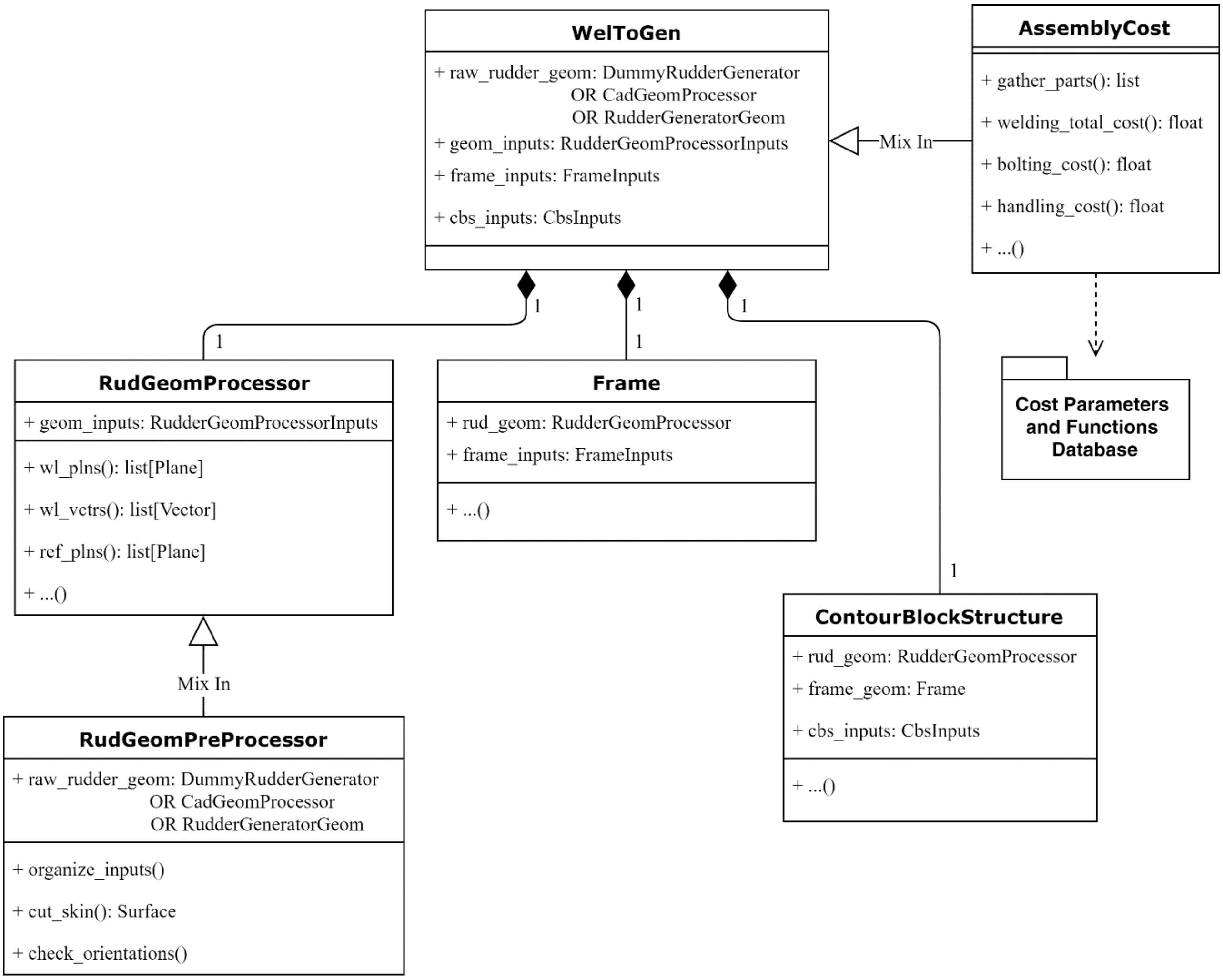

WelToGen
+ raw_rudder_geom: DummyRudderGenerator OR CadGeomProcessor OR RudderGeneratorGeom
+ geom_inputs: RudderGeomProcessorInputs
+ frame_inputs: FrameInputs
+ cbs_inputs: CbsInputs
AssemblyCost
+ gather_parts(): list
+ welding_total_cost(): float
+ bolting_cost(): float
+ handling_cost(): float
+ ...()
Mix In
1
1
1
1
1
1
Cost Parameters and Functions Database
RudGeomProcessor
+ geom_inputs: RudderGeomProcessorInputs
+ wl_plns(): list[Plane]
+ wl_vctrs(): list[Vector]
+ ref_plns(): list[Plane]
+ ...()
Frame
+ rud_geom: RudderGeomProcessor
+ frame_inputs: FrameInputs
+ ...()
1
ContourBlockStructure
+ rud_geom: RudderGeomProcessor
+ frame_geom: Frame
+ cbs_inputs: CbsInputs
+ ...()
Mix In
RudGeomPreProcessor
+ raw_rudder_geom: DummyRudderGenerator OR CadGeomProcessor OR RudderGeneratorGeom
+ organize_inputs()
+ cut_skin(): Surface
+ check_orientations()

Figure 8: WelToGen's UML class diagram.

3.3.1. Geometry inputs and user inputs

The inputs WelToGen requires can be divided in two types: geometry inputs and user parametrical inputs. The former are the rudder geometrical elements explained in section 2.2 needed to create the tooling. The latter are all values that WelToGen needs to run. In the Appendix a list of inputs can be found with their description and specifying if they are required or optional.

The geometry input can come from three different sources. Previous modules ensure the same specified format for WelToGen (ParaPy geometrical elements gathered and labeled in a specific manner). These sources are modules which are not part of the WelToGen, but WelToGen's input creators:

Rudder Generator. RG is Fokker's rudder design program. It generates a full rudder geometry according to automated stress, weight or cost analyses. It is possible to extract the necessary geometry elements for creating the tooling.

Computer Assisted Design (CAD) geometry. The rudder geometry can come from a CAD geometry in Initial Graphics Exchange Specification (IGES) format. A module called CadGeomPreProcessor was created which reads the specified IGES file and extracts the geometrical information from it, translating it into ParaPy elements that can be read by

WelToGen. The IGES file must have a specific labeling for CadGeomPreProcessor to be capable of reading the geometry.

Dummy Rudder Generator (DRG). The DRG is a program created with ParaPy which allows to parametrically create the needed rudder geometry elements. The DRG generates the same geometrical elements than the RG, but instead of according to knowledge rules as the RG does, they are directly decided parametrically by the user. Therefore, the DRG makes the WelToGen a standalone tool for quick design space exploration and performing parametrical studies without the need of modifying CAD geometries or running the RG.

The second type of inputs are values that the user specifies in the script before running the program (see the Appendix). The inputs, for organizational purposes are gathered in three groups: rudder geometry processor inputs (RudGeomProcessorInputs), frame inputs (FrameInputs) and CBS inputs (CBSInputs). The three groups are given to the WelToGen, which passes them to the specific WelToGen's sub-modules that will use the inputs.

3.3.2. Rudder geometry processing

All the modules explained in the following sections already belong to WelToGen, as shown in Figure 7. The UML diagrams of the rudder geometry modules are shown in Figure 8. First, the geometry is pre-processed with the module called RudGeomPreProcessor. This module unpacks the geometry input and re-organizes it for easier access by all other WelToGen's modules (e.g. the list of data planes is broken down, giving a variable in the code for each plane with its specific name). The code also ensures the correct orientation of the inputs (surfaces, planes and curves) according to the selected criteria for WelToGen to work correctly.

Second, a module called RudGeomProcessor takes in the pre-treated input geometry and processes it with the rudder geometry user inputs. The RudGeomProcessor module performs geometrical operations based on both geometry and user inputs. The module creates necessary geometrical entities to create the tooling such as reference planes, points or lines. Through numerical inputs, the definition of these elements can be influenced.

3.3.3. Geometry module

The geometry module creates the tooling geometry based on the RudGeomProcessor's output and performs the geometry feasibility checks: WL gap minimum distance and torch-frame clash. It is composed by two sub-modules, one for each tooling part: the Frame Module (FM), and the Contour-Block Structure Module (CBSM). The geometry is created according to both the rudder geometry input and the user inputs specific for each sub-module. The generated tooling geometry can be inspected in ParaPy's dedicated viewer and it can also be exported to any CAD software in geometry exchange formats such as IGES.

Frame Module (FM). The FM creates the frame geometry and performs the feasibility analyses on it. The FM takes two groups of inputs: RudGeomProcessor outputs and the user frame inputs (FrameInputs). Only one side of the frame is modeled due to the symmetric nature of the tooling. This module automates the part of the design process seen on Figure 6 that concerns the frame creation, except the displacement check which is performed by the Finite Element Model Module (FEMM). The UML diagram of the FM is shown in Figure 9. Each method shown in the UML diagrams gathers several activities performed by the class; the names are simplifications for clarity of the diagram.

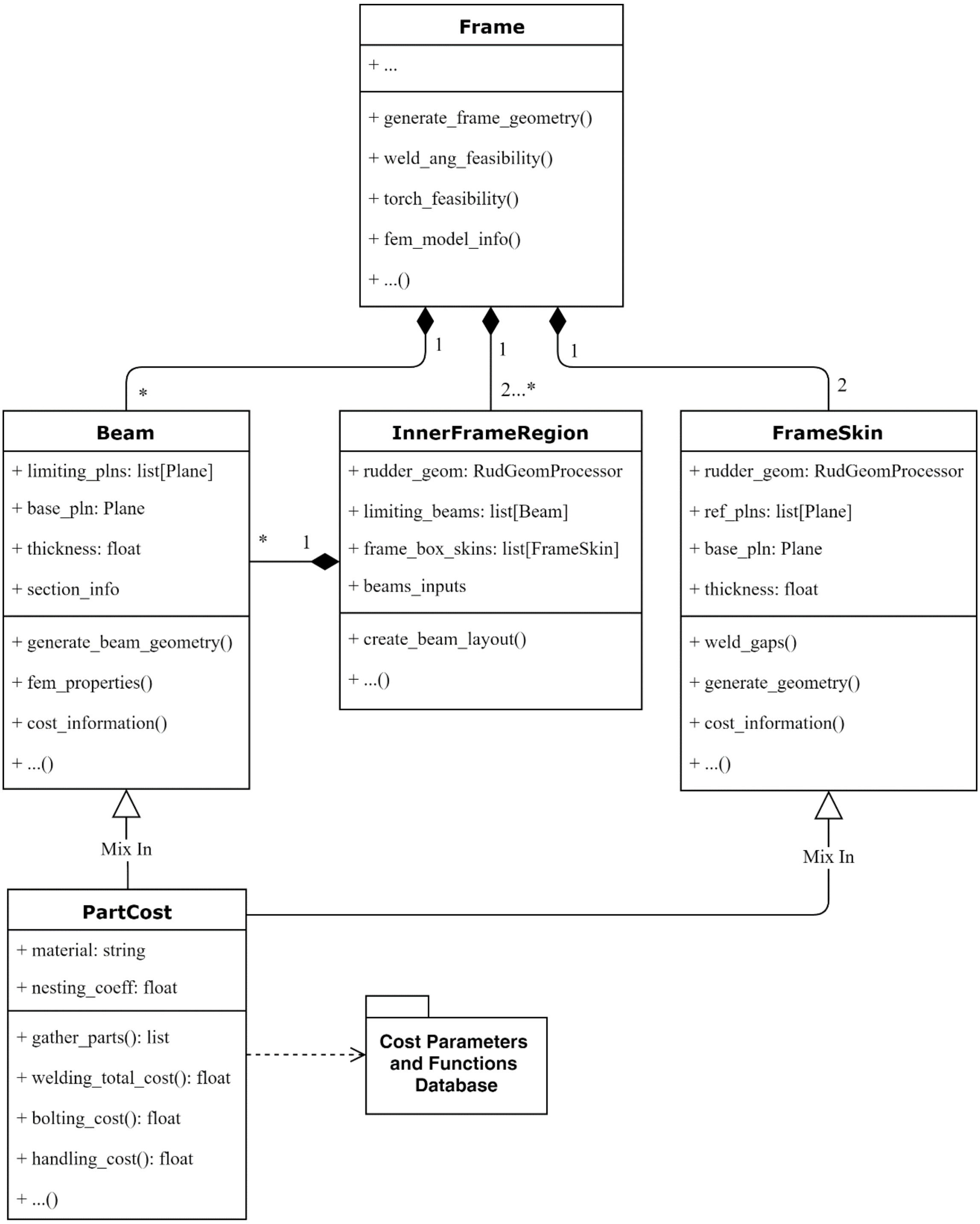

Frame
+ ...
+ generate_frame_geometry()
+ weld_ang_feasibility()
+ torch_feasibility()
+ fem_model_info()
+ ...()
1
1
1
*
2...*
2
Beam
+ limiting_plns: list[Plane]
+ base_pln: Plane
+ thickness: float
+ section_info
+ generate_beam_geometry()
+ fem_properties()
+ cost_information()
+ ...()
*
1
InnerFrameRegion
+ rudder_geom: RudGeomProcessor
+ limiting_beams: list[Beam]
+ frame_box_skins: list[FrameSkin]
+ beams_inputs
+ create_beam_layout()
+ ...()
FrameSkin
+ rudder_geom: RudGeomProcessor
+ ref_plns: list[Plane]
+ base_pln: Plane
+ thickness: float
+ weld_gaps()
+ generate_geometry()
+ cost_information()
+ ...()
Mix In
Mix In
PartCost
+ material: string
+ nesting_coeff: float
+ gather_parts(): list
+ welding_total_cost(): float
+ bolting_cost(): float
+ handling_cost(): float
+ ...()
Cost Parameters and Functions Database

Figure 9: Frame Module's UML Diagram

The FM starts by creating an initial frame box geometry. Then, an iterative search process for finding the spar welding angles which ensure the minimum gap distance specified by the user as was explained in section 2.3. The search process is incremental, meaning that the program will increase the welding angle from null value (ideal welding) until the gap distance requirement is met. The search is done for both spars' welding angles.

Afterwards, the module performs the torch clash analysis. First, torch geometry read from an IGES file is instantiated at the start and end of each WL, since these are the potentially conflictive torch positions as it moves along the entire WL. Next, intersections are searched for between all instantiated geometries and the frame outer structure. If clashes are found, an iterative process for clash avoidance starts. The user specifies a maximum offset that the torches can be from the WL extremes (i.e. how much length of the WL will not be welded at the extremes). The maximum allowed offset value comes from ensuring sufficient weld joint length. Firstly, the algorithm will move the conflictive torches along the WLs iteratively increasing the torch offset until they do not clash with the frame. For the torches which reach the maximum allowable offset and still clash with the tooling, the algorithm starts modifying the frame gaps. The frame gaps are enlarged at the extremes until no intersection is found.

Next, the frame's internal structural layout is created. Structural elements (beams) are arranged without interfering with the WL gaps of the frame, ensuring the torch will be able to go through the frame and reach the rudder. Finally, the closing structure that unites the two symmetric parts of the frame is generated. The displacement feasibility check will be explained in a following section.

Contour-Block Structure Module (CBSM). After the frame has been created, the contour-block structure is created by the CBSM. The CBSM takes as inputs the RudGeomProcessor output, the FM geometry output and the user inputs specific for the CBSM (CBSInputs). The CBS geometry is created by filling the space in between the rudder OML and the frame. The user inputs provide information such as the dimensions of the CBS. The UML diagram of the CBSM is shown in Figure 10.

The CBS is composed by blocks of composite material which are placed around the WLs not interfering with the torch displacement. These blocks are designed by the program by first creating a full solid between the rudder's OML and frame's plane. Then, the necessary volume to allow the torch to reach the rudder is subtracted, splitting the solid into the contour-blocks. The CBS geometry also includes aluminum plates to which the aforementioned blocks are bolted to. The aluminum plates with the blocks attached are then bolted to the frame.

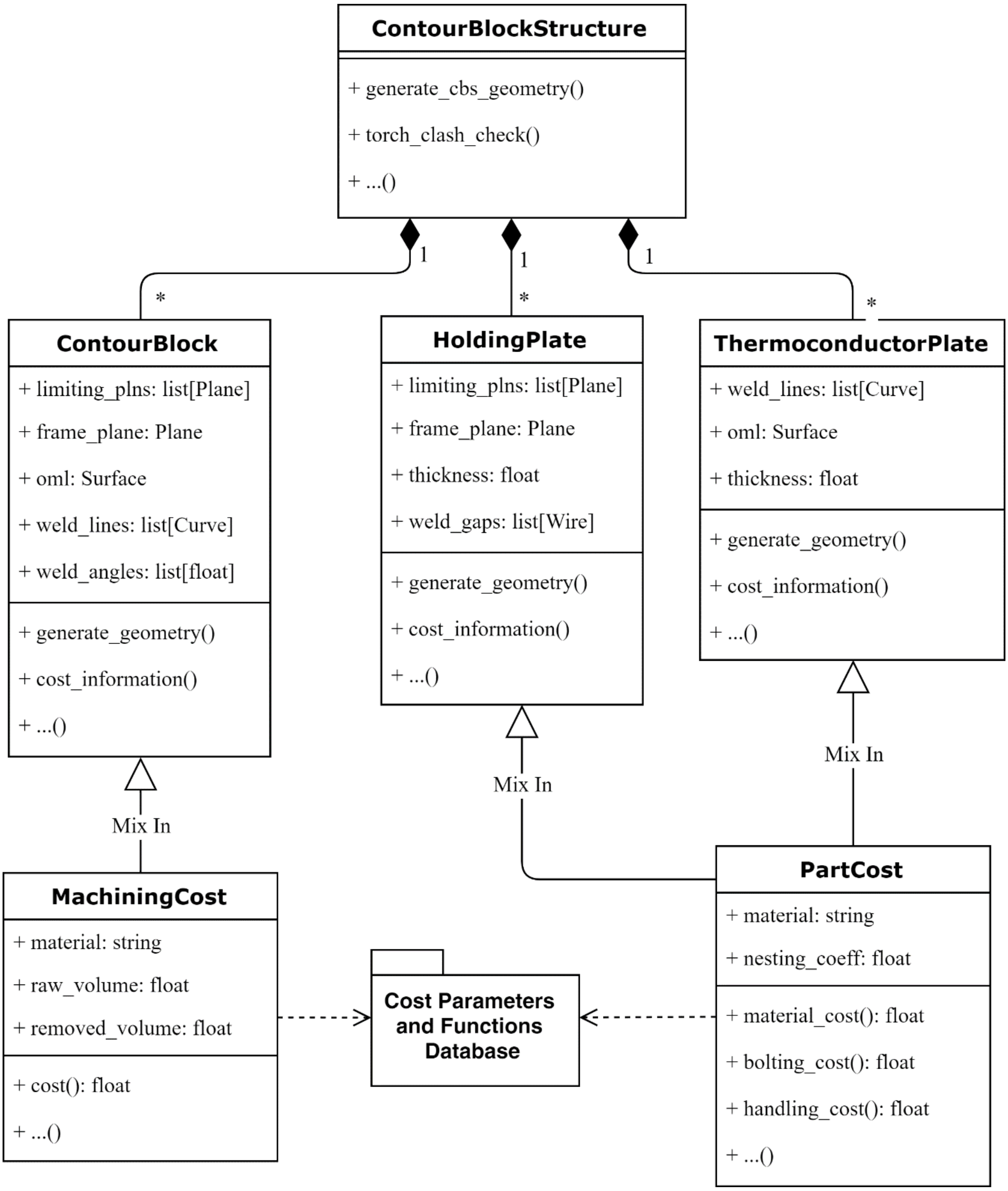

ContourBlockStructure
+ generate_cbs_geometry()
+ torch_clash_check()
+ ...()
1
1
1
*
*
*
ContourBlock
+ limiting_plns: list[Plane]
+ frame_plane: Plane
+ oml: Surface
+ weld_lines: list[Curve]
+ weld_angles: list[float]
+ generate_geometry()
+ cost_information()
+ ...()
HoldingPlate
+ limiting_plns: list[Plane]
+ frame_plane: Plane
+ thickness: float
+ weld_gaps: list[Wire]
+ generate_geometry()
+ cost_information()
+ ...()
ThermoconductorPlate
+ weld_lines: list[Curve]
+ oml: Surface
+ thickness: float
+ generate_geometry()
+ cost_information()
+ ...()
Mix In
Mix In
Mix In
MachiningCost
+ material: string
+ raw_volume: float
+ removed_volume: float
+ cost(): float
+ ...()
Cost Parameters and Functions Database
PartCost
+ material: string
+ nesting_coeff: float
+ material_cost(): float
+ bolting_cost(): float
+ handling_cost(): float
+ ...()

Figure 10: Contour-Block Structure Module's UML diagram

3.3.4. Finite element model module

The Finite Element Model Module (FEMM) performs the stress analysis, one of the necessary steps to perform rudder manufacturability analysis. The tooling displacements have to be kept under a specified allowable maximum at every point of the frame’s box during the pressure application. The module created acts as pre-processor, solver and post-processor. The UML diagram of the FEMM is shown in Figure 11, where it can be seen as a part of the FM.

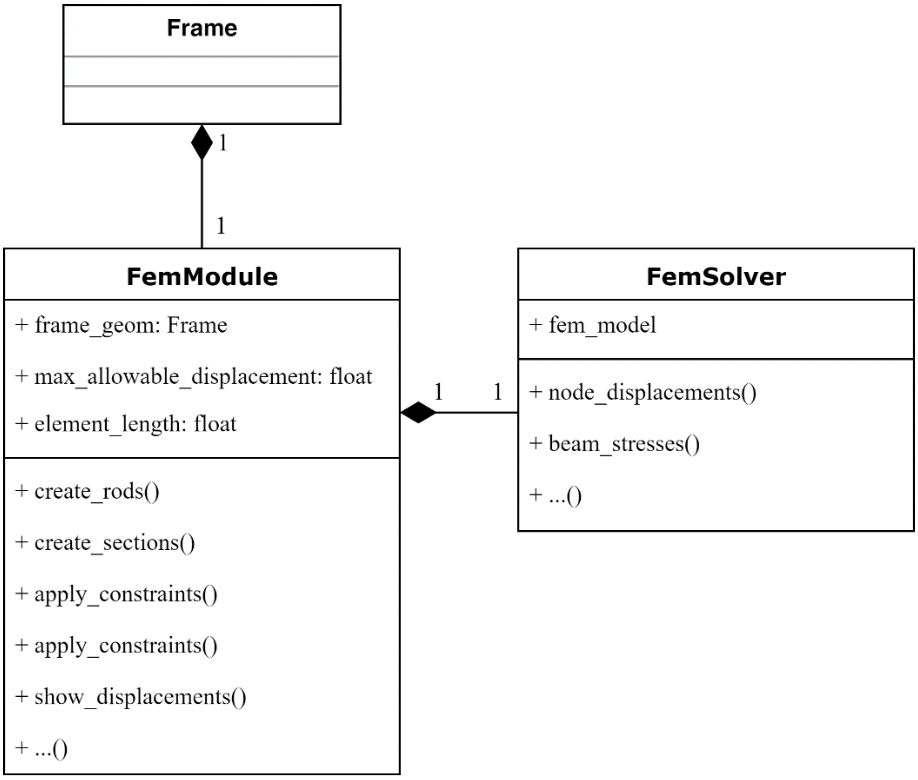

Frame
1
1
FemModule
+ frame_geom: Frame
+ max_allowable_displacement: float
+ element_length: float
+ create_rods()
+ create_sections()
+ apply_constraints()
+ apply_constraints()
+ show_displacements()
+ ...()
1
1
FemSolver
+ fem_model
+ node_displacements()
+ beam_stresses()
+ ...()

Figure 11: Finite Element Model Module's UML Diagram

The solver is a python 3D beam element stress analysis code developed and validated at Fokker and is integrated in the FEMM. This solver is selected instead of commercial software due to the ease of integration and the accuracy/computational time ratio. First, being a python code, the integration is straightforward as the solver's python functions can be directly called from WelToGen. Using any commercial stress software would require the creation of interfaces between the python-coded WelToGen and the software's specific code. Additionally, the impossibility of automating commands of some stress programs makes them not suitable for a KBE application. Secondly, the python solver has a sufficiently high accuracy/computational time ratio for conceptual design due to its simulating speed, as it will be explained in section 3.4.2

The pre- and post-processors were created specifically to integrate the python solver into WelToGen. The pre-processor creates the model for the solver based on the tooling model. The post-processor gathers the results from the solver, presenting them in the ParaPy display and performing the feasibility assessment.

The frame is the tooling part which keeps structural integrity, hence it is the only part modeled in the stress analyses. The tooling support is considered to be infinitely stiff. This modeling approach has already been used in Fokker's full 3D stress analyses of the previously manufactured tooling and the results were consistent with the tooling's actual stress behavior. Only half tooling is modeled so symmetry conditions are applied on the X-Z plane. The frame's geometry is sketched with loads and boundary conditions in Figure 12. The pressurized zone is an offset around the WLs since the pressure is applied to the WLs from the inside of the rudder. The load is assumed to affect a specified area around the originally pressurized lines. The boundary conditions are clamping the frame to where the tooling support is and X-Z symmetry boundary conditions for the middle beam that closes the two sides of the frame.

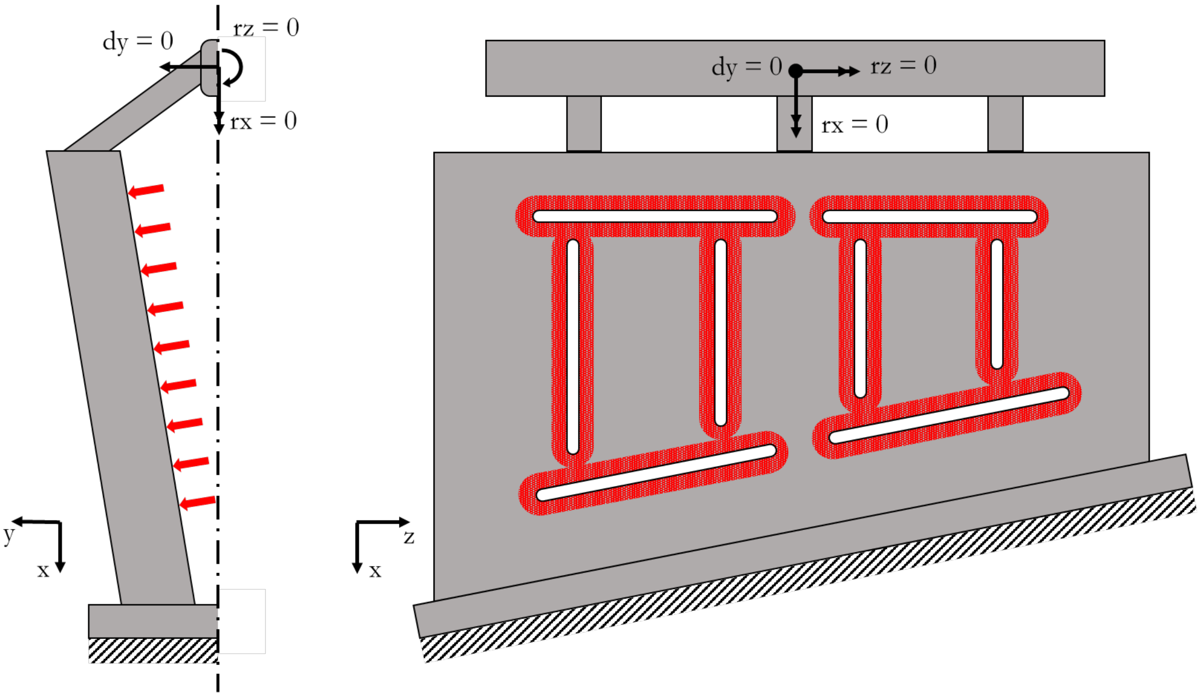


Figure 12: Sketch of one of the symmetric sides of the frame geometry with boundary conditions (black) and load distribution (red).

The pre-processor transforms the geometry, the loads and boundary conditions into a finite element model. The modeling approach consists of transforming the frame structure into a grid of rod elements to which beam section properties are assigned since the python solver can only handle this type of elements. The model is created in several steps:

1 Geometrical information gathering. The frame geometry elements to be transformed into FEM beams are gathered. The pre-processor scans the FM searching for the ParaPy elements which have been generated as beams[3].

2 Create rod elements. Each frame structural element gathered during the scan is transformed in a FEM rod element. From the elements' geometrical information, the intersection points between beams are calculated. With these points, the rod element grid seen in Figure 14 is created. The rods are 1D elements. The rods are discretized into smaller elements according to a user input to increase the simulation accuracy.

3 Assign beam section properties. The solver is only capable of simulating rod elements with beam properties, which means the outer shell of the frame box cannot be directly modeled. However, the box outer plates are included in the flanges of the beam properties assigned to the rod elements. For the modeling, each beam element contains information about the distance to the neighbor beams and if there is a welding gap between them or not. Based on this, the flanges' widths are calculated for each beam. The shell of the frame box is divided in the flanges of the adjacent rod elements. The flange width is kept to a fraction ("n" in Figure 13) of the distance between beams. In section 3.4.2, n's value will be reasoned. In Figure 13 the frame box is sectioned showing the beams and box outer plates geometries and how they are transformed into beam sections.

---

[3] During the geometry creation process many other intermediate geometry elements necessary for the definition of the final geometry are created. Examples of this geometry are points, planes, surfaces or solids. These elements are omitted from the FEM model.

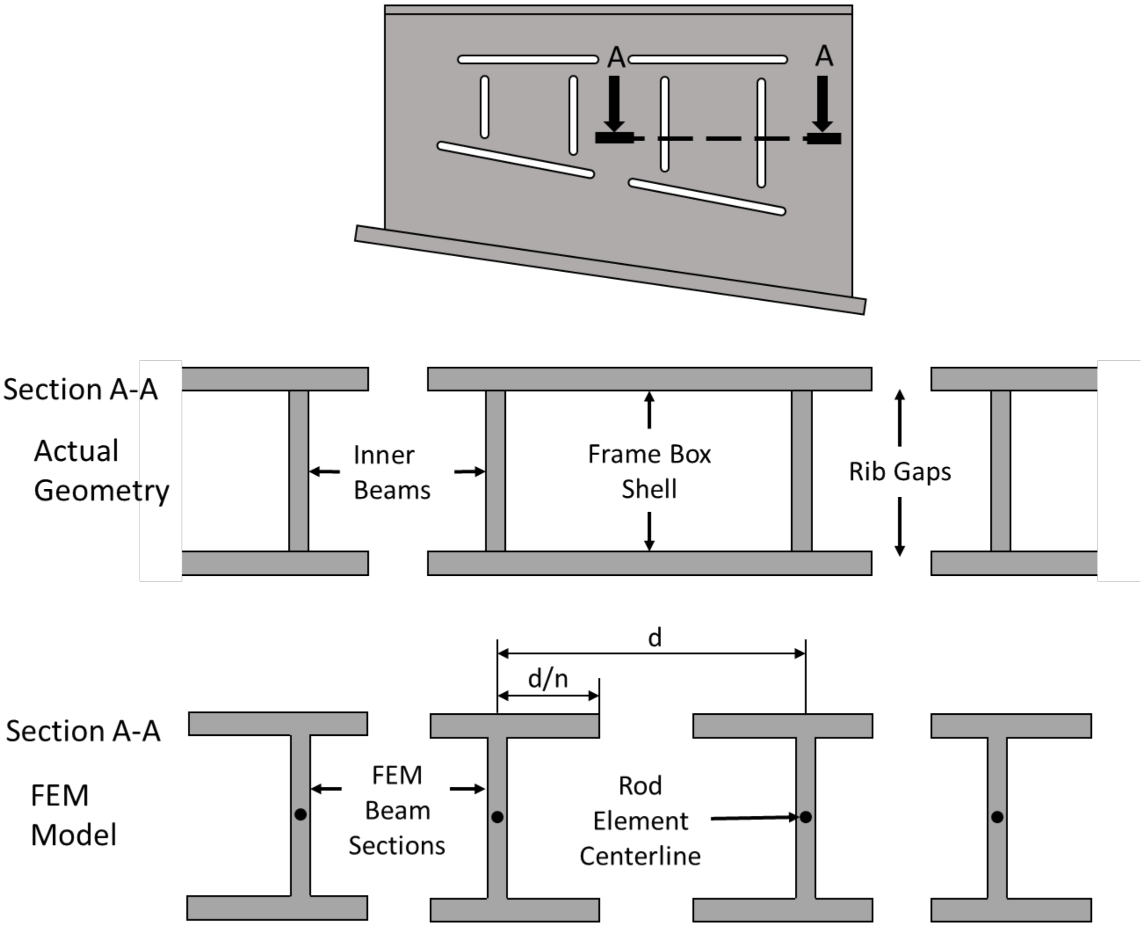


Figure 13: Frame box sectioning and geometry transformation into FEM beam sections

Boundary conditions and loads. Finally, the loads as well as the boundary conditions are applied on the beams. The pressurized zone area is calculated as an offset of the WL on the plane of the frame, the red area around the frame gaps in Figure 12. Then, the total area is multiplied by pressure value, resulting in the total force applied on the frame. Next, the beams (or portion of beams) which are affected by the pressure are determined. The loaded beams are the ones inside the aforementioned pressured area. The total length of the loaded beams is calculated. The total force on the frame divided by the loaded beams total length is the line pressure value that is applied on the loaded beams. Additionally, the symmetry boundary condition is applied to the middle beam while the clamping condition is applied to the lower beam, which is in direct contact with the support. The model (without beam section representation) can be seen in Figure 14.

Once the model is created, the simulation is run. The results provided by the solver are extensive including reaction forces, node (junction between two rod elements) displacement, beam stress, buckling modes and model’s natural frequencies. However, the post-processor collects solely the node displacements, which will determine the feasibility of the tooling design. The post-processor creates in ParaPy point elements, each with data about their displacement. The tooling model’s node displacements are represented in the ParaPy display as a vector field on top of the tooling geometry as shown in Figure 15 (the tooling geometry has been hidden due to confidentiality reasons). Also, the maximum displacement value is available.

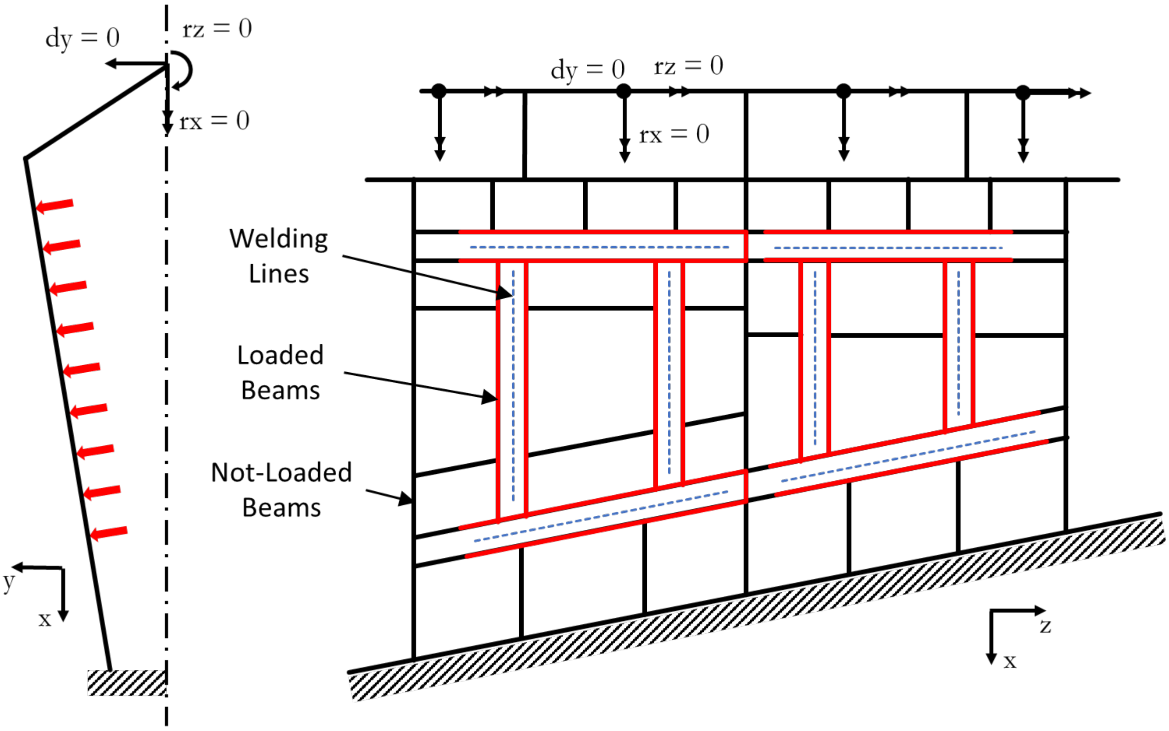

dy = 0
rz = 0
rx = 0
dy = 0
rz = 0
rx = 0
Welding Lines
Loaded Beams
Not-Loaded Beams
y
x
z
x

Figure 14: Sketch of the finite element model showing the welding lines (dashed blue), the loaded rod elements (red), the non-loaded rod elements (black) and the boundary conditions.

The post-processor also includes the displacement feasibility assessment. When running the feasibility function, the post-processor compares the node displacements against the specified maximum allowable displacement. The nodes which do not fulfill the requirement are gathered in a python list for the code to have them available for future calculations, as it will be explained later. Also, the conflictive nodes are shown in black in the display as shown in Figure 15.

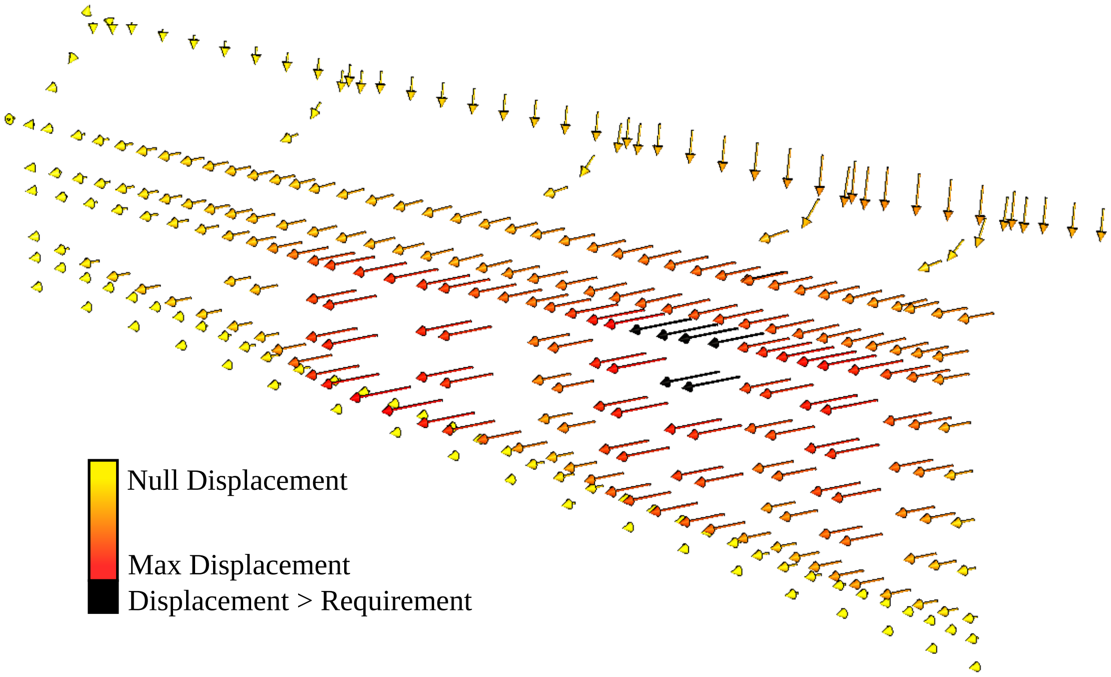

Null Displacement
Max Displacement
Displacement > Requirement

Figure 15: Node displacement display in ParaPy's GUI. Tooling geometry is hidden

3.3.5. Cost module

The Cost Module (CM) is the last necessary component for the KBE application to fulfill the objectives set for a manufacturing analysis. The CM estimates the cost of manufacturing and assembling the tooling in order for it to be included in the rudder cost considerations. In the Rudder Generator, the tooling costs are omitted, taking into account solely the recurring costs. Including the tooling cost in the rudder cost estimation will help making more informed rudder design trade-offs.

The CM estimates cost in a process based manner. A process based method is a cost estimation technique which estimates the cost of each process necessary to manufacture and assemble each part of an assembly. This method is more reactive to changes in design due to its level of detailed compared to top-bottom estimations; yet, for higher detail results more information about the geometry is needed. WelToGen supports process based estimations by producing a sufficiently detailed tooling model. Moreover, top-bottom methods rely on large amounts of historical data to perform regressions. At Fokker, only three welding tooling models have been manufactured, making top-bottom estimations not feasible.

A diagram of the composition of the tooling cost is shown in Figure 16. In this diagram, it is indicated which terms are summaries of the cost of all parts of the tooling as it will be explained hereunder.

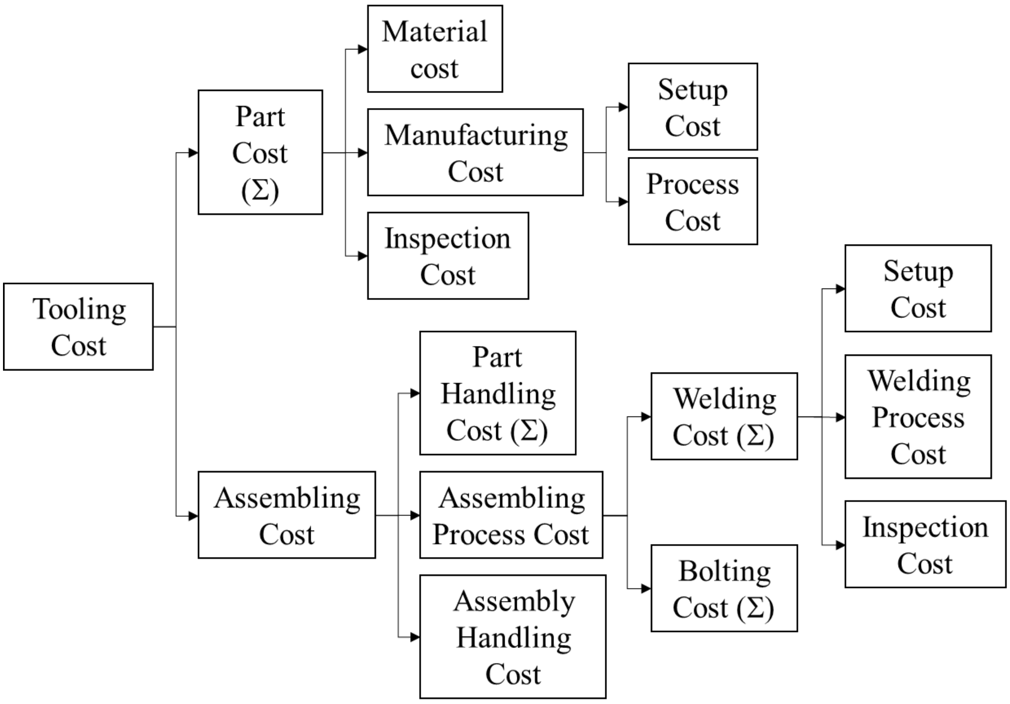

Material cost
Setup Cost
Part Cost (Σ)
Manufacturing Cost
Process Cost
Inspection Cost
Setup Cost
Tooling Cost
Part Handling Cost (Σ)
Welding Cost (Σ)
Welding Process Cost
Assembling Cost
Assembling Process Cost
Inspection Cost
Bolting Cost (Σ)
Assembly Handling Cost

Figure 16: Tooling cost composition

The cost is divided in two main elements, the part manufacturing cost and the tooling assembling cost. The part manufacturing is calculated for each part and then added up. The fact that only half of the tooling is modeled is considered by doubling the manufacturing and assembly costs of the parts with a symmetric one. The equation is:

$$C_{tooling} = C_{parts\,manufacturing} + C_{assembling} = \sum_i C_{part}^i + C_{assembling}$$

Part Manufacturing Cost: First, the cost of manufacturing each tooling part is calculated. The part manufacturing cost is divided in three main aspects, as seen in the part cost equation:

$$C_{part}^{i} = C_{material} + C_{manufacturing} + C_{inspection}$$

Each type of part is manufactured in a specific way, which means a different calculation method for each term of the equation. The meaning of each term of the equation will be explained generally and then the equation for a specific part type will be shown. The type of part are the frame's inner beams. The inner beams are rectangle-shaped flat plates (as seen in Figure 17), which are cut from larger hot rolled plates. The beams include several notches which serve to align the beam with the frame box, which has holes to fit all beams' notches.

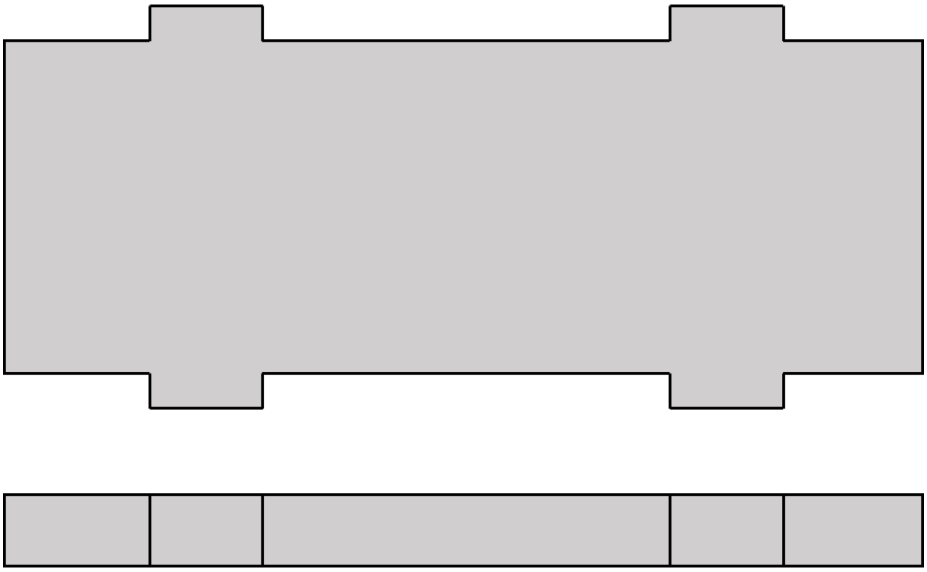


Figure 17: Sketch of the geometry of a frame inner beam

$\boldsymbol{C_{material}}$**:** Cost of the material used to manufacture the part. It is the cost of all the material used during the manufacture process; thus nesting factors and removed material are taken into account.

The beams are cut from hot rolled plates, which material cost depends on the area used and on the thickness. For each beam in the tooling geometry, the values for the two variables, area of the largest face (A_{beam}) and thickness, are obtained from the geometry model created by the Frame Module. The area value is multiplied by a nesting factor, greater or equal to 1, which accounts for the material lost in the process of obtaining the beam shape from the hot rolled plate. The nesting factor is selected depending on the presence or not of notches in the part, the size of them, etc.; its value ranges from 1.0 for beams without notches to 1.4 to the beams with more and largest notches.

The material price is obtained from a table containing information about the price per area depending on the thickness, as shown in Table 2. The program accesses this table with the beam thickness and obtains the price per area of the hot rolled plate from which the beam will be manufactured.

Table 2: Example of price table for steel hot rolled plates

Thickness [mm]	10	12	15	18	20	25
Price [€/m^2]	100	120	150	180	200	250

The values obtained from the geometrical model and from the table are introduced in the equation:

$$C_{material} = A_{beam}[m^2] * nesting\ factor * plate\ material\ price(thickness)[\frac{€}{m^2}]$$

$\boldsymbol{C_{manufacturing}}$**:** The manufacturing cost is divided in the cost performing the manufacturing process, $C_{mfg\ process}$, and on the cost of the process setup, C_{setup}, which includes bringing the material to the process, fixing, setting up process, etc.

$$C_{manufacturing} = C_{mfg\ process} + C_{setup}$$

Despite the type of manufacturing process, calculations for all part types are based in making time estimations and then multiply the time by money-time rates. The calculations in the case of the example beam are based on the perimeter of the beam to be cut from the hot rolled plate and the cutting speed. The cutting depends on the thickness and it is obtained from a table with the same configuration as Table 2. The material handling time, which depends on the beam area, is obtained from a similar table. The equations for the beam example are:

$$C_{mfg\ process} = \frac{perimeter_{beam}[m]}{cutting\ speed(thickness)\left[\frac{m}{min}\right]} * \ cutting\ rate\left[\frac{€}{min}\right]$$

$$C_{setup} = time_{material\ handling}\ (A_{beam})[min] * handling\ rate\left[\frac{€}{min}\right]$$

$\boldsymbol{C_{inspection}}$**:** After being manufactured, the parts must go under inspection. As manufacturing cost, inspection cost is calculated by estimating time and multiplying by rate. The specific way of calculating the time also varies depending on the process. In the case of the example, the inspection time is estimated with the perimeter, since the process consists on checking the entire perimeter. The equation is:

$$C_{inspection} = \frac{perimeter_{beam}[m]}{inspection\ speed\left[\frac{m}{min}\right]} * \ inspection\ rate\left[\frac{€}{min}\right]$$

Tooling Assembling Cost: Once the cost for each part has been calculated, the tooling assembling cost is calculated. As seen in the equation, the assembling cost is divided in:

$$C_{assembling} = C_{part\ handling} + C_{assemblying\ process} + C_{assembly\ handling}$$

$\boldsymbol{C_{part\ handling}}$**:** The cost of handling into the assembly process every part that has to be assembled. Comparable to the part manufacturing cost, the part handling cost is calculated by first estimating the time and it also depends on the part type and on the part geometry. The part handling term is a summary of the cost for each part to be handled in the assembly process.

$$C_{part\ handling} = \sum_i C^i_{handling\ into\ assembly}$$

The cost for each part is calculated based on size. In the case of the beams, the beam area is introduced in a table like Table 2, obtaining the time to handle. The equation is:

$$C_{part\ in\ assy} = time_{handling\ into\ assembly}\ (A_{beam})[min] * handling\ rate\left[\frac{€}{min}\right]$$

$\boldsymbol{C_{assembling}}$**:** Cost of performing the assembling process. The calculation method differs for each tooling component; the steel parts are welded and the aluminum and composite parts are bolted. Therefore, the term is divided in:

$$C_{assembling} = C_{welding} + C_{bolting}$$

Both welding and bolting are a summary of the cost for welding or bolting each part that will be assembled using that method. Therefore, they are expressed as:

$$C_{welding} = \sum_i C^i_{part\ welding} \quad and \quad C_{bolting} = \sum_j C^j_{part\ bolting}$$

For both a process modeling equation is developed. In the case of the example frame inner beam, welding is the method used. The welding process consists of three terms:

$$C_{part\ welding} = C_{setup} + C_{welding\ process} + C_{inspection}$$

The setup is a fixed time for all welds. It is the time that the welder takes to perform actions such as place the part to be welded in the assembly and prepare all the material needed for the weld. The welding process itself is calculated by taking from the geometry the length to be welded. Finally, the inspection will also depend on the length that has been welded.

$$C_{setup} = constant[min] * welding\ rate\left[\frac{€}{min}\right]$$

$$C_{welding\ process} = \frac{l_{weld}[m]}{welding\ speed\left[\frac{m}{min}\right]} * \ welding\ rate\left[\frac{€}{min}\right]$$

$$C_{inspection} = \frac{l_{weld}[m]}{welding\ inspection\ speed\left[\frac{m}{min}\right]} * \ inspection\ rate\left[\frac{€}{min}\right]$$

The CM is integrated in WelToGen, automatically gathering the necessary model information to perform the estimations. The results of the calculations can be obtained for each individual part, as well as the sums and total tooling cost values. The results, apart from being accessible in the code and in the GUI can also be reported in an excel file. The excel file includes:

1. The list of tooling parts, for each of which a time and cost breakdowns are done. The value of each term of each equation is given as well as the totals of each equation, both cost and times. Each part is referred to with its reference chain in the code, this is the sequence of sub-modules to which it belongs.

2. Assembly time and cost breakdowns. The time and cost of each assembly operation is presented. Additionally, the contribution of each part to the assembling time and cost is also accessible in the part list (e.g. the time contribution to the total welding time of a specific tooling part).

Examples of the CM's outputs are seen in Table 3 and Table 4. These tables show partially the output; several cost aspects have been left out for visual clarity. Note that the figures and materials have been modified due to confidentiality reasons.

In Figure 10, it can be seen that for the machined parts, a different cost module has been used. This is the machining cost estimation module developed in [31]. The KBE cost estimation module was easily integrated and used by giving the necessary input information from the CBS model.

Table 3: Example of part cost list as part in the Cost Module's output (modified figures).

	Part Type	**Material**	**Material Cost [Eur]**	**Process Cost [Eur]**	**Quality Check Time [min]**	**Part Cost [Eur]**	**Welding Time [min]**	**…**
frame. regions[0]. fwd_spar_aft_beam	Plate Beam	Steel	12.3	45.6	78.9	12.3	45.6	…
frame. clamping_plates[0]	Machined Plate	Steel	23.4	56.7	89.0	23.4	56.7	…
contourblock_structure contourblock[1]	Contour-Block	Composite	34.5	67.8	90.1	34.5	N/A	…

Table 4: Example of assembly operations cost list in the Cost Module's output (modified figures).

Cost Factor	**Time [min]**	**Cost [Eur]**
Welding Process	123.4	567.8
Welding Quality Check	901.2	345.6
Bolting	789.0	123.4
…	…	…
Assembly Handling	567.8	901.2
Total Assembling Process	N/A	345.6
TOOLING COST	N/A	789.0

3.4. Verification and Validation

The KBE application, WelToGen, was developed following the steps described in section 3.2, including the verification phase. Validation studies were performed for the implemented methodologies in the FEM and cost modules. These two aspects, verification and validation of WelToGen's modules will be further explained hereunder.

3.4.1. Verification

Verification refers to the check if the program conforms to the specifications set for it, i.e. the program is doing what it is intended to do. The standard creation of a KBE application includes verification as a continuous process during development. As the program is written, there are constant checks verifying that the coded rules are correctly written and the application performing correctly its tasks. The modularity of KBE applications allows the deployment of sub-modules of the code and test them individually as they are created.

The verification level can be divided in three levels which vary in detail and frequency of checks:

> **Programmer level.** It is the most frequent type of check. KBE programmers verify the code every time the program is run as a part of the code creation process. In this process, apart from errors typical of programming faults, the verification of the coded rules is done. The KBE programmer is capable of discerning if the program fulfills the specifications since he/she identified and capture the knowledge in the previous phase of KBE creation.
>
> **Expert level.** Less frequent than the previous. In this project, the expert verification was done weekly at the phase of KBE application creation. The KBE programmer has verification sessions with the expert whose knowledge is being captured in the application. In this meetings, the programmer explains the app development since the last session and runs the program. With the explanation of the new implementations and looking at the output of the program, the expert is able to pinpoint possible mistakes in the coded rules or missing rules. The programmer then uses this input to improve the application. The level of detail is higher than the previous type of check since the expert has a deeper understanding and more experience than the programmer.
>
> **Task force level.** The least frequent. In this project, task force meetings were hold monthly. A task force is created for the project consisting of experts from diverse expertise. For WelToGen, the task force included:
>
> - One design engineer,
> - One knowledge engineer,
> - One tooling engineer,
> - One welding process engineer,
> - One thermoplastic welding expert and
> - One senior manufacturing engineer.
>
> In the meetings, the state of the application was debriefed and the program functionalities shown. The feedback received from the task force members is less detailed and specific than the expert feedback, yet useful due to the generality of it. The task force feedback regards the app's functionalities, objectives, and capabilities.

Geometry module. The geometry module was verified by comparing the code's output against the geometry actual tooling manufactured at Fokker. WelToGen was used as a standalone tool, receiving the input from the rudder models. The geometries used for verification were the rudder and aileron of an aircraft, which will be called Business Jet 2 (BJ2). The tooling of these two aircraft components have been manufactured at Fokker and the knowledge captured in WelToGen are the design rules used for their creation. From the full component CAD models, the necessary geometry inputs for WelToGen were extracted and gathered in an IGES file. The file was given to the CadGeomPreProcessor to transform them into ParaPy elements which served as inputs for WelToGen.

The outcome geometry was thoroughly inspected by the programmer and the tooling expert, gradually as the geometry modules were being created. With the comparison to the actual tooling geometry, errors in the coded rules were fixed and improvements were implemented. The process continued until the KBE application included the frame and the CBS geometries, which were set as the minimum necessary geometry for performing tooling analyses. The level of geometry detail was increased until the necessary geometry elements for performing the torch clash feasibility analysis, the displacement analysis and the process-based cost estimation were present in the model.

Other Modules. In the same way as the geometry module, the rest of the modules were checked to ensure they included all the functionalities, which have been explained before, that are needed for the manufacturing analyses.

3.4.2. Validation

Validation refers to ensure that a program meets the needs for which it was created, i.e. the program fulfils its objectives. In this section, validation studies done for the FEM and cost modules will be presented. The fulfilment of the objectives of the overall KBE application will be discussed in chapter 5.

FEM Module. The validation studies of the FEMM consisted in ensuring that the simulation results were accurate enough and obtained fast enough for WelToGen's purpose, tooling conceptual design creation and analysis. In the study, the FEMM was compared to two commercial stress codes: MSC's NASTRAN and Dassault Systemes' CATIA Generative Assembly Structural Analysis (GAS). NASTRAN is used by Fokker as main software to perform stress analyses; the actual tooling's stress reports made with NASTRAN were used as benchmark. NASTRAN was not available at the moment of the research, so GAS was used for further comparisons with WelToGen's FEMM.

For the validation studies, several geometries were created with the Dummy Rudder Generator (DRG) and the results from the FEMM and GAS compared. Additionally, GAS and FEMM were compared against NASTRAN by generating with WelToGen the geometry of the BJ2 rudder's tooling for which the NASTRAN report made by Fokker is available. The tooling maximum displacement simulated with GAS differed less than 1% from the results with NASTRAN, as seen in Table 6. From this point on, GAS was proven to be a valid simulation software to use as benchmark for the FEMM when new geometries for which reports do not exist are simulated.

The validation study was performed to select the best FEM modeling approach. As it was explained in section 3.3.4, the frame box skin is lost when modeling the tooling geometry with 1D rod elements, as was shown in Figure 13. The main problem of not modeling the skin as a continuum is the loss of the closed box that exists between adjacent beams. Closed hollow structures have significantly larger torsion values compared to the same structures when they present a cut in the skin along their centerline (the torsion of the closed structure is of the order of 1000 times of the open one). In order to imitate the behavior of a closed structure with a rod model, the rod section properties are modified. There are two section properties that were varied:

> **Flange width.** The width of the flange represents how much of the skin between adjacent beams is modeled in the beam section (the "n" parameter in Figure 13). According to Fokker standards, when a structure composed by a skin stiffened by stringers is modeled only with the stringers, a quarter of the distance between stringers should be modeled as skin. The value of n equals 4, due to the fact that the amount of shear load that the skin carries at this distance becomes negligible, as seen in Figure 18. However, as it will be seen later in this section, the results were not sufficiently stiff with this value, so values of n = 2 were also tested. The value n = 2 represents modeling the entire skin between two beams, yet the two skin halves not connected since they are flanges which belong to different beams.

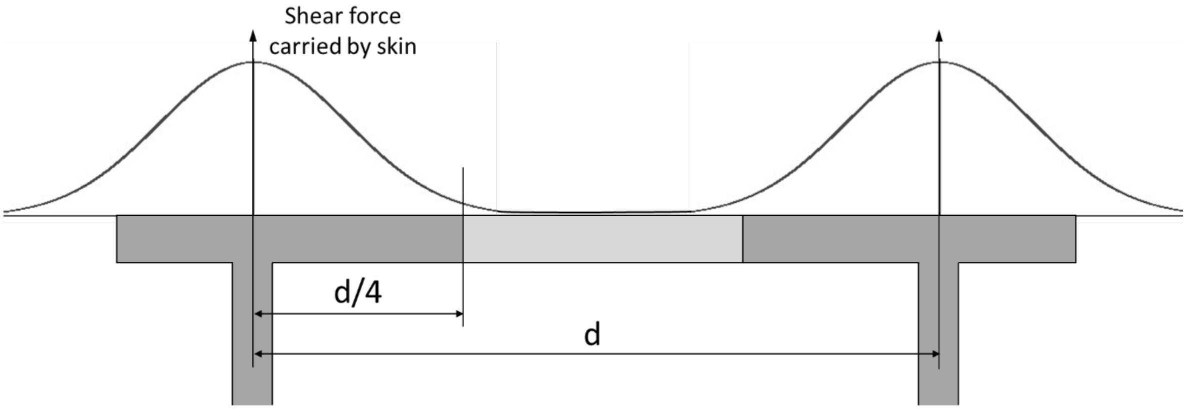


Figure 18: Shear force carried by the skin in a stringer reinforced structure.

Beam section torsion. As it was explained, the torsion of the closed box is lost when a 1D rod approach is used. Hence, artificial torsion values were applied to the beam sections. The methodology used consisted in calculating the closed hollow box's torsion around its center axis. This torsion value was then divided in half and assigned to each one of the two adjacent beams. The original torsion value for each beam, calculated based on the beam section's shape, is overridden with this artificial torsion value.

Several rudder geometries were created using DRG and with WelToGen their tooling designs were generated and the displacement automatically analyzed with the FEMM. The tooling geometries were then exported to CATIA and the finite element model for GAS created manually. To understand the differences in time between the three stress analysis methods, typical timings for creating the model and simulation runs are shown in Table 5.

Table 5: Model creation and simulation run typical times for three stress analysis software.

	FEMM	GAS	NASTRAN
Model Creation	~1 second (Automatic)	~3 hours (Manual)	~8 hours[4] (Manual)
Simulation Run	~1 minute	~15 minutes	~60 minutes[4]

Three geometries were tested: BJ2 rudder and two rudders generated with DRG which are similar in size to BJ2, yet with varying number and position of ribs (DRG1 and DRG2). The three geometries were modeled with FEMM following three approaches: section's torsion with narrow flanges (n = 4), adding the closed box's torsion with narrow flanges (n = 4) and section's torsion with wide flanges (n=2). The results of the simulations can be seen in Table 6.

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[4] Estimations given by a stress expert at Fokker based on the available stress report.

Table 6: Normalized maximum displacement values of three rudder geometries using different software and modeling approaches.

	NASTRAN	GAS	FEMM Section Torsion n = 4	FEMM Added Torsion n = 4	FEMM Section Torsion n = 2
BJ2 Rudder	0.99	1	1.46	1.21	1.19
BJ2 Aileron	0.99	1	1.16	1.04	0.98
DRG1	---	1	1.05	0.94	0.98
DRG2	---	1	1.17	1.09	1.06

The modeling approach using Fokker standards (n = 4) and the section's geometrical torsion gives results that can be up to 46% larger than GAS' results. Hence, this modeling approach is rejected, since such difference is not acceptable for WelToGen's intended use. The second modeling approach tried, adding artificial torsion, reduced the difference by adding stiffness to the structure. The method with added torsion is traded off with the approach of the section's torsion and wide flanges (n = 2). From the two, the latter methodology offers slightly closer results to GAS' than the former and therefore it is selected.

The results obtained with the unmodified torsion and wide flanges show a maximum difference of 19%. The difference is significant, yet it is acceptable for two reasons:

1. The results obtained with FEMM are on the conservative side, except the one which is more accurate (-2% difference). When using FEMM's results for the tooling design, the tooling will be oversized; the actual displacements in the manufactured tooling will be lower than in the simulation. Unlike in aircraft part design, tooling design is not driven by strict weight limitations[5], thus oversizing is an acceptable risk.
2. WelToGen's FEMM is intended to support the displacement feasibility analyses at the conceptual design stage. At the early stages, when design changes are done regularly, it is crucial to be able to perform quick analyses. Later in the design process, when the design is more detailed, a 3D stress analysis is performed to ensure the tooling requirement fulfilment. The combination of accuracy with speed makes FEMM valid for the conceptual stage.

Cost Module. The difficulty for validating the CM lays in not having historical data available at Fokker for welding tooling manufacturing. Hence, the methodology's results cannot be contrasted against actual data. The CM validation was performed with the help of an experienced cost engineer at Fokker. Several meetings were held in which the Cost Module was revised, both the knowledge coded in the module and its output. Three steps were followed:

1. First, the equations of the process-based cost, presented in section 3.3.5, were analyzed. The cost engineer suggested changes and improvements to properly capture the tooling manufacturing and assembling processes.

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[5] Tooling weight limitations need to be checked since the machinery used during installation and operation has limits. However, heavy machinery is used with large safety margins; a design 10-20% oversized will not be problematic.

2. Second, the parameters used in the equations (handling times per size, rates for each activity, inspection times, etc.) were modified using the results in the CM's output. The cost engineer helped providing rules-of-thumb for typically used material-manufacturing and manufacturing-assembling costs proportions, based on experience and Fokker's cost records. In Table 7 some of these proportions can be seen.

   Table 7: Example of typical proportions used in Fokker cost estimation methods.

Steel Material-Manufacturing Costs	40-60 %
Aluminum Material-Manufacturing Costs	60-40 %
Tooling Part Manufacturing-Tooling Assembling Costs	70-30 %

   Each type of part was examined in the cost output's part list and the ratios calculated. Then, the equation parameters were modified until each part type and the entire tooling had ratios similar to the ones the cost engineer provided. The parameter modification was also controlled by the cost engineer so all parameters had values which were in the correct order of magnitude according to his experience.

3. Finally, the price proposal done by the outsource company for the BJ2 rudder tooling when it was built was used for an order-of-magnitude comparison. The file includes a division of the price in several categories. The division is of low level of detail; the price is broken down solely into design, numerical control programming, machining labor, regular labor, material and inspection. The file expresses the figures both in price and in time.

   The BJ2 rudder's tooling cost was estimated with the CM. The cost output was compared to the price file. The comparison was done solely for the time, since the rates of the price file differ from the ones used at Fokker. The comparison showed a similar order of magnitude in each category which is estimated by the CM and helped to further modify the parameters to obtain more similar figures.

3.5. Method Limitations

As it has been explained in the modules' descriptions, the methodology is based on simplifications. The simplifications are made to allow quick automated analyses as early as possible in the design (i.e. with the least possible amount of information about the design), since this is a main point to front load a design process. Apart from the advantage of supporting front loading, the simplifications add limitations to the methodology. Simplifications in the modeling and analyzing reduce the accuracy of the results. The limitations of WelToGen's modules and their effect on the manufacturing analysis results are:

Geometry Module. The tooling geometry generated by WelToGen is not complete and is not as detailed as a finalized design. Tooling sections, components and details are missing. The geometry that WelToGen creates is sufficiently detailed as to perform the required analyses. Parts and details which have no effect on the fulfillment of the requirements have not been modeled.

The existing tooling design knowledge captured in WelToGen is valid for designing tooling for multi-rib components which have two spars. Additionally, the spars must include at least one WL break. All components for which Fokker has manufactured tooling have this configuration. One of the requisites for a KBE application is that the knowledge has to exist before capturing it. In order to test new component concepts, new tooling design rules might need to be defined by the tooling engineers. Afterwards, they could be coded into WelToGen, expanding the application's capabilities.

FEM Module. The modeling approach used, 1D rods with beam section properties, is not capable of fully capturing the tooling stress behavior as was shown in section 3.4.2. However, the FEMM is a valid front loading methodology since time in which analyses can be performed is significantly shorter than more detailed analyses. The accuracy (maximum inaccuracy of 19%) is sufficient for conceptual design, while the results are on the conservative side. It will always be needed to perform a 3D stress analysis later in the design stage, ensuring that the design will meet the requirements. WelToGen lowers the risk of the late analysis showing that the tooling needs changes due to requirement unfulfillment.

Cost Module. The CM performs the cost estimation of the modeled geometry. The geometry lacks sections of the tooling and details that could affect the tooling cost. The parameters used are based on the cost engineers' experience and order-of-magnitude comparisons. Therefore, WelToGen cost results cannot be taken as an absolute final figure of the tooling cost. However, the possibility of using relative cost of designs between each other makes the tool suitable for performing design trade-offs and design exploration in the early stages of design.

4

Experimental Set-Up & Results

A methodology for introducing manufacturing analyses in aircraft component design has been presented. Based on the methodology, a KBE application, WelToGen, capable of generating thermoplastic welding tooling geometry for a given rudder geometry has been created. The program includes automated feasibility assessments and tooling cost estimation. In order to test the efficacy of WelToGen as a manufacturing analysis tool, several experimental set-ups are created and tested. The results from these experiments will show whether the developed methodology fulfills the objectives and how the use of the methodology affects the design process' effectiveness and the effect on the design results.

4.1. Integration with Rudder Generator

WelToGen's development was aimed at being easily integrated in Fokker's rudder front loaded automated design program, Rudder Generator (RG). After WelToGen was created and validated, the integration took place.

In the RG, a new functionality was implemented which automatically takes from the rudder model the necessary geometry inputs for WelToGen, as explained in section 2.3. The geometrical elements are instances of ParaPy elements with which the WelToGen can operate directly. The geometry is grouped as WelToGen requires and remains available as parts of the main RG class. WelToGen is instantiated as a child-object of the RG main class. WelToGen is integrated as a capability module in the RG with the objective of setting a precedence for future manufacturing analysis capability modules (e.g. layup tooling generator, tolerance analysis, production plant simulations, etc.). In Figure 19, the RG product tree with WelToGen integrated can be seen. Integrated in this way, WelToGen can access the RG model, thus can obtain the necessary input geometry. In ParaPy's display, both the rudder and the tooling can be shown together. The integration with RG was successfully achieved; WelToGen positively communicated automatically with the other RG's modules, receiving the input geometry.

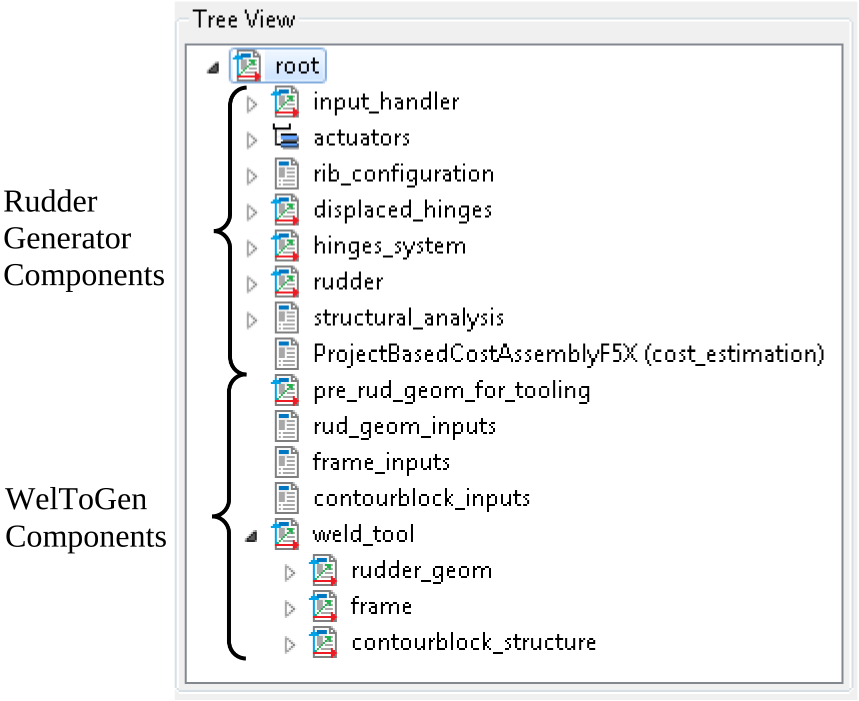
Rudder Generator Components
WelToGen Components
Tree View
root
input_handler
actuators
rib_configuration
displaced_hinges
hinges_system
rudder
structural_analysis
ProjectBasedCostAssemblyF5X (cost_estimation)
pre_rud_geom_for_tooling
rud_geom_inputs
frame_inputs
contourblock_inputs
weld_tool
rudder_geom
frame
contourblock_structure

Figure 19: Rudder Generator's tree structure with WelToGen integrated.

Despite the successful integration, it was not possible to perform rudder design and tooling design studies with this setup. It was found that the rudders created by the RG did not fulfill the requirements to be welded[6]. The RG defines the rudder WLs without accounting for manufacturability due to the lack of manufacturing knowledge in the RG's coded rules. From a manufacturing point of view, the WLs are incorrectly defined. Examples of the incorrectly defined WLs are:

- The aft spar WL is continuous; it does not include any break. Without breaks, no separator beams can be placed inside the frame box. Also, the WL is longer than the maximum WL length allowed.
- Some forward spar WL breaks are too far apart from each other, i.e. some WL segments are longer than the maximum length allowed. Also, other WL breaks are too close to each other, i.e. the welding process cannot occur due to the shortness of the WL segment.
- The distance between some of the ribs is too small. The tooling design rules encoded in WelToGen are not prepared for the rib WLs to be so close to each other due to clash between tooling rib beams.

The tooling design knowledge coded in WelToGen requires the input geometry to respect welding tooling requirements. Therefore, WelToGen is not capable of creating tooling for input geometry defined by the RG, running into errors which stop the tooling creation process when the input given is not suitable for one of the operations of tooling creation.

The impossibility of obtaining results is a valuable result for Fokker. WelToGen's integration identified exact missing knowledge in RG's rudder design rules. It is out of the scope of this thesis to include the missing rudder design knowledge in the RG. However, analyzing the errors which WelToGen encounters, it was possible to create a list of WL definition knowledge rules from the manufacturing perspective. The created report is included in the database of knowledge to be implemented in the RG in future work. Once the RG team implements the necessary knowledge and the rudder design respects the thermoplastic welding constraints, optimization studies and design exploration can be done with the RG with WelToGen integrated.

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[6] Note that the Rudder Generator is a KBE application still in development, hence it lacks rudder design knowledge. The implementation of new functionalities and lacking knowledge is a work in progress.

4.2. Tooling Design Protocol

WelToGen generates tooling designs given the input geometry and tooling design inputs, allowing to discern their feasibility according to the welding requirements. However, WelToGen has no capabilities to select the tooling design inputs, apart from selecting the welding angles and torch offset distance to ensure frame gap feasibility and torch clash feasibility, respectively (refer to section 3.3.3). To fully complete the automated tooling design, a design protocol must be created to select the tooling design inputs. The protocol will perform design modifications to ensure the fulfilment of the displacement requirement and afterwards, the Geometry Module's feasibility capabilities will be run to obtain the welding angles and the torch offsets. This protocol is created to be used for the experimental cases presented in chapter 4 which will test WelToGen's capabilities.

The protocol will be based in starting with the cheapest tooling possible (i.e. all elements to the thinnest standard thickness, lowest number of reinforcement elements, etc.) and then scaling up the stiffness until the displacement requirement is met. The minimum, maximum and allowed values for each parameter will be explained in the following sub-section. Before defining the protocol, some considerations used to design the protocol steps will be explained. In Figure 2 the nomenclature of the tooling inner elements can be checked. The principle of the cheapest tooling is not followed in two cases:

1. **Frame Closing Beams' Reinforcement.** The closing structure of the frame is composed, as was seen in Figure 1, by a middle beam and the closing beams, which are welded to the middle beam and clamped to the frame. The closing beams are present in pairs and in the original tooling design they can be of two types, seen in Figure 20, standard or reinforced. The reinforced beams include an extra metal plate between the pair and do not include cuts in the beam pair. In Fokker's welding tooling, the two types coexist in the same tooling, being the pairs of closing beams of the reinforced type in the zones where more displacement occurs. In WelToGen, an input was included to select which of the closing beam pairs are reinforced.

   The reinforced beams are a design choice which strongly influences the tooling stiffness, yet do not imply a significant difference in cost. Two tooling models with five closing beam pairs were created; five is a typical number for tooling for business jet sized rudders, while the smallest tooling would have three and a tooling for a single aisle passenger aircraft would have eight. One of the models had all closing beam pairs standard and the other all pairs reinforced. The tooling cost was estimated for both models using WelToGen's CM and the maximum displacement value obtained with the FEMM. The results of the comparison are shown in Table 8.

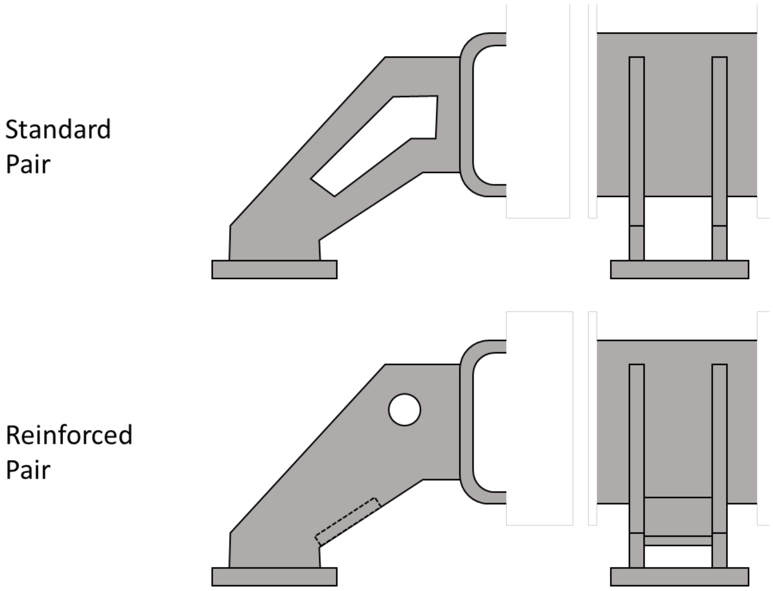


Figure 20: Standard closing beam geometry vs. reinforced closing beam geometry.

Table 8: Displacement and cost comparison of tooling with standard closing beams and reinforced closing beams. The tooling design has 5 closing beam pairs.

	Maximum Displacement (Normalized)	Tooling Cost (Normalized)
Standard Closing Beams	1.0	1.0
Reinforced Closing Beams	0.952	1.0

It was found that the reinforced tooling, with an increase of less than 0.05% in cost (outside of WelToGen's precision), presented a reduction of almost 5% in maximum displacement. The reason for having standard closing beam pairs in the actual tooling is for weight reduction purposes. The closing structure needs to be moved for every rudder produced in order to place the components before the welding and take out the welded rudder. It would be necessary to perform weight studies, yet the added weight of the closing beams over the total tooling weight to be lifted is expected to be not relevant considering the safety margins of the machinery used in tooling operation, as was previously explained. For these reasons, it was decided to always select in the protocol the reinforced pair, despite not following the principle of cheapest tooling. Setting the protocol to always reinforce closing beams eliminates one parameter to be varied, hence simplifying the protocol.

2. **Frame Box Width.** The width of the frame box has a significant impact on the tooling stiffness. The width of the frame determines the height of all beam sections inside the frame box. The height of a beam section determines the moment of inertia by a power of three. Finally, the stiffness of a beam in bending depends on the moment of inertia. This chain of relations shows that the tooling displacements will be reduced approximately by the power of three of increasing the width:

$$displacements \propto \frac{1}{beam\ moment\ of\ intertia} \propto \frac{1}{section\ height^3} \propto \frac{1}{frame\ width^3}$$

On the other hand, the cost will be approximately linearly increased with the frame width. The frame width increases the volume linearly, and thus the material used linearly. Since the frame width affects to all the elements in the frame box, it can be said that approximately the volume and thus the cost of the tooling increase linearly with the width:

$$tooling\ cost\ \propto material\ volume\ \propto frame\ width$$

To prove this, tooling models were created with the same parameters except the frame width. The results are shown in Figure 21:

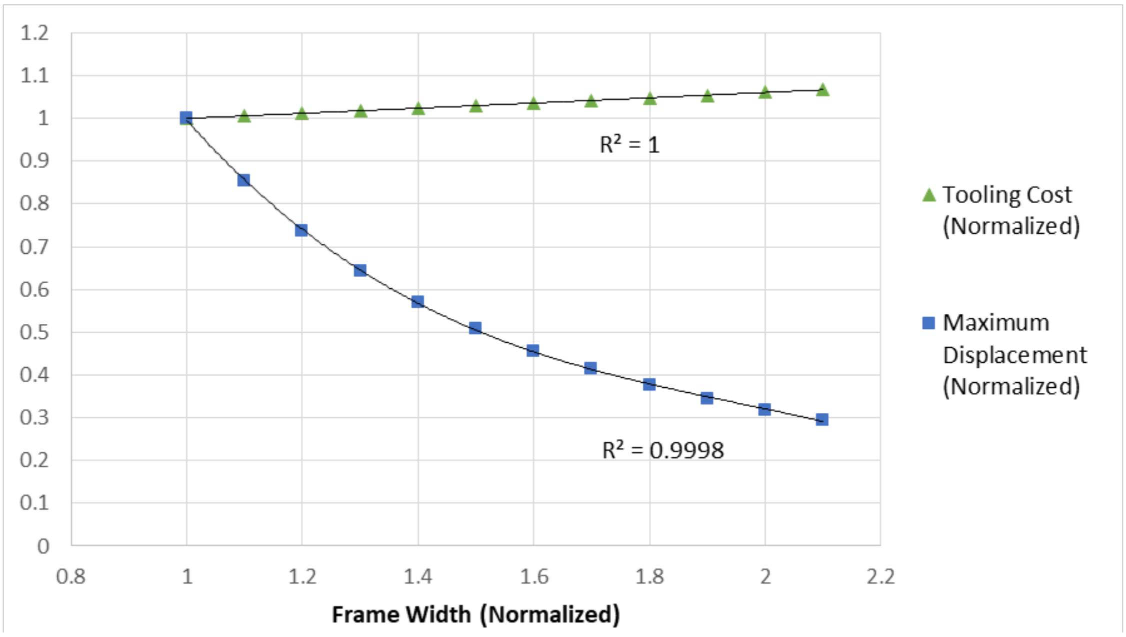


Figure 21: Tooling cost and maximum displacement vs. frame width.

The results are shown with regression lines, linear for the cost and third-degree polynomial for the displacement. The high coefficient of determination (R) values show how the aforementioned relations with the frame width are valid. Due to this, the tooling models will always be started with the maximum allowed width. The maximum allowed width will be explained in the following section. In the cases in which the tooling is oversized, the frame will be reduced as will be further explained when detailing the protocol.

Additional tooling input variables are eliminated to simplify the protocol when examining the cross beams in the frame box. Inside the frame box, between the spars, there are cross beams which run from rib to rib, parallel to the spar lines, as shown in Figure 2. These cross beams were added to the design by the outsource company as reinforcements inside the torsion boxes between rib beams. In the same way as the closing beam reinforcement, two tooling models were created with WelToGen, one with several lines of cross beams and one without any cross beams. The results are shown in Table 9.

Table 9: Displacement and cost comparison of tooling without cross beams and with cross beams.

	Maximum Displacement (Normalized)	Tooling Cost (Normalized)
No Cross Beams	1.0	1.0
With Cross Beams	0.993	1.03

The results showed that the presence of cross beams stiff the structure, obtaining a 0.7% less displacement. However, the increase in cost is much more significant, a 3%, due to the increase in part count. These results were shown to the tooling engineer at Fokker, who could not give a clear explanation about why the outsource company decided to keep the cross beams in the design. It is apparent that no study similar to this one was performed, hence the effect of the cross beams on cost and deflection were unknown for the engineers. With WelToGen, studies similar to this one can be performed, avoiding uninformed design decisions such as including cross beams. It was decided for the protocol to create all tooling models without any cross beam, simplifying the variable choice. In this case, cross beams imply not one additional variable, but one for each region in the frame box, since the number of cross beams is selected independently for the regions.

An automated optimization algorithm set to minimize cost while fulfilling displacement searches for the parameters which variation increases the most stiffness while having the least increase in cost or even positive effects in cost. Therefore, it is expected that if automated optimization would be used for the tooling design, the algorithm would make all closing beams reinforced and would create the design without cross beams. It was decided to already create the designs without cross beams and with all closing beams reinforced as default.

4.2.1. Protocol Definition

Having eliminated tooling design variables, the tooling design parameters that are varied in the protocol are:

- **Frame width.** As explained, the frame width will be at the maximum allowed and be reduced in steps if the frame is oversized.
    - **Maximum Value:** The frame width cannot exceed the torch head length or there will be clashing with the robotic arm which holds the torch head.
    - **Minimum Value:** The frame width has a minimum value set for pneumatic and electrical systems to be fitted inside the box.
- **Inner beam thicknesses.** These will be varied independently for each beam according to specific sub-routines that will be further explained in this section. The beams widths are selected from a list of standard hot rolled plate thicknesses. The program can only select the standard values.
    - **Maximum and minimum values:** Recommended maximum and minimum standard thicknesses by the tooling engineers.
- **Thickness of the frame box's skins.** The starting point for the skins thicknesses is the minimum allowed value. The thickness of the plates are also selected from the standard thicknesses of hot rolled plates.
- **Pitch of the extra reinforcement beams.** The initial tooling always starts with a minimum amount of one reinforcement beam per tooling region (due to code restrictions, at least one beam is necessary). The pitch is reduced in steps.
    - **Maximum Value:** One reinforcement beam per region.
    - **Minimum Value:** Set with tooling engineer.

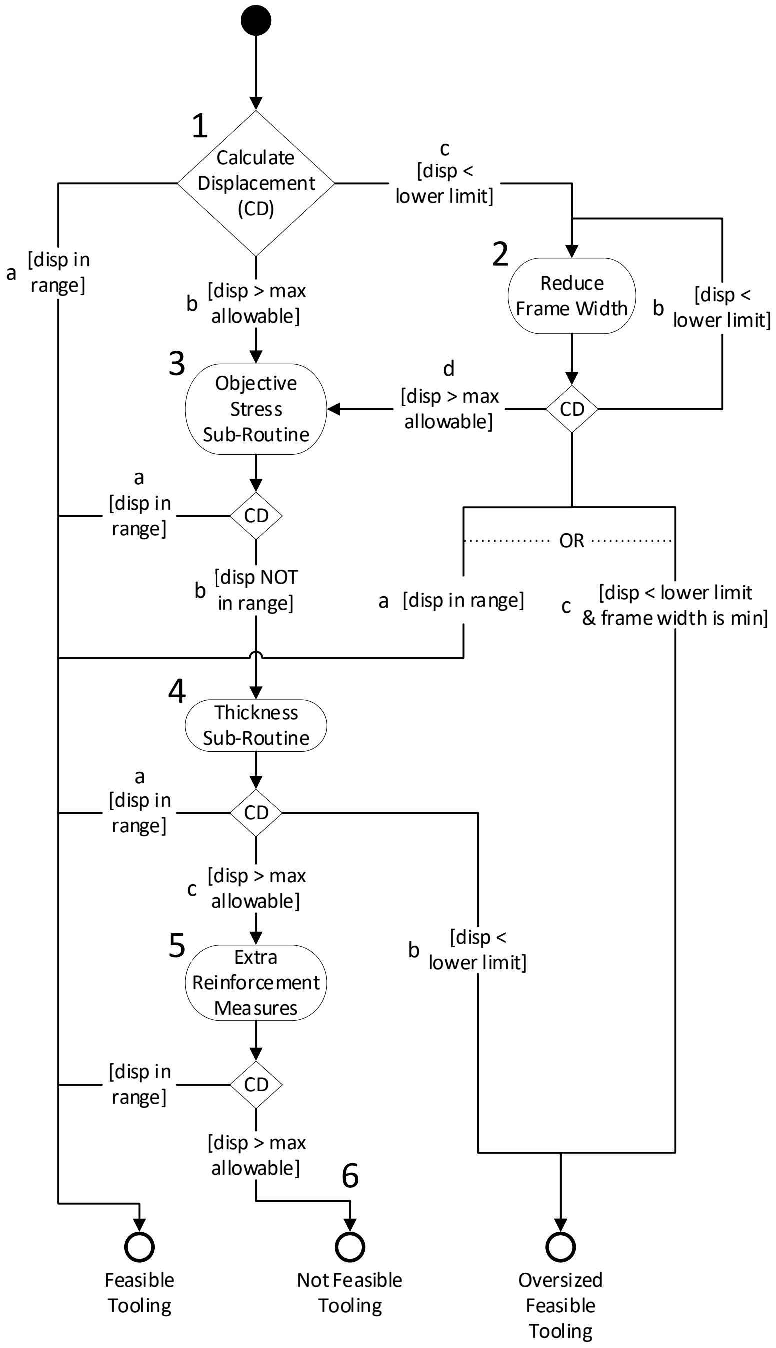
Two inputs are needed for the protocol: the maximum allowable displacement value and the delta for requirement fulfilment. Tooling design is aimed at fulfilling the requirement as close as possible to the maximum allowable, since oversizing will imply unnecessary cost and weight. The given delta is the stopping criterion for the protocol (i.e. how close to the maximum allowable is acceptable to stop modifying the design). Therefore, the protocol will stop if the tooling displacement fulfills the condition:

$$\textit{maximum allowable} > \textit{tooling maximum displacement} > \textit{lower limit},$$

$$\textit{with}: \quad \textit{lower limit} = \textit{maximum allowable} - \textit{delta}$$

For simplification, the values in between the maximum allowable and the lower limit will be called "allowable range" and the maximum tooling displacement value will be called "displacement", from this point on.

As explained, the initial point for every tooling design given to the protocol is minimum thickness for all elements, maximum frame width and maximum extra reinforcement beams' pitch. Each step of the protocol will be explained; the protocol activity diagram can be seen in Figure 22.



1
Calculate Displacement (CD)
c [disp < lower limit]
a [disp in range]
b [disp > max allowable]
2
Reduce Frame Width
b [disp < lower limit]
3
Objective Stress Sub-Routine
d [disp > max allowable]
CD
a [disp in range]
CD
b [disp NOT in range]
OR
a [disp in range]
c [disp < lower limit & frame width is min]
4
Thickness Sub-Routine
a [disp in range]
CD
c [disp > max allowable]
b [disp < lower limit]
5
Extra Reinforcement Measures
[disp in range]
CD
[disp > max allowable]
6
Feasible Tooling
Not Feasible Tooling
Oversized Feasible Tooling

Figure 22: Activity diagram of the tooling modification protocol.

The protocol steps indicated in Figure 22:

1. The initial tooling's displacement is calculated:
    a. If $displacement\ in\ allowable\ range$, the protocol stops; the initial tooling fulfills the requirement.
    b. If $displacement < lower\ limit$, the initial tooling is oversized, thus the frame width is reduced (step number 2).
    c. If $displacement > maximum\ allowable$, the tooling is not stiff enough, thus inner frame elements will be reinforced (step number 3).
2. The frame width is reduced iteratively. There is a defined width step value which is reduced from the frame width. After each reduction, the displacement is calculated:
    a. If $displacement\ in\ allowable\ range$, the protocol stops.
    b. If $displacement < lower\ limit$, another frame width reduction step is taken.
    c. If $displacement < lower\ limit$ and the tooling has reached the minimum frame width allowed, the protocol stops. The tooling cannot be made cheaper.
    d. If $displacement > maximum\ allowable$, the frame width reduction made the tooling too flexible, thus inner frame elements will be reinforced (step number 3). Modifying the inner elements instead of going back one step in frame reduction is done since the inner frame modification sub-routines are more precise in changing the displacement, while the frame width implies big changes in displacement each step.
3. The frame inner elements need to be modified due to displacements larger than the maximum allowable. First the objective stress sub-routine is run (note, this routine is run only once). The sub-routine will be explained next. Then, the displacement is calculated:
    a. If $displacement\ is\ in\ allowable\ range$, the protocol stops; the modified tooling fulfills the requirement.
    b. If $displacement\ is\ not\ in\ allowable\ range$, the iterative thickness modification sub-routine is run (step number 4).
4. The thickness modification sub-routine is run if the displacement is not in the allowable range; whether the displacement is higher than the maximum allowable or lower than the lower limit. As it will be explained later in this section, the sub-routine will run iterations until the requirement is met or until the frame cannot be any longer modified. Therefore, the possibilities after all iterations have been run are three:
    a. If $displacement\ is\ in\ allowable\ range$, the protocol stops; the modified tooling fulfills the requirement.
    b. If $displacement < lower\ limit$, the protocol stops with an oversized tooling since the thickness cannot be reduced any further. The tooling cannot be made cheaper.
    c. If $displacement > maximum\ allowable$, the tooling is at the maximum thickness allowed and the two sub-routines have been applied still not managing to make the tooling stiff enough. Extra steps for increasing stiffness are tried (step number 5).
5. To further increase the stiffness, there are more variables that can be modified, which were found to have a lower stiffness-to-cost ratio than the stiffening measures used in previous steps. The extra reinforcement measures are left to be modified only if all the other processes did not succeed in making the tooling meet the displacement constraint. The protocol is to apply these incrementally as they are listed here, checking at every change if the displacement is met. The order was decided by the programmer due to the inexistence of reasons to select

a specific order. If after any of these changes, the requirement is met, the protocol exits; the tooling is stiff enough. The list of changes is:

   a. Ensure that the region beams have the maximum allowed thickness.
   b. Ensure that the spar beams have the maximum allowed thickness.
   c. Increase the frame box's skins thickness.
   d. Reduce the pitch of the reinforcement beams.

6. In case all the changes introduced do not suffice for meeting the displacement requirement, the protocol exits with a warning message; the tooling is not sufficiently stiff and cannot be made stiffer.

Two sub-routines are used in the protocol, objective stress thickness increase and the iterative thickness modification. The processes followed by the two sub-routines are:

Objective Stress Thickness Increase. This sub-routine is used for increasing the thickness of the inner elements when the displacement constraint is violated. The process is based on calculating the objective stress that the beams should have in order for the tooling maximum displacement value be the maximum allowable. Once this objective stress is known, the beams' thicknesses are changed to obtain that stress in all of them.

The objective stress method starts by having the information from the displacement analysis; the maximum displacement node, the displacement value and the stress of each beam are known. Then, several steps are followed:

1. The tooling region in which the maximum displacement point is located is determined by the program. Once the region is known, it is possible to determine the longest load path that goes from fixing point to fixing point passing through the maximum displacement node. This path is seen in Figure 23.

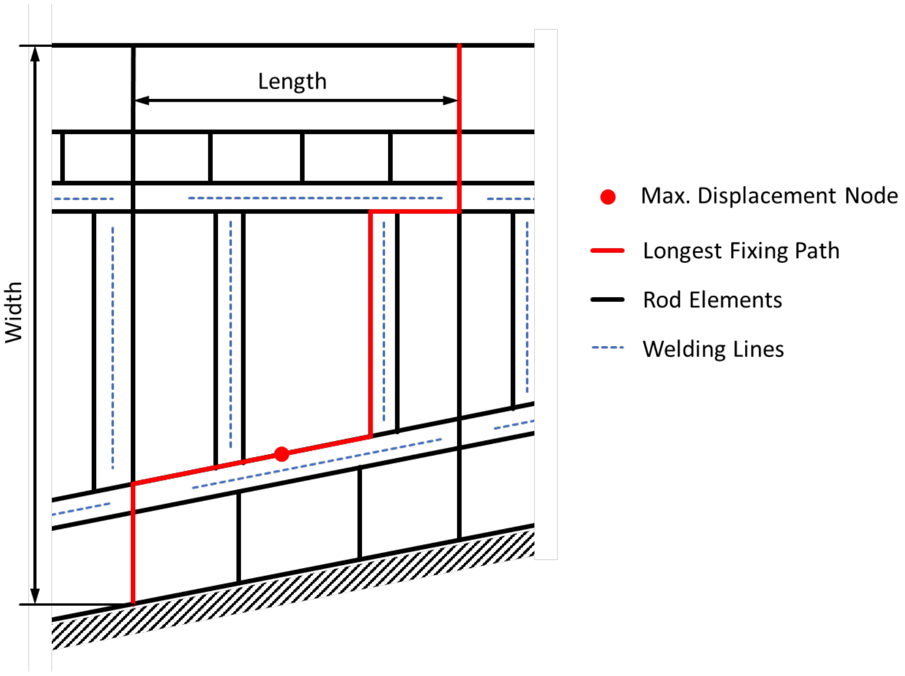


Figure 23: Maximum displacement node in the tooling and longest path between fixing points.

A beam of the same length as the longest load path is created, i.e. a beam composed by all the beams that are in the longest path. As was seen in Figure 23, the longest path can be represented by a beam which length is the sum of the region's width plus the region's length.

It is assumed that the beam is composed entirely by loaded beams, thus it is completely loaded with a line load. This beam, of length L and which properties are EI, is seen in Figure 24.

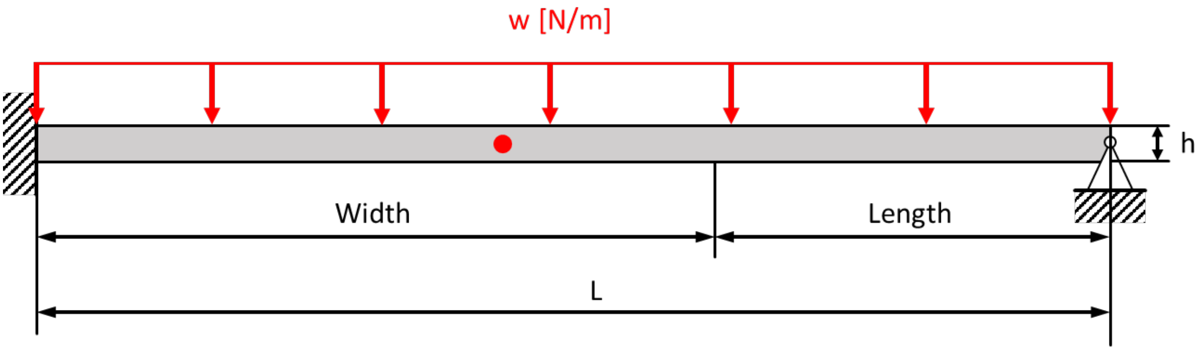


Figure 24: Beam equivalent to the sum of beams which compose the longest path.

The objective of the method is to calculate the stress in the beam if the displacement of the maximum displacement node is set to the maximum allowable displacement, thus being called the objective stress. For calculating the objective stress, the equations of stress, moment and displacement for a beam supported as the equivalent beam are used:

$$\left.\begin{aligned} d = \frac{5}{384}\frac{wL^4}{EI} \quad \rightarrow \quad I_{objective} &= \frac{5}{384}\frac{wL^4}{E \cdot d_{maximum\ allowable}} \\ M &= \frac{wL^2}{8} \\ \sigma_{objective} &= \frac{M}{I_{objective}}\frac{h}{2} \end{aligned}\right\} \rightarrow$$

$$\rightarrow \quad \sigma_{objective} = \frac{\frac{wL^2}{8}}{\frac{5}{384}\frac{wL^4}{E \cdot d_{maximum\ allowable}}}\frac{h}{2} = \frac{24}{5}\frac{E \cdot d_{maximum\ allowable}}{L^2}h$$

2. The ratio between the objective stress of the equivalent beam and the actual stress of each beam obtained on the displacement simulation is obtained. Additionally, with the stress formula, the ratio can be applied to the beam moment of inertia since the moment and beam height are equal:

$$\frac{\sigma_{objective}}{\sigma_{actual}} = \frac{I_{actual}}{I_{objective}}$$

The moment of inertia for a beam with I section of height h and thickness t is:

$$I = \frac{1}{12}th^3$$

Therefore, the objective thickness in relation to the actual thickness can be obtained:

$$t_{objective} = \frac{\sigma_{actual}}{\sigma_{objective}}t_{actual}$$

3. For each beam present in the frame, the actual stress obtained in the simulation is compared to the objective stress. The thickness is modified using the aforementioned relation. The thickness that is actually applied to the beam will be the standard hot rolled plate thickness closest to the value obtained from the relation. If the stress ratio is lower than the unity but the beam is already at the lowest thickness, the beam will be unmodified. The same will happen if the stress ratio is higher than the unity but the beam is already at the maximum standard thickness.

   Iterative Thickness Modification. This sub-routine will be used in case that after the objective stress thickness modification the displacement is not within the range, whether the displacement is higher than the maximum allowable or lower than the lower limit. The sub-routine is used iteratively until the displacement is within the allowable range. There is a possibility that the thicknesses cannot be modified any longer and the requirement is still not met. In those cases, the sub-routine is programmed to stop the iterations and display a message.
   The modification of the thicknesses is done iteratively, depending on the tooling displacement at the moment of calling this sub-routine:

1. If the displacement is smaller than the lower limit, the tooling is oversized; cost can be reduced while still meeting the displacement requirement. For increasing the displacement, the thicknesses of all beams are reduced one step on the list of standard thicknesses. The beams which thickness is already the lowest one, are omitted.
2. If the displacement is larger than the maximum allowable, the tooling needs to be stiffer. For reducing the displacement, the thickness of the beams in the stress top 10% is increased one step on the list of standard thicknesses.

The aim of decreasing all thicknesses disregarding their stress level while increasing thicknesses of only the top 10% stressed beams is to reduce the variance in stress within all frame beams. While the stress is increased for all beams when decreasing thicknesses, only the most stressed beams will see their stress reduced when increasing thicknesses. In this manner, the stress peaks will be reduced leading to a more homogeneous stress distribution in the frame structure.

4.3. Tested Rudder Geometries

With WelToGen, rudder designs can now be easily analyzed for manufacturing. Several rudder cases have been given to WelToGen as inputs, then the protocol has been run and the outputs analyzed. The cases tested are divided in three types:

- Components for which the tooling has already been manufactured: BJ2’s rudder and aileron.
- Components for which the tooling was manufactured previously with different knowledge to the one captured in WelToGen: Business Jet 1’s (BJ1) rudder.
- Components which are within Fokker’s potential future contracts: single-aisle narrow body airliner (NBA) and general aviation light aircraft (LA).

WelToGen was run on a computer with a processor with maximum frequency of 2.67 gigahertz and 8 gigabytes of memory. In Table 10, the times that it took to perform each step of the tooling generation and analyses are presented for the reader to obtain an order of magnitude. The times shown are for an average business jet rudder (similar to BJ2), the times being approximately 20%

shorter for the smallest rudders (LA) and 20% longer for the largest rudders (NBA). The times are valid also for the results that will be presented in section 4.4. The approximate total amount of time to generate a conceptual tooling design, ensure its feasibility and analyze its cost is 10 minutes. Fokker's traditional design method requires to generate a detailed tooling model before the feasibility assessments are performed. The time for creating such a detailed model is in the order of weeks or even months.

Table 10: WelToGen's computational time for each activity in the manufacturing analysis. Processor maximum frequency of 2.67 gigahertz and 8 gigabytes of memory.

Activity	Geometry Generation	Ensuring Torch Clash Feasibility	Ensuring Welding Angle Feasibility	Displacement Calculation	Frame Sizing (Running Protocol)	Cost Estimation
Time	2 min	3 min	1 min	15 sec	4 min	1 min

Components with existing tooling.

The tooling of BJ2's rudder and aileron fall into this category. These two tooling models belong to the last generation of tooling manufactured by Fokker, being an improvement of the first generation of tooling, the BJ1 rudder's tooling. BJ2's tooling was designed differently from the first generation, based on the lessons learned from the first. The knowledge rules used to design these tooling models are the rules coded into WelToGen. In the future, Fokker will continue using the second generation's rules.

BJ2's tooling was used for the verification and validation of WelToGen. The tooling geometry and the stress reports are available at Fokker and were used for comparison. WelToGen's code was improved until its output was sufficiently similar to the actual tooling for the purposes of this project, as has been explained in section 3.4. BJ2's inputs (both BJ2's rudder and ailerons geometries) were given to WelToGen and the tooling geometries obtained were imitating the actual tooling geometry. In addition, the displacement requirement was met, while being similar in value to the stress reports, as was shown in Table 6 (section 3.4.2).

Also, the protocol was run on the tooling models. Previously, the tooling design inputs were set to the starting point of the protocol (minimum thicknesses and reinforcement beams, maximum frame width), instead of the actual BJ2 tooling original inputs. The characteristics of the tooling models obtained with WelToGen using the protocol for designing are compared to the tooling models generated by WelToGen imitating the actual tooling, as can be seen in Table 11.

Table 11: Characteristics of BJ2 rudder and aileron tooling generated with WelToGen, with the Fokker manufactured tooling inputs vs. using the modifying protocol.

	Maximum Displacement (Normalized with maximum allowable)	Tooling Cost (Normalized)
BJ2 Rudder Fokker Tooling	0.99	1
BJ2 Rudder Protocol Tooling	0.934	0.946
BJ2 Aileron Fokker Tooling	0.965	1
BJ2 Aileron Protocol Tooling	0.931	0.969

The tooling models for which design the protocol was used present lower cost than the tooling models designed to match the manufactured tooling. The rudder tooling after the protocol is estimated to be 5.4% cheaper while the aileron tooling 3.1% cheaper. The tooling models designed with the protocol also present lower displacements, being further from the maximum allowable displacement. The reduction in cost is due mainly to the absence of cross beams and the reinforcement of all closing beams. Without cross beams, the part count is considerably lower, implying less material used and less part manufacturing and assembly processes. The reinforcement of the closing beams allows for the inner structure to not be so reinforced (less reinforcement beams and thinner inner beams).

The generation of these conceptual tooling models and the performance of their analyses was done in a fast manner with WelToGen. WelToGen proved to be capable of bringing manufacturing analyses to the early stages of design with little information about the detailed design while delivering conceptual results which show improvement with respect to tooling designs generated with Fokker's traditional methods.

Components with first generation tooling.

The BJ1 rudder tooling was created at Fokker with different knowledge rules to the ones that are used currently in the tooling design process. The BJ1 input geometry was given to the WelToGen and the protocol was run. WelToGen generated a tooling which fulfilled all the tooling requirements. This tooling will be further used in the following section.

Fokker is currently working in updating BJ1's tooling, creating tooling for the same rudder geometry yet with the second generation knowledge. The tooling created for BJ1's rudder by WelToGen should be comparable to the tooling being designed at Fokker at the moment. However, the existence of the tooling update project became known only at the end of this thesis research project; it was not possible to compare WelToGen's output to the current state of Fokker's new tooling design.

The new tooling design is still a work in progress, hence Fokker can benefit from WelToGen to explore the design space for BJ1 rudder tooling. The tooling engineer at Fokker responsible of working with the outsource company on the BJ1 update project showed interest in supporting the rest of the tooling development with WelToGen. WelToGen can significantly enhance the conceptual design stage by shortening the tooling generation and analyses times and increasing the tooling engineer's design awareness.

Components from potential future contracts.

Fokker has created tooling only for three components in the past (BJ1 rudder and BJ2 rudder and aileron). The three geometries were similar in size and characteristics. However, Fokker's capabilities to design and manufacture tooling for components of different configuration is unknown. Therefore, two geometries which enter into Fokker's potential production are tested on the WelToGen, the rudder of a single-aisle narrow body aircraft (NBA) and the rudder of a light general aviation aircraft (LA). The inputs for WelToGen from both rudders were generated with the Dummy Rudder Generator (DRG), based on typical dimensions and characteristics of similar aircraft.

The NBA rudder was generated based on dimensions of aircraft from this category, such as the A320 and the B737. The rudders of these aircraft are approximately 50-60% larger than the rudders of business jets. The rudder model was given to WelToGen and the protocol run to select the tooling parameters. For the first geometry given, it was not possible to find feasible tooling; the displacement requirement was not met. The length of the spar beams was large, resulting in large deflections. It was found that, in order to design feasible tooling for large components using Fokker's current tooling design knowledge, the spar welding line (WL) breaks should be placed with a maximum distance between each other. The separator beams which serve as important structural elements of the tooling are placed at each WL break. The distance between two consecutive separator beams should not be large in order to reduce the spar beams displacements. Spar WL breaks were added in the aforementioned first rudder model until the protocol was capable of generating a feasible tooling for the rudder. The conceptual tooling model was checked by the tooling engineer, who did not find any design infeasibilities in the design and was engaged by the idea of analyzing tooling for larger rudders than the ones done at Fokker. The length of the regions (i.e. the distance between WL breaks) that was found to be the maximum limit was approximately the same as the length of the regions in the business jets' tooling models. Therefore, larger feasible tooling models can be generated if the distance between WL breaks does not exceed an approximate maximum, which is the region length of Fokker's existing tooling.

The LA rudder was generated based on the dimensions of a four seat, twin engine, propeller-driven aircraft, Diamond Aircraft Industries' DA42 Twin Star, which rudder is approximately 40% of a business jet rudder. The tooling generated was feasible in spite of having all thicknesses and frame width to the minimum due to the rudder's small size and low pressure applied (low number of ribs and spars). The tooling for small rudders is oversized (as will be seen in the following section, Table 12) since the tooling design rules were created to tackle stiffness issues in larger rudders. Oversized tooling might lead to discarding producing these type of components due to non-profitability. The tooling model was checked by the tooling engineer, who suggested that the model should be further analyzed to determine new design rules in order to create cheaper tooling. Changing the design for small component tooling geometries could open the possibility of making profitable the project of small thermoplastic welded rudders.

4.4. Parametrical Studies

Parametrical studies are a useful way of increasing design awareness, profiting from the automation of KBE applications. With an automated manufacturing detailed analysis tool, it is easily possible to study the influence of design parameters on the outcome's performance. Three aircraft component design parameters which affect the tooling design will be varied: component length, number of ribs and number of spar WL breaks. For each component design, the tooling will be generated with the protocol initial values and the protocol will be applied. The feasible tooling models' cost will be compared for each variable variation as well as compared with Fokker's current tooling cost estimation method.

As it has been explained, Fokker's welding tooling knowledge is not mature; the tooling design performance analysis at the conceptual design stage has been performed until now with a simple and not detailed method due to lack of design knowledge. Fokker's current welding tooling cost estimation is based on the length of the component for which the tooling is going to be created. The equation used is:

$$Tooling\ Cost = constant[€/m] * length_{component}[m]$$

Using such a method only provides rough estimations not suitable for design space exploration. Any changes in the component design which do not modify the length will not be captured by this method, hence not being possible to trade off such changes in the design. WelToGen's CM will provide a more detailed cost estimation, showing the effect that any change in the rudder definition will have in the tooling cost.

4.4.1. Component length

The component length is the only component design parameter that Fokker's cost method can capture. The models of different sized components have been given to WelToGen. The rudders are, from smallest to largest: LA rudder, BJ1 rudder, BJ2 rudder, BJ2 aileron and NBA rudder. The goal of this study is to analyze the influence of the component length over the tooling cost and to compare the results to Fokker's tooling cost estimation method. The tooling models generated in this study have been used to explore the potential of designing tooling of different size to the one manufactured in the past at Fokker, as was explained in section 4.3.

The tooling models were generated using the design protocol explained in section 4.2. All tooling models were designed to fulfill the displacement requirement and the welding angle and torch clash routines were also run, leading to fully feasible models. The normalized results obtained are shown in Figure 25.

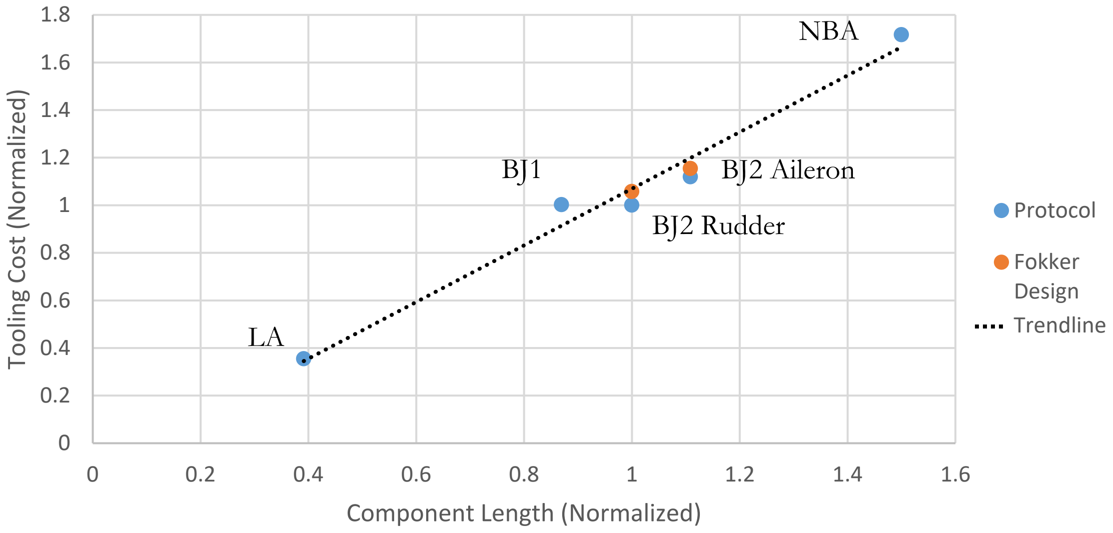


Figure 25: Tooling Cost vs. Tooling Length. Cost is normalized to the BJ2's cost and length.

In Figure 25, the cost of BJ2's tooling models designed to imitate Fokker's designs have also been included. The cost of the two models manufactured by Fokker is higher than the ones created with the protocol, as was already shown in Table 11 (section 4.3). The maximum displacement values for each tooling are presented in Table 12.

Table 12: Maximum displacement values (normalized with the maximum allowable) for the tooling models of the length study.

Light Aircraft	Business Jet 1	Business Jet 2 Rudder	Business Jet 2 Aileron	Narrow Body Aircraft
0.470	0.988	0.934	0.931	0.978

The tooling models created with WelToGen do not exactly follow a linear distribution as Fokker's estimation equation. The difference in cost estimation is due to the fact that the studied components differ with each other not only in length but also in other design characteristics such as number of ribs or number of spar WL breaks. The cost of the tooling does not depend solely on the component length and therefore Fokker's estimation method does not manage to capture in detail the component design's influence on the cost. Performing component design trade-offs using Fokker's estimations might lead to loss of opportunities when component designs are discarded expecting a high tooling cost than it would be if manufactured (points under regression line resembling BJ2 components). Also, Fokker's estimations might lead to high risk situations if a component design is selected expecting tooling cost lower than it is when manufactured (points over regression line alike BJ1 or NBA rudders).

WelToGen allows to perform more detailed design analyses, giving results which take into consideration more design parameters. The use of WelToGen in the early stages of design is possible due to the little design information needed and the ease and quickness of performing analyses of the design.

4.4.2. Number of ribs

The number of ribs in an aircraft component has a strong impact on the welding tooling performance. The amount of ribs influences the amount of pressure applied on the frame as well as the number of beams inside the frame box. A rudder with similar specifications to BJ2's rudder was created with the Dummy Rudder Generator (DRG). The number of ribs in this model was varied from 7 to 14 (typical range on rudders of this size), without varying the rudder length or the number of welding line breaks. The rudder geometries were given to WelToGen and the protocol was run. The results obtained are shown in Figure 26.

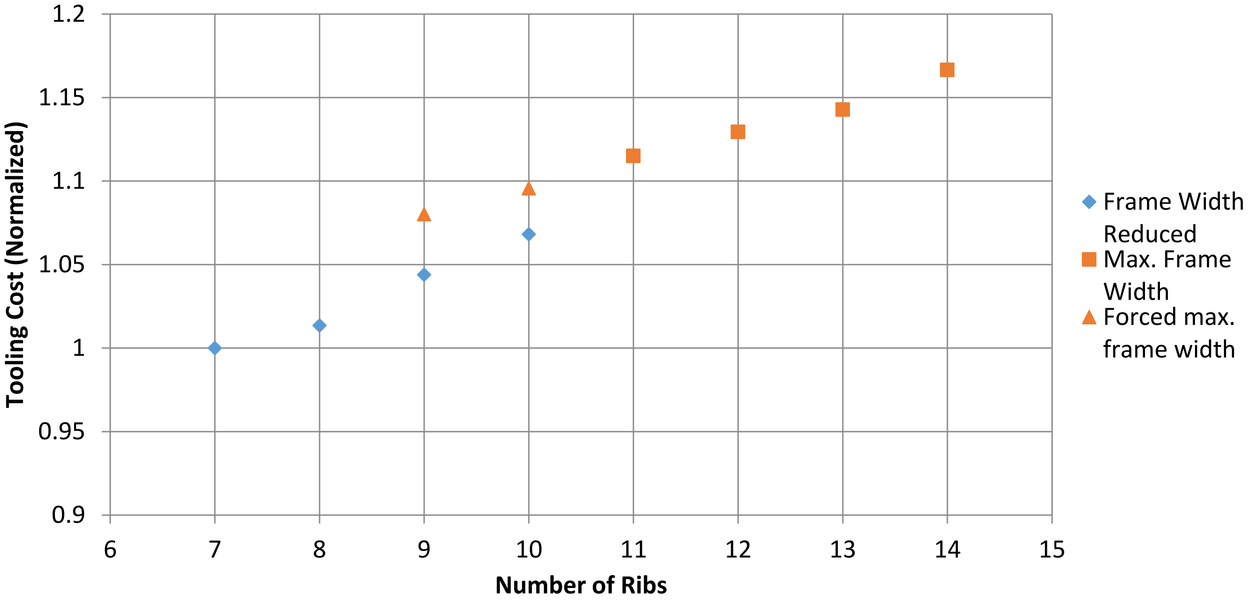


Figure 26: Tooling Cost vs. Number of Ribs. Cost is normalized to 7 ribs.

The results are divided in two groups, depending on the steps that the protocol applied on the model. For some models, the protocol had to reduce the frame width due to initial oversizing (lower number of ribs). For some other models, the protocol left the maximum frame width in addition to modify the inner structure to increase the stiffness (higher number of ribs). The results show two different regression lines for each of these protocol paths. The change from one protocol path to the next one is found when changing from 10 to 11 ribs. The amount of pressure applied on the frame reaches a threshold for which the protocol must keep maximum frame width in order for the tooling to be feasible. Increasing the number of ribs over the threshold will imply changing the design process, hence an increase in tooling cost (additional to the increase due to more pressure and more tooling parts). The threshold is different for each component geometry since it depends on other parameters of the component design which define the tooling geometry such as the component length or the WL breaks. Both the tooling engineer as well as rudder design engineers were interested in the implications of these results. When designing a component, knowing this threshold can be a decisive information for making design choices on the number of ribs.

Also, the protocol was forced to design the 9 and 10 ribs' tooling models performing the same steps as for the tooling models with more ribs. These results allow to see more clearly the two different regression lines depending on the protocol path. Also, the results show the ability of the created protocol to change the design path taken finding cheaper feasible tooling. The maximum displacement values for each tooling are presented in Table 13. In the table, it can be seen how the tooling models for 9 and 10 ribs which have been forced to maximum width are oversized. The tooling models which followed the standard protocol path reach fulfill the displacement requirement but closer to the maximum allowed and thus they are cheaper.

Table 13: Maximum displacement values (normalized with the maximum allowable) for the tooling models of the number of ribs study.

Number of Ribs	7	8	9	10	11	12	13	14	9 (forced)	10 (forced)

Maximum Displacement (Normalized with maximum allowable)	0.918	0.908	0.916	0.913	0.924	0.927	0.953	0.954	0.474	0.536

4.4.3. Number of spar welding line breaks

The number of breaks in the spar WLs determines the number of separator beams in the frame box. The separator beams are placed at each WL break and have an important task: structurally connecting the two fixing points (the closing beams and the clamping to the tooling support). More WL breaks will imply more separator beams, also closer to each other, thus a stiffer tool. The WL breaks also entail a higher part count in the tooling and worse joint properties due to more interruptions and shorter welded length.

With the DRG, a rudder of similar characteristics as the BJ2 rudder was generated. The number of breaks in the spars of this rudder was varied from 1 to 4. These rudder geometries were given to WelToGen and the protocol run to design their tooling. The protocol managed to find feasible tooling for all geometries except the rudder with only one WL break, as it will be further explained. The possibility of generating tooling for a rudder without any WL break was discarded after finding that it was unfeasible with one break. The results are shown in Figure 27. The tooling cost is normalized to the cost of 3 WL breaks since this is the number of WL breaks in the BJ2 rudder.

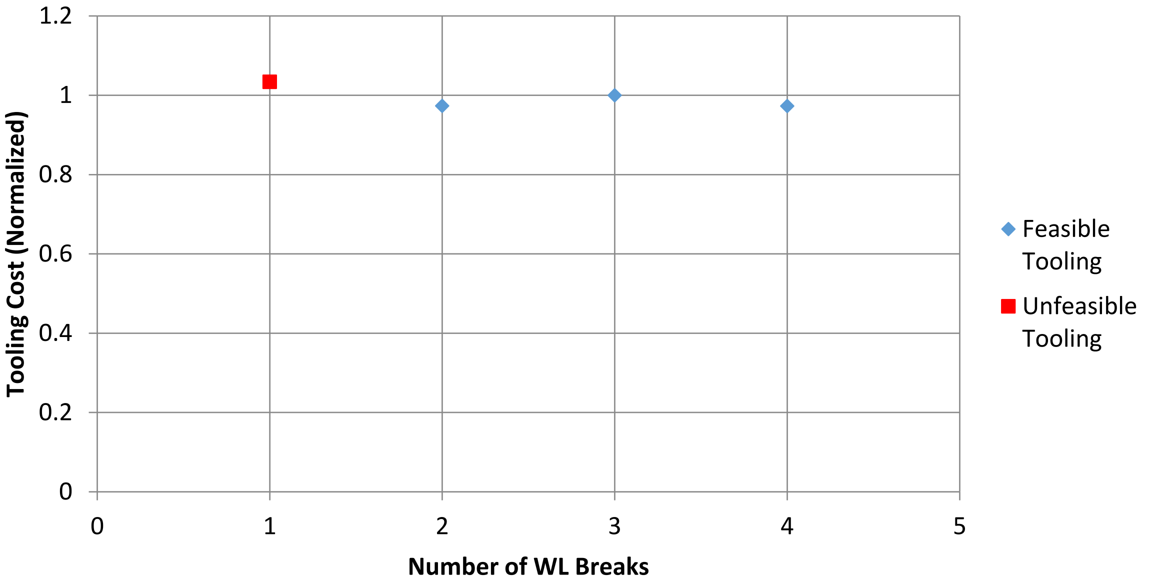


Figure 27: Tooling Cost vs. Number of Welding Line Breaks. Cost is normalized to 3 breaks.

The results show that the unfeasible tooling is the most expensive one. The protocol tried to make this tooling as stiff as possible until no more parameters could be changed, still not managing to find a feasible tooling as seen in Table 14. This tooling presents all thicknesses, frame width and number of reinforcements at the maximum value, consequently at the maximum cost. The reason why it is not possible to generate feasible tooling is due to the spar beams, which due to their length bend considerably without any reinforcement restricting their movement. Shorter regions will reduce the bending of the beams within the regions.

It is seen that the maximum cost is for the tooling with 3 breaks. The tooling for a rudder with 4 breaks has a lower cost since the reduction in thicknesses, frame width and number of reinforcements implies a reduction in cost larger than the increase of cost due to part count. The tooling for a rudder of 2 breaks found by the protocol is the cheapest of the four tooling models. Despite having longer regions, the increase in cost due to stiffening design parameters does not trump the decrease in cost due to lower part count. In Table 14, the displacement results show that the tooling for 3 breaks is oversized compared to the tooling models for 2 and 4 breaks. This can explain the differences in cost. A comparison in which the maximum displacement of the three tooling models is more similar should be performed.

WelToGen is capable of estimating the tooling cost, yet the existence of the WL breaks affect other costs that should be looked at. The spar WL breaks implies having more interruptions during the welding process, since every break in the WLs forces the torch to stop welding, exit the frame’s gap, move to the following gap, enter the frame and start welding. The recurring cost of an interrupted welding process is much higher than a continuous process due to the lost time in stopping the process. The reduction in recurring costs could be another reason to select the rudder design with 3 WL breaks. In addition, the engineering time for preparing a welding process with less breaks is lower, also affecting recurring costs not accounted for by WelToGen. Recommendations will be given in the last chapter for

The tooling for 3 breaks is the tooling which resembles the BJ2 tooling, meaning that the tooling design manufactured at Fokker could have been cheaper according to WelToGen if the rudder had been designed with 3 WL breaks. This design decision should also be studied for other rudder design requirements. If WelToGen had been available at the rudder design early stages, the rudder design team would have had more information when trading off different component designs. Furthermore, the decisions could be made accounting for other costs such as the welding time and the welding process engineering time if more manufacturing analysis tools were added.

Table 14: Maximum displacement values (normalized with the maximum allowable) for the tooling models of the number of spar welding line breaks study.

Number of Spar WL Breaks	1	2	3	4
Maximum Displacement (Normalized with maximum allowable)	1.34 (unfeasible)	0.956	0.912	0.933

5

Conclusions & Recommendations

The limitations of Fokker's design methods, both traditional (Concurrent Engineering) and new front-loaded-based methodologies (Rudder Generator) were presented. In order to reduce the time inefficiency of the former and the latter's limited implementation of manufacturing rules, a methodology for performing manufacturing analyses was developed. A Knowledge Based Engineering application, WelToGen, was developed, capable of generating welding tooling conceptual design for a given rudder geometry as well as analyzing its feasibility and estimating the tooling cost. In addition to WelToGen, a protocol for sizing the tooling was created. The protocol modifies the tooling design parameters until a feasible tooling is found.

Several tests were performed to analyze WelToGen's efficacy in fulfilling the project objectives in addition to answer the research questions. In this chapter, conclusions on the results obtained in chapter 4 will be drawn and discussed with respect to the problem statement. Finally, recommendations for future work will be given based on the methodology's limitations and in the results found.

5.1. Conclusions

WelToGen, together with the tooling design protocol, automates the tooling creation process and the feasibility and performance analyses. WelToGen supports the front loading of the tooling design process making available in the early stages of design more information about the design, its performance and its feasibility. The research was created with four objectives, which fulfillment will be analyzed based on the results obtained with WelToGen.

> **Obtain higher rudder quality.** This project is aimed at improving the rudder design process, both with traditional methods as well as with the new front loaded methods. WelToGen was created to be able to be used in both methods: as a standalone tool to support the traditional design process and as a module to be integrated in Fokker's Rudder Generator.
>
> Rudder geometries in which rudder design parameters were modified were given to WelToGen, which created feasible welding tooling models based on these geometries. WelToGen allowed to perform feasibility assessments for new configurations which had not been considered at Fokker due to lack of knowledge and resources to analyze them. Also, the results of the parametrical studies show the impact that some rudder design changes have on the manufacturing performance. The result were shown to Fokker engineers, who showed interest in the design recommendations that come out from the results. If WelToGen was to be used by the rudder design team, more information about the rudder design choices would be known, enabling more informed trade-offs, ultimately increasing the probabilities of creating higher quality rudder designs (lower cost and weight).

WelToGen was integrated in the Rudder Generator. However, the RG is not mature enough to create feasible inputs for tooling generation. The integration of WelToGen showed RG's lack of manufacturing knowledge; the RG does not define feasible welded joints from a manufacturing perspective. The rudder design rules necessary for it to be feasible to generate tooling were given to the RG team and will be implemented in the future as part of the application development. Once this is done, the rudders created by the RG will have been improved, since they will be designed with more manufacturing knowledge. In addition to this improvement in rudder design, the RG with WelToGen integrated will enable automated design space exploration and optimization, further improving the rudder design quality.

Obtain higher tooling quality. With the use of WelToGen's quick analysis capabilities, it is possible to perform parametrical studies and understand the impact of tooling design choices on the tooling performance. During the creation of the tooling design protocol, two tooling design parameters (the number of cross beams and the closing beam reinforcements) were found to be not relevant to stiffness compared to their negative effects on cost. It is recommended for future tooling designs to not include cross beams and reinforce all closing beams.

By using the tooling design protocol, WelToGen has found tooling models 3 to 5 % cheaper than the ones manufactured at Fokker for the same component models. Moreover, the cost reduction show only the effect of the modeled tooling parts by WelToGen; the reduction could be larger if the entire tooling was looked at.

Fokker's tooling engineer received the results and the tooling design recommendations and was interested in the potential of continuing exploring the tooling design parameters with WelToGen. Also, the tooling engineer is keen on using WelToGen's capabilities to support current tooling design projects at Fokker.

Shorter design time. WelToGen, being a KBE application, automates the conceptual tooling design process, including manufacturing analyses. In traditional tooling design, detailed design was created before the feasibility assessments were performed. The times to have a detailed model are in the order of magnitude of weeks or months. WelToGen is capable of performing the tooling feasibility and performance assessments using conceptual tooling design, hence reducing the time of the manufacturing analysis to approximately 10 minutes. Calculating the tooling cost is the only activity in which Fokker's current traditional method is faster than WelToGen, due to Fokker's method simplicity. WelToGen's cost estimation method is able to capture much more detail of rudder design changes.

Despite WelToGen not delivering detailed tooling design, the ability to perform the manufacturing analyses quickly on conceptual tooling designs significantly accelerates the first stages of design. Additionally, WelToGen's support for front loading the tooling and rudder design process will enable to make more informed design choices, reducing the probability of redoing work at the late stages of design due to infeasibilities found then, thus reducing the overall lead-time.

Less risk and missed opportunities. WelToGen can be used to front load the tooling design process, making available more design information early in the design. WelToGen's results show the necessity of including breaks in the spar welding lines not further away from each other in order to obtain sufficiently stiff tooling. WelToGen enables the designers to distinguish the infeasible zones of the design space. With the traditional method, this is not possible in such detail, hence there is a much higher probability to find the design not to be feasible later in the design process when more detailed analyses are performed. Therefore, WelToGen reduces the risk and the design waste in the form of work redone.

Furthermore, the results obtained with WelToGen have shown the feasibility of manufacturing tooling for larger or smaller rudders than the sizes manufactured until now at Fokker. WelToGen enables Fokker to explore design space regions which were unknown before due to the time limitations of the traditional methods. Fokker engineers showed interest in the potential of manufacturing models for differently sized rudders. Fokker's competitiveness can be increased with the use of WelToGen.

The results obtained show that the methodology developed fulfills the objectives that were set for the project. The methodology, based in generating the tooling model, performing feasibility assessments and analyzing the manufacturing performance through cost is a useful way of performing design manufacturing analyses. The application of this methodology to thermoplastic welding with WelToGen has fulfilled the objectives set for the project. Positive results of lead-time reduction and higher rudder and tooling quality have been found when analyzing a single manufacturing process in detail. The benefits of this methodology could be multiplied if the methodology would be applied in the same manner to other manufacturing processes such as layup tooling, tolerance analysis or production plant simulations. The application to other processes would be possible finding each process' feasibility conditions, creating feasibility assessments based on these conditions and estimating the cost of the process. As more manufacturing processes are gradually included, the level of detail and the extent of the manufacturing knowledge in the front loading process will be increased, leading to higher quality design results and less risk and design waste.

The results also show how the inclusion of the manufacturing analyses in both the traditional and the front loaded design processes has affected the design outcome and the design processes themselves. Fokker engineers have confirmed the potential of WelToGen based on the results. First, the tooling engineer intends to use WelToGen to support currently active tooling design projects at Fokker, being interested in the time reduction for manufacturing analysis and the potential of reducing redone work. Second, the Rudder Generator team is interested in expanding the program's capabilities by integrating WelToGen in the RG program suite. Furthermore, future manufacturing analysis capabilities will be added to the RG using the methodology developed on this project, creating new modules alike WelToGen for other manufacturing and assembly processes.

5.2. Recommendations

Fokker engineers, both from the Rudder Generator team as well as tooling engineers, showed interest in using WelToGen in the design processes. The recommendations given will aim at facilitating WelToGen's use as well as to improve the application. In addition, WelToGen should be considered a successful implementation of the manufacturing analysis methodology, hence it is recommended to use the methodology for other manufacturing and assembling processes. The recommendations for WelToGen's use in the RG and to support the traditional design method are:

Cost Module. The equations used to model the tooling manufacturing and assembling processes can be improved to better capture the manufacturing and assembly processes. Also, the parameters used in the equations should also be studied to achieve more accurate estimations. Both the equations and the parameters can be studied in detail and reviewed with manufacturing experts in the company. Also, there are tooling parts which are not modeled by WelToGen since they do not influence the feasibility analyses. However, since these parts influence cost, a methodology should be created to increase them in the cost estimations (e.g. estimate the tooling support cost from its volume, which can be known due to the frame's geometry).

On a more general level of cost estimation, when performing aircraft component trade-offs, all types of cost should be looked at. The tooling cost is only part of the non-recurring costs. The recurring costs of operating the tooling and of performing the welding should be considered. Furthermore, in these cost estimations the batch size should be considered to divide the non-recurring cost within all manufactured parts.

Rudder Generator’s Manufacturing Knowledge. As it was explained, the RG is not capable of creating rudder geometries which are valid as input for WelToGen. The design rules necessary to define valid welding lines were given to the RG team. Here they are included without specific numbers due to confidentiality reasons:

- The spar welding line breaks must be placed at specific distances from the rib planes.
- The breaks in the aft spar welding lines should be placed in the plane where a forward spar welding line break exists.
- The length of the spar welding line segments should not exceed the maximum length allowed by the pneumatic system.
- The length of the spar welding line segments should not be smaller than the minimum length allowed by the welding process start and end necessary lengths.
- The rib pitch should be larger than the rib pitch which makes the tooling rib beams of adjacent ribs to clash with each other. Or implement a design rule which allows to use a single rib beam for two ribs.

Finite Element Model Module. The modeling approach of using 1D rod elements omits the frame box skins, which play an important role in stiffness; a new modeling approach might be needed. It is a possibility to link with a commercial code such as CATIA’s structural analyses: the model creation can be automated and the level of detail can be selected to have fast simulations but with enough accuracy for early design.

Additional recommendations are given to improve or expand WelToGen:

Automated optimization. For this project, a tooling design protocol was designed based on the tooling design knowledge acquired in the project and in the study of some of the design variables. The protocol managed to find feasible solutions with lower cost than the models designed by Fokker. However, this protocol is manually created without full knowledge of the effect of design changes over tooling stiffness and cost. An optimization process should be implemented, performing automated design exploration, which would fully profit WelToGen’s potential.

Geometry Module. The GM’s level of detail could be increased to obtain better cost estimations. Also, the tooling main parts which are not currently modeled could be included to obtain an overall tooling cost. The GM’s code could also be modified to be able to take non-symmetric aircraft components; using the same design rules for each side of the tooling and joining them in one whole tooling. Finally, additional rules could be coded which allowed to test new component configurations such as multi-spar, single-spar or close pitch between ribs.

Rudder Feasibility Module. WelToGen is not capable to process non-feasible rudder geometries. It can be tedious for WelToGen’s user to find where the error is coming from to modify the rudder geometry to make it feasible. Therefore, it is recommended to create a module that works before the Input Geometry Pre-Processor which checks the input given to ensure that it is a feasible rudder from the welding point of view. The module can give visual feedback in the geometry for the user to easily find the conflictive rudder element.

Weight Feasibility Check. The tooling weight might become another requirement to fulfill. The protocol has found better tooling designs which have a higher weight (e.g. always including reinforced closing beams). It is expected that the cranes used for tooling installation and operation are capable to take the added weight these designs have, yet a check could be implemented. In this way, the search for designs will also take into account this feasibility aspect.

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Appendix:
List of WelToGen's Inputs

In this section, a list of the inputs needed by WelToGen, according to their name in the code, is given. It is indicated if they are required, not required or if they have a default value. Also, a brief description is given. Note that the default values are not given due to confidentiality reasons. The inputs are divided depending on the sub-module to which they belong.

RudderGeomProcessor Inputs	**Required**	**Description**
fwd_offset	Default	Distance from spar plane to leading edge cutting plane.
reg_plns_table	Yes	Region planes table. These are the planes that delimit the regions of the frame. They are always placed where a rib is. This list of lists indicates [[rib index, offset from that rib], ...].
ref_fwd_spar	Yes	Index of reference forward spar. Spar which direction is used for all the aft spar WLs (0 is first).
ref_aft_spar	Yes	Index of reference aft spar. Spar which direction is used for all the aft spar WLs (0 is first).
ref_rib	Yes	Index of reference rib. Rib which direction is used for all the rib WLs (0 is first).
spec_tooling_length	No	Tooling length. If None is specified, it will be calculated according to knowledge rules.
ref_plns_offsets	Yes	Offsets for the tooling reference planes. These are the tooling forward, aft and root. The tooling tip plane is calculated by adding the tooling length to the root plane. Modify tooling length to control the tooling tip plane. Given as a list of [fwd, aft, root].
pnt_offsets	Yes	Offset for each of the three points that are used for the frame reference plane. With them it is possible to adjust the normal direction of this plane.

Frame Inputs	Required	Description
offset	Yes	Offset of the inner plate w.r.t. the base plane of the rudder.
frame_width	Yes	Frame box inner width.
no_cross	Yes	Number of cross beams on each frame region.
ib_ob_t	Yes	Inboard and outboard frame box skins’ thickness.
fwd_aft_t	Yes	Forward and Aft beams' thickness.
separator_plates	Yes	Thickness of the region separator plates.
bp_xtra_w	Yes	Bottom plate extra width on the inboard direction (how much wider the bottom plate is w.r.t. the frame's inner plate).
spec_weld_angs	No	Welding angles for the two spar WLs. If no values are specified, the code will calculate them according to the gap minimum distance. It is possible to specify only one of the two angles.
ang_step	Default	Angle increase per step in the iterative search in case specified angle is set to None.
gap_min_dis	Default	Minimum distance to keep between spar gaps and rib gaps in the inboard and outboard plates in case specified angle is set to None.
region_beams_t	Yes	Thicknesses of all the inner beams in the frame regions. It is given as a list according to a certain organizational order.
spec_no_xtra_beams	No	Specified number of reinforcement beams on the frame regions. If None is specified, the number will be calculated according to the pitch.
xtra_beams_pitch	Depends on Previous	Minimum pitch between reinforcement beams.
closing_beams_reinf	Default	List of Boolean values to select which closing beams are reinforced or not. True for reinforced.
clampling_pnts_offset	Default	Span-wise offset distance of the clamping points w.r.t. the frame region planes (0 places the clamping point at the region plane).
c_p_dimensions	Default	Clamping plates' dimensions. They are given in a list as [length (Z dir), width (y dir), thickness].
max_torch_offset	Yes	Maximum allowable torch point offset for torch feasibility analyses
torch_offset_step	Default	Increase step for each loop of the torch offset feasibility iteration.

Contour-Block Inputs	**Required**	**Description**
fwd_offset	Yes	Forward offset of the plates w.r.t. the outer frame forward plate.
aft_offset	Yes	Aft offset of the plates w.r.t. the outer frame aft plate.
plates_width	Default	Thermoconductive plates width
plates_t	Yes	Thermoconductive plates thicknesses. Given in a list as [fwd spar plates, aft spar plates, ribs plates].
tilt_offset	Yes	The tilted plane that delimits the first CBS region aluminum plate is calculated as an offset plane from the plane that unites the end of the two first rib WLs (the first rib WL is shorter). This value is the offset distance of the plane.
plates_wl_offset	Default	Thermoconductive plate offset from WL. This is the length that the plate will be larger than the WL to which it belongs.