A knowledge based engineering tool to support front-loading and multi-disciplinary design optimization of the fin-rudder interface

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ABSTRACT

Socio-economic challenges and global competition drive high-tech industries to combine their cutting-edge technology with improved time-to-market and cost efficiency. In order to meet these challenges, Tier 1 and Tier 2 companies need to organize and formalize their product development process and align their core competencies with the regulations, processes and tools of their customers i.e. Original Equipment Manufacturer (OEM). In order to reduce time-to-market, improvements in product development lead time are necessary, which, in turn requires a combination of a streamlined product development process and systematic design space exploration capabilities. A way forward to reduce lead time, improve cost efficiency and enhance competitiveness is to apply the so-called front-loading product development approach. Front-loading relies on the company's ability to develop (semi-) automated design systems and knowledge bases (KBs) that store their consolidated knowledge. These design systems and KBs are established before the actual start of a project, so as to enable their quick deployment for the preparation of proposals and to trigger new development processes to further reduce design lead time. Effective design space exploration needs to be carried out to generate better designs (even families of design variants) for the customer. This is made possible by performing MDO studies in advance and storing the results in the company's KBs. The research presented in this paper illustrates how the application of front-loading can help an airframe manufacturer, performing fin-rudder interface design, with the rapid generation of proposals for OEMs. It is demonstrated as to how the use of knowledge based engineering in combination with PIDO (Process Integration and Design Optimization) tools enables multi-stage front-loading process, thus supporting design studies ranging from basic "what-if" assessments to full blown single and multi-objective optimization. The presented technology demonstrator shows a potential lead time reduction of over 90% and an improvement in product performance of up to 30%.

KEYWORDS: *Front-loading, Knowledge Based Engineering, Multidisciplinary Design Optimization, Fin-rudder interface design*

NOMENCLATURE

CAD – Computer Aided Design
COTS – Commercial Off The Shelf
DOE – Design of Experiments
FEM – Finite Element Methods
FEA – Finite Element Analysis
HDOT – Hinge system Design and Optimization Tool
KB – Knowledge base
KBE – Knowledge Based Engineering
MDO – Multi-disciplinary Design Optimization
MOO – Multi-objective Optimization
MS – Margin of Safety
OEM – Original Equipment Manufacturer
OML – Outer Mold Line
PIDO – Process Integration and Design Optimization

1 INTRODUCTION

Fokker Aerostructures specializes in the design and production of aircraft movables (rudders, flaps, ailerons, speed brakes, etc.) for various OEMs. Similar to other movables, the design of the rudder starts with a data set provided by the OEM that consists of the fin outer mould line (OML), the plane in which all the hinge lines are located, the actuator location (relative to some fin ribs) and a set of load cases. On the basis of this limited set of inputs, Fokker Aerostructures starts investigating the most convenient hinge system design to achieve a *good* rudder design proposal for the OEM. Where, a good design refers to a design that can be achieved in a few manual design iterations and satisfies the design requirements.

The formulation of such a proposal includes the determination of the ideal location of the rudder rotation and actuator hinge lines on the hinge plane, and the sizing and/or selection of the actual hinge parts, e.g. lugs, sleeves, bushes, bearings, bolts, etc. **Figure 1** shows the location of the fin-rudder interface and its major components. The design of the fin-rudder interface, also addressed as hinge-system, is critical because it directly affects the structural definition of the overall rudder, i.e. (a) the number and location of ribs and spars and (b) the thickness and material selection of ribs, skin panels and spars. Improper design of the fin-rudder interface can therefore lead to an expensive or heavy rudder or, in some cases, costly redesign iteration(s).

With the current design approach, Fokker Aerostructures needs several weeks to design a suitable hinge system for a given OEM data set. This long design lead time is mainly due to the large amount of manual activities in the design process and the involvement of different experts, often distributed across different sites. Furthermore, any change in the OEM data set (e.g. actuator box location), requires a restart of the hinge system design process and a re-assessment of weight and cost. As a result, the current design approach, coupled with the typically tight delivery schedules, only allows for the determination of a handful of feasible designs, without offering the possibility to perform any optimization and deliver, for example, Pareto fronts of optimal cost–weight solutions.

This research work proposes a design methodology that front-loads the design of the hinge system by drastically reducing the design lead time through the generation of knowledge bases and automation of the manual and repetitive activities involved in the current hinge system design approach (Section 2). To this purpose, a Knowledge Based Engineering (KBE) tool called Hinge System Design and Optimisation Tool (HDOT) has been developed to quickly and automatically supply geometry, mesh and data to various Fokker-proprietary sizing tools, in order to carry out hinge system design. Each time a change occurs in the OEM data, HDOT is able to quickly update or reconfigure the hinge system design, by consistently reapplying the design process formalized in the KBE application code (Section 3).

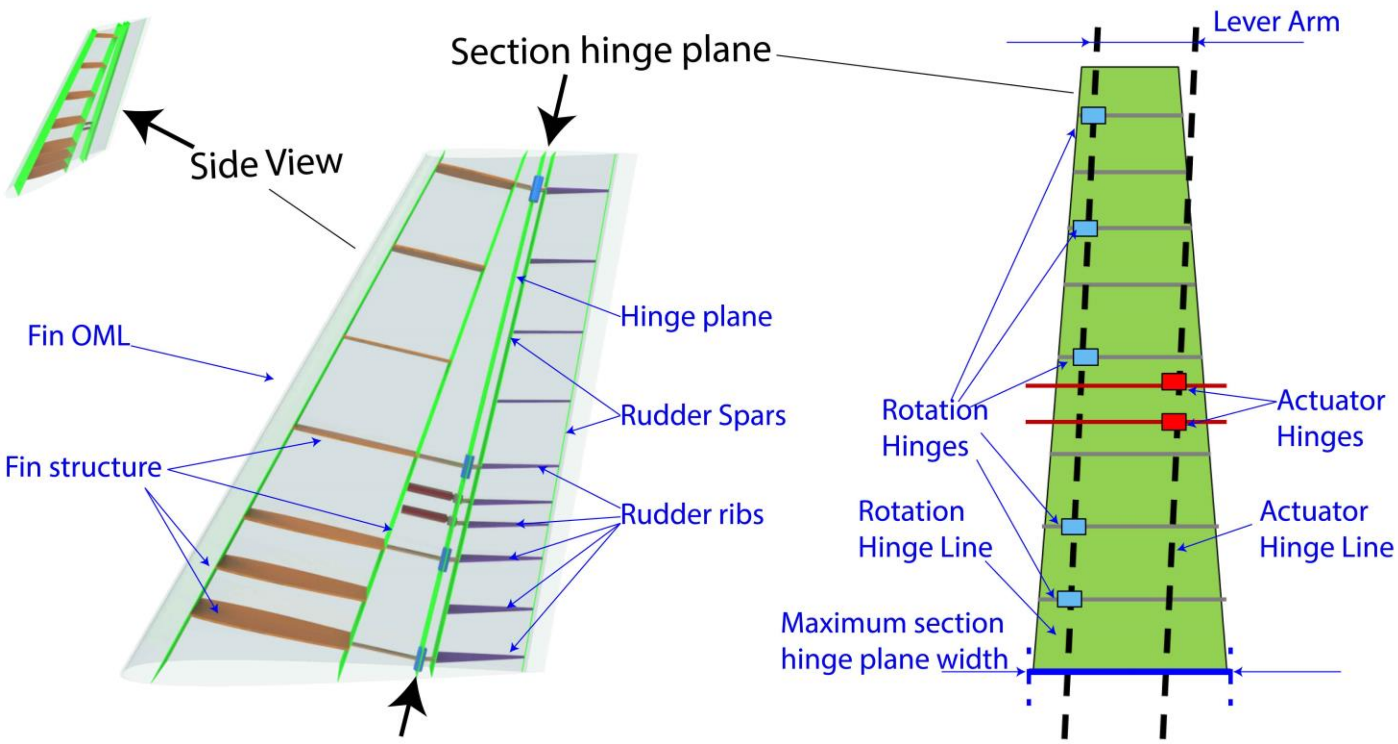

Figure 1: Location of hinges and hinge lines in the fin-rudder interface *[1]*

In addition to reducing the fin-rudder interface design lead time, the achieved level of automation also enables (Section 4):

1. DOE (Design of Experiments) to efficiently sample and explore (and visualise) the design space by accounting for disciplinary couplings and design constraints.
2. The application of MDO technology, which accounts for and exploits the disciplinary couplings and design constraints in view of finding optimum design solutions

In the design of fin-rudder interface, disciplines such as cost estimation, weight estimation, geometry modelling, Finite Element Analysis, aerodynamic load calculation and stress analysis are involved. Both DOE and MDO can be useful in the front-loading of fin-rudder interface design. The results of the DOE can help engineers make design decisions rapidly when OEM input changes. MDO helps engineers deliver a fin-rudder interface design with reduced weight and cost.

2 FRONT LOADED DESIGN OF FIN-RUDDER INTERFACE

Fokker Aerostructures is working on reducing the product development time to allow "what-if" studies and improve product performance. **Figure 2** qualitatively shows how Fokker Aerostructures benefits in terms of design lead time when they use concurrent engineering (in use today) instead of sequential engineering process.

Concurrent engineering implies that multiple design tasks are carried out simultaneously in order to increase productivity and profits and reduce lead time and last minute work necessary to meet the delivery deadlines [2]. Some of the design activities in such a concurrent engineering process are dependent on one another which means that assumptions need to be made for the unavailable dependent information at the start of the project. Such assumptions are called ***advance information***. The advance information is not limited to the exchange of information between the four product development phases of setup, requirements, design and manufacturing as shown in **Figure 2** but also includes the exchange of information between two teams in the same product development phase. For example, for the nut design team, the advance information would be the bolt diameter which is provided by the bolt design team, where, both teams function in the same phase i.e. design phase

Though the design tasks can be started in parallel using advance information, additional time and cost is needed for the preparation of such information. In addition, there is added burden on the engineers to reduce the time spent on generating the advance information. This creates time pressure on upstream activities thus not allowing engineers to work out their designs thoroughly, which leads to conservative designs and eventually added cost. [3]. In a manual design process, design teams need to discard a part or whole of their work and restart the design process when the advance information changes. This leads to wastage of time, effort and computational resources. This wastage also causes aversion to changes within design teams as engineers feel their work is being discarded.

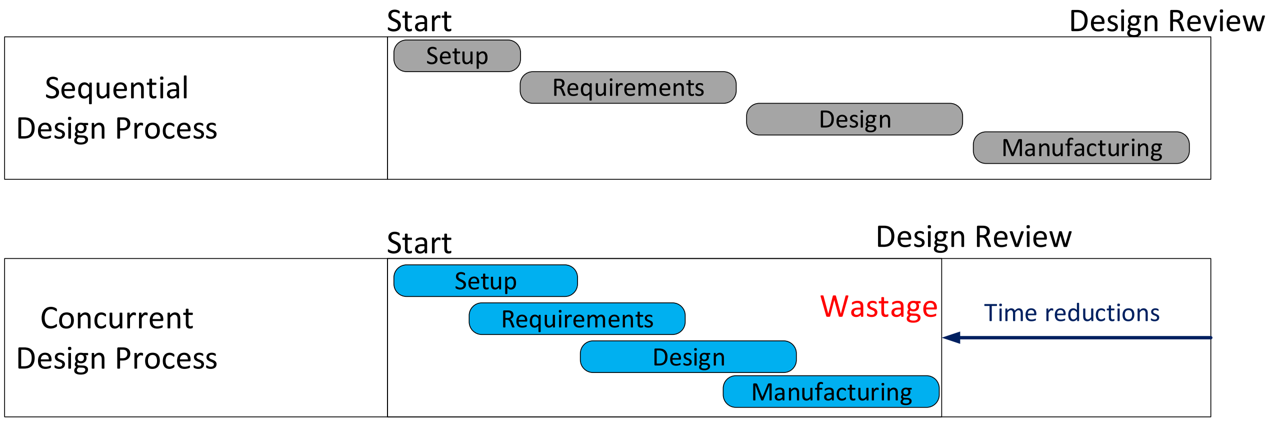

Figure 2: Effect of concurrent engineering on improving time to market *[4]*

Depending on the design problem at hand, there might be multiple ways of defining the advance information. However, this flexibility in defining advance information makes the formalization of design tasks challenging, as one engineer can have a significantly different view of the design process from another, which could lead to considerable rework or infeasible designs in case of changes in OEM inputs and/or advance information. For example, when FEM analysis is involved in the design process, a reference geometry is necessary. If the reference geometry is considered advance information and the engineers start designing the product based on a hypothetical geometry, considerable rework needs to be done when the final geometry is made available. This rework is particularly tedious when it predominantly involves manual tasks. The wastage of time and resources in concurrent engineering cycle is shown as wastage in **Figure 2**.

In order to address the shortcomings of concurrent engineering, Fokker Aerostructures in collaboration with Delft University of Technology started investigating alternative and potentially more efficient methodologies for product development. Front loading was the proposed [4] alternative to reduce both the design time and the wastage of resources due to the rework taking place with the concurrent engineering approach (**Figure 3**). Front-loading involves ***anticipating*** the critical bottlenecks in the design process and ***streamlining*** them by developing automated design processes and Knowledge Bases which can be used to rapidly design products at the start of a new project. The design automation activities and development of knowledge bases i.e. front-loading happens before the start of the actual project and makes use of [5]:

1. **Project to project knowledge transfer:** This process seeks to transfer information of problems from one project to the next similar project. This saves time required to solve similar problems. It also allows engineers to work on a problem at an early stage of the project/ before the start of the project.
2. **Rapid problem solving:** Advanced technology and methods are used to reduce the time required for problem-solving. For example, the use of CAE instead of physical prototyping. Rapid problem solving is also a method of obtaining problem related information by repeated problem solving procedures/ iterative processes such as DOE or optimization.

At the end of the front-loading phase, design automation tools and KBs are available for use in new projects. When the OEM inputs are available, the project is setup by selecting appropriate disciplinary teams, design automation tools and KBs necessary to complete the project. Once the project setup is complete, the requirements can be fed into the design automation tools which triggers the design activities. If a converged design is obtained, the front-loaded design process can be further expanded to manufacture the first prototype to study the manufacturability of the designed product. This is depicted schematically in **Figure 3**.

While front-loading itself is not a new idea ([6], [7]), the challenges and diversity of its application and the resulting benefits vary from one use-case to another. Often, between the steps of project to project knowledge transfer and rapid problem solving, the transferred knowledge must be formalized. As a result, engineers responsible for front loading the design must:

1. Select a suitable computing environment that can be used in rapid problem solving phase
2. Formulate the design process in such a way that it captures the design rationale

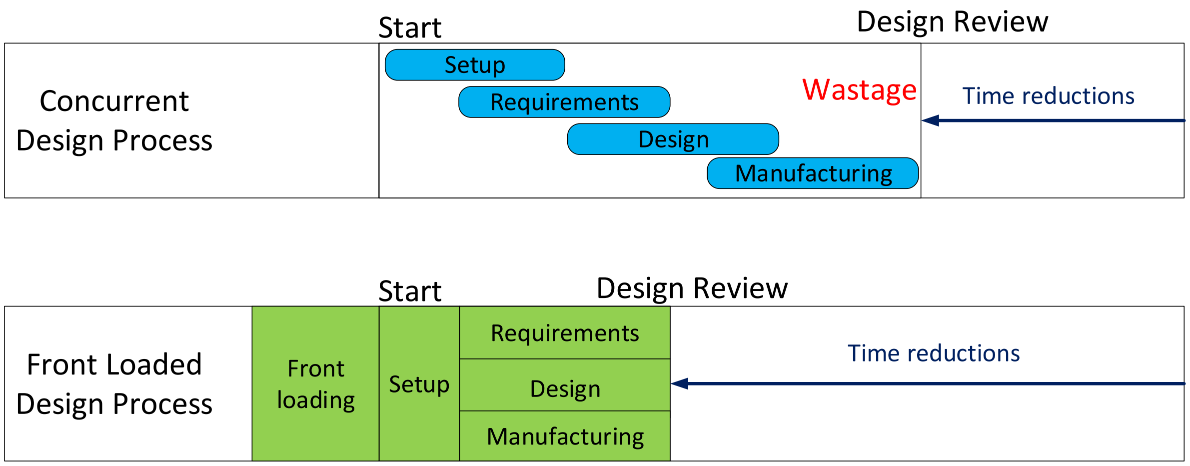

Figure 3: Effect of front loading on improving time to market *[4]*

In this research work, as part of the initiative to front-load the fin-rudder interface design, both project to project knowledge transfer and rapid problem solving are used. For project to project knowledge transfer, different disciplinary specialists who are directly/indirectly involved with the design of the fin-rudder interface were consulted. The aim was to understand the current design process and the critical tasks that *must* be accomplished in order to complete the design of fin-rudder interface. From these consultations, it was concluded that engineers need to carry out the following tasks to complete the design of fin-rudder interface:

1. Determine the location and number of rotation hinges
2. Generate the structure of the rudder using the location and number of rotation hinges
3. Mesh the generated rudder to carry out structural analysis
4. Apply external loads acting on the rudder based on the specified load cases and run the structural analysis software
5. Retrieve the forces on all the hinges to size and select hinge components for every hinge
6. Estimate the cost and weight of the fin-rudder interface

Often, carrying out these tasks once is not sufficient as one design iteration will not guarantee a feasible design that meets all the requirements. Therefore, these design tasks must be iterated at least until a feasible design is obtained. The combination of number of hinges and the lever arm (**Figure 1**) determines the forces acting on the hinges. These forces are in turn used to size the various components of the hinge such as bolt, nuts, bearings, sleeves, lugs, bushes and nuts. If the forces on the hinge components are too high, their dimensions become very large and fitting them within the rudder OML becomes difficult. Thus, the size of the hinge components can be reduced by changing the number of hinges and/or the lever arm. However, to do so without significantly increasing the cost and/or weight requires iterations.

To carry out the tasks listed above for the design of fin-rudder interface, different types of disciplinary experts are involved as shown in **Figure 4**. These can be broadly classified as:

1. Design engineer: A design engineer typically works on the design synthesis of various components i.e. determination of dimensions of the components he/she designs.
2. Stress engineer: A stress engineer typically works on the analysis of the various components designed by the design engineer i.e. determination of the loads acting on the components and their margins of safety in the influence of those loads.
3. Costing expert: A costing expert estimates the non-recurring cost of the designed components

In addition, these disciplinary experts need to interact with one another to produce a consistent design.
As part of project-to-project knowledge transfer, the concurrent engineering process used for fin-rudder interface design is studied. **Figure 4** shows an overview of the exchange of data and advance information among different disciplinary experts when fin-rudder interface design is carried out using concurrent-engineering process. **Figure 4** is circular because design teams start working on fin-rudder interface design concurrently. Teams that need information from other teams initially assume the necessary advance information. When sufficient design maturity is reached, the correctness of the assumption needs to be verified by consulting other disciplinary teams. Often such a verification process involves manual steps such as obtaining the design report from other teams, extracting the relevant information and verifying the assumptions. This manual verification process is time consuming. This can be significantly reduced by automating the design process such that the "right" advance information reaches the destination with minimal manual interference. Such an automation can help engineers tackle the re-work associated with changing advance information better.

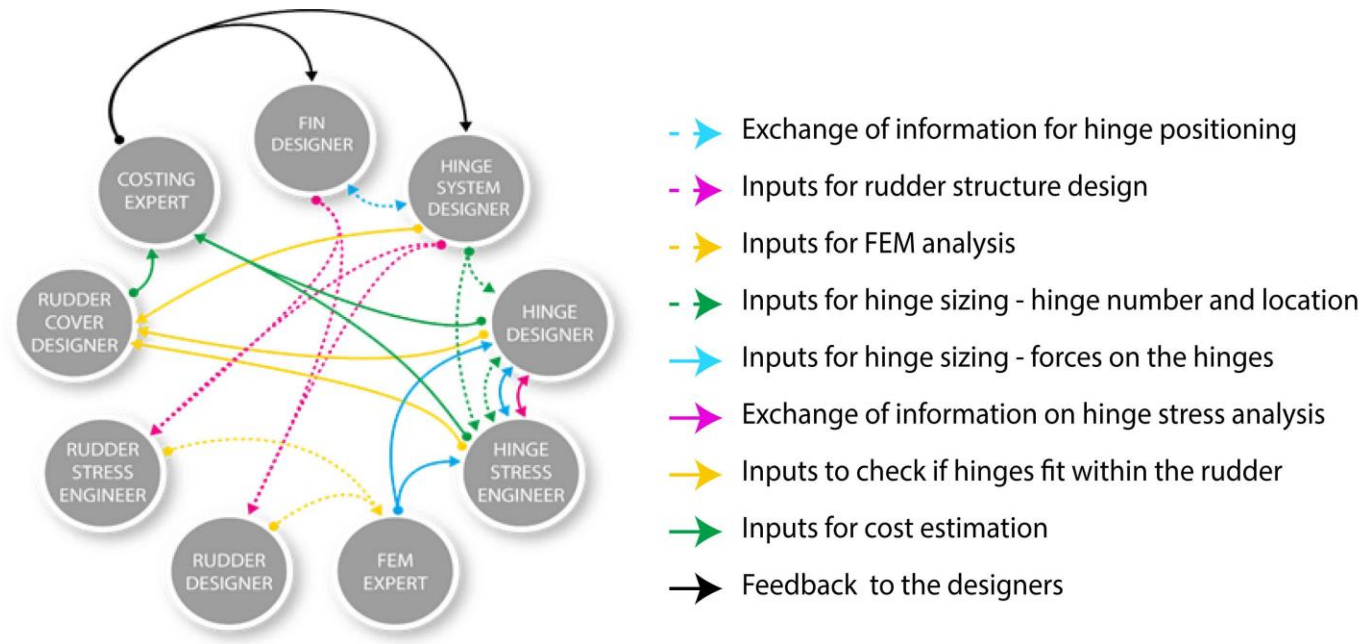

Figure 4: Interaction between different experts during the fin-rudder interface design process at Fokker Aerostructures

Once the project to project knowledge transfer is complete, an appropriate computing environment (intended here to refer to a set of design and analysis tools and methods) needs to be set-up which can be used in the rapid problem solving phase. Based on the specific activities to be carried out in the design of fin-rudder interface, the following needs were identified:

1. Multidisciplinary teams should be able to work on different aspects of the product model. When one or more teams update the requirements and/or the product model, other teams should automatically get the updates of these changes. This requires a computing environment that can keep track of dependencies in the product model and use such dependencies to help disciplinary experts rapidly evaluate the effect of changing advance information on the part of design pertaining to their competence.
2. The iterative nature of fin-rudder interface design requires continuous update of CAD models. The performance of current CAD systems (even of those based on advanced macros) are still not adequate to support design iterations, especially automatic optimization loops [4]. This requires the use of a computational environment that has generative modelling that can rapidly update geometry to support iterative design processes.
3. Fin-rudder interface design requires the use of high fidelity analysis such as finite element analysis (FEA). For such an analysis, interoperability between CAD and FEM software is essential. This leads to two problems. The first one being the loss of time in executing the transfer of data from CAD software to FEM software. The second being the loss of dependency between the CAD model and FEM model due to such a transfer. Thus, a computational environment is needed where both CAD and FEM preprocessing kernels co-exist such that changes in topology are immediately recognized by the FEM kernel to update the FEM model.
4. In the rapid problem solving phase, use of DOE and MDO becomes essential. These require an understanding of algorithms and their corresponding couplings [8]. This knowledge is often not available among the engineers of aerospace structural design companies like Fokker Aerostructures. The envisioned computational environment should be able to help engineers having little or no experience with MDO and/or DOE to setup the problem rapidly for execution.

Based on these requirements, a computing environment consisting of a KBE system, a PIDO tool and a FEM solver is chosen for rapid problem solving phase.

1. **Knowledge Based Engineering (KBE) System:** KBE systems can capture and systematically reuse product and process knowledge which helps in automating repetitive and non-creative tasks. In addition, KBE has been found able to support MDO in different phases of design process [9] [10]. A KBE system, ParaPy[1] , is used in the front-loading of fin-rudder interface design.

2. **Process Integration and Design Optimization (PIDO) tools:** PIDO tools are used to automate the set-up and execution of simulation and analysis tools by creating simulation workflows. [11] In an industrial setting, when software tools are available to carry out different disciplinary simulation and analysis, PIDO tools can help engineers in rapidly connecting these tools. Furthermore, when one or more tools need to be used to carry out design space exploration such as DOE or Optimization, PIDO tools can be useful as they are packaged with predefined sampling and optimization algorithms. PIDO tools, such as Optimus[2], which was used in this research, are especially useful in an industrial setting where deep understanding of optimization algorithms and their implementations is not common knowledge.

3. **Structural analysis solver:** In order to complete the structural analysis, a FEM solver needs to be used to determine the forces, moments and displacements experienced by the designed model. For this, MSC Nastran was used which is a widely accepted software for structural analysis of aerospace components.

Using this computing environment, the fin-rudder interface design process can be front-loaded in multiple ways:

1. The design can be formalized and automated which could lead to rapid generation of proposals for OEM

[1] https://www.parapy.nl/
[2] https://www.noesissolutions.com/

2. Engineers can use the automated design process to manually study the impact of change in the design on the weight and cost of fin-rudder interface
3. A DOE can be carried out to better understand design space and to improve the empirical rules that are currently in use
4. MDO studies can be carried out for a set of expected inputs from OEM to create a catalogue of "pre-generated" designs which can be used when request for proposal is made
5. Multi-objective optimization can be carried out with cost and weight both being objectives and a Pareto front can be created to allow Fokker Aerostructures to make a trade-off between cost and weight.

3 KNOWLEDGE BASED ENGINEERING TOOL TO SUPPORT FIN-RUDDER INTERFACE DESIGN

This section details the features of KBE tool called Hinge-system Design and Optimization Tool (HDOT) developed to front load the fin-rudder interface design process. HDOT automates the tasks of fin-rudder interface design explained in section 2. It has the ability to carry out quasi-exhaustive search of possible hinge components to determine the best hinge assembly, in terms of cost and/or weight, that satisfies the stress requirements at every hinge location. To enable this quasi-exhaustive search, HDOT quickly and automatically generates a simplified rudder structure, based on user defined specifications, meshes it and carries out structural analysis (using COTS tool NASTRAN) to determine the forces acting on the hinges. These forces are an essential input to the sizing process of all hinge components. HDOT is composed of six main modules, each one responsible for one of the six main functions listed in section 2 (**Figure 5**). The functions of the six modules are described from section 3.1 to 3.6.

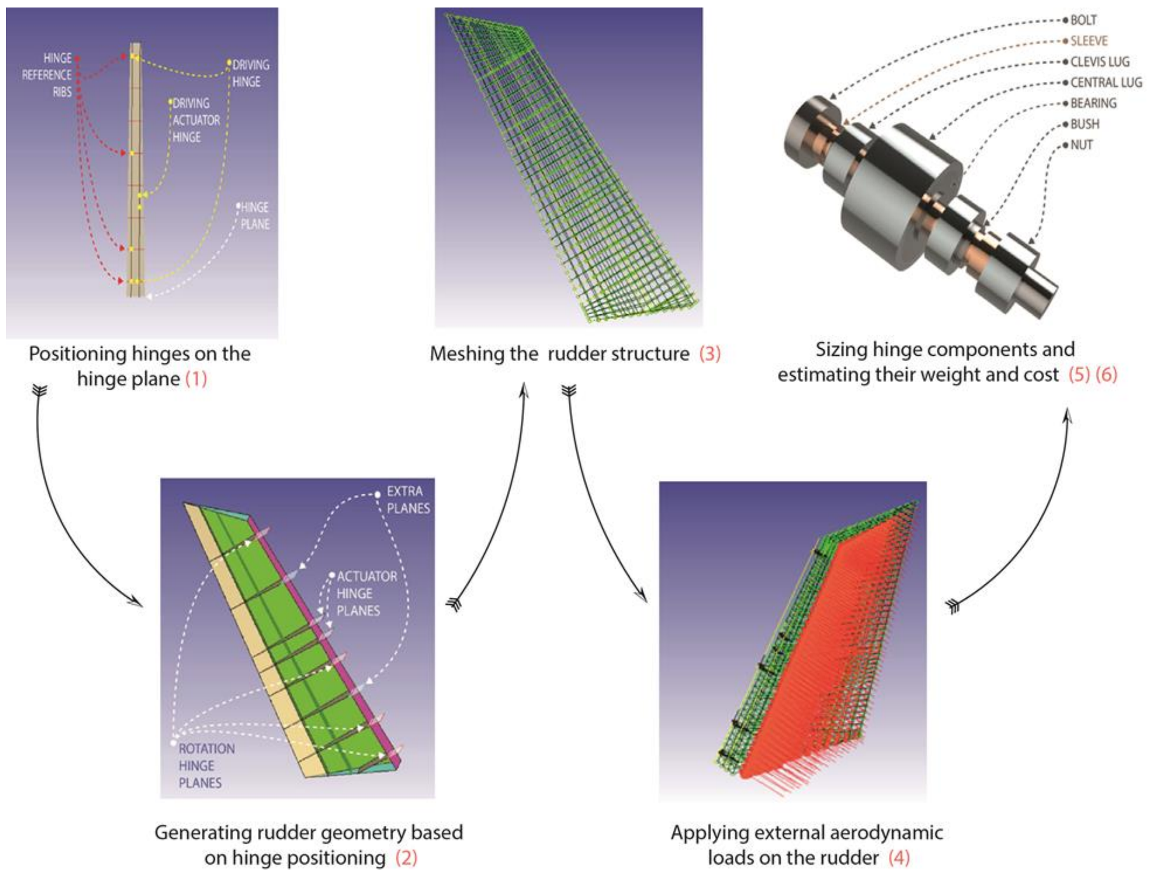

Figure 5: Functions of HDOT

3.1 Hinge positioning module

The positioning of hinges in the hinge plane is based on rules established at Fokker Aerostructures that HDOT applies in combination with the inputs provided by the OEM (such as the OML, the position of the hinge plane and fin ribs, and the location of the actuator). This module also allows the user to reposition the hinges to carry out what-if studies.

3.2 Geometry generation module

This module generates a simplified geometry of the ribs, spars and skin panels to generate the rudder structural layout. This rudder structure is generated based on the hinge positions and user inputs such as maximum allowable distance between ribs, rib thickness, spar thickness and number of spars.

3.3 FEA pre-processing module

FEA is necessary to estimate the forces acting on the hinges for various loads acting on the rudder. The steps involved in FEM calculations are meshing, applying properties to FEM elements, applying loads, running the solver and generating the report. In the pre-processing module of HDOT, the geometry is meshed by HDOT such that the mesh adheres to Fokker Aerostructures' mesh quality requirements. The complete automation of all the steps involved in the preparation and execution of the FEA model is key to the font-loading of the fin-rudder interface. It not only guarantees a fast execution of the process, but also full compliance to company rules and prevents the typical human errors occurring in the manual approach.

3.4 External load distribution and application module

At the start of the project, the OEM provides the total lift and total moment expected of the rudder. This is used to determine the pressure distribution on the rudder. While in the conventional design approach, the pressure application is carried out manually, which is a repetitive, time consuming and error prone process, HDOT allows for its automatic execution, either through an externally defined excel macro or by means of internal routines. This, in addition to being fast, improves the accuracy and lowers the time required to check the model for inconsistencies. Based on these inputs, FEA is carried out to determine the reaction forces at all the hinge points.

3.5 Hinge sizing module

The forces acting on ***each*** hinge, as computed using the FEA, are used to size the hinge components. A hinge component is either a standard part that has to be selected from a catalogue or a machined part that has to be sized and are specifically manufactured for the given fin-rudder interface design. Bearing and nuts are typical standard parts, whereas bushes, bolts, lugs and sleeves are manufactured parts[3] in the hinge assembly.

The selection of standard parts and machined parts is carried out such that consistent hinge-assembly is possible, for example, the bolt and the nut fit with each another. Furthermore, HDOT eliminates those hinge assemblies where two or more components react or corrode when they come in contact. This allows HDOT to propose realistic designs at every hinge location.

For both standard and machined parts, adherence to MS (margin of safety) policy is a strict requirement in the hinge sizing process. The determination of the margin of safety is based on certification requirements. Tools are available at Fokker Aerostructures to determine the margin of safety of a component based on its dimensions and material properties. These tools are used by HDOT to check if a component satisfies the MS-Policy.

For the design of standard part, selection is made from a library by HDOT such that the selected part meets the design requirements. HDOT comes with some predefined standard parts but allows user to add more if necessary. The activity diagram for the selection of standard part is shown in **Figure 6**.

[3] In some specific cases not considered in this work, bushes, bolts and sleeves can also be standard parts depending on the use case.

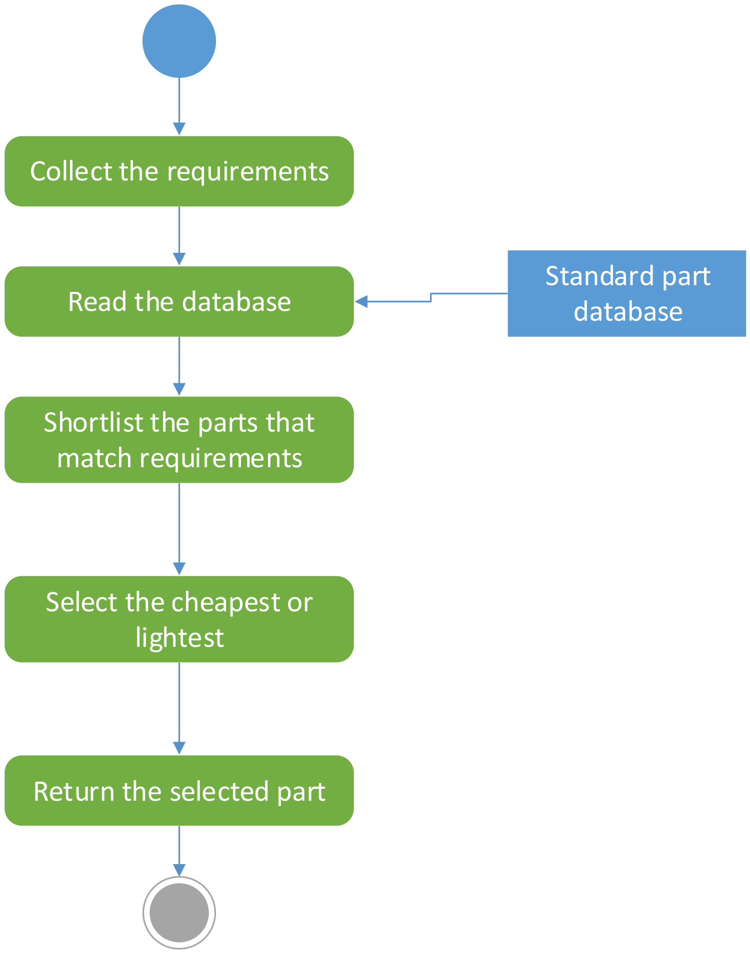

Figure 6: Standard part selection procedure

For a machined part, the design process is more elaborate. HDOT determines the material to be used and the part dimensions by means of the iterative approach shown **Figure 7**. The first iteration loop designs a machined part per material available in the database. As with the standard part database, HDOT comes with a material database that can be modified as per user requirements. For each material, a second iteration loop is triggered. This loop involves a bisection search to arrive at the cheapest or the lightest possible component per material. For this bisection search, the cost and weight module (explained later in this section) are invoked at every iteration. The bisection search is terminated when the value of Margin of safety reaches the tolerance value predefined in HDOT. Once all the materials in the database have been used, the cheapest or the lightest (as requested by the user) component among all the evaluated parts that satisfies the MS policy is selected.

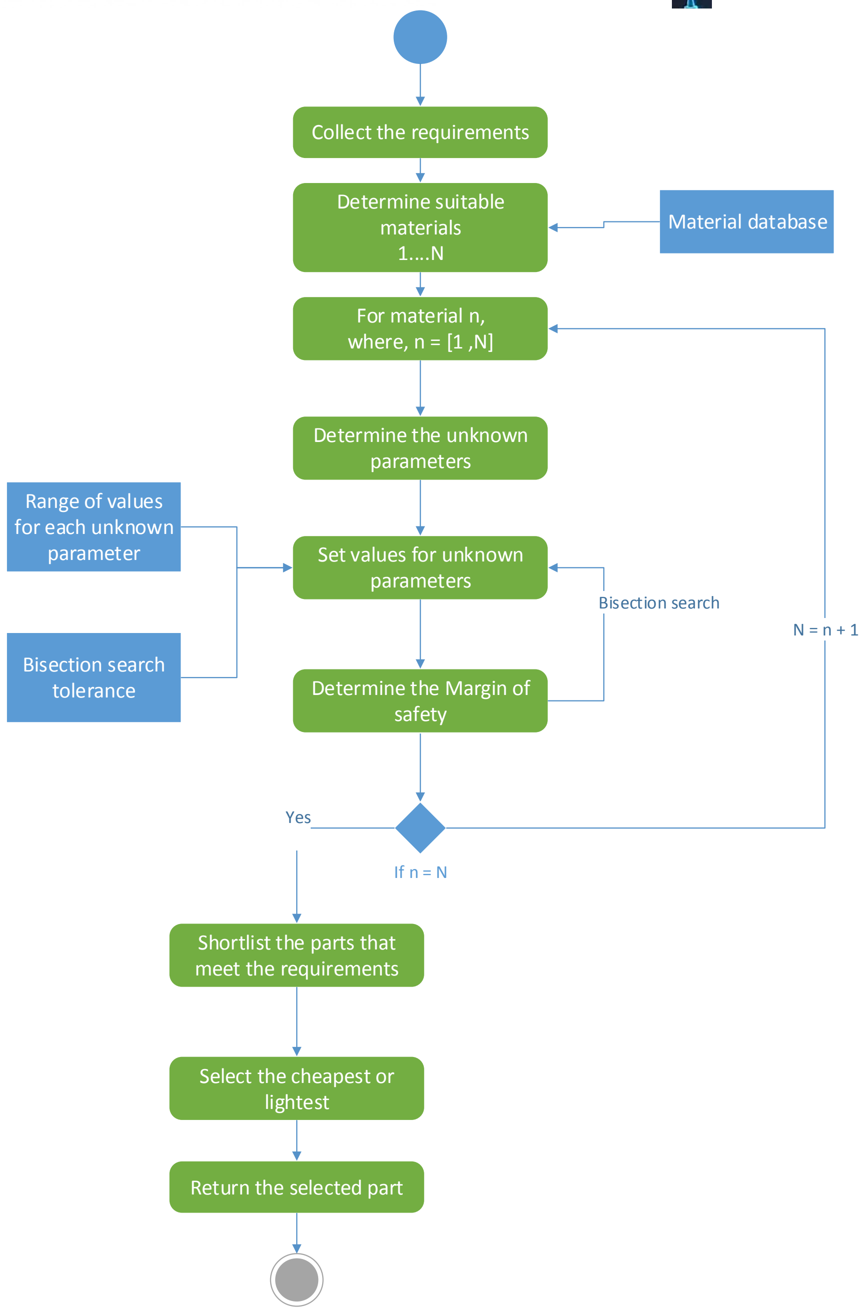

Figure 7: Machined part design process

The selection procedure for standard and machined parts mentioned above is easily accomplished when only one hinge part is considered at a time. This becomes much more complicated when seven such components must be simultaneously designed while making sure that the design is consistent and the design constraints are met. The number of evaluations that must be carried out to obtain a hinge assembly for a database that has five materials and five standard parts is about 250,000,000. As the size of the database increases, the number of evaluations needed to arrive at the cheapest or the lightest hinge increases exponentially.

To tackle this problem, HDOT makes use of a quasi-exhaustive search method. The problem formulation for this is shown in **Figure 8**. Here, the seven hinge components namely the bearing, central lug, sleeves, bushes, clevis lugs, nuts and bolts are designed in sequence. A N^2 diagram for this is shown in **Figure 9**. Each diagonal element, except the element named constraint, is a sizing module that sizes and selects the hinge components. The position of a sizing module on the diagonal represents the order of its execution (from top-left to bottom-right). The constraint block ensures that the selected hinge assembly meets all the design requirements for example, adherence to MS Policy. The off-diagonals element marked with x represent the transfer of information from the design of one component to the other. Furthermore, rules are used such that the infeasible combinations are eliminated prior to the start of the bisection search. Serial execution in combination with the elimination of infeasible designs greatly reduces the number of evaluations. This makes rapid generation of hinge designs possible. It is important to note that the aim of such a quasi-exhaustive search is to deliver a consistent design rapidly rather than an optimal design. In order to achieve an optimal design, actual optimization approaches are necessary. The quasi exhaustive search has two other points of attention:

1. The order in which the components are designed can have an impact on the final results as some possible designs are eliminated to ensure feasible design is obtained rapidly
2. The search method is only valid for fairly small databases. With increase in database size, the time for convergence increases exponentially.

Minimize:

objective = f(hinge-assembly cost ***or*** *hinge-assembly weight)*

where,

hinge-assembly components = f (lugs, bolts, nuts, clevis, bearings …)

Subject to:

$MS_{hinge-assembly\ components} \geq 0$

$Geometry\ constraints_{hinge-assembly\ components} \geq 0$

W.r.t:

Hinge-assembly components dimensions, Allowable material combinations

Figure 8: Problem statement for hinge assembly selection

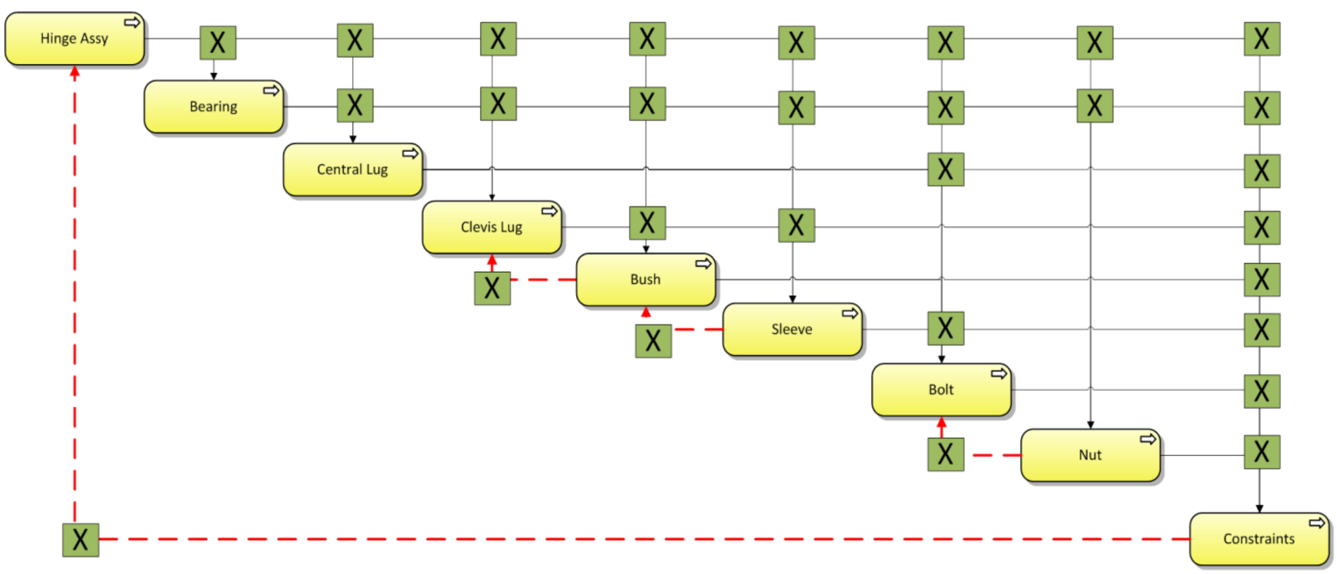

Figure 9: N^2 ***diagram showing the sizing modules available in HDOT to size and select hinge components***

3.6 Cost and weight estimation module

For standard parts, the weight is directly retrieved from the standard part library. For non-standard parts, the weight is estimated on the basis of the geometry of the part and the type of material used in manufacturing the part.

For cost estimation, HDOT makes use of a separate tool called CERCOPS (Cost Estimation Routine with Commonality for Optimization Studies) [12]. CERCOPS is a KBE tool developed to estimate the cost of different aircraft parts and assemblies. The input to CERCOPS varies depending on the phase of design it is used. In early design stages, when the design details are few, CERCOPS uses low fidelity cost-estimation methods which estimate the cost of a component based on the weight of the component and a costing power formula.

When the design reaches a level of maturity where more details are available, CERCOPS uses high-fidelity cost estimation methods where, the time needed for various tasks in the manufacturing process and its resulting cost, the cost of raw materials and material costs are evaluated to determine the cost of the component. Here, detailed geometrical definition, manufacturing steps involved and the cost of raw materials form the input to CERCOPS. To support the designers and costing engineers, CERCOPS comes with pre-loaded database of raw materials and manufacturing steps. CERCOPS is designed to allow easy enhancement of the database thus making it useful for a wide range of components. In addition to evaluating the cost of individual components, CERCOPS also supports the cost estimation of assembly of components on the basis of the time needed to assemble a product.

4 FRONT LOADING CASES FOR FIN-RUDDER INTERFACE DESIGN

HDOT was developed to provide engineers with an opportunity to conduct "what-if" studies, carry out design space exploration and perform design optimization studies. These are made possible by reduction in design lead time due to the automation of fin-rudder interface design process. This section quantifies the benefits of front-loading the fin-rudder interface design. All the results in the following sections are normalized for confidentiality reasons. For all the case-studies, one and the same load case is considered for demonstration purposes, namely the full rudder deflection case. The forces and moments acting on the rudder and the OML are also kept the same for all the case-studies.

4.1 Case study 1: Time benefits

The idea behind front loading is to make use of design automation and KBs to rapidly design products at the start of a new project. In order to evaluate the time reduction benefit delivered by new front loaded approach, several Fokker engineers were requested to provide an estimate of the time usually spent on the various phases of the concurrent rudder-fin interface development process. Some average values were gathered, showing a good agreement between the various interviewed engineers. The outcome of this analysis is summarized in ***Table 1***. This study compares the execution time of HDOT for particular design activities with the time spent by engineers to carry out the same task in the traditional design process. The time required for the development of HDOT and the time needed to further improve HDOT for its commercial implementation is *not* accounted in this case study.

Table 1: Time reductions obtained by front-loading fin-rudder interface design

Design task	**Time reduction due to front loading**
Sizing hinges	99%
Finite Element Analysis (pre-processing)	99%
Cost Estimation	94%

The time reductions are shown per disciplinary team existing at Fokker Aerostructures and not as the overall design process as the engineers find it difficult to estimate times when tasks are carried out in parallel. As a result, the time lost in transferring information from one team to the other and the waiting time are not included in this study. Whether the time reductions in individual tasks result in overall lead time reductions depends on the total development process of the fin-rudder interface and the rudder the. Initial studies indicate the use of front-loading could result in overall lead time reduction, however, this remains to be investigated by including the front-loading of rudder design.

4.2 Case study 2: DOE to study the effect of hinge positioning on fin-rudder interface weight

The importance of iteration in fin-rudder interface design process was discussed in Section 2. In this case study, the fin-rudder interface design process is iterated using DOE. To carry out this DOE, HDOT is invoked by a Process Integration and Design Optimization (PIDO) tool, called Optimus (**Figure 10**). The workflow generated in the PIDO tool can be used to perform DOE or a complete optimization. The PIDO tool comes with pre-loaded algorithms to carry out DOE and Optimization.

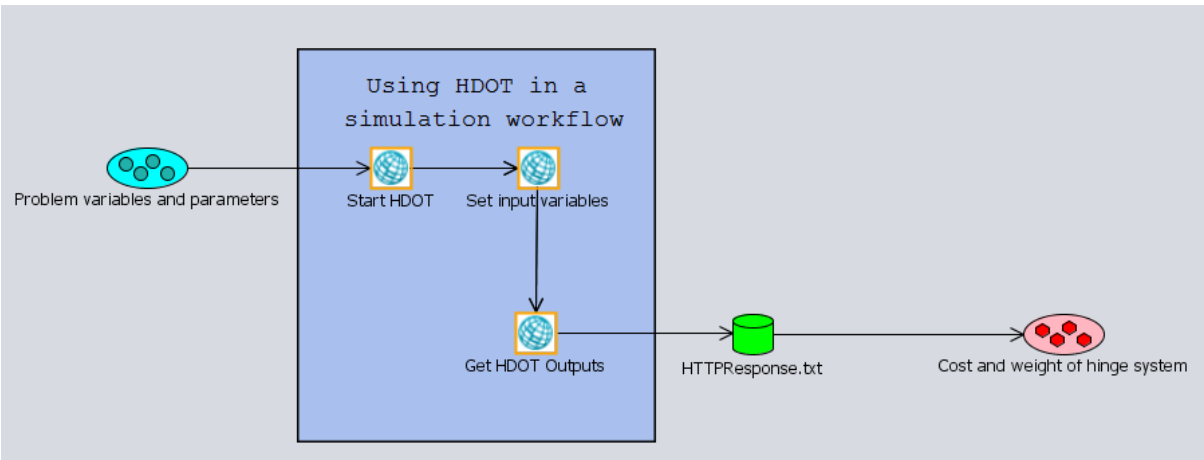

Figure 10: Use of HDOT in Optimus to carry out DOE and MDO

The DOE was performed to study the effect of changing the lever arm, span-wise distribution of the rotation hinges and number of rotation hinges on the weight of the hinge system. The design variables used for this case study are detailed in **Table 2**. Latin Hypercube algorithm that was available in the PIDO tool was used to carry out DOE. 225 fin-rudder interfaces were investigated in this study, which took about 18.75 hours to complete.

The results of the DOE are shown in **Figure 11**. A scatter plot of the effect of changing the lever arm and the number of hinges is plotted. The normalisation is carried out with respect to a reference design. It is observed that, in general, increasing the number of hinges increases the weight of the hinge system as more number of parts are involved. However, increasing the number of rotation hinges reduces the force acting on the hinges and thereby reducing the size of the components. Occasionally, the reduced size of hinge components offsets the weight added due to the presence of more number of components. This is the reason for ***some*** 5 hinge systems being lighter than 4 hinge-systems and ***some*** 6 hinge systems being lighter than 5 hinge-systems for the same lever arm. No clear effect of span-wise distribution of the rotation hinges could be seen on the weight of the fin-rudder interface.

In this DOE, lever arm is considered a design variable with bounds ranging from 10-80% of maximum section hinge plane width(**Figure 1**). However, depending on the design constraints, such a bound might change. For example, the bound could be 10-15% of maximum section hinge plane width. In such a case, a 5 hinge system might be more beneficial as they can withstand the forces acting on the rotation hinges even with a small lever arm. This is shown with a black circle in **Figure 11**. In this diagram, infeasible designs have been omitted. These are designs where the combination of materials and/or parts violate one or more constraints. Of the 225 hinge systems attempted in the DOE, 172 designs were feasible.

Table 2: Design variables to study the effect of hinge positions on hinge system weight (DOE and MDO)

Variables	Range		Notes
Lever arm	10 – 80 % with a step size of 1 %		It is defined as the percentage of maximum section hinge plane width (**Figure 1**)
Number of rotation hinges	4-6 hinges		-
Span-wise distribution of rotation hinges	4 hinge system	[10%, 20%, 40%, 80%]	A list of percentage of the span of the rudder at which a rotation hinge is placed is used to determine the span-wise distribution of rotation hinges. For a **given** number of hinges, the PIDO tool chooses one of the three span wise distribution.
		[10%, 30%, 50%, 80%]	
		[10%, 40%, 60%, 80%]	
	5 hinge system	[10%, 20%, 40%, 50%, 80%]	
		[10%, 20%, 40%, 60%, 80%]	
		[10%, 20%, 40%, 70%, 80%]	
	6 hinge system	[10%, 20%, 40%, 50%, 60%, 80%]	
		[10%, 20%, 40%, 50%, 70%, 80%]	
		[10%, 20%, 40%, 60%, 70%, 80%]	

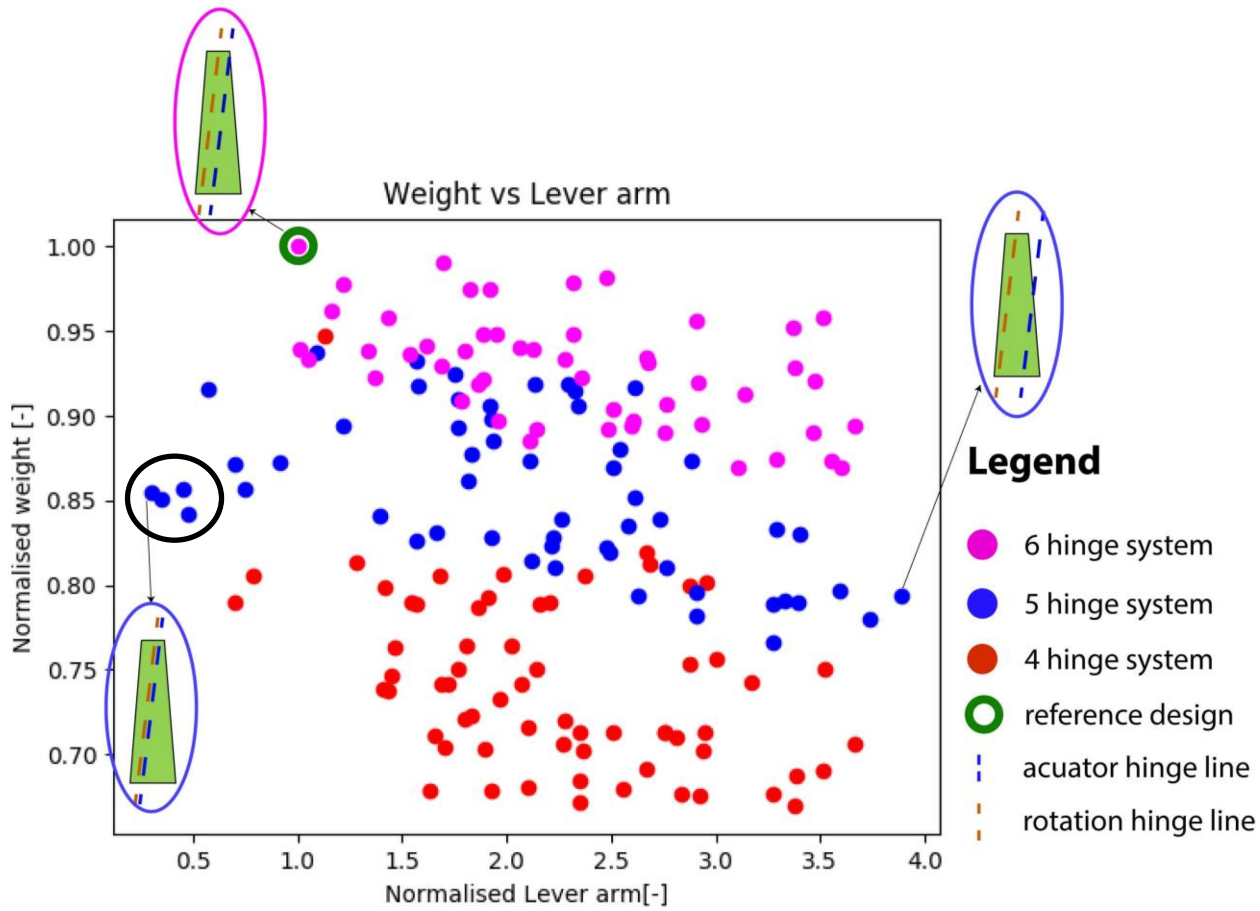

Figure 11: DOE results on the effect of number of hinges and the lever arm on the weight of the hinge system

Such a DOE can help engineers understand the design space better and know what type of hinge system must be chosen with varying requirements In order to arrive at an optimal design, MDO needs to be carried out for a certain objective function. This is further discussed in the following case studies.

4.3 Case study 3: MDO to study the effect of hinge positioning on fin-rudder interface weight

DOE can be useful in performing MDO as a DOE can help understand the design space and ensure that the design variables used are relevant for optimization. With the same design variables as described in **Table 2**, an MDO study was carried out. The disciplines involved in this MDO study were cost estimation, weight estimation, geometry modelling, FEA, aerodynamic load calculation and stress analysis. In the specific case of fin-rudder interface design problem, the disciplines could be executed such that there were no feedback loops. To benefit the most from this, a Multi-discipline Feasible [8] architecture was used in this MDO Study.

A genetic algorithm available in the PIDO tool was used to optimize the weight of the hinge system. The optimization run used a population size of 20 iterated over 30 generations. Hence, a total of 600 hinge systems were evaluated in this optimization run which took about 50 hours to complete. Of the 600 designs, 495 designs were feasible. The feasible results of this MDO study are plotted in **Figure 12**. The results were normalized with a reference design shown in **Figure 12**.

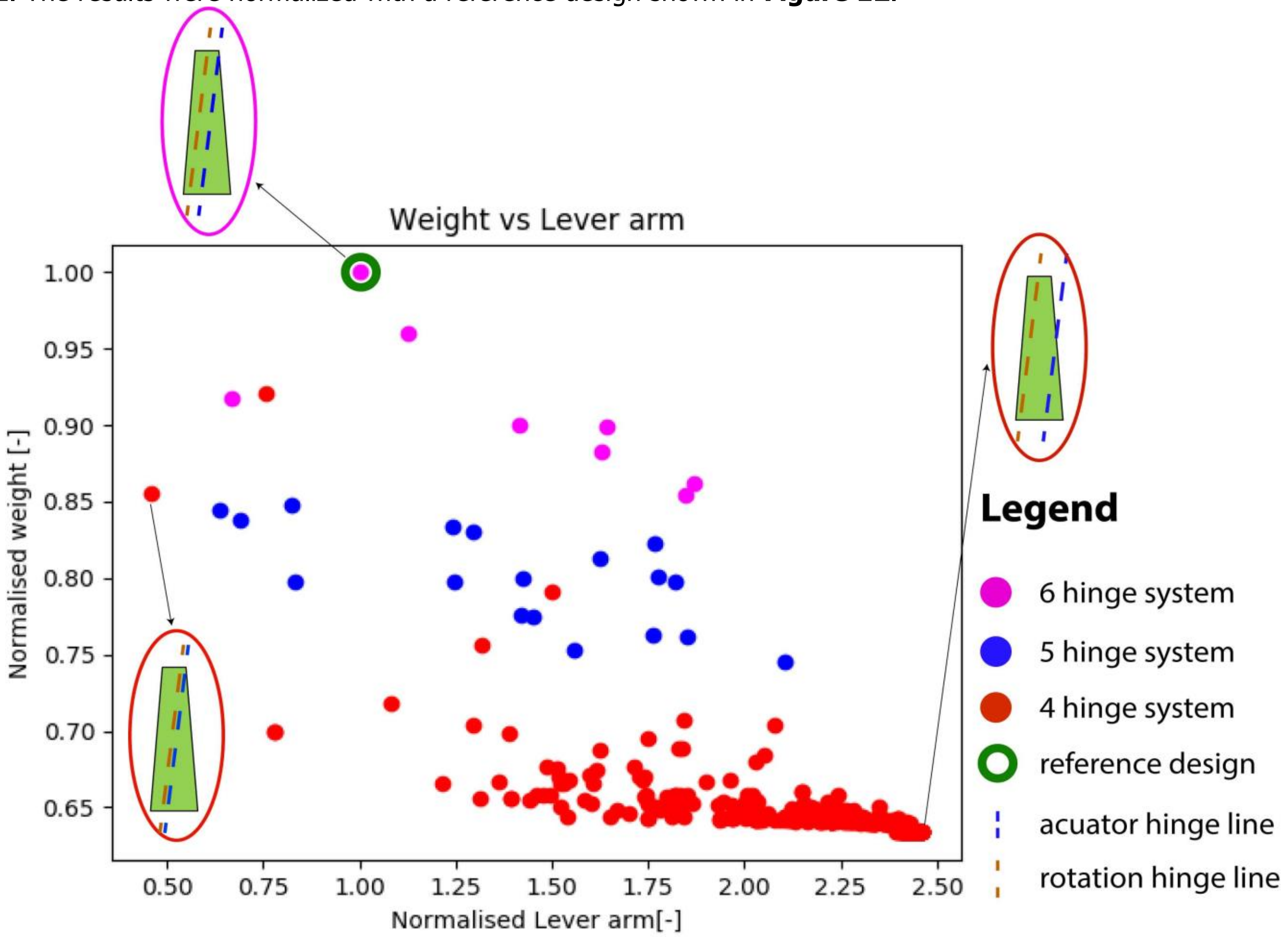

Figure 12: MDO results on the effect of number of hinges and the lever arm on the weight of the hinge system

The results indicated that the optimizer preferred the 4 hinge system as there were less parts involved and hence lower weight. Furthermore, the optimizer tried to move towards designs that allow the highest lever arm. It can been seen that the optimizer used a lever arm that was 2.4 times that of the reference design. Obviously, the higher the lever arm the lower the forces acting on the hinge, thus the lower the hinge size and weight. An MDO study of this type helps quantify how large the lever arm should be in order to minimize weight while at the same time satisfying all the design requirements.

In order to study the effectiveness of the design process, a manual design of the hinge system was carried out (see reference design in **Figure 12**), which when compared to the optimization results, proved to be 37% worse than the optimum design in terms of the weight. It is important to note that the improvement shown was only for the demonstration of the technology and the effect of the fin-rudder interface design on the rudder design must be accounted before a final conclusion on design improvement is made. This remains to be studied and is not a part of this research work.

4.4 Case study 4: MOO to study the effect of hinge positioning on fin-rudder interface cost and weight

In an industrial context, cost is an important design driver. While weight of aerospace systems directly translates into operational cost, the initial manufacturing cost is equally important and must be given due consideration by the designer. To study the effect of manufacturing cost, a multi-objective optimization was carried out using the PIDO tool. For this study, the NSEA++ algorithm, a variation of genetic algorithm, was used. It used a population size of 8 and was iterated over 20 generations. Hence, 160 hinge systems were investigated for this study of which 67 designs were feasible and took about 13 hours to complete. This study was carried out to demonstrate the capability of Multi-objective Optimization (MOO) and was limited to small design population owing to the time limitations. The design variables for the MOO study are detailed in ***Table 3***.

Table 3: Design variables to study the effect of hinge positions on hinge system weight (MOO)

Variables	Range	Notes
Lever arm	20 – 80 % with a step size of 5 %	It is defined as the percentage of maximum section hinge plane width (**Figure 1**)
Span-wise distribution of rotation hinges	[10%, 20%, 40%, 80%]	A list of percentage of the span of the rudder at which a rotation hinge is placed is used to determine the span-wise distribution of rotation hinges.
	[10%, 30%, 50%, 80%]	
	[10%, 40%, 60%, 80%]	
	[10%, 20%, 60%, 80%]	
	[10%, 30%, 60%, 80%]	
	[10%, 40%, 60%, 80%]	

The results of the MOO study are plotted in **Figure 13**. Only the results that satisfied all the design requirements are plotted here. The trade-off points are marked by the red circle. Trade off points are those design points where losing one quality or aspect results in gaining another quality or aspect. Here, trade-off points imply increased weight results in reduced cost of the product and vice-versa. For example, for the points marked, a 5.5% reduction in cost can be obtained for 0.2% increase in weight. Both these designs have same lever arm which is 60% of maximum section hinge plane width and both have 4 rotation hinges. However, they differ in the span-wise rotation hinge distribution. The fin-rudder interface which has a distribution of *[10%, 40%, 60%, 80%]* has lower weight and higher cost than the fin-rudder interface that has a span-wise distribution of *[10%, 30%, 60%, 80%]*. Considering the small population that was used to carry out this MOO, only two trade-off points could be obtained which is not sufficient to make a proper Pareto front. However, studies with larger population sizes are envisaged in the future work that might lead to the determination of one or more Pareto fronts depending on the design cases, if it exists.

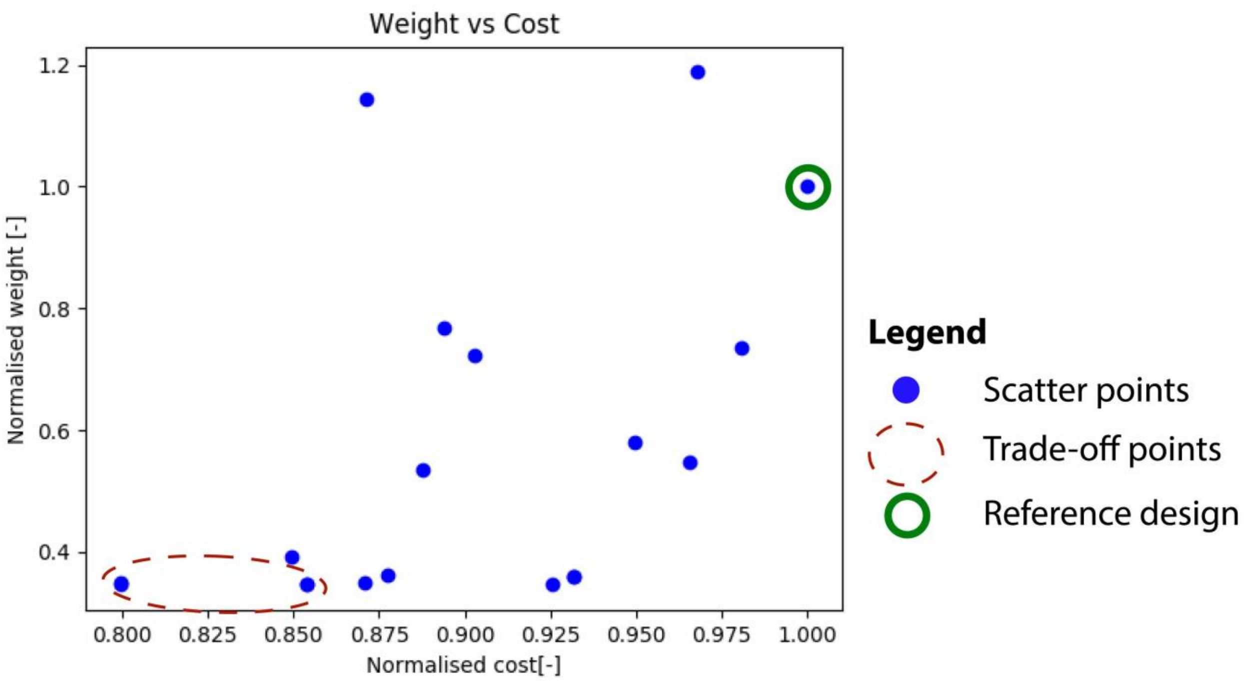

Figure 13: Scatter plot of MOO study of hinge-system weight vs cost

5 DISCUSSION AND CONCLUSIONS

This principal aim of this study was to improve the product development process and product performance. As discussed in section 1, this is possible by reducing design lead time and carrying out systematic design space exploration. In order to enable these improvements, as an alternative to the existing concurrent engineering process, front-loading was proposed. For the specific case of fin-rudder interface design, the lead time improvements and the design space exploration capabilities and benefits were quantified in section 4. In this section, the benefits of using front-loading in an industrial context are discussed. Furthermore research recommendations are made to enhance the applicability of this research. Finally, some non-technical effects of using such a front loaded design process are discussed.

Front-loading has been demonstrated in previous studies and multiple examples are available in the literature [4] [6]. As explained in section 2, the challenge lies in selecting the right computing environment to front-load a given design process. In the past, especially in an industrial setting, the computing environment that was selected often had limitations in incorporating the changing inputs from OEM for aircraft component design. [4] The development of KBE tools helped in solving this problem as the tools evaluate the effect of any changes in the input rapidly to determine the weight, cost and margins of safety of the fin-rudder interface. This makes the idea of front-loading viable in an industrial context as the effect of changes in the inputs such as loads and OML can be evaluated on the fly with minimum manual intervention. Furthermore, KBE tools can be easily used in an MDO framework which is useful in carrying out detailed design space exploration to improve product performance.

The detailed design space exploration carried out in this study can be used by companies like Fokker Aerostructures to rapidly generate proposals for OEMs. The results of DOE, single objective and multi-objective optimization studies can be stored in a KB. This KB can be further extended by carrying out design space exploration for varying loads and OML.

When a request for proposal is made to Fokker Aerostructures by an OEM, the engineers can look up the KB which contains the results of front-loading in the form of fin-rudder interface configurations that are optimal for a given set of rudder loads and OML. This KB can then be used to select a design solution that best matches the design problem at hand. Based on this selection and the time available for proposal generation, the selected design solution can be verified to ensure that the solution meets all the requirements and an optimization can be carried to check if better design solutions exist for the given set of requirements. This can help companies like Fokker Aerostructures get distinct competitive advantage as they not only provide a compliant design but also an optimized compliant design in a limited time frame which was previously not possible with manual concurrent engineering process.

In the specific case of fin-rudder interface design, this research work focused on the design and optimization of the hinge-system alone. While a compliant rudder was designed for every new hinge system, there was no optimization of the rudder structure and material. This could be an interesting use case and extension of this research work. Even for hinge sizing operations, quasi-exhaustive search was used as they are faster than full-blown MDO. As a result of this quasi-exhaustive search, potential optimal design solutions could be lost. As a next step in the research, front-loading of hinge sizing operations must be carried out to eliminate quasi-exhaustive search to improve the product and process performance.

In conclusion, initial studies demonstrate the benefits of front loading the fin-rudder interface design. If a such a front loaded methodology is verified and validated and used in a commercial project, even by conservative estimates, over 90% reduction in design lead time can be achieved. From a non-technical perspective, using this demonstrator in commercial applications requires allocation of significant man-power and focus to test, validate, verify and further develop the existing tools. In addition, the fear of engineers losing jobs due to such an automated design process can be laid to rest as much more work in generated in terms of carrying out "what-if" studies and analyzing the results of design space exploration. If anything, such a front-loaded process will allow engineers to focus on creative engineering tasks while leaving out the manual repetitive tasks to the computers while at the same time helping companies like Fokker Aerostructures improve their product and process performance.

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