Dynamic MDAO Workflows to Enable Design for Manufacturing of Aircraft Structural Components

MSc. Thesis Report

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TU Delft

Challenge the future

Dynamic MDAO Workflows to Enable Design for Manufacturing of Aircraft Structural Components

MSc. Thesis Report

by

Mikhail Nikitin

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Preface

This master thesis research represents the end of my five-year-long journey in the world of Aerospace Engineering at TU Delft. Carried out within the framework of DEFAINE, the study focused on implementing design manufacturability analysis into the design process and testing a novel methodology for executing optimisations. This work challenged me in many ways but I am proud of the results my efforts led to, which are presented in this report.

First and foremost, I would like to thank my thesis supervisor Dr.ir. Gianfranco La Rocca for all the useful feedback and for reminding me to never overlook the bigger picture and the importance of this work. I would also like to express my deepest gratitude to ir. Anne-Liza Bruggeman, my daily supervisor, for her unwavering support and guidance, assisting me in work when it was most needed. Always going above and beyond to provide invaluable advice, she is the best supervisor one could wish for. Additionally, I extend my appreciation to Dr.ir. Otto Bergsma for sharing his wisdom and work on composite manufacturing to improve the scientific value of my research. My thanks also go to Dr. Fabrizio Oliviero for chairing my examination committee.

Last but not least, I must thank every single individual who has been part of my life in these last five years. My friends from The Hague and Delft, in the Netherlands and all around the world, were essential to help me get through all the work and stress of studying at TU Delft. They made the bright moments of my life shine even brighter and ensured that I maintained my mental well-being. Furthermore, none of this would have been possible without my family, who supported and helped me in every way possible. Even while most of the time we were entire continents apart, I always felt your love and attention. Without any of you, this journey would not have been the same.

A special thanks goes to TU Delft and every member of the Aerospace Engineering faculty. Their teachings and expertise shaped me into an engineer and the individual I stand as today, and I am deeply grateful to the many inspiring people whom I encountered through this remarkable chapter of my life. I will forever cherish this experience.

Mikhail Nikitin
Delft, January 2024

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NOMENCLATURE

ABBREVIATIONS

Abbreviation	Definition
AFP	Automated Fiber Placement
ANA	Automated Manufacturability Analysis
CA	Collaborative Architecture
CATMAC	Cost Analysis Tool for Manufacturing of Aircraft Components
CMDOWS	Common MDO Workflow Schema
CNC	Computer Numerical Control
CPACS	Common Parametric Aircraft Configuration Schema
DEE	Design and Engineering Engine
DOE	Design of Experiments
DFM	Design For Manufacturability
FPG	Fundamental Problem Graph
IDF	Individual Discipline Feasible
KADMOS	Knowledge- and graph-based Agile Design for Multidisciplinary Optimization System
KA	Knowledge Architecture
KBE	Knowledge-Based Engineering
MBSE	Model-Based Systems Engineering
MDAO	Multidisciplinary Design Analysis and Optimisation
MDF	Multidisciplinary Feasible
MDG	Multidisciplinary Data Graph
MIM	Manufacturing Information Model
MOO	Multi-Objective Optimisation
MPG	Multidisciplinary Problem Graph
MPM	Mass Properties Module
OML	Outer Mold Line
OOA	Out-Of-Autoclave
PIDO	Process Integration and Design Optimization
RCG	Repository Connectivity Graph
RMM	Requirements Management Module
TRL	Technology Readiness Level
UCI	User Customized Interface
WOT	Wings Of Tomorrow
WP	Work Package
XDSM	eXtended Design Structure Matrix
XML	eXtensible Markup Language

SYMBOLS

Symbol	Definition	Unit
η_s	Plasticity correction factor	[-]
ν	Poisson ratio	[-]
τ_{cr}	Critical shear stress	$[N/m^2]$
C	Plate boundary condition factor	[-]

Symbol	Definition	Unit
b	Lightening holes spacing	[m]
D	Lightening holes diameter	[m]
E	Young's Modulus	[Pa]
f_s	Net shear stress in the web	[Pa]
G	Shear modulus	[Pa]
G_s	Shear secant modulus	[Pa]
h	Two-thirds of rib height	[m]
q	Shear flow	$[N/m]$
t	Rib thickness	[m]

INTRODUCTION

With the demand for air transportation set to double by 2040 [1], companies need to stay competitive by optimizing the aircraft design process. Multidisciplinary Design Analysis and Optimization (MDAO) has emerged as a key strategy, facilitating effective analysis and optimization of complex design systems [2]. While multiple aspects of design have already been included in optimisation studies, a notable gap exists in evaluating designs based on their manufacturability.

Although manufacturing information is available, it is often not documented efficiently, hampering manufacturability considerations integration in the design process [3]. This hinders the ability to perform early estimations of manufacturing time and costs [4], leading to an inefficient work process [5].

This thesis project aims to integrate manufacturing considerations into an MDAO workflow, to aid in early identification of potential production issues caused by the product design. For this, a new methodology is implemented and tested, consisting of making the MDAO workflow dynamic, hence able to adapt its structure based on the current optimisation point. Therefore, the main research objective for this thesis is **to investigate the possibility and impact of implementing manufacturing considerations in the design process, at early design stages, via the integration of multiple manufacturing techniques into a dynamic MDAO workflow**.

This report is structured in three main parts. Part I of the report consists of the scientific paper which discusses the methodology for product manufacturability assessment and dynamic workflow formulation. The described methodology is implemented on a wing rib design case to investigate the impact of integrating manufacturing considerations in design optimisation studies, and the dynamic MDAO workflow performance when compared to static systems. Part II of the report presents the Literature Review that was performed to support the thesis project and was previously graded under the AE4020 course. Finally, Part III of the report includes additional supporting work: an expanded methodology behind the wing rib module structural calculations and additional explanations of the machining module verification.

I

SCIENTIFIC PAPER

Dynamic MDAO Workflows to Enable Design for Manufacturing of Aircraft Structural Components

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With growing demand for air transportation, it is crucial to improve the efficiency of aircraft systems design. A key area of focus is the implementation of manufacturability considerations into the design process at early stages. This could be done by integrating manufacturability analysis modules into an MDAO workflow, however, each production method places unique requirements on the system. This study investigates the impact of considering manufacturing in the initial design phase, using a novel dynamic MDAO workflow that is capable of changing its analysis disciplines, design variables and constraints based on the current design point within an optimisation. This methodology was tested on a wing rib design case, with two production methods available: machining for metal ribs and stamp-forming for composite ribs. Integrating DFM analyses into the design study improved the trustworthiness of optimum results, removing non-manufacturable rib designs. Dynamic MDAO workflows yielded faster multi-objective optimizations and efficient handling of correlated objectives compared to conventional static workflows while providing similar results.

Nomenclature

η_s	=	Plasticity correction factor
ν	=	Poisson ratio
τ_{cr}	=	Critical shear stress
E	=	Young's Modulus
h	=	Two-thirds of rib height
q_{cr}	=	Critical shear flow
t	=	Rib thickness
CATMAC	=	Cost Analysis Tool for Manufacturing of Aircraft Components
CMDOWS	=	Common MDO Workflow Schema
DFM	=	Design For Manufacturability
KADMOS	=	Knowledge- and graph-based Agile Design for Multidisciplinary Optimization System
KBE	=	Knowledge-Based Engineering
MBSE	=	Model-Based Systems Engineering
MDAO	=	Multidisciplinary Design Analysis and Optimisation
MOO	=	Multi-Objective Optimisation
OML	=	Outer Mold Line
PIDO	=	Process Integration and Design Optimization
RMM	=	Requirements Management Module
UCI	=	User Customized Interface
XDSM	=	eXtended Design Structure Matrix

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I. Introduction

With the demand for air transportation likely to double in size by 2040 [1], companies must ensure their competitiveness in the market. A critical imperative for achieving this lies in enhancing the cost and time efficiency of the aircraft design process. The ultimate objective is to accelerate the introduction of new products, design enhancements, and innovations to the market. Multidisciplinary Design Analysis and Optimisation (MDAO) has emerged as one strategy to achieve this due to its capacity to effectively analyze and optimize large design systems comprised of multiple disciplines. The use of MDAO frameworks facilitates the repeatability of the design process, enabling engineers to perform detailed configuration comparisons more rapidly [2].

While various design tools related to structures, aerodynamics, and control have been successfully integrated into MDAO systems, one notable absence is the assessment of designs from a manufacturability perspective. Despite the significant amount of manufacturing information accumulated over years of aircraft design, inadequate documentation often hinders its integration into the product design process [3]. Additionally, limited knowledge about the design production process makes early estimations of manufacturing costs and time challenging [4], resulting in the postponement of considerations related to design production to later stages [5]. Currently, addressing these challenges involves incorporating manufacturing experts and designers in early product development discussions, a process that lacks formal structure and effective methods for systematically leveraging manufacturing knowledge during design [5–7]. Recently, there has been a growing push to adopt design-for-manufacturability (DFM) practices, which consider manufacturing requirements from the conceptual design phase onward [3, 4].

The current thesis project aims to bridge this gap by integrating manufacturing considerations into an MDAO workflow. The use of MDAO workflows enables to address and exploit the coupling and mutual interactions between disciplines, as design and manufacturing choices influence one another. Furthermore, by incorporating manufacturing requirements early in the design process, an early identification of potential manufacturing challenges can take place, before prototypes or final products are built, minimising costly redesigns, thereby shortening the time-to-market [3, 6]. To achieve this goal, a new methodology has to be adopted. Therefore, a dynamic MDAO workflow which can adapt its structure (design variables, disciplines and constraints) based on the current design point has to be established. This is necessary as each manufacturing technique is expected to impose different requirements on the system configuration. Consequently, the research objective defined for this work is:

To investigate the possibility and impact of implementing manufacturing considerations in the design process, at early design stages, via the integration of multiple manufacturing techniques into a dynamic MDAO workflow

This research objective can be translated into two main research questions that will guide the project:

1) How do the **design process** and **overall product design** change when manufacturing is considered at the start, rather than at subsequent design phases?
2) What are the **advantages** and **disadvantages** between static and dynamic workflows when applied to a design including manufacturing analysis?

To answer these questions, a dynamic MDAO workflow that includes two different manufacturability assessment modules will be formulated and executed. In this work, a wing rib design case study will be considered.

II. Methodology

To investigate the possibility and influence that dynamic MDAO workflows could have on design optimisation studies, a wing rib design optimisation problem is defined. This design problem was chosen as a wing rib offers sufficient design complexity for manufacturability assessment with different manufacturing methods while not over-complicating the problem for a proof-of-concept study. It will be studied using conventional, static, MDAO workflows as well as using the new dynamic implementation. This design problem is further enhanced with the inclusion of manufacturability assessment modules that will enable DFM considerations to be implemented in the optimisation. An overview of the desired MDAO workflow structure can be seen in Figure 1. The eXtended Design Structure Matrix (XDSM) represents a dynamic MDAO workflow where a wing rib model is created based on the optimiser's inputs, and subsequently evaluated on its production cost and manufacturability, with the manufacturing module changing dynamically with the optimisation point.

To obtain this workflow, first, the individual disciplines were created, such as the wing rib module and the cost assessment modules. These will be discussed in subsection II.A and II.B. Furthermore, two separate manufacturing modules were developed to assert whether a given design is manufacturable. The implemented production methods are *machining* to produce metal ribs and *thermoplastic stamp-forming* to produce composite ribs and will be discussed in subsection II.C and II.D. These manufacturing techniques were selected due to being proven manufacturing technologies for such applications [8, 9]. Then, the methodology behind workflow formulation and execution for static and dynamic workflows is presented in subsection II.E. Lastly, the execution strategy to obtain useful results is discussed in subsection II.F.

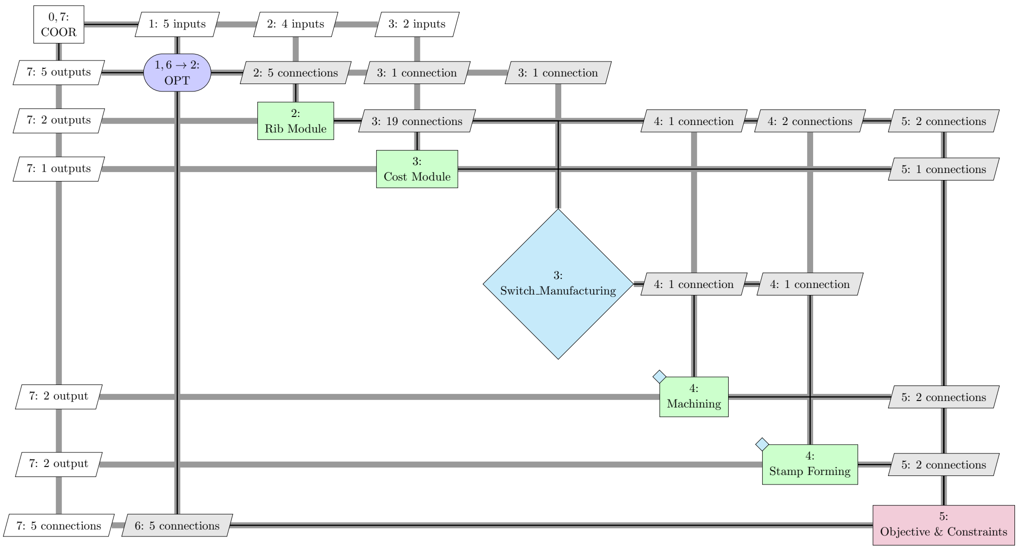


Figure 1. XDSM of the desired MDAO problem architecture

A. Wing Rib Module

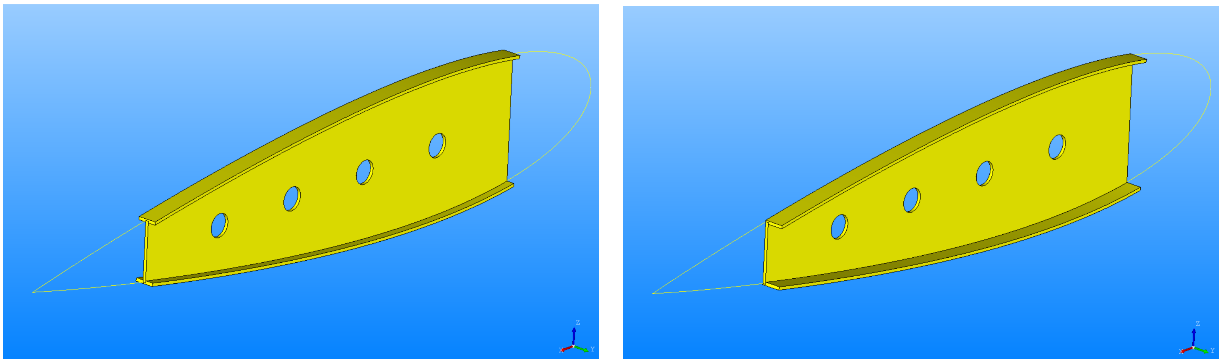
For the purpose of this study, a wing rib model was developed using the ParaPy Knowledge Based Engineering (KBE) software, which is used to capture engineering logic and design rules, and allows rapid adaption of the rib design and generate CAD geometries. This is enabled via dependency tracking and demand-driven evaluations when the fully parameterised wing rib model is adjusted.

For this model, the outer geometry of the rib is defined by an airfoil, the chord length, as well as the spar(s) location(s). The former can either be a NACA 4 and 5-digit airfoil or imported from a data file. Modifying these inputs will affect the outer mold line (OML) of the rib, adapting the rib shape to a desired placement location within the wing. The rib model can operate in the sizing or analysis mode; it can take as an input the design loads and then generates a rib seized for the load requirement, or it can take geometrical inputs and based on them compute the maximum loading of the provided design. The latter working mode is the one used in this work. To perform the structural analysis of the rib, the methodology suggested by Sedaghati and Elsayed [10] for lightly-loaded ribs was selected. Assumed to only be subject to aerodynamic loads, the rib is sized for critical buckling stress, and must not buckle or yield under the loads. This critical buckling stress for rectangular plates is found using Equation 1.

After the buckling stress is computed, a check is performed on whether its value is below the yield shear strength of the material. In the case cut-outs are present in the rib, the same verification happens for the net shear stresses in the web between the holes and in the vertical direction across the hole. These checks ensure that buckling would occur before the rib yields. Lastly, this critical buckling stress can be then converted to shear flow using the Equation 2.

$$\tau_{cr} = \eta_s C \frac{\pi^2 E}{12\left(1-\nu^2\right)}\left(\frac{t}{h}\right)^2 \quad (1) \qquad \tau_{cr} = \frac{q_{cr}}{t} \quad (2)$$

Next, the rib model shape is altered depending on the selected production method (see Figure 2). During machining, the material can be removed from both sides of the initial metal block, allowing for a symmetrical product design, as in Figure 2a. During stamp-forming, however, the geometry is obtained by deforming an initial composite sheet into the desired shape, with holes subsequently cut from the web. This results in an asymmetric design as shown in Figure 2b. Although the rib model can also take as input the desired material, in this study, the choice is constrained to Aluminum AL-2024 when *Machining* production is selected, and Carbon LM-PAEK (Toray Cetex TC1225[1]) for the *Stamp-forming* option. This flexibility enables the generation of desired rib geometries for specific needs and analysis tools, depending on which input the rib model receives from the optimiser.



(a) Machining **(b) Stamp-forming**

Figure 2. KBE rib model design based on the selected manufacturing technique

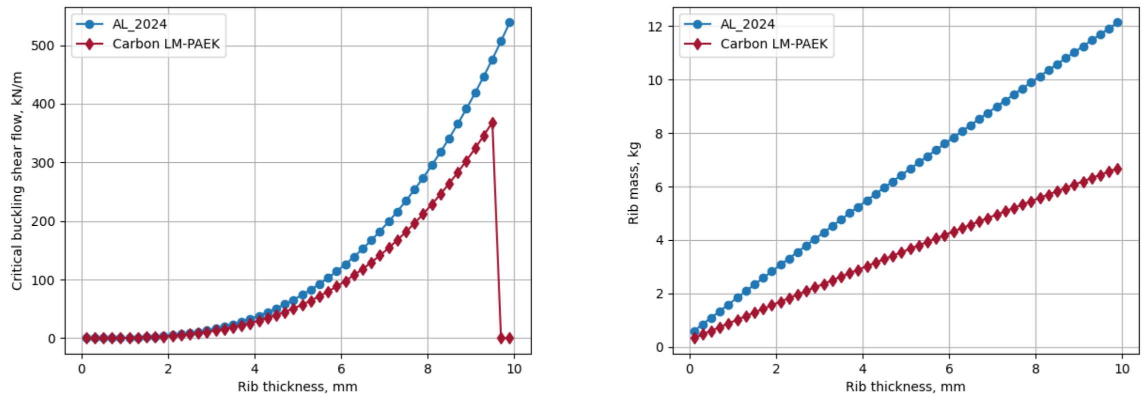
Lastly, to this lightly-loaded rib model, stiffeners are added for the manufacturability analysis. They are meant to represent any type of stiffening elements that need to be added and placed on the rib to improve its performance. Although they are not taken into account for the calculation of the maximum stresses that the rib can withstand, their addition aims to provide an instrument to analyse and quantify the impact of including machining manufacturability into the analysis. The stiffeners are, however, taken into account for the rib mass and are placed close to the leading edge of the rib. Since the web height increases from the leading edge to the maximum thickness point, a greater stiffener spacing will increase the length and hence weight of the stiffeners. Therefore, this placement was chosen to incentivise the optimiser to balance the need guarantee manufacturability while minimising the overall weight by reducing the stiffener spacing.

[1] `https://www.toraytac.com/product-explorer/products/gXuK/Toray-Cetex-TC1225`, accessed on 29/11/2023

1. Tool Verification

The rib model does not only output the CAD rib shape but also key rib sizing and performance parameters necessary for cost analysis and design optimisation. While most of the sizing parameters are extracted using embedded ParaPy functions, the correct implementation of the critical buckling shear flow calculation has to be verified. From the combined Equation 1 and Equation 2, it can be seen that the shear flow $q \propto t^3$. Therefore, a cubic relation is expected to appear if the model's shear flow output is plotted against rib thickness (see Figure 3a). The sudden drop of the critical buckling shear flow that can be seen for the Carbon LM-PAEK curve is due to the implemented checks for the net shear stresses in the web that were discussed previously.

Rib mass is another key output used in the optimisation. Although it is derived from the part volume computed by the software and the provided material density, the correct function behaviour needs to be ensured. Figure 3b shows a linear behaviour between mass and thickness, which is expected for beam-like structures of rectangular nature, and also confirms the correct relation to density (the Carbon LM-PAEK slope is lower as it is a lighter material).



(a) Shear flow change with thickness

(b) Rib mass change with thickness

Figure 3. Verification of the KBE rib model

B. Cost Module

To derive a cost approximation for the rib design, the CATMAC (Cost Analysis Tool for Manufacturing of Aircraft Components) software developed by GKN Aerospace [11] will be utilised. It is an open-source Python package that can provide a cost estimation using the geometrical design features of a product. CATMAC divides the manufacturing process into sub-steps and estimates the costs related to the required materials, hourly rates for the machines and labour at each step.

To calculate results, CATMAC requires the information to be provided in a single XML file where the different parts of a product are defined, together with their design parameters and methods of assembly. Although in general production method-specific tools are expected for cost estimations, CATMAC can be used for both the metal and composite ribs. This only requires alterations in the XML file structure to accommodate the different input needs for the machining and stamp-forming production cost estimations. In the case of a machined rib, it is made of a single part from which material is removed. For the stamp-formed rib, the web and the stiffeners are split into individual parts, which are then manufactured separately and subsequently assembled. For both production methods, CATMAC needs the overall part dimensions, weight and interface area. For composites, additional information regarding the internal structure of the composite part is required. The correct creation of XML files and implementation of the tool were tested by inputting the values from the

CATMAC-provided example files, and verifying that the expected cost results are obtained.

An important consideration is that while the exact cost results of CATMAC can deviate from the actual production values by up to 50% [11], the tool nevertheless provides correct cost-trend estimations. This enables to perform meaningful comparisons of designs for production costs.

C. Manufacturing Module 1: Machining

To assess a metal rib's manufacturability for the machining production method, hence the ability to machine the rib without production issues and redesign, the *accessibility* criteria suggested by Hoefer et al. [12] was selected. It relates to the ability of the machining tool to remove all the material without impacting other features. In essence, the criterion assesses whether the spacing between features is enough for the tool to pass in between. Furthermore, to avoid machine chatter and part distortion during manufacturing, the minimum rib web thickness has to be above 0.794 mm [2].

The machining module takes as input a CAD .STL file as well as the range of machining tool diameters that are available. Then, using the python *numpy-stl* package[3], it converts the provided shape into an array of mesh triangles and their respective normal vectors. In an .STL file, the normal vectors point outwards (away) from a mesh triangle, hence a given feature is found between two normal vectors in the same direction but opposite in orientation (pointing away from each other). Using this logic, the start and end points of each feature can be found. Since the stiffeners in the rib are parallel to each other in the ZX-plane and oriented orthogonally to the XY-plane, their meshes will be described by a unit vector in the negative or positive X-direction, representing the start or the end of a stiffener respectively. The machining module records these positions and measures the spacing between two adjacent stiffeners.

This stiffener spacing is converted to an accessibility grade, which ranges from -1 to 1. A negative grade means that the features are too close to each other, and even the smallest available tool cannot remove the material between them, with -1 given for a spacing of 0. If the grade is equal to or above 0, the rib can be deemed manufacturable, with a higher grade meaning that a larger tooling diameter can be used during manufacturing. After the maximum tooling diameter is reached, the grade is kept at one, meaning all available tools can be used during manufacturing. The grading trend is shown in Figure 4.

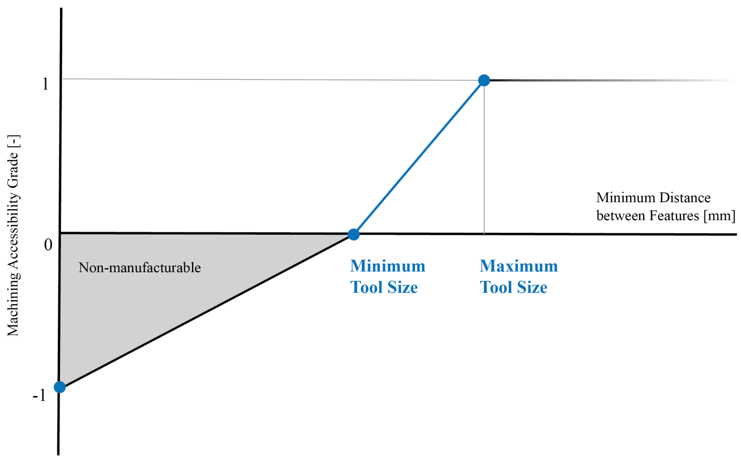


Figure 4. Machining accessibility grade trend

The logic behind the grading stems from the fact that with greater spacing between features, the greater

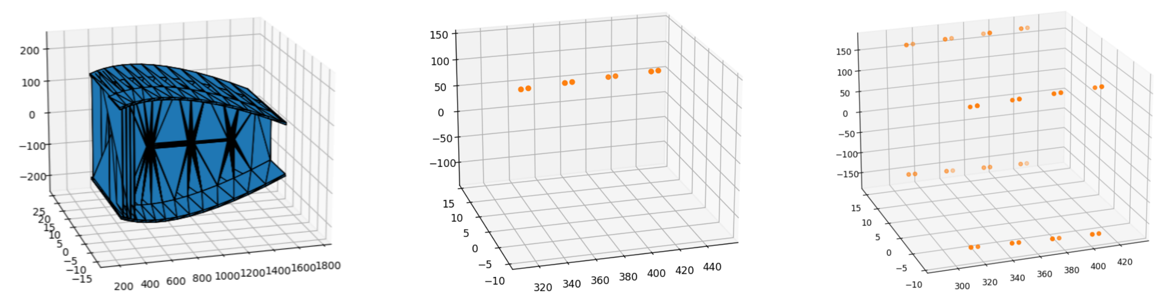
[2] `https://www.xometry.com/resources/machining/cnc-machining-thin-walls/`, accessed on 21/12/2023
[3] `https://pypi.org/project/numpy-stl/`, accessed on 30/11/2023

the tooling diameter can be. A larger tool removes more material per revolution, which can accelerate the production rate. Furthermore, fewer tooling swaps will be required with larger spacing between features, interrupting the production less. This again impacts production time and process efficiency. The continuous rather than binary (manufacturable or not) nature of the grade serves to provide the optimisation algorithm with more information regarding the problem and the input-output dependencies.

This grade for machinability criteria is highly dependent on the available tooling at each factory. For this study, the available tooling range was set between 10 and 20 mm. Hence any spacing between design features that is equal or above 10 mm will be deemed machinable.

1. Tool Verification

To ensure the correct working of the tool and the accessibility criterion implementation, a different method using *numpy-stl* was added to verify that the stiffeners were identified correctly, and the results were also compared to the rib model inside the ParaPy software. The new method consisted of explicitly providing the thickness of each stiffener to the analysis function. Compared to the default implementation which gets no information on the CAD model, this should enable more accurate detection of the stiffeners. The comparison of the two methods can be seen in Figure 5. Figure 5a shows the provided CAD model with four stiffeners close to the leading edge of the rib, while Figure 5b and 5c illustrate that both the main and the verification methods for detecting stiffeners provide the same results. The main implementation only stores a single start and end point per stiffener while the verification method stores all stiffener points, causing the visual differences between Figure 5b and 5c. Lastly, these results were also verified visually, comparing them to the constructed model in the ParaPy software.



(a) Rib CAD with four stiffeners **(b) Main method results** **(c) Verification method results**

Figure 5. Verification of the Machining module's ability to detect stiffening elements in a rib CAD file

D. Manufacturing Module 2: Composite Stamp-Forming

During the stamp-forming process, the initial material sheet is deformed into the desired final shape. When the forming is performed using a composite woven fabric (shown in Figure 6), the angle between two initially perpendicular threads might change [8]. This occurs through the Trellis (shearing) effect when rotation is taking place between interlaced fabric threads due to their point of contact acting as a pivot [13] (see Figure 7). The fabric shear causes high strain, up to 30% in practice [14], and the angle between two weaves is reduced until the smallest, locking, angle is reached. Assuming the material is incompressible, this will affect the product's dimensions as the distance between parallel fibres will reduce, and local thickness will increase [13, 14].

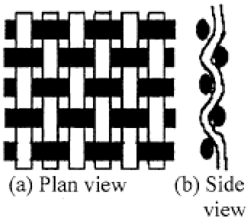


Figure 6. Woven fabric structure [13]

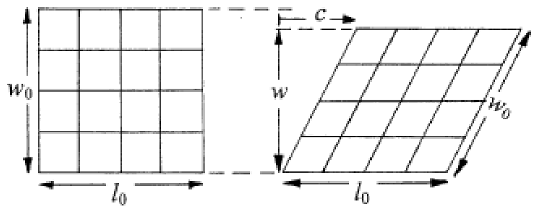
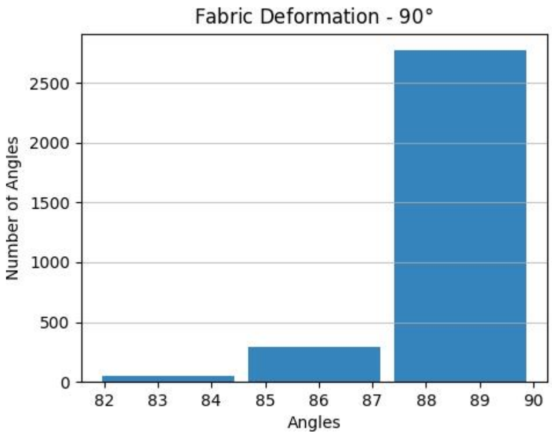
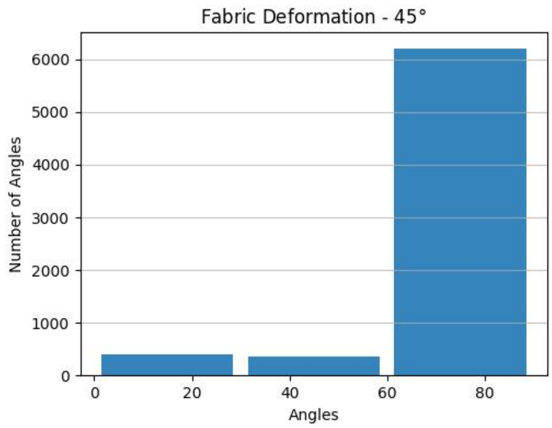


Figure 7. Trellis shearing of a woven fabric [13]

Therefore, to avoid the deformations mentioned above, it is necessary to ensure that the angle between two adjacent weaves remains sufficiently large after the product is formed. To determine whether a given product is manufacturable by forming composite fabrics and to simulate potential future manufacturability problems, the Drape tool [14] was developed by Dr. ir. Otto. Bergsma at the Delft University of Technology. This tool was validated against manufactured products [14] and hence will be implemented in the current work to analyse the weave angles post-deformation. The software takes as input the CAD model of the rib as well as the fabric type and orientation, and outputs a text-style file. The latter is then processed to extract all the weave angles of the deformed fabric. Since composite ribs comprise multiple composite plies with different orientations, the rib design will be examined for fabrics at a 90° orientation and a 45° orientation. An example of the weave angles distribution for a rib obtained with the Drape tool is shown in Figure 8.



(a) Fabric placed at a 90° **orientation**



(b) Fabric placed at a 45° **orientation**

Figure 8. Weave angles distribution example for composite fabrics after being formed into a rib shape

Similarly to the machining discipline, a grade for weave angle deformation is defined. It is recommended that the weave angles remain above 30° for a design to be deemed producible, hence this will be used as the lower bound for passing the manufacturability requirement. This is set as a grade value of 0. If the smallest weave angles are above 60° there is a lower likelihood of manufacturability issues and the designs get a grade of 1. The grade varies linearly between 0 and 1 when the weave angles are between 30° and 60°. However, if the drapability analysis indicates that angles below 30° are present, a negative grade for the design is obtained, going down to -1. The grading is visually illustrated in Figure 9. When assigning a score, the lowest 1% of the obtained angles are not taken into account and are discarded to remove any irregularities potentially originating from the tool itself rather than the given rib model.

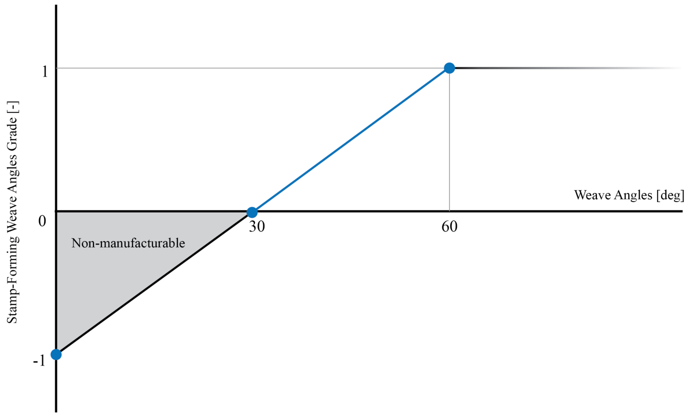


Figure 9. Stamp-forming weave angle grade trend

E. Workflow Formulation & Execution

To create the various optimisation workflows that will be necessary in this research an automated approach was adopted, taking inspiration from the Design and Engineering Engine concept suggested by Bruggeman and La Rocca [15]. This methodology aims to increase the efficiency and speed of workflow formulation and execution processes.

The first step to generate the optimisation problem is to define a list of product and manufacturing requirements. These are imposed on the design space and are defined and stored inside the Requirements Management Module (RMM), which is a Model-Based Systems Engineering (MBSE) tool [16] created to enable a requirements-driven formulation process. When specifying the requirements inside RMM, their problem roles are specified, as well as the tools responsible for verifying the design's compliance with the requirements. These constitute a direct link between the requirements and the MDAO problem. The requirements used in this work are presented in Table 1.

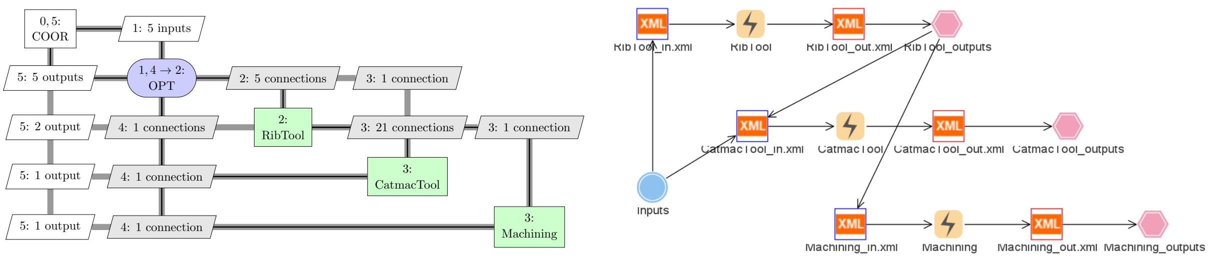
Table 1. Optimisation problem design requirements

Requirement ID	Role	Definition	Test Case Tool
PR-0001	Design variable	The rib shall be produced using machining or stamp-forming	Rib Module
PR-0002	Design variable bound	The rib shall have a web thickness between 2 and 10 mm	Rib Module
PR-0003	Design variable bound	The rib shall have a stiffener spacing between 0 and 30 mm	Rib Module
PR-0004	Design variable	The rib shall have between 0 and 4 web cut-outs	Rib Module
PR-0005	Design variable bound	The rib cut-outs shall have a radius between 10 and 40 mm	Rib Module
PR-0006	Objective	The rib shall have a mass below 20 kg	Rib Module
PR-0007	Objective	The rib shall have a cost below 5000 $	Cost Module
PR-0008	Constraint	The rib shall have a critical buckling shear flow of at least 150 kN/m	Rib Module
Manufacturability			
MR-0001	Constraint	The rib shall have a machining accessibility grade of at least 0	Machining Module
MR-0002	Constraint	The rib shall have a forming weave angle grade of at least 0	Stamp-Forming Module

The first requirement PR-0001 is on the production method variable which defines which outputs the different modules will produce. Based on this design variable, the structure of the workflow will also be adapted, as will be described in subsubsection II.E.1. The requirements PR-0002 to PR-0005 are related to the rib geometrical aspects such as the thickness, number and size of lightening cut-outs as well as the spacing between stiffeners. Then, PR-0006 and PR-0007 are there to ensure the resulting rib is sufficiently light and cost-efficient. Lastly, a rib structural sizing requirement is defined, ensuring the rib design can withstand the loads during operation. The last two requirements linked to the design's manufacturability are added to the problems when it is necessary to evaluate this design aspect. In the static workflow optimisations, only one of the two is included whereas both are necessary in a dynamic problem.

After requirement definition, the RMM tool creates a requirements database, serving as a single source of truth for the entire problem, which is then converted to a problem graph where all the involved disciplines as well as their interconnections are stored. Subsequently, the entire workflow can be formulated with KADMOS, a graph-based tool [17] developed at TU Delft. KADMOS takes as input the necessary tools from the tools repository, the problem graph and the chosen solution strategy (e.g., multidisciplinary convergence study, design of experiments, multidisciplinary analyses) to produce a Common MDO Workflow Schema (CMDOWS) file [18] containing the entire problem definition. CMDOWS is a standardised data-schema format for storing and exchanging MDAO workflow definitions between Process Integration and Design Optimization (PIDO) platforms [19], which are the programs where the workflow execution takes place. In this work, the commercially available NOESIS Optimus[4] software is used. Additionally, KADMOS can produce an XDSM representation of the problem that was formulated, both for the static MDAO workflows (see Figure 10a) as well as for dynamic ones (see Figure 11).

For Optimus to process the workflow correctly, the CMDOWS .XML file is converted to an .OPT file (Optimus-specific file format to represent workflows). This is executed via the Optimus-CDMOWS-Plugin developed at TU Delft, which currently works only for static workflows. The produced .OPT file is imported into the Optimus platform and the optimisation is ready for execution (see Figure 10b). As among the requirements in Table 1 categorical variables are present (production method and number of web cut-outs), the optimisation algorithms must be able to handle them. Among the ones available inside Optimus (2021.1SP2), the single-objective NAVIRUN and multi-objective NSEA+ evolutionary optimisation algorithms can do so and hence were selected.



(a) XDSM representation **(b) Optimus implementation**

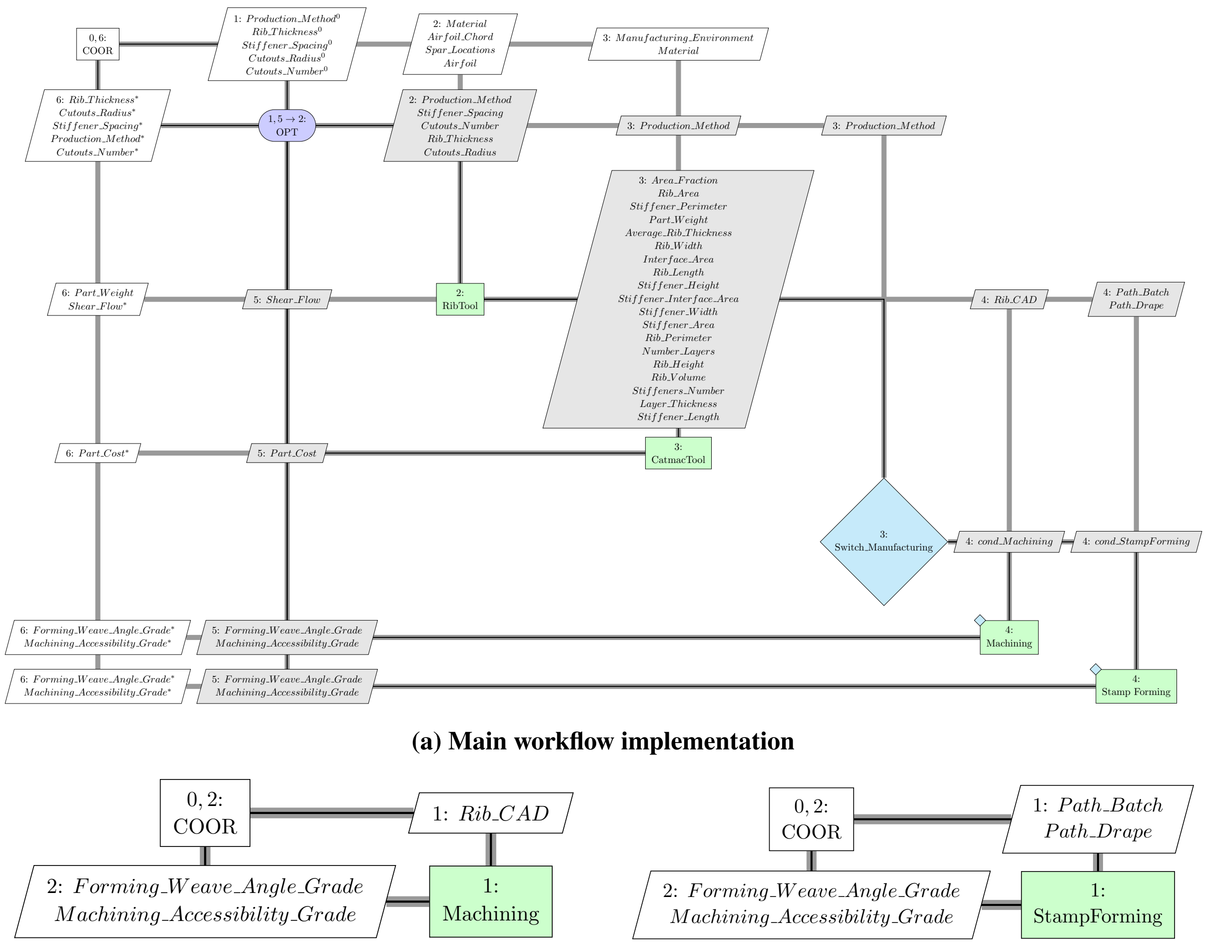
Figure 10. Static MDAO problem

Although the whole workflow formulation process is done in multiple steps, it allows for a rapid (within minutes) modification of the optimisation problem architecture or the disciplines involved. This is advantageous for the current study since, as will be presented in subsection II.F, multiple separate workflows with various structures will have to be created and executed.

[4]`https://www.noesissolutions.com/our-products/optimus`, accessed on 30/11/2023

1. Dynamic Workflow Implementation

While the dynamic MDAO workflow formulation methodology is largely the same as described above for the static workflows, some variations in the process are present. The key difference is that the manufacturing modules are now implemented as separate workflows within the main workflow. Named the subworkflows, they are placed in independent branches and a switch function is added to go to one subworkflow or to another depending on the specified condition. The XDSM of the formulated dynamic MDAO problem with the new switch and subworkflows is shown in Figure 11a. Separate XDSMs are also constructed for the subworkflow, which can be seen in Figure 11b and 11c.



(a) Main workflow implementation

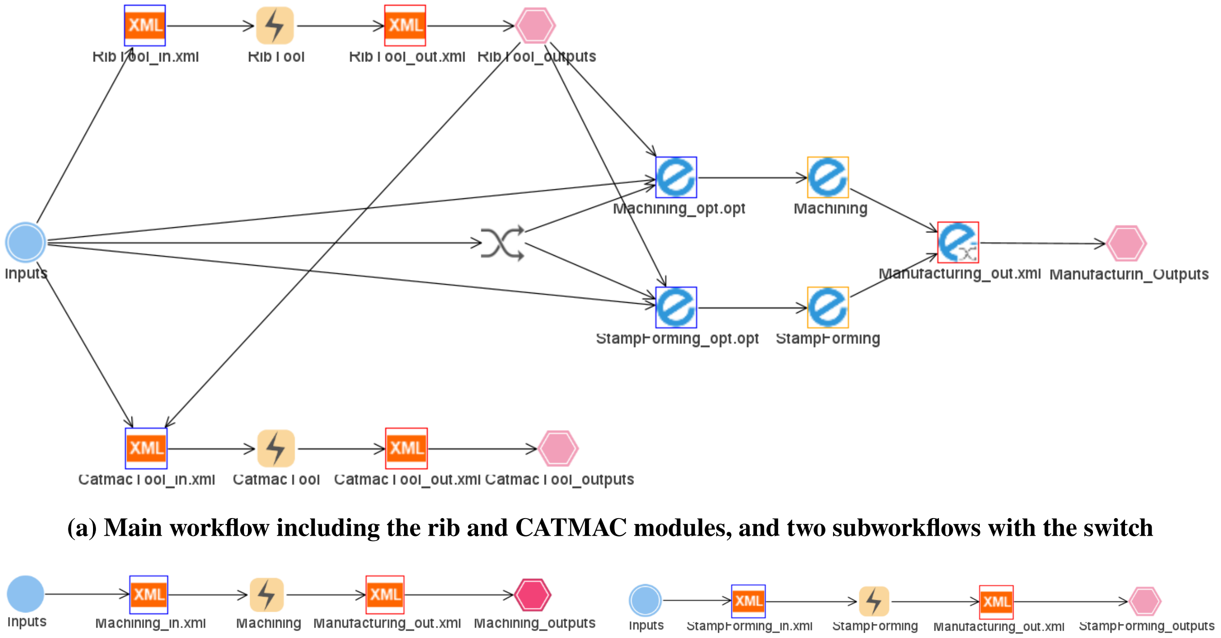
(b) Machining subworkflow implementation **(c) Stamp-forming subworkflow**

Figure 11. XDSM representation of the implementation of the Dynamic MDAO problem in Optimus

In the implemented optimisation problem, the condition for switching from one subworkflow to another depends on the value of the production method design variable. For instance, if the "machining" is selected, the switch will point to the branch of the machining subworkflow. The same occurs for the stamp-forming branch. Also, although the subworkflows can adopt the same solution strategies as the regular workflows, in this work, they are implemented as simple analysis workflows consisting of a single discipline.

Further differences occur in the implementation of the workflows in Optimus. Since dynamic workflows are new and still in development, the aforementioned CMDOWS-Optimus plugin does not support them. Hence, the workflows were reconstructed manually inside the Optimus platform. While the subworkflows, branches and switches were already part of the Optimus software, a user-customised output interface was developed by ir. Anne-Liza Bruggeman at the Delft University of Technology to combine these features. The Optimus implementation of the problem can be seen in Figure 12, with the main workflow in Figure 12a and two subworkflows in Figure 12b and 12c. The new UCI output is represented as a blue "e" in a red frame. The main functionality of the new UCI is to feed the output of the subworfklows into the main one.

The current implementation of the switch within Optimus also introduces a limitation on the tools' outputs which now must be the same for the switch to work. Hence, both matching and stamp-forming modules have to provide a *machining accessibility* grade and a *forming weave angle* grade. This requirement is satisfied by introducing an additional dummy output to each manufacturing module with a value of 1.



(a) Main workflow including the rib and CATMAC modules, and two subworkflows with the switch

(b) Machining subworkflow **(c) Stamp-forming subworkflow**

Figure 12. Optimus implementation of the dynamic MDAO problem

F. Execution Strategy

To investigate the impact of conducting dynamic MDAO workflow optimisations, as well as the inclusion of DFM analyses, several key performance indicators (KPIs) will be recorded and used during the comparison of resulting optimum rib designs. These are the rib weight, cost and whether it is manufacturable using the selected manufacturing technique. Additionally, the optimisation architectures' performance will be evaluated based on the total run time of the optimisation, the number of iterations required as well as the average iteration time. Three types of optimisations will be executed:

- Run 1: Rib weight minimisation
- Run 2: Rib cost minimisation
- Run 3: Multi-Objective Optimisation (MOO) of rib weight and cost

Each of these three optimisation problems will be applied to a static MDAO of a metal rib design, a composite rib design, a metal rib design including machining analysis, and a composite rib design including stamp-forming analysis. This will result in 12 optimisation runs. Furthermore, three more runs will be executed using the dynamic MDAO workflow, leading to a total of 15 optimization studies to be conducted. For each study, a separate MDAO workflow will be created

The comparison of single objective runs for static workflows without and with manufacturing analysis modules will be useful for assessing the impact of manufacturability considerations on the produced rib designs. Furthermore, comparing the dynamic MDAO to the single and multi-objective static MDAOs should showcase the impact of executing a single dynamic workflow instead of multiple equivalent static ones.

III. Results

The previously described methodology and execution strategy was adopted to perform optimisation studies on a wing rib. The results of single and multi-objective optimisations for both static and dynamic workflows will be discussed, and compared in terms of execution speed and produced rib design. Furthermore, the impact of implementing manufacturing considerations into optimisations will be examined.

A. Reference Static Workflow Optimisations

1. Metal Rib

The results for metal rib design optimisations can be seen in Table 2. Starting with the weight minimisation, the optimums were found to be at a rib thickness value of 6.46 mm, which is the smallest rib thickness required to withstand the imposed shear loads on the rib without buckling or yielding. The radius of the web cut-outs was also maximised to reduce the rib mass, although only the optimisation with the manufacturing module ("Weight + DFM") maximised the number of holes. Thus the latter obtained a slightly lighter design at 8.36 kilograms with a cost of $ 901.

Table 2. Metal rib single-objective optimisations results, without and with manufacturability analysis

Objective	Weight	Weight + DFM	Cost	Cost + DFM
Inputs:				
Rib thickness, mm	6.46	6.46	10	10
Stiffener spacing, mm	1.05	13.56	0.0	10.55
Number of cut-outs, -	2	4	4	4
Radius of cut-outs, mm	38.68	40	10	29.44
Results:				
Rib weight, kg	8.53	8.36	12.66	12.40
Rib cost, $	901.5	901.1	892.3	892.1
Manufacturable, -	No	Yes	No	Yes
Execution:				
Total run time, sec	1520	3678	1402	2799
Number of iterations, -	142	279	127	211
Average iteration time, sec	10.7	13.18	11.04	13.27

For the cost minimisation runs, the optimiser brought the thickness to the maximum value of 10 mm which reduced the costs down to $ 892. As higher web thicknesses mean less material needs to be machined away, this result was expected. For the cost + DFM run, the weight was reduced by 260 grams due to an increase in cut-out radius compared to the cost run without a manufacturability analysis.

Without the manufacturability modules, the optimiser mainly focused on changing the rib thickness as other design variables have a lower effect on weight and cost. From the results in Table 2, it can be seen that the inclusion of manufacturability analysis pushed the algorithm to explore more of the design space for both objectives, leading to more optimal results from the weight and cost standpoint. It also affected the stiffener spacing of the designs to assure manufacturability, which will be discussed further in subsubsection III.A.3.

The outputs from the multi-objective runs are presented in Figure 13, where a Pareto distribution for MOO with and without machining analysis is depicted. It can be observed that the objectives for minimum weight and cost drive the rib design in different directions, which matches Table 2 results. The lower weight is obtained when the rib thickness is minimum, however, the production costs are minimised for maximum rib thickness value. This is explained by the machining costs being related to the amount of material that needs to be removed from an initial material block. Higher rib thickness leads to less material to be removed. These observations are true for both MOO runs. Overall, within the given design variable bounds, the rib cost difference between designs is less than 1% while the weight values vary by up to 42%.

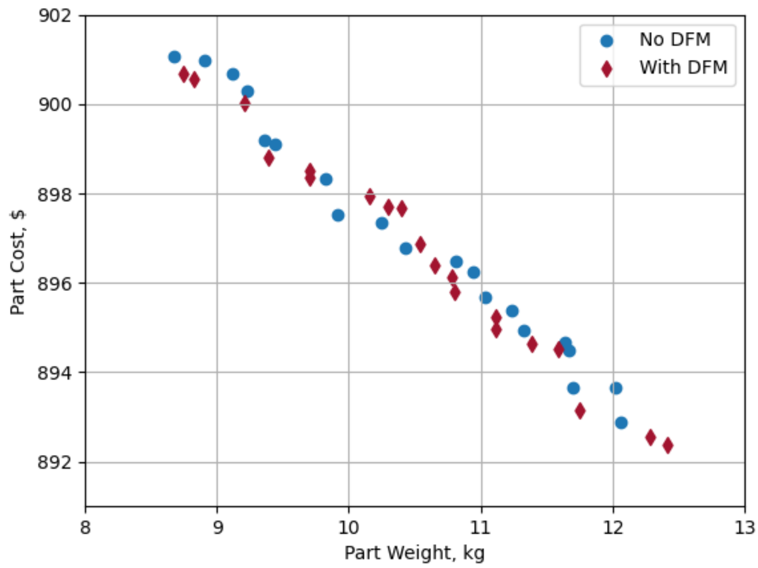


Figure 13. Pareto front for metal rib "weight + cost" multi-objective optimisation

2. Composite Rib

For composite rib optimisation, there are no clear pattern differences between weight and cost optimisations. From Table 3, it can be seen that in all optimisation runs the thickness is the same at 7.04 mm which represents the lowest thickness under which the load requirements are satisfied. Furthermore, the number of cut-outs is maximised to reduce the amount of material needed during manufacturing. The size of the cut-outs is slightly more correlated to the weight than the cost, hence the optimiser raises the cut-out radius value more in the weight minimisation runs.

Nevertheless, there is an absence of clear trend differences between the optimisations based on their objectives. This can be explained by examining the selected production material and method. A composite rib is comprised of multiple composite fabric layers which are added until the required strength performance is obtained. A thicker rib leads to more plies which results in both higher production costs (more material and work is needed to stamp-form the part) and higher rib weight. Therefore, in the case of a composite rib, the two objectives are significantly correlated (Pearson correlation factor of 0.994). No Pareto front could therefore be obtained from the multi-objective optimisation as it produces a single design point (see Figure 15).

Table 3. Composite rib single-objective optimisation results, without and with manufacturability analysis

Objective	Weight	Weight + DFM	Cost	Cost + DFM
Inputs:				
Rib thickness, mm	7.04	7.04	7.04	7.04
Stiffener spacing, mm	0.70	20.09	20.72	1.20
Number of cut-outs, -	4	4	3	4
Radius of cut-outs, mm	22.23	32.66	18.22	10.30
Results:				
Rib weight, kg	5.09	5.02	5.13	5.14
Rib cost, $	2284.8	2281	2296.5	2292.1
Manufacturable	Yes	Yes	Yes	Yes
Execution:				
Total run time, sec	1432	2709	1594	2640
Number of iterations, -	142	145	142	141
Average iteration time, sec	10.08	18.68	11.23	18.72

When comparing the composite rib designs to the metal ones, it can be seen that the composite ribs are advantageous from the weight perspective, with 40% lighter designs. However, this weight benefit comes at a significantly higher average cost of $ 2290 representing a 255 % increase compared to aluminum ribs.

3. Effect of Manufacturability Analysis Implementation

From the reference runs, it is possible to analyse the impact of implementing manufacturability analyses into design optimisation workflows. First, Table 2 for metal rib optimisations shows that both initial runs that did not include DFM analyses produced unfeasible rib designs. In the weight minimisation study, the optimiser reduced the stiffener spacing to reduce the overall weight while in the cost minimisation, it did not find the impact of stiffener spacing on cost significant to change the variable. The Pareto front results in Figure 13 also illustrate that for the metal rib designs, the inclusion of manufacturing analysis doesn't affect the overall optimisation problem. The Pareto front trend and shape are similar with and without DFM modules. However, only 65% of the designs produced by the static MDAO workflow without assessing the rib machinability are indeed manufacturable, with 35% not complying with the machining accessibility criteria. An example of such an unfeasible design is shown in Figure 14.

For the composite fibre weave angle deformation due to thermoplastic forming, the selected optimisation design variables mostly did not affect the manufacturability grade. Only the rib thickness had a low to moderate correlation with the manufacturing grade, with a Spearman correlation coefficient ranging between 0.25 and 0.396 depending on the optimisation run. It was observed that most of the negative grades were obtained when rib thickness was below 3 mm. However, even under that threshold, there were still more manufacturable designs than not. Overall, the tool still did confirm that 95.2% of designs were manufacturable, and removed potentially problematic ones.

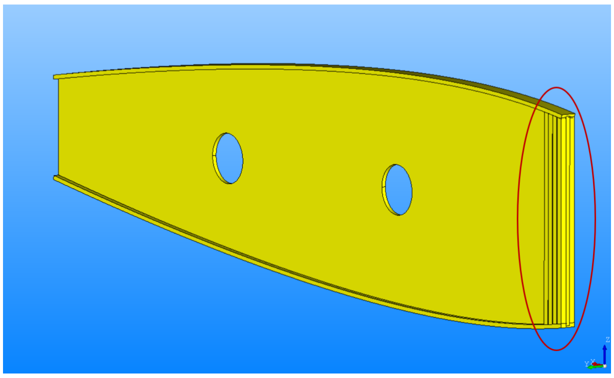


Figure 14. Non-machinable metal rib design, weight minimisation problem result

The inclusion of manufacturability modules into the optimisation workflow also had an impact on the overall execution time. For the metal rib problems, the duration and number of iterations increased, leading to a rise in the total run time by 100-140% compared to optimisations without DFM analyses. Similarly, the execution time for the composite ribs also increased but to a lower extent, by 65 to 90 %. This is due to the number of iterations remaining the same as for non-DFM workflows, for the reasons described above. The observed differences in optimisation execution times between runs using machining and stamp-forming analysis tools are impacted by the inherent accuracy of the tools. The machining module is a simpler, low-fidelity tool, whereas the Drape tool is a higher-fidelity program. The execution of the Drape tool takes approximately 8 seconds per iteration, compared to 2.2-2.5 seconds for the machining analysis.

B. Dynamic Workflow Optimisations

After the static MDAO runs, the dynamic workflows can be executed and compared to the static ones. The dynamic MDAO system architecture directly incorporates both manufacturing modules in separate subworkflows, which are activated based on the selected production method. The results of single-objective dynamic optimisations are shown in Table 4. The output of the dynamic workflow matches the observations made in subsection III.A. As the dynamic workflow is searching for the optimum rib design both in the metal and composite design spaces, it determines that composite ribs are lighter while metal ones are cheaper. Furthermore, not only do the selected production methods match the expectations, but the design points are also similar.

Table 4. Dynamic workflow single-objective optimisations results

	Dynamic Run 1: Weight	Static Composite Run	Dynamic Run 2: Cost	Static Metal Run
Inputs:				
Rib thickness, mm	7.04	7.04	10	10
Stiffener spacing, mm	3.93	20.09	21.84	10.55
Number of cut-outs, -	2	4	3	4
Radius of cut-outs, mm	39.30	32.66	29.81	29.44
Results:				
Production method, -	Stamp Forming	Stamp Forming	Machining	Machining
Rib weight, kg	5.05	5.02	12.48	12.40
Rib cost, $	2280.5	2281	892.3	892.1
Manufacturable	Yes	Yes	Yes	Yes

For the composite rib, selected for the minimum weight objective, the thickness value is also 7.04 mm leading to a similar weight of 5.05 kg. Although the dynamic workflow does not maximise the cut-out number, it does maximise their size as well as minimising stiffener spacing to reduce the weight (smaller spacing leads to shorter and lighter stiffeners). Also, in the second dynamic run, the rib thickness and cost values match the static results for metal ribs, while the stiffener spacing is sufficiently high for the design to be scored as manufacturable.

1. Effect on Run Time

Since the dynamic part of workflows is related to the manufacturability tools, the comparison between dynamic and static workflows' execution times is performed uniquely using static workflows that include DFM modules.

Starting with the weight optimisation results in Table 5, comparing the runs individually shows that the dynamic optimisations have a higher total execution time, and each iteration last longer. This can be expected since the optimiser has a wider design space to evaluate to find the optimum design. Furthermore, the switch function introduces additional overhead as subworkflows are stored in separate files and locations. However, the dynamic MDAO system is executed instead of two static ones, hence comparison must be made for the combined execution times of static workflows. The results show that the dynamic workflow outperforms running the two static ones. In this case, the dynamic run took 40.3 % less time to be executed while providing a similar rib design.

Table 5. Run time comparison between dynamic and static workflows, for minimum weight objective

	Dynamic Run 1	Static Metal Run	Static Composite Run	Static Runs Combined
Total run time, sec	4553	3678	2709	6387
Number of iterations, -	226	279	145	-
Average iteration time, sec	20.15	13.18	18.68	-
Run time difference, %	-	-19.2 %	-40.5 %	+40.3 %

Table 6 produces a slightly different result. In the rib cost optimisation case, the dynamic workflow is 2.7% faster than the combination of static runs. While in this comparison the dynamic workflow time advantage is not as significant as in the previous case, these results do not take into account the additional time required to set up each workflow and to process the results, which would be higher for a combination of two static runs. Comparing the execution of Dynamic Run 2 with Dynamic Run 1 in Table 5, it can be observed that the number of iterations is similar, however, the average iteration time increased by 3.6 seconds, or 17.8%. This difference is caused by the addition of the CATMAC in the workflow, which was not necessary for the weight optimisation.

Table 6. Run time comparison between dynamic and static workflows, for minimum cost objective

	Dynamic Run 2	Static Metal Run	Static Composite Run	Static Runs Combined
Total run time, sec	5296	2799	2640	5439
Number of iterations, -	223	211	141	-
Average iteration time, sec	23.75	13.27	18.72	-
Run time difference, %	-	-47.1 %	-50.2 %	+2.7 %

Finally, the comparison between dynamic and static multi-objective optimisations is shown in Table 7. From the results, it can be seen that this last comparison is skewed in the dynamic workflow's favour due to the composite run having correlated objectives, which caused the multi-objective algorithms to struggle with creating a Pareto front. This led to a 420.6% faster optimisation for the dynamic workflow, showing an additional benefit of running dynamic optimisations as they can efficiently deal with configurations that present correlated objectives. However, even when the comparison is made fairly, using a single-objective optimisation for the composite rib, the dynamic workflow is still 16.5 to 18.5 % faster (3414 seconds against 3976 or 4045 seconds) compared to executing two independent static workflows.

Table 7. Run time comparison between dynamic and static workflows, for multi-objective optimisations

	Dynamic Run 3	Static Metal Run	Static Composite Run	Static Runs Combined
Total run time, sec	3414	1336	13023	14359
Number of iterations, -	140	80	600	-
Average iteration time, sec	24.39	16.7	21.7	-
Run time difference, %	-	-60.9 %	+381.5 %	+420.6 %

2. Effects on Rib Design

The effect of dynamic MDAO is also assessed from an optimisation behaviour point of view. A Pareto front for the cost and weight of various rib designs obtained using multi-objective optimisations is presented in Figure 15. The dynamic workflow captures the Pareto front of the entire design problem and matches the designs produced by multiple static workflows. The rib design with minimum weight is close to the result of the composite rib optimisation, and the dynamic run's Pareto front for metal ribs mimics the trends and values of the Pareto presented earlier for the static MDAO system (see Figure 13). The dynamic MDAO results also present a region in the design space where no optimal solutions could be found for either metal or composite ribs, corresponding to the combined results of static optimisations.

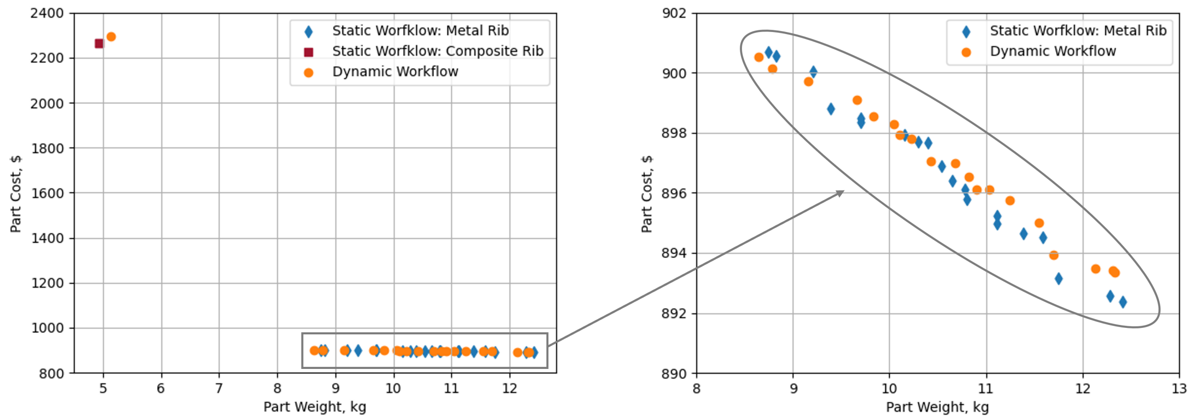
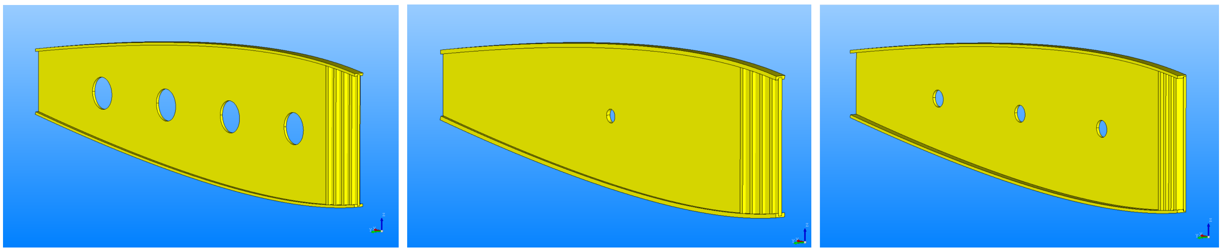


Figure 15. Pareto front comparison between dynamic and static workflow multi-objective optimisations

From this final optimisation, three optimal design points are shown in Figure 16. The minimum-weight metal rib has a thinner web with a higher number of large cut-outs, while the minimum-cost metal rib is thicker with only a single small cut-out. Both models have their stiffener spacing sufficiently larger for the machining tool to pass, which is not the case for the composite rib as its manufacturability does not depend on this design parameter. Corresponding to the expected outcomes, the resulting rib models can seem unrealistic due to the stiffeners' positions. However, it is important to note again that the addition of stiffeners is made for the purpose of assessing manufacturability and real-world lightly-loaded rib designs would not have these stiffening elements.



(a) Minimum weight - metal rib **(b) Minimum cost - metal rib** **(c) Optimum - composite rib**

Figure 16. CAD models of optimum rib designs for different objectives

IV. Results Discussion

The results from section III demonstrate the advantages of introducing manufacturability assessment of the design and performing dynamic MDAO optimisations.

Examining the results of design manufacturability, while for stamp-forming composite ribs it did not yield any significant results, with 92.5% of designs deemed manufacturable, it did have an impact on the aluminum designs. As was demonstrated via the metal rib optimisations case, implementing manufacturing into conceptual design studies can lead to a reduction in production problems during product development. It was shown that up to 35% of the initial designs could have posed production problems. If one of them had been chosen as the design to go with, the redesign would have been necessary introducing additional costs [6]. Hence, this DFM implementation could have potentially reduced the back-and-forth between design and production engineers, removing unnecessary rework and improving the design workflow.

Regarding the dynamic MDAO workflow performance in terms of execution time, as soon as multiple different product design variations have to be examined, each requiring its own workflow configuration, running a single dynamic workflow will outperform running multiple static ones. From this study case, with a single switch and only 2 possible rib configurations, the dynamic MDAO systems took 40.3%, 2.7% and 16.5-18.5% less time compared to a combination of two reference runs for the two single and one multi-objective optimisation respectively. Furthermore, these results disregard the additional time necessary for formulating and setting up each individual static workflow. An increment in the number of switches or subworkflows per switch would lead to a factorial escalation in the number of static workflows required for execution, rendering comparison with a single dynamic MDAO system impractical.

While providing a benefit in terms of run time, the rib design results remained similar to the expectations set by the static workflows. More specifically, the composite rib designs were on average 40% lighter while costing 255% more compared to aluminum wing ribs, with the Pareto front matching static MDAO results. This confirms the correct implementation of the dynamic parts of the optimisation workflow, as the dynamic architecture is expected to only affect the execution of the optimisation and not the problem's nature.

V. Conclusion & Recommendations

The research goal of this work was to enhance the MDAO workflow by integrating manufacturing considerations, aiming to identify potential manufacturing challenges early on in the design process. For this, the objective was to establish a dynamic MDAO workflow that adapts its structure based on the varying manufacturing requirements, imposed by individual production methods.

The proposed methodology takes advantage of a requirement-driven automated MDAO workflow formulation process. Using product and manufacturing-specific requirements, contained in a single requirements database, the workflow structure and composition can be adapted based on the problem selection. The dynamic workflow capability is enabled via the integration of subworkflows that are activated depending on the current design point. The activation is performed by a switch function and a new UCI output that transmits the subworkflow output back to the main workflow.

For the DFM analysis, two production disciplines were implemented into the optimisation systems, one for machining metal ribs and one for stamp-forming composite ribs. The output of manufacturability analysis modules is a continuous grade between -1 and 1. Choosing a continuous output aids the algorithm in finding the relation between the inputs and the manufacturing grade. These modules are complemented by the CATMAC cost analysis tool.

Together, all of the modules enable the rib design to be assessed on weight and cost. In total, 15 static and dynamic workflows were executed to investigate the impact of implementing manufacturability assessment into the design problem as well as the performance of dynamic MDAO systems compared to conventional static ones. Applying this methodology on a wing rib study case, the two research questions defined at the start of the project were answered:

1) *How do the **design process** and **overall product design** change when manufacturing is considered at the start, rather than at subsequent design phases?*

Starting with metal ribs produced using machining, the DFM analysis integration resulted in a more dependable design process. While all aluminum rib designs from the static workflows with the DFM tool were scored as manufacturable, 35% of rib designs did not satisfy the accessibility criterion when the DFM analysis was excluded from the problem. Consequently, introducing DFM considerations in the preliminary design stage did reduce the chance of proceeding to the next design stage with a flawed design from a production perspective, removing the non-viable options from the start.

For composite ribs, examined from the stamp-forming production perspective, the results were not affected by including the manufacturability module. This is due to the marginal impact of selected design variables on the rib geometry. Nevertheless, the assessment served as a means to confirm that the composite designs are producible.

2) *What are the **advantages** and **disadvantages** between static and dynamic workflows when applied to a rib design including manufacturing?*

Analysing the optimisation execution times, the dynamic systems were found to outperform multiple static workflows, completing optimisations in a shorter amount of time. In the multi-objective optimisation case, the time advantage of using a dynamic system was in the order of 16.5 to 18.5 % while producing a similar design Pareto front. Additionally, dynamic workflows provided a significant time advantage when executing multi-objective design studies where one of the configurations has correlated objectives not known a priori. The dynamic system avoided time losses due to ineffective optimum search. This was the case for composite rib designs, for which the minimum weight and cost objectives lead to the same optimum point.

Overall, the assessment of multiple manufacturing methods was enabled by the inherent advantage of dynamic MDAO workflows to activate desired disciplines when they are required, changing the optimisation structure during the optimisation itself. This new architecture also reduces design process time, removing the need for multiple workflow set-up and execution. The excess time necessary to formulate each individual static workflow compared to a single dynamic one was not accounted for in this research.

For future studies, it is recommended to investigate how the formulation and execution time advantages scale with the number of implemented subworkflows, serving as a validation of this research's results. While the expectation is that the time advantages of dynamic MDAO systems will grow factorially with the number of subworkflows, proving it experimentally will further strengthen the case for dynamic MDAO systems adoption. Such results would accelerate the transition to dynamic MDAO workflows for the industry and research institutes, improving their design processes.

Furthermore, it is suggested to increase the complexity of the product and analysis disciplines. The presented problem implementation served the purpose of providing a proof-of-concept, with a simpler product model and manufacturability tools. Evaluating this methodology in a more realistic design process could provide more indicative results.

Lastly, it could be interesting to couple this research and its product, rib, model with the Manufacturing Information Model (MIM) [20] previously developed at TU Delft. The latter is a software package that stores production-related information and can perform high-level checks determining the compatibility between every component of a product and the selected material, production process and equipment. Hence, MIM assesses whether the product has the potential to be manufactured but does not evaluate the manufacturability of each component's design, providing a synergy potential with the current study.

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II

Literature Study
Graded under AE4020

1

Introduction

1.1. Background

In the current, fast-paced world, it is a crucial necessity to improve the cost- and time-effectiveness of the aircraft design process. The ultimate goal is to reduce the time needed to introduce new products, design improvements and innovations to the market. Multidisciplinary Design Analysis and Optimisation (MDAO), is one strategy that has attracted attention as it, in theory, permits the effective study and optimisation of large complex design systems where several interrelated disciplines are involved. Furthermore, the use of MDAO frameworks renders the whole process easily repeatable, enabling engineers to conduct detailed configuration comparisons in a shorter amount of time than it currently takes [2, 6]. Being in development for more than three decades, the process is still not widely adopted although many improvements to the methodology and formulation have been made enabling the formulation of vast and complex MDAO frameworks [7].

In the spirit of innovation and constant will to improve the procedures within the industry, a new challenge has appeared. Over the time of designing and building aircraft and their subsystems, a significant amount of manufacturing information has been accumulated and is familiar to experts in the field. However, this information is often inadequately documented making it challenging to integrate it into the product design process [3]. Furthermore, due to limited knowledge about the design production process, at early design stages, manufacturing cost and time estimations are difficult [4]. Therefore, the design production subject is only considered in later design stages [8]. These issues are often addressed by involving manufacturing experts and designers in early product development discussions and critical reviews. Unfortunately, this process lacks formal structure, and there are no effective methods to enable designers to systematically leverage the knowledge of manufacturing experts during the design process using a model-based approach [5, 8, 9].

This is where the potential synergy between MDAO systems and the desire to improve the design procedures with respect to manufacturing appears. Including manufacturing considerations into an MDAO workflow can provide various advantages, and make the process more in line with the Design-for-Manufacturability (DFM) approach [3, 4] to designing products. It can enable designers and engineers to create products that are not only functional but also efficient and cost-effective by taking manufacturing requirements into account alongside other design objectives right from the conceptual design phase. Firstly, introducing DFM into a multidisciplinary design optimization workflow can help reduce the time and expenses associated with design iterations. By including manufacturing requirements early on in the design process, designers can identify and address potential manufacturing challenges before prototypes/final products are built [3, 5]. This can help to minimize costly redesigns while also shortening the time-to-market. Not only that, but the absence of redesign and/or remedial corrections of design flaws (from a manufacturability perspective) will have an impact on the overall quality and efficiency of the end-product. Often, the changes made to the design to make it manufacturable result in an increased weight of the structure meaning that it could in effect be sub-optimal to another design that was perhaps dismissed during the conceptual/preliminary design phases [10]. Next, an important aspect that must not be overlooked in today's world is that the inclusion of DFM in an MDAO workflow can lead to more sustainable designs. By optimizing the design for efficient and cost-effective production, it is possible to reduce waste, energy consumption, and emissions throughout product creation, leading to a more sustainable design process with a lower environmental footprint. Together, all these measures will increase the competitiveness of the overall product on the market due to the higher cost-effectiveness of the design and its better sustainability. Therefore, it is of crucial importance for both academia and industry to work towards automated solutions that include DFM aspects within their design processes, such as the MDAO workflows.

Several challenges are, nevertheless, present in the industry that slow down the process of DFM adoption. One of the challenges to solve observed by El Souri *et al.* [3] was that the aerospace industry is that the design and production does not take place under the "same roof". Effectively companies tend to do the design in-house, and outsource the production to external parties, making the knowledge management more complex. Furthermore, the management of digital information is sometimes inefficient, hindering the mechanism of identifying the root cause of manufacturing defects and capturing this knowledge. Additionally, organisational factors such as lack of formalised information storage and communication procedures may obstruct the process of systematic knowledge feedback from manufacturing teams to engineering ones [3]. Lastly, these reporting activities may not be often perceived as a priority in the fast-paced manufacturing industry.

1.2. DEFAINE PROJECT

This thesis enters in the context of a new multinational collaboration project DEFAINE (Design Exploration Framework based on AI for froNt-loaded Engineering), an overview of which is given in Figure 1.1. Sponsored by ITEA4, the DEFAINE initiative aims to "deliver an advanced design exploration framework which reduces recurring design costs and lead times for design updates"[1], by January 2024.

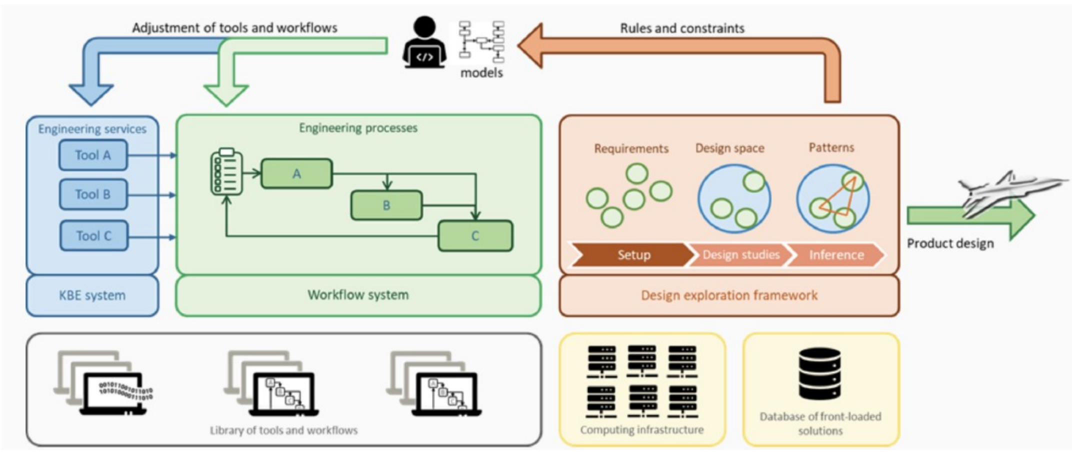


Figure 1.1: DEFAINE project overview [11]

With the rising demand for air transportation that is expected to soar by as much as 50% by 2035 [11], it is key for companies to ensure their competitiveness in the market. The key developments that will be targeted to construct the powerful large-scale design exploration, data analysis, and framework enhanced with integrated machine learning and AI algorithms are:

1. A Knowledge-Based Engineering (KBE) methodology development to effectively capture knowledge and enhance design automation solutions, allowing for flexibility and adjustment throughout a design study.

2. A systematic method for automatically (re)formulating multidisciplinary design optimisation workflows.

3. Implementation of an intelligent, scalable, and cost-effective computing infrastructure that leverages virtualization and containerization technology.

[1] https://www.defaine.eu/ (Accessed on 13/03/2023)

4. A methodology that combines automated data analysis techniques and machine learning algorithms to analyze extensive design data sets, enabling the identification of trends and relationships, and facilitating knowledge discovery.

The aforementioned four innovations, combined, should result in a potential reduction of recurring costs in aircraft systems by 10% while reducing by 50% the lead time for design updates. The thesis will directly contribute to the DEFAINE project by examining the possibility of developing an MDAO tool that incorporates a manufacturing discipline to ensure the manufacturability aspect of the generated designs. If successful, it will directly contribute to point #1 (and potentially #2) by improving the feasibility of the automated design solutions.

1.3. RESEARCH OBJECTIVE AND RESEARCH QUESTIONS

Defining a clear research objective is crucial for the success of any thesis study. After reviewing the background information and motivation, the main research objective to guide the research has been identified:

To investigate the possibility and impact of implementing manufacturing considerations at early design stages via the integration of multiple manufacturing techniques into the MDAO workflows using a wing rib as a case study

This objective can further be developed into separate research questions to tailor the research even further. These are defined as follows:

1. How can the **manufacturability** of a design be assessed and/or directly insured during the design process?
2. What should be the guidelines for **design parameterisation** to ensure compliance with manufacturing methods requirements?
3. How does the **work process** and **design quality** change when manufacturing is considered at the start, rather than at subsequent design phases?

Another important aspect of the research will be to develop and use a new type of MDAO workflow, the *dynamic* MDAO workflow. As it is expected that various manufacturing techniques will impose different requirements on the system configuration and components, it is necessary to enable the optimisation system to adapt based on the current design point, which is what a dynamic MDAO system should be. Therefore, it will be interesting to answer an additional question as part of this research:

4. What are the **advantages** and **disadvantages** between static and dynamic workflows when applied on a rib design including manufacturing?

This Literature Study report aims to conduct a first assessment of the current state-of-the-art practices with respect to the topic of MDAO, production methods and design practices for achieving manufacturability. First, Chapter 2 will present the advancements with respect to the optimisation workflows and how these can be optimally constructed. It will also expand upon the adopted structure and tools that will be used during the thesis. Next, Chapter 3 will provide a review of the current production methods employed in the industry and the use of different materials that could be investigated during this thesis project. As mentioned in the research objective, the study will be done using the design of an aircraft wing rib as a test case, hence the focus of the *Production Methods* chapter will be on manufacturing methods for ribs. Chapter 4 will then outline some design principles related to design parameterisation and wing rib design practices. Based on the literature study observations, a research plan will be presented in Chapter 5. Lastly, Chapter 6 will summarise the main conclusions, touch upon the limitations of the current study as well as provide general recommendations.

2

MDAO Workflows

This chapter will present the standard MDAO systems and their development (Section 2.1), and how the said system formulation and execution has been improved with new advancements (Section 2.2). Additionally, Section 2.3 will touch upon the motivation behind going towards dynamic workflows, and challenges that the latter introduces. Lastly, an overview of the entire system will be shown in Section 2.4.

2.1. Standard MDAO Workflows & Issues

Taking roots more than 30 years ago, MDAO has been an encouraging design method, bringing together multiple disciplines such as aerodynamics, structures, propulsion and many more, for optimizing complex engineering systems. The idea behind this is clear; improve the efficiency of the product designs as well as the overall design process, making it smarter and increasing the rapidity of conceptual investigations and design variations in a given time frame. Since then, much development in this domain has occurred, although no real industrial application for a complete aircraft design has been made [7].

The first generation of workflows consisted of highly integrated applications, where all the disciplines and the optimiser were placed together with direct interfaces. Additionally, such systems were monolithic and would mostly be operated by a single specialist [2, 7]. Effective coupling techniques are typically used during implementation to capture how specific design parameters affect the entire system. Due to improvements in discipline solvers and breakthroughs in optimisation techniques, these procedures are computationally efficient in terms of running time [2]. These advancements have shortened the design system's operational time, allowing it to provide optimal solutions to engineers faster. However, this type of monolithic architecture also comes with some disadvantages. Firstly, such systems typically lack flexibility when it comes to exchanging or updating the integrated disciplines/modules in order to adjust the system towards investigating novel configurations. Secondly, once a system is built, it requires a lot of effort to scale it up, for instance, if new modules are desired to be included, as it will require a major system reconfiguration. Therefore, the first-generation MDAO were mostly employed in studies which involved conceptual design investigations that make use of simplistic models, and in physics-based optimisations with very few disciplines [2].

The second generation of workflows are distinguished by the distribution of analysis capabilities on specialised computational facilities, which are called by a centralised design and optimisation process [2]. This newer generation of workflows offers the necessary flexibility to exchange or update the design modules, without causing a complete system reconfiguration, and optimises the computing facilities to the needs of each individual module. In these environments, separate teams can be responsible for individual disciplinary modules while one team performs the role of process integration and central optimisation set-up. This allowed to exploit the benefits of distributed computational capabilities and for multiple teams to collaborate. Furthermore, to automate the exchange of data between disciplines, CAD and geometric product models were used, which led to the creation of Knowledge-Based Engineering (KBE) systems such as ParaPy[1] to facilitate and support such interactions.

[1] https://parapy.nl/ (Accessed on 06/05/2023)

Generally, from a holistic perspective, an MDAO project can be split into three main phases [7] (see Figure 2.1);

1. *Setup Phase*: Creation of a tool repository that contains all the required tools and disciplines

2. *Operation Phase*: Definition of the MDAO problem that needs to be solved, selection of the architecture based on the desired strategy, and implementation of said strategy as an executable workflow.

3. *Solution Phase*: Execution of the MDAO workflow, adjustment of the architecture (if necessary), and acquisition of a converged (optimal) solution.

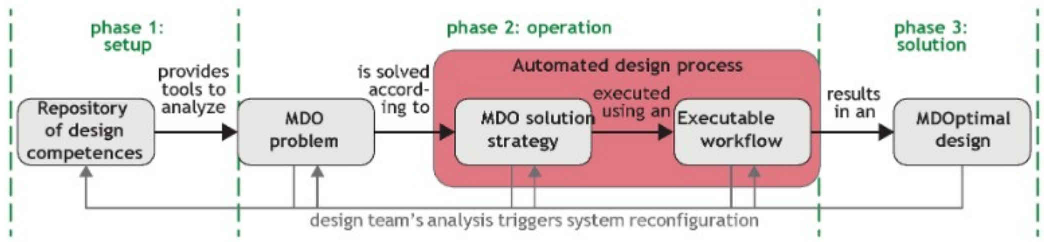


Figure 2.1: Overview of five stages of an MDAO system [7]

A major issue with most MDAO frameworks is the time it takes to assemble them. Flager and Haymaker [6] demonstrated that with MDAO systems it takes more time to reach the first design iteration. For instance, during a design study of a hypersonic vehicle by Boeing, engineers took 14 weeks to obtain an initial design using an MDAO implementation methodology, compared to the 6 weeks it would take them using a more traditional approach. Similar conclusions were also observed for other MDAO projects [12] where 60 to 80% of the project duration would be taken for the workflow construction. Both studies, however, show that significant efficiency benefits, when compared to more conventional methodologies of obtaining designs, are obtained once the formulated MDAO application is used for future iterations, hence justifying the initial time investment. In the same study by Boeing, it took engineers only 1.5 hours to get a second design iteration, compared to the 4 weeks it would take them before [6].
This problem is accentuated with the increasing number of disciplines, as the complexity of interconnecting the tools, selecting the best problem formulation, which design variables to be varied by the users and the optimiser grows exponentially [7, 13]. Furthermore, due to the high level of system complexity, there is a risk of a reduced ability to ensure each individual discipline operates consistently and as expected, as there is less direct supervision from engineers over the processes within them [7]. Hence, additional effort must be put in to identify and verify the observed trends to ensure that obtained results are reliable and can be used to make design decisions.

Another issue regarding older MDAO environments, relevant to both generations, is the difficulty in scaling up and reconfiguring a preexisting MDAO system [2, 7]. This limitation hampers designers from exploring new insights gained from initial analyses, incorporating new/modified design requirements, or incorporating additional design capabilities into the existing automated design process. This is especially important for novel design exploration studies as the required structure might need frequent changes at early stages [7].

Lastly, at each stage, additional concerns due to intellectual property, tool availability and licensing can introduce unexpected technical, managerial and legal challenges, rendering the creation of complex MDAO systems a highly complicated task [7].

2.2. IMPROVED FORMULATION AND EXECUTION METHODOLOGIES

The number of projects involving automated multidisciplinary design optimisation frameworks is increasing and it is neither smart nor efficient to develop project-specific, monolithic, solutions starting from the ground up every time. Therefore, much effort was put during the last decades to improve the methodologies behind formulating and executing MDAO workflows, among others with international collaborative projects like IDEaliSM[2], AGILE [2], AGILE 4.0[3] or DEFAINE.

2.2.1. AGILE Paradigm

In 2015, a new innovative project was started, under the umbrella of the European Commission's Horizon 2020[4] research and innovation funding program, named *Aircraft 3rd Generation MDAO for Innovative Collaboration of Heterogeneous Teams of Experts* or AGILE. The goal was to develop a 3^{rd} generation MDAO collaborative environment specialising on conceptual aircraft designs, and address some of the aforementioned issues of older MDAO frameworks (see Figure 2.2). In particular, the target was to improve the formulation and integration time, provide architecture reconfiguration ability, facilitate collaboration between heterogeneous teams, and enhance the system's global overview. Together, the measures lead to a 40%-time reduction for setup and solving of an MDAO problem [14].

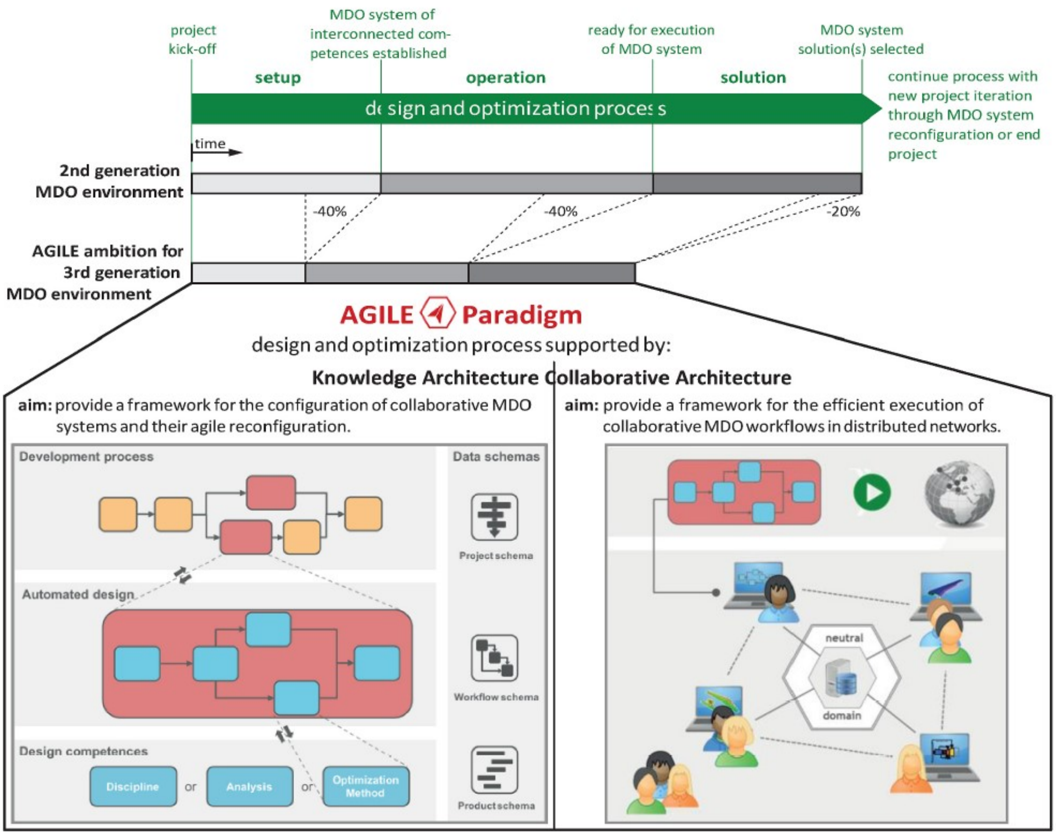


Figure 2.2: Conceptual Overview of the AGILE Paradigm [7]

The project proposed a new methodological approach to create MDAO workflows under the name of *AGILE Paradigm* [7, 14]. The success of the project rested on two main pillars: the Knowledge Architecture (KA) and the Collaborative Architecture (CA). While the CA part serves as an enabler for MDAO workflows to be deployed and executed over a distributed network, advancing collaboration, the KA establishes a structured methodology to formulate, configure and adjust fully defined MDAO systems. Furthermore, as part of the KA work, multiple tools were developed to facilitate the entire process, and some of them will be discussed in the following subsections. Since the thesis will be performed by a singular student, no collaborative network is required. Therefore, the KA is the main point of interest for this literature study.

One of the key layers of the Knowledge Architecture is a more structured and formalised MDAO development process. The AGILE paradigm defines five key stages of composing an MDAO system [7], which can be seen in Figure 2.3:

[2] https://itea4.org/project/idealism.html (Accessed on 30/04/2023)
[3] https://www.agile4.eu (Accessed on 01/06/2023)
[4] https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-2020_en (Accessed on 06/05/2023)

- *Stage 1: Define design case and requirements.* Information and requirements are gathered regarding the product, the MDAO system, and the design competences.
- *Stage 2: Specify a complete and consistent product model and design competences.* The design resources are verified, validated, and connected to shared data schema.
- *Stage 3: Formulate design optimization problem and solution strategy.* Based on the requirements and design resources identified in the previous steps, the automated design process is formalized, preparing it for execution.
- *Stage 4: Implement and verify collaborative workflow.* The formulated architecture and design of the MDAO workflow are translated into an executable workflow to be later used by process execution platforms.
- *Stage 5: Execute collaborative workflow, select design solution(s) and/or go back to an earlier step for reconfiguration.* The MDAO workflow is being run, generating the results. Based on the latter, the system can be reconfigured to adjust for potential new requirements.

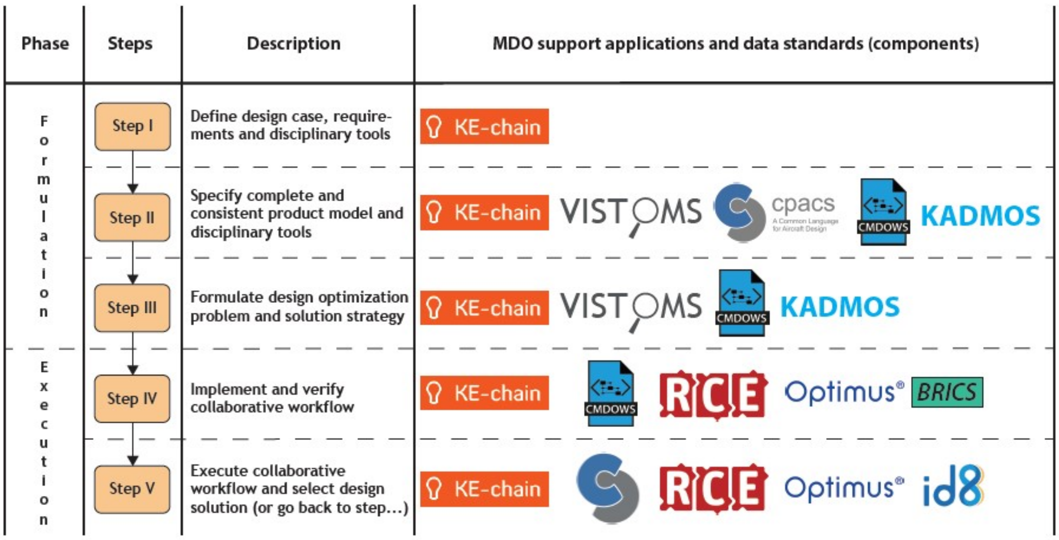


Figure 2.3: Five Stages of AGILE development process [14]

To increase the MDAO design automation, for some of these stages, new tools were used/developed and are displayed next to each stage in Figure 2.3. Some of these, relevant to this thesis, will be discussed in the following subsections. Furthermore, the other layers of KA stipulate that in order for the MDAO system to be more efficient, the design and analysis tools must share a common data-schema to streamline the communication between the disciplines. These will be discussed in Subsection 2.2.5.

2.2.2. RMM

As stated previously, one of the first key steps in any MDAO project is to gather all the requirements from the stakeholders of the said project. These have a great impact on how a study will be carried out and its objectives, and ensuring requirement compliance throughout the design process is vital for the project's success. An innovation brought to improve the requirement's management and compliance supervision was the development of the Requirements Management Module (RMM) [15]. It is a Model-Based Systems Engineering (MBSE) tool that ought to go away from document-based requirements. It has two main goals; automatic requirement compliance verification and the ability to compose MDAO systems and subsystems based on the specified requirements. Hereby, it aimed to ensure the design and optimisation process is requirements-driven.

First, the requirements have to be defined in a standardised way using patterns, as illustrated in Figure 2.4. Currently, this process is done through an Excel Sheet, as the one shown in Figure 2.5, however this can change in the future and other software could be employed for that task. Various roles are assigned at later

- **Performance**
  The SYSTEM shall FUNCTION with PERFORMANCE [and TIMING upon EVENT TRIGGER] while in CONDITION
- **Design (constraint)**
  The SYSTEM shall [exhibit] DESIGN CONSTRAINTS [in accordance with PERFORMANCE while in CONDITION]
- **Environmental**
  The SYSTEM shall [exhibit] CHARACTERISTIC during/after exposure to ENVIRONMENT [for EXPOSURE DURATION]
- **Suitability**
  The SYSTEM shall exhibit CHARACTERISTIC with PERFORMANCE while CONDITION [for CONDITION DURATION]

Figure 2.4: Requirements pattern (optional fields are between brackets) [15]

stages to the requirements using RMM [15], depending on the desired role the requirement should fulfil; design variable, design variable bound, input parameter, constraint, objective, and quantity of interest.

The RMM creates a *requirements database* that acts as one single source of truth for the system. These requirements are transformed into one graph with nodes representing the various system elements (such as the tools or disciplines) and edges showing how these elements are interconnected. The graph can be visualised and interacted with through the yEd[5] tool. This allows for the parties of interest to inspect how a given workflow was generated based on the provided demands, hence leading to an improved traceability of the system. However, the real game-changing feature of the RMM tool is that using this graph, in combination with the KADMOS tool (Subsection 2.2.3), it has the capacity to formulate the entire MDAO workflow architecture, ready for being executed.

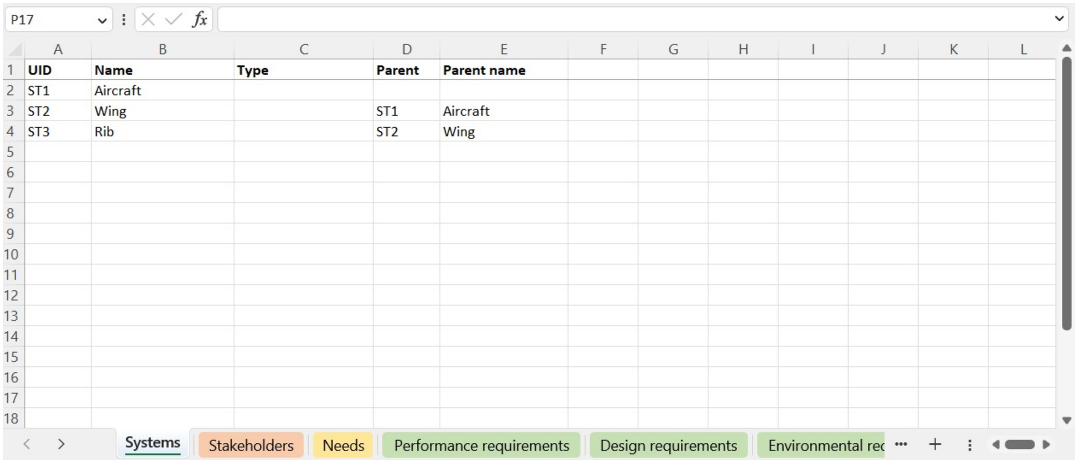


Figure 2.5: RMM Interface

Essentially, RMM automates the definition of the workflow based on requirements and facilitates architectural changes if requirements change. This feature will be extremely useful for this study as each production method that will be included in the MDAO system has a set of unique requirements that can require major changes in the parametrisation/design variables/bounds/constraints. Therefore, the RMM will be used to generate production workflows, which will then be integrated into the main workflow in the form of subworkflows. This process can happen seamlessly in the background during the optimisation, and won't require human interaction. Additionally, as mentioned earlier, the tool can also generate a compliance report to show to what extent the obtained design matches the requirements imposed at the very beginning of the project by the stakeholders and engineers.

[5] https://www.yworks.com/products/yed (Accessed 25/04/2023)

2.2.3. KADMOS

One of the software tools developed within the AGILE framework, to support the aforementioned *AGILE Paradigm*, was the KADMOS (Knowledge-and graph-based Agile Design for Multidisciplinary Optimization System) open-source Python package. Inspired by the work of Pate *et al.* [13], KADMOS is an improved digital implementation of the novel graph-based methodological approach to enhance the process of formulation and integration of large MDAO workflows [16] as it has the capability to rapidly assemble, analyze, adjust, and reconfigure the latter.

The methodology employed by the tool follows several steps. First, KADMOS starts by analysing the repository of tools, and based on it generates a Repository Connectivity Graph (RCG) displaying the tools (functions), their inputs and outputs as well as potential connection issues (as shown in Figure 2.6). Then, it transforms that graph into a Fundamental Problem Graph (FPG) which is a study-tailored RCG, containing only the tools and variables necessary to formulate and solve the given MDAO problem, removing all redundancies. The user(s) can then indicate the desired solution strategy among the ones supported by KADMOS (for example multidisciplinary convergence study, DOE, MDF, IDF) [16]. Finally, from FPG KAMDOS derives the two main graphs, the data graph (MDG) and the process graph (MPG), together describing the whole system. The former shows the interactions between variables and functions while the latter focuses on the execution order of the functions (see Figure 2.7). Together, they can be combined into a single eXtended Design Structure Matrix (XDSM), describing the whole system and making it ready for being executed [11, 16].

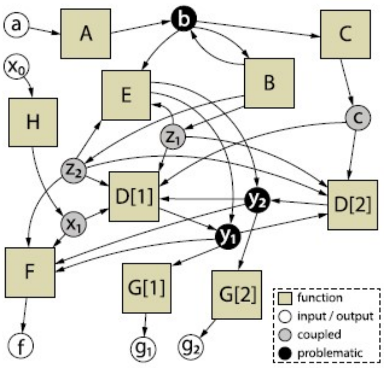
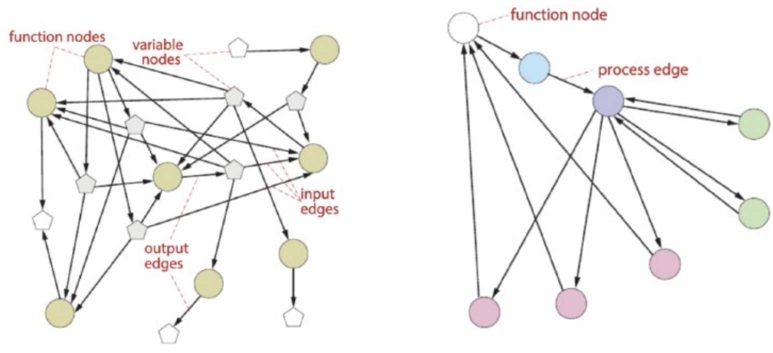


Figure 2.6: Example of RCG [16]



(a) Data graph

(b) Process graph

Figure 2.7: Illustration of Data and Process Graphs [11]

Overall, KADMOS can reduce the whole formalization process by 50% or more compared to setting up the workflow manually, regardless of the number and complexity of the tools involved, even when the latter have to be adapted to function with common product data schema such as CPACS [16]. The time and cost benefits increase even further when taking into account the flexibility of KADMOS to modify the MDAO architecture within minutes (for instance, going from DOE to MDF) or if additional design variables need to be integrated. Furthermore, the MDAO architecture can be easily visualised using the co-developed VISTOMS tool, which enables interactive visualisation of XDSM diagrams [17].

2.2.4. PIDO TOOLS

The Process Integration and Design Optimization (PIDO) programs are software packages designed to perform multi-domain system design and optimisation. It can facilitate Design of Experiments (DOE) or MDAO studies and allows to create and execute a workflow once a desired MDAO architecture is selected [11], using the aforementioned KADMOS for instance. Among multiple available tools, for the purpose of this thesis research, the Optimus[6] program provided by Noesis is most likely to be used. The software can be interacted with through the tool's interactive user interface, as shown in Figure 2.8. However, during this thesis project, effort will be made to automate as many actions as possible to minimise the number of required GUI interactions. This will be performed using a CMDOWS workflow data-schema importer, written in Python. With this python package, that is currently still in creation, a CMDOWS file will be automatically translated into an executable Optimus workflow. This importer will have to also contain the information on the algorithm that must be employed for the MDAO study. For a global optimisation, the *Self-Adaptive-Evolution* algorithm

[6] https://www.noesissolutions.com/our-products/optimus (Accessed on 03/05/2023)

is used [18]. Optimus also allows to conduct multi-objective optimisations which could be useful if, for instance, the best trade-off between cost and weight has to be obtained [18].

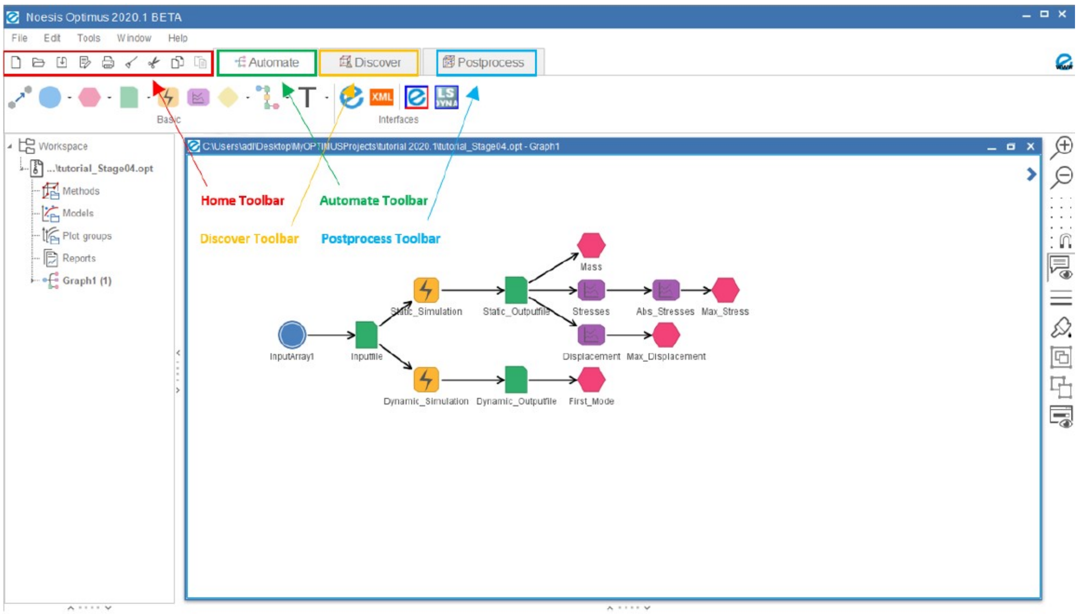


Figure 2.8: Optimus program [18]

Other comparable software do exist such as the open-source Remote Component Environment[7] (RCE) tool developed by DLR that was also previously used at TU Delft for research [14], or the OpenMDAO[8] which was used in previous thesis studies like [11]. However, both of these software have their own disadvantages.

Starting with RCE, it was found to be significantly slower in MDAO workflow executions compared to OpenMDAO while providing identical results [19]. On the other hand, the Python-based tool OpenMDAO is more restrictive compared to Optimus. It does not offer the flexibility, for instance, to alter the variable vector sizes or to modify and change the number of variables that interact between the disciplines. Also, additional constraints are applied on the format of the variables (some must be floats and can't be strings). Furthermore, there are additional uncertainties that are always present when using an open-source software package (support, maintenance, the addition of new/required features, etc.). Therefore, it was chosen to go with the Optimus commercial software package as Noesis provides several free education licenses to the FPP department, and has shown willingness and desire to collaborate and facilitate the development of novel features that might be required for the academic studies carried out at TU Delft.

2.2.5. STANDARDISED DATA EXCHANGE SCHEMAS

With the growth of international MDAO collaborations, such as the IDEaliSM or AGILE aircraft design initiatives, the variety of programs involved in said projects has greatly increased, leading to more interactions between heterogeneous disciplines within a single MDAO system. While in smaller projects building unique connections between the different MDAO elements might not be too time-consuming, it becomes a problem for larger systems where a multitude of tools and disciplines are interacting with one another, and creating individualised links for each element would require too many efforts. A common data exchange model is therefore required to reduce the number of interfaces and facilitate decentralised and inter-team collaboration [20]. In fact, utilising a centralised data interface, as shown in Figure 2.9, can reduce the total amount of links from $N(N-1)$ to just $2N$ [20], with N representing the number of tools.

One example of such central data exchange schema, used within the aerospace industry, is the Common Parametric Aircraft Configuration Schema, otherwise known as CPACS[9] [20]. It is a data definition and ex-

[7] https://rcenvironment.de/ (Accessed on 03/05/2023)
[8] https://openmdao.org/ (Accessed on 03/05/2023)
[9] https://github.com/DLR-SL/CPACS/releases (Accessed on 01/06/2023)

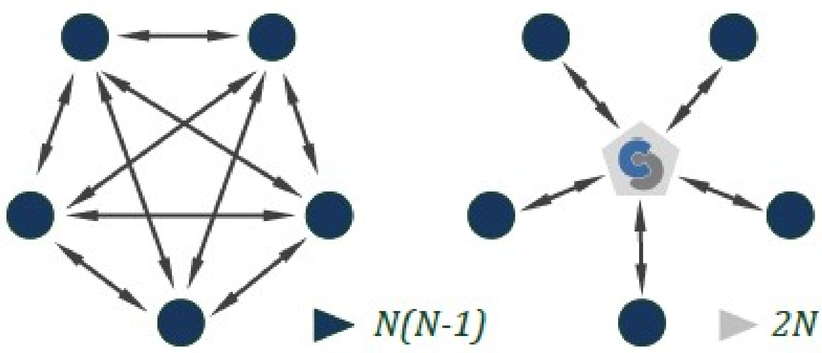


Figure 2.9: Project Specific vs Centralised Interface Architectures [20]

change format standardized for the air transportation industry, with the purpose of enabling engineers to exchange information between different tools, enabling multidisciplinary and multi-fidelity design in distributed environments. The schema is designed to describe the characteristics of different aircraft types, rotorcraft, engines, fleets, and missions, as well as climate impact, in a structured, hierarchical manner [20]. It captures not only product information but also tool-specific and process-specific data (such as the DOE design space and state parameters), which can assist in setting up workflows for analysis modules [20]. A great advantage of the central model approach of CPACS is that it helps in reducing the number of interfaces required between the various workflow elements. Essentially, it provides a hierarchical structure to store all the important data useful for the preliminary aircraft design while, crucially, serving as one common data model for multiple analysis tools to communicate with each other. While CPACS XML (eXtensible Markup Language) schema might not directly be used in this thesis study due to the limited scope of the latter, some of its hierarchical structure and descriptions might serve as a basis for the rib model development.

A more useful data schema, in the context of the current thesis, is the Common MDO Workflow Schema, or CMDOWS [21]. It is a new format for storing and exchanging workflow data between different applications within a given MDAO system, and this capability is enabled, similarly to CPACS, via the use of a neutral XML-based data representation. Developed under the AGILE, this XML-based schema was devised in order to achieve two goals: to facilitate the integration of the various MDAO support applications in the MDAO environment, as shown in Figure 2.11, and to allow the storage of an MDAO system architecture at different stages of its creation [14].

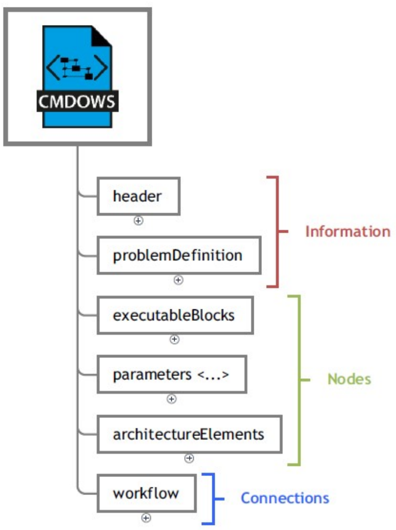


Figure 2.10: CMDOWS Structure [21]

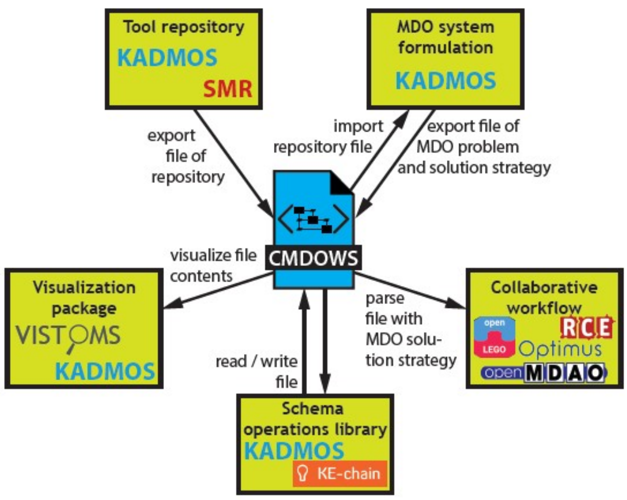


Figure 2.11: CMDOWS role as a central data schema, linking various MDAO applications [14]

As explained in Subsection 2.2.3, KADMOS generates a graph-based MDAO system workflow formulation. Next, it transforms the graph into a CMDOWS output file [22], with the generalised structure shown in Figure 2.10. The disciplines in CMDOWS are depicted in terms of inputs and outputs connections, with the relationships between the tools specified [21]. The first benefit of CMDOWS is that it facilitates the process of MDAO workflow translation from an in-executable into an executable workflow by acting as a bridge between the KADMOS and various process integration and design optimization tools (Subsection 2.2.4). Furthermore, it can not only store fully complete workflows but also the repository of competences (Stage 2 of the AGILE paradigm) [7] making it a very diverse and valuable tool at multiple stages of MDAO creation process.

The AGILE project has shown that at all stages of MDAO workflow formulation, CMDOWS provided the required support capabilities [21]. This standardised format for interactions and storage of information also aids in accelerating the process of MDAO workflow creation, hence reducing overall setup and reconfiguration time. This time reduction was estimated to be around 10-20% [21]. CMDOWS is also constructed in a relatively straightforward way resulting in very short (2-3 days) familiarisation time [21].

As mentioned already, CMDOWS is already compatible with tools such as KADMOS or VISTOMS (Subsection 2.2.3), which will be used during this study, and a plug-in is currently in development for the OPTIMUS PIDO software.

2.3. DYNAMIC WORKFLOWS

The current generation of MDAO workflows, such as the ones described in the Section 2.1 and Section 2.2, can be called static workflows meaning that the design variables, optimisation objective, and constraints imposed on the design space and disciplines, as well as the structure of the system remain constant throughout an optimisation cycle.

Dynamic MDAO systems enable workflow parameters modification throughout the optimisation process, based on the current design point. In other words, within a given iteration, a dynamic MDAO environment enables the system architecture to be modified in real-time, in contrast to the rigidity of static MDAO systems. This novel approach is crucial for the thesis' study success as depending on the selected production method that is being evaluated, the requirements imposed on the design and system architecture will be different, leading to a change of the workflow structure as is illustrated in Figure 2.12. This signifies that the overall workflow has to be made in a way allowing for flexibility and adaptability on the fly, with a large degree of process automation. The aforementioned RMM tool will be used for that purpose, in combination with KADMOS. Overall, the dynamic MDAO method could make design optimisation studies more efficient and successful since it permits the study of a larger design space and the discovery of novel, potentially superior designs.

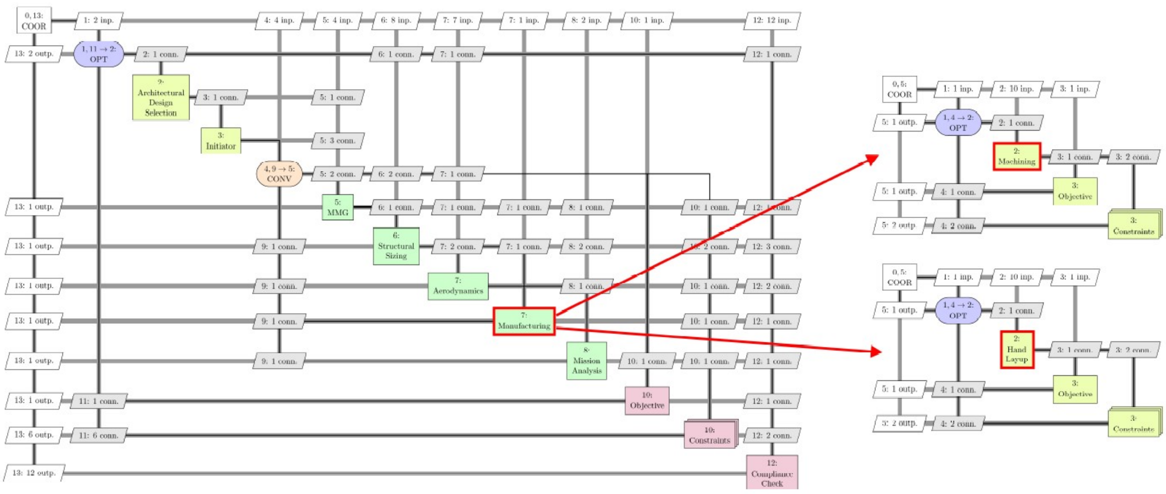


Figure 2.12: Dynamic Workflow XDSM example [23]

As it is a novel system concept, no literature could be found on the structure, composition and development methodology for Dynamic MDAO workflows, as well as its performance in concrete design studies. Therefore, this thesis study in combination with the active work of an FPP team at TU Delft will be a first major investigation into the viability of such optimisation architectures. Nevertheless, some hypotheses on the expected behaviour and performance of the new architecture, compared to a more 'traditional' static MDAO system, could already be made and are elaborated in Table 2.1.

Table 2.1: Assumed Dynamic Workflow Advantages and Disadvantages

	Effect	**Reasoning**
Advantages	New Architectures and Studies	Dynamic MDAO systems may allow to conduct studies that would not have been possible before. For instance, projects requiring an optimisation between various disciplines within an optimisation that would involve an architectural change like within the simultaneous design of a product and production process as described by Bruggeman and La Rocca [23].
	Greater Design Space and Flexibility	Workflow can accommodate system changes during the optimization process, which allows for the exploration of a broader design space and the identification of more efficient designs that may not have been discovered otherwise.
Disadvantages	System Complexity	More sophisticated optimization algorithms and simulation tools are necessary, as well as the formulation difficulty of constraints and variables increases
	Number of Iterations	At a given iteration step, more evaluations will have to be performed (ex: different manufacturing methods).
	Computational Time	As the number of iterations might be higher, the computational time might increase as well. Furthermore, a larger design space also increases the number of possible variations the optimiser can explore.

2.4. ENTIRE SYSTEM OVERVIEW

Section 2.2 and Section 2.3 illustrated some of the improvements and development directions in the path to automate and improve MDAO systems. The results of these innovations, combined together, can be seen through the creation of a so-called Design and Engineering Engine (DEE) framework [23]. Leveraging the use of MBSE requirements management, automated workflow formulation and execution tools, standardised data storage and sharing, and knowledge-base engineering platforms, it establishes a conceptual methodology for setting up optimised MDAO systems. An overview of a DEE can be seen in Figure 2.13.

Essentially, the five steps highlighted in Subsection 2.2.1 can now be performed using the newly developed tools together, aiding in the formulation and execution of MDAO workflows. Therefore, an overview of the thesis' program structure and interactions between the different elements within the workflow as well as the connecting elements can be seen in Figure 2.14. The Figure 2.14 should only be regarded as a preliminary mapping of the MDAO system from a software point of view.

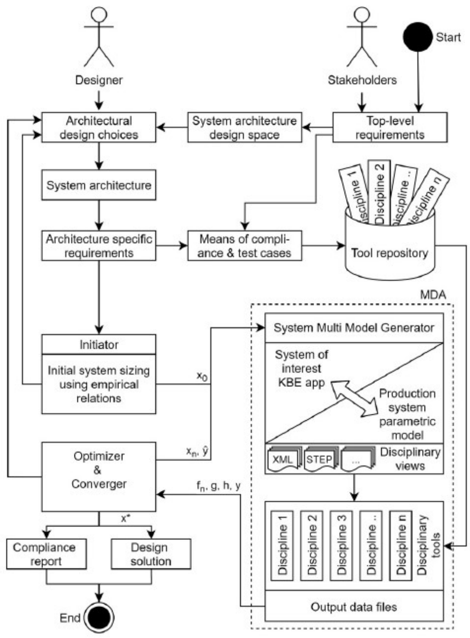


Figure 2.13: DEE overview for simultaneous design and manufacturing optimisation [23]

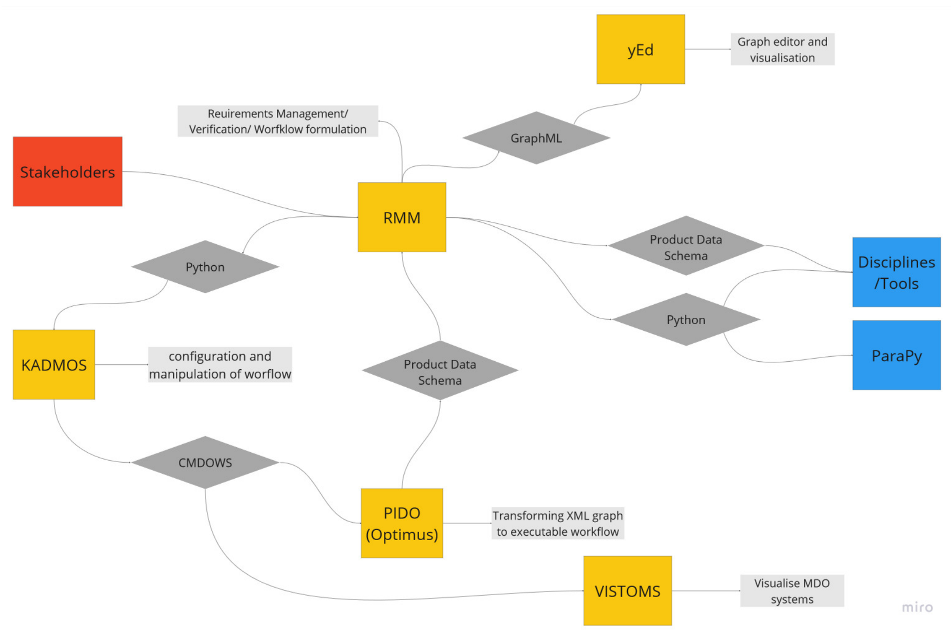


Figure 2.14: Overview of thesis MDAO applications interaction

2.4.1. Important Considerations

A point to highlight is that the inclusion of a *manufacturing* discipline will add the challenge of transitioning from a static MDAO workflow to a dynamic one, which to the author's best knowledge, hasn't been performed before. This might lead to unexpected difficulties arising during the creation of the workflow as well as potential unexpected behaviours from already existing tools. Hence, effort will have to be put into the verification of the system to ensure it works as expected and provides consistent results. As it is also the first implementation of the dynamic MDAO workflows concept, it is important to document and quantify the system's creation process and performance respectively.

Another interesting thought to examine will be if a certain MDAO problem execution strategy is more beneficial than others. For instance, a question to answer will be if the system performs better using an IDF or MDF structure, or a hybrid between the two.

3

Production Methods

A key aspect of the thesis research is the integration of manufacturing methods into the optimisation workflow. However, due to time and resource constraints, it is necessary to establish which production methods should be prioritised for implementation, with a focus on manufacturing techniques compatible with aircraft wing rib production. This is important as the selected production methods have to be future-proof (be applicable for current and future designs) and be sufficiently different from one another to be able to observe variations in designs based on the chosen manufacturing method.

One of the major factors differentiating the manufacturing techniques are the materials that are used. In the aerospace industry, the two most common ones are aerospace-grade aluminium and composites. Hence, it would be beneficial to include at least one production method for each of those two materials. This chapter aims to provide an overview of suitable methods involving both metal alloys and composite materials, in Section 3.1 and Section 3.2, as well as suggest possible ways to quantify and compare the performance of designs from different production methods, which is presented in Section 3.3.

3.1. Metals

Metals have been the most commonly used material during aircraft manufacturing for the last decades. Now, however, composite materials are becoming more and more popular due to the ability to tailor-design their performance and hence reduce the total weight of the aircraft structure [24, 25]. Currently, several wing components of the newest aircraft are manufactured using them, yet wing ribs are still mostly manufactured using metal alloys[1][2].

3.1.1. Metal Alloy Selection

In the aerospace industry, the most common metals employed in the aircraft structure are the aluminum, titanium and steel alloys. Tungsten is also sometimes used for balancing of the aircraft to minimise vibrations but due to its extremely high cost and softness, however, it is not used directly for components production. For manufacturing wing ribs out of metal alloys, mainly aluminum is considered for their optimal combination of density, strength and price.

Among the aluminum alloys, multiple options are available to designers to choose from. Typically, the three most widely used alloys are the Al2024, Al7075 and Al6061 alloys families. For wing tension members, such as ribs, alloys 2024 and 7075 are often being chosen for their high strength properties[3]. Although the Al7075 alloy has a higher yield and ultimate tensile strength, meaning that a part will be lighter for the same mechanical performance, the 2024 aluminum is preferred for fuselage and wing components as it has a higher fracture toughness and is more resistant to fatigue-crack propagation[4]. The exact choice of alloy, however, is not too

[1] https://www.flightglobal.com/787-design-highlights-systems-and-materials/102094.article (Accessed on 05/06/2023)
[2] https://www.aero-mag.com/wing-rib-cycle-times-cut-to-the-bone (Accessed on 05/06/2023)
[3] http://www.totalmateria.com/Article96.htm (Accessed on 25/04/2023)
[4] https://www.aaaairsupport.com/what-are-7075-2024-and-6061-aluminum-alloys/ (Accessed on 19/05/2023)

important for the study as the main purpose is to investigate the whole possibility of manufacturing discipline implementation, so the characteristics of Al2024-T3[5] will be used.

3.1.2. METAL PRODUCTION PROCESSES

For the aluminum-made ribs, there are two distinct types of production methods that are commonly used in the industry; machining and sheet forming.

Starting with machining, it is the process by which material is removed from an initial uniform block to create the required parts. Typically done via Computer Numerical Control (CNC) machine, it allows to manufacture monolithic structures with a very high degree of complexity and accuracy, enabling designs to have detailed features, varying thicknesses, and unconventional configurations. A depiction of the process can be seen in Figure 3.1.

Figure 3.1: CNC Machining of a Wing Rib[6]

Being made from one material block, the rib benefits from higher structural integrity and strength, as well as a reduced weight compared to ribs produced with other methods. However, this process is relatively slow, compared to the sheet forming method, and expensive due to the high requirements placed on the initial material block (the latter must be stress-relieved). Furthermore, due the nature of the production method, large quantities of scrap are produced. The cost of the CNC machinery and tooling also has to be taken into account as maintenance will be required.

Forming, or sheet/stamp forming, is another method actively used in the aircraft industry. To manufacture ribs with stamp forming, first, the external shape of the part is blanked on sheet metal. Subsequently, cut-outs for weight reduction and mouse holes are produced by either cutting or piercing techniques. Finally, the part is bent to the desired shape, with flanges being formed to later be used as attachment points during the assembly of the wingbox. Sheet forming is widely regarded as a cost-effective manufacturing technique due to its high manufacturing speed and good repeatability or large-scale production runs. It is also a highly automated process, requiring little human interaction. However, specific tooling and dies are extremely expensive and require a to be produced with low tolerances. Furthermore, the rib designs will be limited to a single thickness and limited out-of-plane design features [26]. This leads to additional stiffening elements having to be fastened using rivets to the rib web, increasing its weight and potential points of failure.

[5] https://www.matweb.com/search/DataSheet.aspx?MatGUID=57483b4d782940faaf12964a1821fb61&ckck=1 (Accessed on 25/04/2023)

[6] https://www.interempresas.net/MetalMecanica/Articulos/24229-La-aeronautica-aprende-de-la-automocion.html (Accessed on 27/03/2023)

Among the presented methods, machining is most likely to be used since it offers a higher degree of design complexity and freedom, enabling manufacturers to produce ribs with better performance. It is also the reason why companies such as Airbus actively use machining for their aircraft wing rib manufacturing [7].

3.2. COMPOSITES

As with the metal production processes, there are multiple methods used to manufacture composite components. Furthermore, there is a great variety of possible combinations of fibre and resin materials that need to be considered.

3.2.1. COMPOSITE SELECTION

The first choice that must be made when evaluating composites is which material should be used for the fibres. The main options are carbon, glass, aramid and Dyneema composite fibres. Each fibre has its own advantages and disadvantages making them useful for certain applications. From the TU Delft's *AE4ASM001: Design of Lightweight Structures I: Composites and Metals* course[8], it is understood that carbon fibres are the optimal choice for rib-alike components manufacturing as they are strong under both compressive and tensile loads, offer great fatigue characteristics and are environment resistant. It also has a lower density compared to glass fibres.

Glass fibres are very strong, with some having higher strength and stiffness compared to carbon fibres. They also behave better in compression, where carbon fibres lose about 30% of their strength. These benefits come at a price of higher density as well as poor environment and fatigue resistance. Furthermore, their performance is reduced due to static fatigue, when the fibre is subject to sustained loads. Aramid and Dyneema fibres have a lower density, have comparable strength and E-modulus to some glass fibres and are lighter, especially true for Dyneema fibres which have lower than water density values. However, both of these fibres make for poor materials for components such as ribs as they cannot bear high compressive loads. Compared to their tensile strength, their compressive strength is around 10% and 1% respectively.

Another selection that must be made concerns what type of resin matrix will be used. As will be illustrated Subsection 3.2.2, the projects involved in developing novel composite structures for aircraft of the future have a large preference towards the use of thermoplastics. Specifically, for most components carbon fibres with a PEEK or low-melt PAEK (LM-PAEK) matrix are the materials of choice. As shown in Figure 3.2, both thermoplastic polymers have a semi-crystalline structure, and are mostly used for high-performance components.

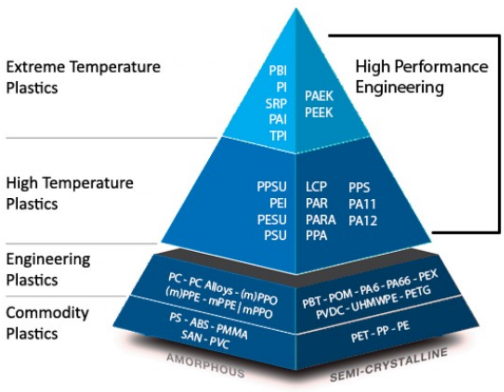


Figure 3.2: Thermoplastic polymers, their structure and use [27]

The main difference comes from the temperature necessary to melt the polymer. The advantage here is for the LM-PAEK which requires 305°C to melt, compared to 350°C for PEEK[9]. Low-melt PAEK works well with automated fiber placement (AFP) as it allows for faster AFP speeds while still achieving in-situ consolidation.

[7] https://www.radical-departures.net/articles/makino-provides-lift-for-a380-wing-rib-production/ (Accessed on 13/03/2023)
[8] https://brightspace.tudelft.nl/d2l/home/498878 (Accessed on 12/05/2023)
[9] https://www.compositesworld.com/articles/peek-vs-pekk-vs-paek-and-continuous-compression-molding (Accessed on 19/04/2023)

This is thanks to much better flow (compared to PEEK), and therefore leads to faster production rates. The material is also well-suited for stamp forming and thermoplastic welding. With the technical performance of both materials being similar, LM-PAEK, therefore, is the preferred material. However, these advantages come at the cost of being more expensive than PEEK tapes. Furthermore, a design limitation introduced by either of the material tapes is their maximum thickness. Currently, the industry developed tapes that are 0.13 to 0.18mm thick, with the biggest players moving towards 0.25mm tape thickness[9].

3.2.2. COMPOSITE PRODUCTION PROCESSES

To gauge which production method to choose, and gain a general sense of the direction to follow, it was decided to examine what the key players in the industry are currently focusing on. Although the process of rib manufacturing using composites is still an ongoing development process, the companies believe that composite ribs will offer several advantages over the traditional aluminum ones, making the effort worthwhile[10]. The first obvious reason is the expected reduction in the weight of the elements. Additionally, current and future aircraft wing surfaces and elements will be manufactured more and more with composites, using the same/similar material for the ribs will reduce the chance of corrosion and reduce the internal stresses as it would remove the difference in thermal expansion. Lastly, the inspection of the parts will be made easier as ribs will experience less fatigue (hence fewer fatigue cracks are expected).

For instance, the French aerospace supplier Daher has shown that large-scale aircraft wing ribs can be manufactured[11]. The study was performed under the *Wings Of Tomorrow (WOT)* initiative[10] started by Airbus to investigate new solutions that would allow for reducing the industry's emissions. One of the focuses of Daher was to develop a composite wing rib for a potential future single-isle aircraft, and it created five rib versions of different sizes, which are shown in Figure 3.3.

Figure 3.3: Daher-manufactured composite ribs[11]

The composite materials used for their production were unidirectional (UD) carbon fibre with low-melt polyaryletherketone (PAEK) tapes, produced by Toray Advanced Composites and Victrex. From the supplier web page, it was found that most likely a variant of Toray Cetex TC1225[12] was used for this rib's production. The data sheet for this material is available and hence could be used as the basis for composite material performance. As advertised by the manufacturer, this low-melt PAEK resin allows to reduce the processing temperatures by up to 60°C. Another advantage of this material is that Toray offers the possibility to coat the material in a thin glass layer to protect the material against galvanic corrosion, and therefore enable the use of this composite in a mostly metal structural assembly.

The largest rib has a length of 2 meters and a width of 1 meter with a maximum thickness of 12mm for one of the ribs. First, flat blanks were produced with automated fibre placement (AFP), and then the lay-ups were consolidated in the oven. Then, stamp-forming (process shown in Figure 3.4) was used to convert these into

[10] https://www.compositesworld.com/articles/wing-of-tomorrow-ribs-one-shot-thermoplastic-ooa-consolidation (Accessed on 19/04/2023)

[11] https://www.compositesworld.com/articles/out-of-autoclave-vbo-rear-spar-thermoplastic-ribs-target-wing-of-tomorrow (Accessed on 19/04/2023)

[12] https://www.toraytac.com/product-explorer/products/gXuK/Toray-Cetex-TC1225 (Accessed on 25/04/2023)

desired shapes. For instance, some features such as the 'L' flanges were obtained (Figure 3.3). Due to the nature of the production method, in order to have additional stability, another set of L-shaped composite flanges had to be mechanically fastened to the main rib.

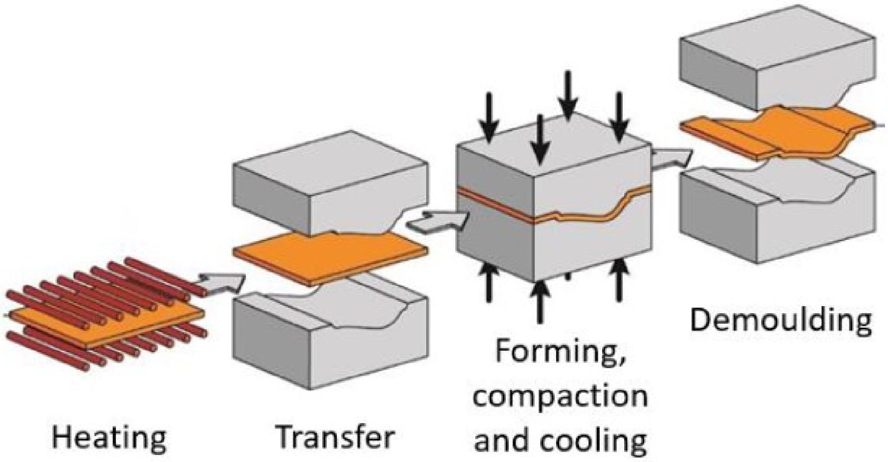


Figure 3.4: Stamp-forming process [27]

Nevertheless, the current capabilities already allow to introduce additional complexity to the rib. For instance, a bracket (made of thermoset composites) for connecting with the flap track attached to the rib was one of the specialized characteristics, as was a sequence of holes or ply drops in the ribs to reduce their weight. It remains, however, a simplistic and cost-effective design to make sure it is competitive enough from a customer perspective[11]. The short-term goal of Daher is to reach a technology readiness level (TRL) 6 by the end of 2023 for the production method employed to create larger and higher-loaded ribs. A challenge that has to be addressed is the thickness of the ribs. For the biggest rib, to ensure the desired mechanical properties a thickness of 12 mm was required. When thicker fabrics are used, they tend to wrinkle or deform during the stamp-forming process (for which new manufacturing ways had to be tried), hence it is a complex task to reach the correct final shape and finish.

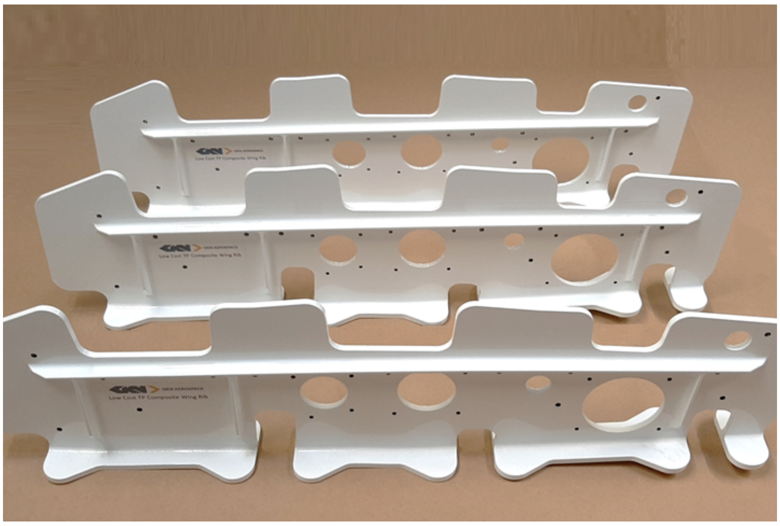


Figure 3.5: GKN Aerospace thermoplastic ribs[10]

Another manufacturer participating in the Wings of Tomorrow project was GKN Aerospace. After an investigation of the new wing structure, a decision was made to produce the four larger, bulkhead, ribs out of aluminum while the remaining ribs should be made with composites[10]. Hence, a variety of thermoplastic ribs, with the largest being 90 x 24 cm, were produced, and the result of their work is illustrated in Figure 3.5. For these ribs, the material of choice was Solvay's APC carbon fibre and polyetherketoneketone (PEEK-FC)[13]. It is necessary to point out, however, that due to the benefits of low-melt PAEK and its use by their French counterpart, GKN is now also investigating its use for future rib structures.

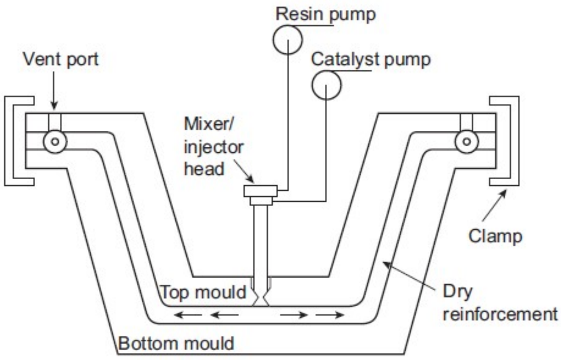


Figure 3.6: Resin transfer moulding process [28]

The more common method of manufacturing thermoplastic composite ribs, stamp forming, was eliminated as the ribs would need to be very thick to be able to support the compressive and tensile loads. Furthermore, stamp forming doesn't allow the creation of double-sided flanges, which is also confirmed by Daher's choice to rivet an additional flange support to its thermoplastic rib (see Figure 3.3). Therefore, GKN created a new out-of-autoclave (OOA) one-step consolidation process to manufacture thermoplastic components. First, the composite thermoplastic tapes are preformed to desired shapes, then loaded into a co-consolidation press that works similarly to a resin transfer mould (see Figure 3.6). After the press is closed, a 'bladder system' is used to generate vertical and horizontal pressure similar to the ones in an autoclave. The developed, modular, system can accommodate elements of up to 6 meters long[10]. The entire manufacturing process takes around 45 minutes from start to end, meaning more than a dozen ribs can be manufactured during a standard shift.

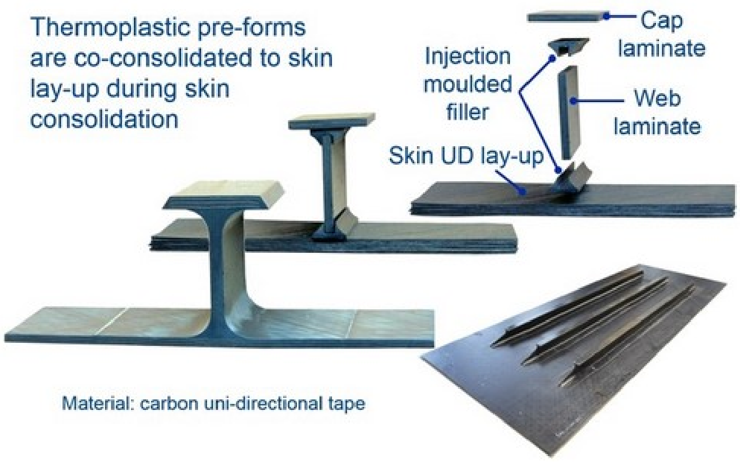


Figure 3.7: Butt-joint technology using injection moulded fillers[14]

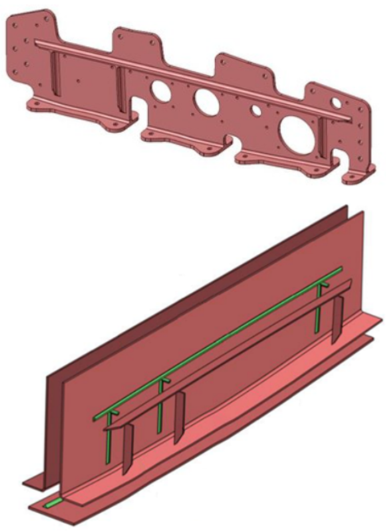


Figure 3.8: Composite rib with additional stiffening elements[10]

This process also allows to co-consolidate multiple preforms together to incorporate additional complexity into the rib design with GKN's proprietary butt-joint technology (Figure 3.7). Co-consolidating parts together

[13]https://www.solvay.com/en/product/apcpekk-fcs2 (Accessed on 28/04/20232)

enables the elimination of the mechanical fasteners, which can reduce the weight and costs of the part by 10% and 20% respectively. Welding could also have been used, and actually was used by GKN during their TAPAS composite fuselage study[14]. The result of fastener-less production methods is a variety of integrated stiffening elements in multiple orientations, leading to more complex designs as illustrated in Figure 3.5 and in Figure 3.8.

3.3. PERFORMANCE ANALYSIS & TRADE-OFF

An important aspect to consider during the optimisation, that will directly impact the trade-off between different designs and manufacturing methods, will be the associated costs for the given aircraft system design. From the literature, it was found that the approach to cost estimation could be summarised into these three categories [29]:

- Analogous: estimation based on historical data for costs of similar products. Differences between old and new designs' costs could be compared, however, this method is very limited for the later designs as there might be an absence of parts/products that could directly be compared.
- Parametric: this method employs cost estimation relations (CERs) to directly estimate the cost of a product. CERs are mathematical expressions derived from historical data of comparable products, which link the cost to specific product characteristics such as weight or dimensions.
- Process-Based/Bottom-up: in these cost estimation methods, all information about the resources used during product manufacturing, including processes and steps, is taken into account. This method requires more preliminary data compared to formulaic and similar cost estimation methods. However, it has the advantage of being more adaptable to new products and processes that might not have any relatable historical data available.

Furthermore, it is always possible to combine the different cost estimations strategies, for instance by considering both the historical costs and the design features to achieve a more accurate approximation. In the case of an MDAO analysis, to implement the aforementioned methods, a cost tool would be required to be implemented in the MDAO analysis. The main difficulty with these manufacturing cost-estimation tools, however, is the fact that they are not publicly available as they are either sold as commercial products (like aPriori[15] or SEER-MFG[16]) or contain proprietary information preventing these models from being distributed.

Nevertheless, there are open-source tools capable of providing a cost estimation based on design features. One such example is the CATMAC (Cost Analysis Tool for Manufacturing of Aircraft Components) open-source tool developed by GKN Aerospace [30], in the framework of the AGILE 4.0 project. Although it is not necessary to understand the exact cost estimation methodology embedded in this tool, having a general overview is useful. The tool links cost estimations to the actual geometrical design features. It breaks down every manufacturing method into sub-steps that need to be performed and provides an approximation for the costs due to materials and hourly rates of the resources needed to accomplish those. Subsequently, the resulting expenses are summed to form the total manufacturing expenditures for a given product. The three main parameters used to generate estimates are the overall design geometry (ex: sheet area, length, volume, etc.), the acceleration parameter to reach 63% of steady-state production and the overall steady-state speed of the manufacturing process. It also makes use of the *design complexity* and *delay* factors to compute the final results.

It is a Python-based tool which communicates using XML formatted inputs and outputs, enabling easy integration with other tools in the MDAO framework. Below are provided details regarding input requirements as well as the generated output:

- Input: XML file containing information on all the parts and connections of a given product (in the case of a rib it could be the rib itself or the components it is composed of such as the web and flanges). The tool requires the part name, material information, manufacturing information, geometrical details and complexity information. For the connections, the information on which parts are connected, the type of connection and its geometry must be supplied.

[14]https://www.compositesworld.com/articles/thermoplastic-primary-aerostructures-take-another-step-forward (Accessed on 10/05/20232)
[15]https://www.apriori.com/solutions/products/ (Accessed on 11/04/2023)
[16]https://galorath.com/products/seer-for-manufacturing/ (Accessed on 11/04/2023)

- Output: XML/XLSX/PDF file containing only the total cost and or production times for assembly components and connections, or all details for all sub-processes of all manufacturing techniques. In that instance, all costs and times associated with all manufacturing processes are presented.

The CATMAC tool will most likely be used in the context of this thesis work as it can provide meaningful cost-trends estimations (the actual values might be off by as much as 50% [30]) that will allow for the comparison of different designs with respect to manufacturing cost and time to be made. Additionally, it also has a database of materials. Currently, it only contains the unit cost and density of each material as usable information. Potentially, it could be enriched with additional information related to the performance characteristics of the materials. This would make it useful to be used by other disciplines too, as well as allow to further improve the CATMAC by providing a possibility to derive some additional results related to the performance-cost trade-off.

Another, equally important aspect to consider during the design trade-off will be the weight of the product as influences the performance of the entire aircraft system. Since the weight is linked to a given material and production method, it will be necessary to obtain the right balance between it and the production cost/time. There are multiple ways the weight could be obtained. A first method could be to compute the part volume, and with the material proprieties such as density, retrieve the weight. This could be implemented relatively straightforwardly within the ParaPy KBE environment. A second method could be to use an already existing package called *Mass Properties Module* (MPM), created by GKN Aerospace, that derives the product's mass [29]. However the latter is an in-house developed package, and hence its availability for use might not be assured due to its proprietary nature.

3.4. IMPORTANT CONSIDERATIONS

One of the key observations and takeaways of the literature study touching upon the use of composites for aircraft wing components/rib manufacturing, is the early stage of development at which the industry is currently, as well as the uncertainty related to the best material and production method choice that comes with it. As was shown in the Subsection 3.2.2, currently the two companies investigating and producing composite ribs, Daher and GKN Aerospace, went for two different production methods. One makes use of the stamp forming method, which is cheaper and for which more experience is available, while the other created a new production process that is similar to resin transfer moulding. It will be necessary to closely monitor the advancements in this topic, and attempt to contact the company representatives to further investigate on the material/production aspects and current hurdles.

For the metal rib production, the industry has accumulated a lot of experience, and the material and production methods are well established. The main material used for the wing ribs are the aluminum alloys of the 20- and 70- series, with a preference for the former for its superior fatigue qualities. If the ribs are made for smaller aircraft and need to be relatively cheap, or do not require high level of complexity, the sheet forming production method can be used. On the other hand, larger aircraft have ribs manufactured using CNC machining, as more design features and higher level of detail can be achieved. Furthermore, the rib is one, integral part, improving its weight and mechanical performance characteristics. Hence, the latter production method will be implemented in this thesis. Metal sheet forming could also be included, as it is expected to have similar design requirements to the ones set by the composite stamp forming process.

4

Design Manufacturability

The key part of the study revolves around the manufacturability assessment of the desired aircraft system. In this study, the manufacturability of the rib will be examined. First, Section 4.1 will present the conventional rib design methodology, as well as some additional requirements the machining and composite methods bring. Then Section 4.2 will mention some of the already developed tools for DFM analysis. After, Section 4.3 will highlight the rib model implementation stages during this thesis. Lastly, Section 4.4 will mention a couple of additional considerations to keep in mind and investigate.

4.1. Rib Design Considerations

The rib is one of the core structural elements of the aircraft wing, alongside the skin and the spars. Together, they form the so-called wingbox which ensures the rigidity of the wing throughout the flight and airframe life cycle. Ribs allow the wing to retain its aerodynamic profile, transfer the aerodynamic loads to other airframe components and prevent skin buckling from occurring. They are typically placed along the airflow direction and not perpendicular to the spars (although it would have been more practical from a manufacturing perspective).

Throughout the years thousands of rib designs were created and perfected, and therefore a lot of experience has been gathered. Many companies define design standards to follow during the rib design, and although different companies may have different design conventions, they are mostly similar since they are all based on the industry's historical experience and mechanical tests [31]. For instance, ribs composed of multiple pieces riveted together could follow the rules-of-thumb described in [31] (for instance, the rivet pitch should be no less than 4 times the rivet diameter). The study also empirically links the overall rib dimensions to the Outer Mold Line (OML) (outer aircraft surface, in this case a wing) instead of drafting CAD models [31]. Although this study will not make use of fasteners for metal ribs, the approach to relate the rib structure to the OML dimensions could be reused, and it can be one of the design variables impacting the rib geometry.

Alongside the normal web and flanges, the wing ribs typically contain cut-outs. This is done both for weight saving as well as for practical reasons since the inside of an aircraft wing is typically used as a fuel storage tank and wiring needs to be placed. According to the study by Dharmendra *et al.* [32], the weight advantage of including elliptical cutouts can be in the order of 20-22%, using either Aluminum or Carbon Epoxy. Additionally, not only do the cut-outs reduce the weight of the structure, but their shape can also influence the buckling performance. It was found that circular holes can improve the rib's buckling strength, albeit it also increases the stress concentration [32].

To design a rib, the first step is to determine the exerted aerodynamic forces on the wing, and then compute the resulting loads and shear flow in the structure. Then, based on the shear flow and the material properties, the shear stress can be expressed as a function of the wing rib thickness. Subsequently, failure modes like critical buckling are analysed to ensure the structure can withstand them. Then, using empirical data, the rest of the rib sizing can be performed. Lastly, the size and spacing of the lighting holes are computed. The complete methodology with required formulas, that will be used to design the ribs, was defined by Sedaghati and Elsayed as part of the MOSAIC project in [33]. It was developed with the mindset of having this systematic design approach digitised for later implementation in design optimisations studies. The methodology follows similar guidelines to the ones taught in the TU Delft *AE2135-I Structural Analysis & Design* course[1], being a more in-depth version of it. Sedaghati and Elsayed described two step-by-step procedures for designing ribs, depending on the load case scenario. A choice between a lightly loaded or highly loaded case must be made for this thesis in order to choose the method.

4.1.1. MACHINED RIBS

In this study, metal ribs will be assessed from a machinability perspective. This will not change the general design procedures significantly from what was stated previously. The advantage of machining is that the rib will be manufactured out of a single material block. Hence, the web, flanges, and vertical and horizontal stiffening elements will be part of one single integral structure, and will not require to be joined together. This simplifies design assessment as fastening methods can be disregarded.

However new considerations are added. Machining adds the freedom to have variable thicknesses through the rib. Hence, if the rib is divided into several sections, split by vertical and/or horizontal stiffeners, the design can accommodate various thicknesses to reduce the weight of the rib. A limitation, however, will be that with a simple 3-axis CNC machine the operations on the YZ and ZX planes cannot be performed without the removal and manual repositioning of the part in the machine. Additionally, no angled surfaces or complex curvature shapes will be possible, since this would require much more expensive and complex tooling such as a 5-axis CNC machine, used to produce intricate turbine and compressor blades[2]. Nevertheless, these restrictions could be very useful for formulating production requirements. Furthermore, as illustrated by Figure 4.1[3][4], the level of complexity that can be achieved with a 3-axis machine is sufficient for the current high-level study.

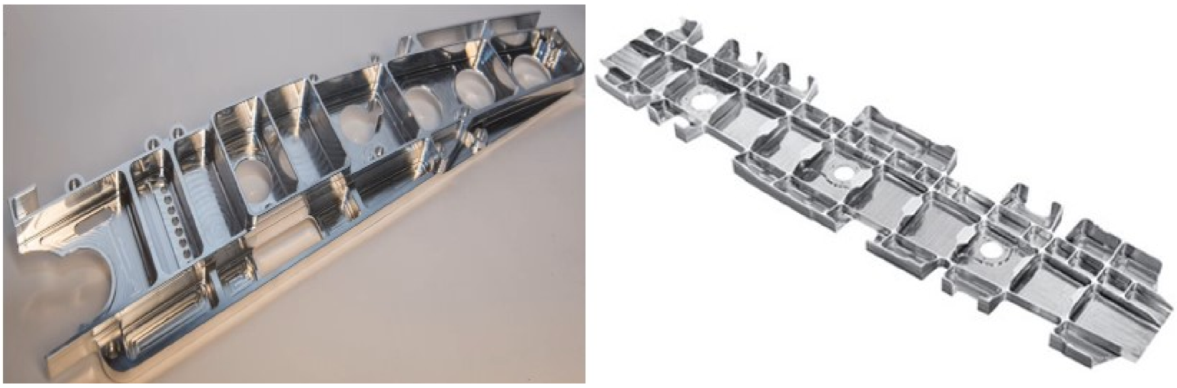


Figure 4.1: Example of 3-axis machined ribs

Therefore, apart from the limit of working only on the XY-plane and being able to machine only in Z-depth, the design methodology is the same with less stringent requirements placed on the design as thickness uniformity is not required.

4.1.2. COMPOSITE RIBS

A study by Astwood went into depth to study the production of components with composite materials, and defined 9 rules to follow during the design of a composite lay-up structure made of uni-directional (UD) plies [34]:

1. Laminates should be placed in a symmetric configuration, around an imagined neutral axis. Therefore, an equal amount of plies is required above and below it. In case perfect symmetry cannot be produced, the asymmetry should lie as close to the neutral axis as conceivable.

2. To improve the balance of the laminate, plies of perpendicular orientations should be present in equal numbers. This applies to either the +/-45 degree plies or to 0/90, depending on the loading scenario.

[1] https://brightspace.tudelft.nl/d2l/home/512864 (Accessed on 27/05/2023)
[2] https://www.youtube.com/watch?v=TRmvk6Mw03Y (Accessed on 28/05/2023)
[3] https://www.youtube.com/watch?v=BWoUBMOlydI (Accessed on 28/05/2023)
[4] https://www.makino.eu/en-us/digital-showroom/wing-rib (Accessed on 28/05/2023)

3. Each orientation should represent at least 8% of the total laminate thickness and no more than 67%. With this, the design can resist the compression load due to the poisson effect.

4. Outer plies should not be placed in the direction of the main loads, as they are more likely to experience damage.

5. Grouping the plies with the same orientation should be avoided, as it would increase coupling effects leading to inter-laminate stress concentrations.

6. Maximum number of plies with the same orientation should be 3, or around 1mm of thickness when placed together.

7. For improved buckling performance, the plies of 0-degree orientation (main loading direction), should be placed as far away from the neutral axis as possible, as the centre of the laminate is not subject to compressive and tensile loads.

8. To minimise coupling effects, +/-45 degree plies should not be put together in adjacent pairs. Following this rule will reduce the chance of laminate distortion.

9. To reduce shear effects between laminates, it is necessary to place plies with the smallest orientation angle difference. For instance, put +/-45 degree plies between the 0 and 90 ones.

These guidelines are also backed by the TU Delft *AE4ASM001: Design of Lightweight Structures I: Composites and Metals* course[5], that stipulates similar requirements for the composite structural components. The course adds a few more suggestions:

- Reduce amount of free edges in the design. As loads vary for different edges, find the most important loads and try to create a lay-up yielding compressive edge stresses.
- Thin layers should be preferred to thicker ones, although it is more expensive and more layers require more time for manufacturing.
- Make inter-laminar normal stress, σ_{zz}, compressive to prevent delamination.
- For ply drops, reduce free edges by having the ply drop in the middle and smaller than 0.5mm, and leave d = 10/15 ply drop height between two ply drops.

It must also be highlighted that it will be difficult to achieve all of the suggestions simultaneously, so a trade-off must be made with respect to the design case. Nevertheless, they will constitute the core of manufacturing considerations involving composite methods for this thesis project.

Additional considerations should be taken into account when designing components with composites. Composite manufacturing involves high temperatures, and hence thermally-induced deformations need to be investigated. As opposed to the metal sheet forming method, where an important consideration is the spring-back of the part when pressure is removed, for composites, it is the spring-forward effect that must be addressed. Since it is required to cure the composites such that the resin is hardened and desired strength and stiffness properties are achieved, thermal effects are introduced during the cooling of the composite part the spring-forward effect is observed and needs to be accounted for [35, 36]. He *et al.* [36] presents an analytical solution found to estimate the spring-in effect for thermoset ribs, and recommended to perform the cut-outs prior to curing. Another study by Jain *et al.* [35] performed a similar investigation for composite rib spring-in, and the results could be used to assess the rib part spring-in.

Another important design aspect that needs to be considered is the increased material thickness, present at the locations where fibre orientations change [10], as displayed in Figure 4.2. As a part can be split into several areas, or patches, to be optimised separately, an optimisation algorithm might output that the fibre orientation must be different between the two patches. However, it does not account for the fact that, in practice, to change from one orientation to another, a fibre overlap must be created. Hence the optimisation results underestimate the real weight of the structure [10]. Furthermore, such thickness ramps must be made smooth to ensure structural integrity, as stipulated by the ply-drop recommendation above. A detailed example of such a ply structure, with additional mass due to thickness mismatch, is shown in Figure 4.3.

[5] `https://brightspace.tudelft.nl/d2l/home/498878` (Accessed on 12/05/2023)

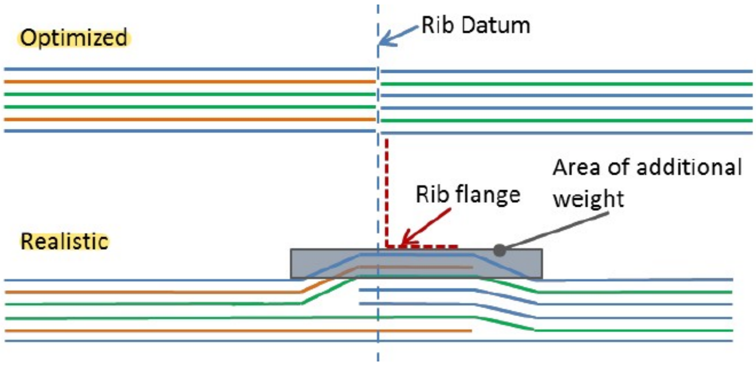


Figure 4.2: Additional ramps for stiffener placement [10]

For composite ribs, the methodology will be slightly different from the one stated for the general ribs. Although the loading case is the same, more attention will have to be paid to the areas around the cut-outs. For instance, in metal components material would typically get added to reinforce the area around the edges of the cut-outs, in the case of composites, it is actually beneficial to reduce the amount of fibre closer to the whole, to reduce the risk of delamination occurring.

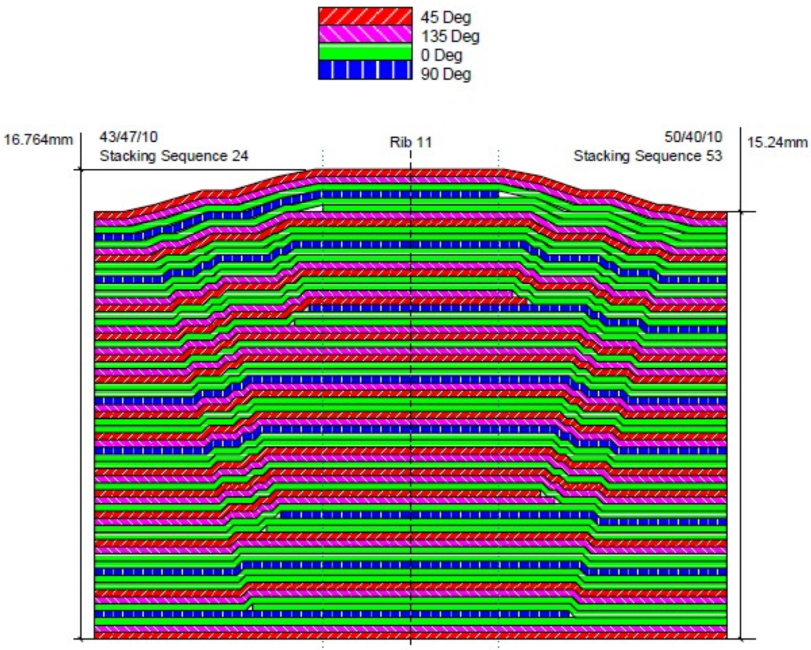


Figure 4.3: Example of lay up structure due to reinforcements [34]

4.2. MANUFACTURABILITY ASSESSMENT TOOLS

Assessing the manufacturability of a product is a topic gaining increasing attention from the industry, as incorporating DFM could reduce the time and cost of production and assembly. A substantial part of available DFM tools and studies are mainly focusing on providing an early estimation of the costs and time required for manufacturing of a given product [31, 37, 38]. There are a few, however, that focus more on the actual assessment of the design from the manufacturability standpoint, and subsequent design improvement.

4.2.1. MACHINING MANUFACTURABILITY

A study carried out in 2017 by Hoefer *et al.* at Iowa State University proposed four criteria [39] that could be used to evaluate the manufacturability of a given part design. These are listed below and graphically illustrated in Figure 4.4:

- *Visibility*: This criterion measures the degree to which a surface area is visible from the tool's perspective. The visibility of each facet is assessed from the x, y and z-axis, and is converted into a percentage of the total part surface.
- *Reachability*: This criterion measures the tool's reach, i.e. how deep can the tool move while still being in contact with a model's surface. Reachability is scored based on the required tool length to machine each part area. The longer the required tool is, the lower the score since lower feed rates are required to minimise tool deflections.
- *Accessibility*: Similar to the previous criteria, it measures the ability to machine a model feature without tool collisions with other model surfaces. Instead of length, the accessibility criterion is influenced by the tooling diameter (and part geometry), and scores the design based on the percentage of total surface that is manufacturable without collisions.
- *Setup Complexity*: this criterion quantifies the number of setups needed to machine all the features of a part. Intricate features on multiple surfaces would necessitate additional setups due to the need for changing the model's orientation to facilitate tool access.

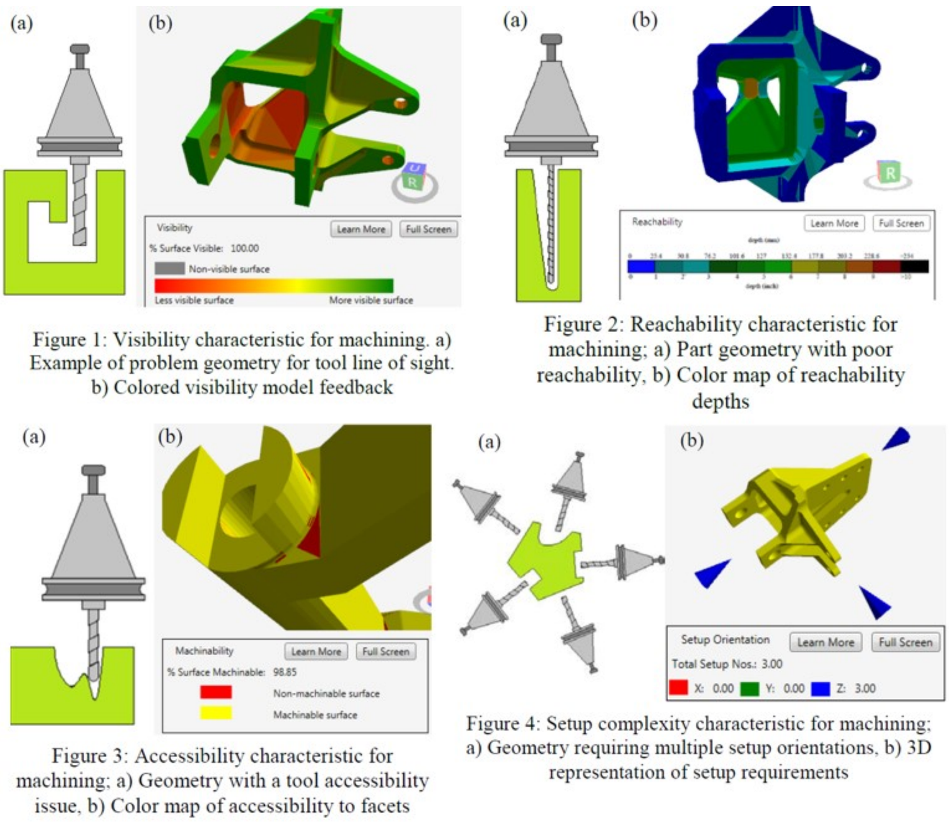


Figure 4.4: Machinability defining characteristics [39]

The result of this paper was the creation of a feature-free geometric analysis tool ANA (Automated Manufacturability Analysis). Through surface inspection algorithms, it can based on a CAD file (.stl) provide visual and quantitative feedback on any arbitrary geometry manufacturability, aiding the obtention of feasible and improved designs [39]. As of the paper's publication, the examination of manufacturability was constrained to the machining process, with casting, die-casting, and welding modules under development [39]. It is likely that the work has now been finalised, although no recent papers from the author confirming it were found. Although this tool is not publicly available, a request was sent to the author (Hoefer *et al.*) to provide access to it for the given thesis study. If the answer is positive, it could greatly aid this project and accelerate its development. Otherwise, considerations such as reachability, accessibility and visibility could be implemented during this thesis project. They can be integrated as requirements on the design (maximum feature depth, minimum distance between adjacent stiffening elements, etc.). To develop these consideration modules, the approach of Samarghandy and Li [40] could be taken as a starting point. It consists of taking into account the required tooling approach direction and its size and forms a 'machining boundary' that is projected onto the surface that will be pocketed. Later, the algorithms assess whether this boundary intersects any design feature other than the surface that will be machined.

In another study [38], a software for DFM analysis called DesMod was created. Extracting data automatically from CAD files, it evaluates the geometrical properties of the model such as design features, size, thickness, etc. Among the various factors the authors use to rate the designs, the most interesting one for this study is the *Shape Factor*. Criteria influencing the score for this factor can vary with production methods. For the machining method, these can be; cross-section and wall thickness uniformity (higher features standardisation), external and internal features such as local curvatures and corner radii, as well as a variety of tooling required to machine the part [38, 41]. DesMod provides the users with graphical and textual results highlighting the scores for each criterion and suggesting improvements. Being currently under development, the authors envisage offering the capability to assess a single design manufacturability simultaneously for machining, casting and injection moulding production methods. Similarly to ANA, DesMod is not publicly available (to the author's best knowledge), hence effort was made to contact the owner of the tool (Abdelall *et al.*) to acquire more details on its inner workings and evaluate potential opportunities for this thesis project.

One more tool of interest would be the Xometry[6] add-in to the Solidworks CAD software. It assesses the designs given a manually specified manufacturing process, material, and finish, and can automatically locate features/areas in the design that require modifications to improve the manufacturability. One limitation of the add-in is that the features are available only for manufacturing processes related to plastics and metals. Hence, within the scope of this study, the tool could only be used for metal ribs. Nevertheless, it is a proven solution and is worth investigating. Although TU Delft provides Solidworks licenses for students, it remains to be seen if the Xometry features are disponible under that licensing agreement and if the manual tasks of specifying the material and production method could be automated (via a macro) to enable the use of the software as a discipline in the MDAO workflow. Furthermore, an equally important question is the extraction of the tool's DFM analysis and if it is/can be translated into a quantitative metric, interpretable by the optimiser.

4.2.2. COMPOSITE MANUFACTURABILITY

The processes of manufacturing using composites is still an ongoing investigation. Studies on the subject of manufacturability often focus on analysing and adapting the manufacturing process itself rather than on the design [27, 42]. Moreover, in the case of manufacturing thermoplastic ribs even using the composite stamp-forming manufacturing process, that has been studied for several decades [43], is still not a well-defined procedure and, for instance, Daher is aiming at reaching only TRL 6 by the end of 2023[10]. It was also observed that manufacturability of composite structures is often assessed using proprietary software tools such as PAM-COMPOSITES[7] or the packages present in CATIA/ABAQUS[8]. These can assess, for example, the strain and internal stresses that the composite part will have due to its design, or if due to the production method, some composite wrinkling will occur[7]. Furthermore, they have the capability to provide recommendations on the optimal fibre lay-out for manufacturing.

For the implementation of composite manufacturability assessment in this project, several approaches will be taken. First, the aforementioned guidelines (Subsection 4.1.2 for composite product designs could be used. They can be reversed and instead of generating a rib design that respects these rules, a design produced by the optimiser could be checked to measure to what extent it conforms to them. Based on the number of rules the design successfully complies to, a manufacturability score is given, working as a design ranking system. This topic will be further investigated during the development of the MDAO system. It will also be crucial to contact manufacturability experts involved in the production of thermoplastic composite parts to gain additional industry knowledge of what are the main limitations/restrictions imposed on the design by the composite production procedures.

[6] https://www.xometry.com/cad-add-in-for-solidworks/ (Accessed on 18/05/2023)
[7] https://www.esi.com.au/software/pamcomposites/ (Accessed on 30/05/2023)
[8] https://my.3dexperience.3ds.com/welcome/compass-world/3dexperience-industries/transportation-and-mobility/on-target-vehicle-launch/composite-engineering-and-manufacturing-preparation (Accessed on 30/05/2023)

4.2.3. MIM

With the global goal of improving the synergy between designing and producing an airframe component, it is also compelling to link the current manufacturability study, which aims at introducing the manufacturability discipline into the MDAO workflow, with a previous thesis study conducted by Bansal that resulted in the creation of the Manufacturing Information Model (MIM). MIM is a newly developed software package that contains three subpackages; a *database*, a *manufacturing model* and an *assembly model* [29]. The first is a directory with data files specifying the various characteristics of the production methods, materials, equipment and manufacturing sites. The *manufacturing model* module is the core of MIM and can be seen in Figure 4.5. It splits the product into "primitives" (a parametric building block defining the product) and, using the design-specific characteristics and the database, provides the manufacturing information associated with the production process selected for a given primitive. The last module determines the production operations that need to be performed, based on the previous module's results, and establishes an assembly sequence.

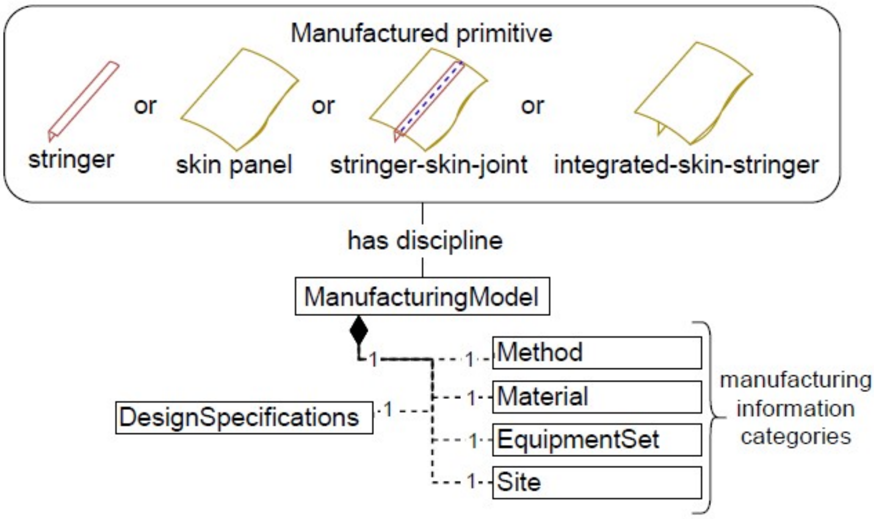


Figure 4.5: Manufacturing model information categories and relation to manufactured primitives [29]

The MIM had as target to improve the inclusion of manufacturing considerations in the design process by creating a data system that can store production-related information and perform a top-level check of whether all the components of a part/product are compatible and can be produced given the selected material and method specifics. Hence, the MIM assesses if the product can be fabricated, but doesn't check if each individual component's design is manufacturable, and that is where the work of the current study could be used. The possibility of fully merging the two will be assessed further in this thesis project, however right from the start, an attempt will be made to make use of the already existing database module. In particular, the author developed a *compatibility* package [29] which determines the compatibility between the selected material, production method, equipment and design. This package could be reused and enriched with the inclusion of new considerations.

4.3. RIB MODEL IMPLEMENTATION

Implementing the rib model into the MDAO workflow will be one of the key tasks during the thesis project. However, time must also be allocated to achieve other thesis goals such as investigating the capability for integrating multiple manufacturing techniques and affecting the requirements of the system in a dynamic way. Therefore, it is logical to integrate, at first, a lower-fidelity rib model into the system, and increase its complexity subsequently. The rib modelling complexity can be split into three stages:

- *Stage 1*: A rib model consisting only of a main skin element with flanges positioned on the top and bottom. While this represents the simplest model of the rib, it offers several advantages. Firstly, it can be quickly constructed for efficient workflow implementation, allowing to start executing the MDAO system and obtaining results quicker. The latter can also be more easily verified using simple calculations.

- *Stage 2*: Improve the model by adding vertical and longitudinal stiffening elements such as the rib beads, as can be seen on the bottom of Figure 3.8. This will require to also consider the assembly of the elements for the composite manufacturing method, and performing additional research into composite welding and what considerations it brings to the design.
- *Stage 3*: Include cut-outs within the rib skin. This step will result in a rib closely matching the real-life wing parts, like the one designed by GKN Aerospace (top Figure 3.8). These holes can be made within the rib web as well as in the region where the rib is in contact with a spar/skin. However, it will be performed last since it will require to have a higher fidelity stress model, and include more complex design practices some of which are mentioned in Subsection 4.1.2 for cut-outs in composite matrices.

To create the model in question, ParaPy will be used as the KBE tool in order to facilitate the information exchange between disciplines and ease the parametrisation adjustments that might be required at later stages. The said parametrisation with ParaPy might take inspiration from the rib parameterisation structure that is used in the CPACS schema (under the *ribDefinition* element[9], although this will be further examined during the construction of the workflow. Also, it is important to create a model that can easily adapt to changing wing specifications (for instance if the engineer alters the NACA airfoil shape), hence a *kbeutils* package, developed at TU Delft, will also be used.

4.4. IMPORTANT CONSIDERATIONS

As stated previously in Section 4.1 and Section 4.3, aircraft wing ribs can have very complex designs requiring advanced tools and design procedures. However, this study will mostly focus on developing a highly simplistic rib model, meaning that some of the conclusions related to the trade-off between different designs or production methods might not be applicable for real-life use. Since it is highly likely that in the subsequent stages MDAO of development higher system fidelity will be required, it will be essential to create the rib model in a way that enables a straightforward model complexity increase in the future.

Another interesting aspect to take into account is that in case one of the manufacturability tools, mentioned in Section 4.2, will become available for use but won't be easily implementable in the workflow, it could still serve a very important purpose: verification and validation. Effectively, some of the tools like ANA or DesMod were developed by different institutions, hence it could be valuable to see how the different approaches measure to each other as well as to the work performed during this thesis. On the other hand, commercial tools such as Xometry could be a benchmark to validate the developed models as it is expected that a commercially sold tool must be of a higher fidelity.

Lastly, as the involvement of thermoplastic production methods for ribs and other aircraft components are a state-of-the-art topic, an effort must be made to contact the current industry and academia players in order to obtain additional information on composite manufacturing. Among others, GKN Aerospace has worked on the Wings-of-Tomorrow project and it will be essential to investigate if some (high-level) knowledge and information can be shared.

[9] https://www.cpacs.de/documentation/CPACS_3_0_0_Docs/html/057a162f-e4c3-9565-897b-5cf3a336520e.htm (Accessed on 17/05/2023)

5

Research Plan

From the literature review, the main tasks for the thesis work can be summarised as follows: creation of a dynamic workflow, rib model development, and assessment of design manufacturability. To create a structured approach, several work packages (WP) will be defined to be performed in sequential order:

- *WP1: Accustomisation with workflow formulation tools.* As was presented in the Chapter 2, many tools and software packages will be used to automate the composition of the MDAO system. Prior to attacking the thesis problem, a short period will have to be dedicated to getting accustomed to the tool's functionality. This will be done via the creation of a simpler, static, workflow with dummy disciplines and a uncomplicated objective. It will be also interesting to examine if and how it can be transformed into a dynamic workflow. In case a dynamic workflows will not work yet, a static workflow will be used throughout the subsequent stages until the functionality is developed.
- *WP2: Stage 1 rib model formulation.* The goal of this WP is to develop a simple KBE rib model, sufficient to start conducting first design studies. It should have an adequate level of detail and a structure allowing further expansion and complexity increase, while not being too intricate. More details into proposed rib fidelity increase stages can be found in Section 4.3. This rib model should then be integrated into the MDAO system of WP1.
- *WP3: Introduction of preliminary manufacturing method.* After the rib model is devised and integrated into the workflow, the core of the thesis work will start with the creation of the manufacturing disciplines. The goal is to create two distinct methods that would place different requirements on the rib design and workflow structure, to test how the workflow of WP1 responds and adapts. Secondary tools such as CATMAC and a weight estimation module (MPM or self-developed) will be implemented.
- *WP4: Rib and Manufacturing complexity increase.* Following the results of the previous WP3, the target is to bring the complexity of the entire system to the desired level to start obtaining valuable and meaningful results. If time allows for it, the integration of MIM could be envisaged.
- *WP5: Verification & Validation of results.* For any research, it is crucial to ensure that the work performed is done correctly and answers the challenges it was aimed to solve. Although it is indicated as the last work package, work on this aspect will have to be conducted continuously through the implementation of code and results verification for each of the previous WPs.

Considering the timing of activities, it is necessary to examine the overall thesis project timeline. Between the end of *Literature Study* and the *Mid Term Review* 15 weeks will be available, with 8 additional weeks prior to the *Green Light Review*. Therefore, the aim is to have WP1 to 3 done prior to the Mid Term, and have the WP4 and WP5 ready by the *Green Light Review*. Subsequently, 2 weeks are given for thesis report finalisation and official *Thesis Hand-In*. Finally, 2 more weeks are available to prepare for the *Thesis Defence*. Aside from the technical tasks, time needs to be devoted to the organisational aspects of the thesis such as articles and report preparations. In order to make sure no details get lost and the time management with respect to official deadlines is on-point, throughout each stage of the thesis the performed tasks will be continuously documented.

6
Conclusion

With the rising demand for air transportation and the desire for companies to maintain their competitiveness in the market, it is crucial to improve the procedures revolving around designing aircraft systems. One of the key issues observed in the current process is the low usage of manufacturing information and considerations at the preliminary stages of product design. Effectively, manufacturability is addressed at later stages of the component design. In both cases, the lack of direct implementation of production considerations can result in the part's redesign, leading to increased manufacturing times and costs as well as delayed introduction into the market, or lower-than-expected performance.

The concurrent optimization of design and manufacturing parameters, that could be enabled by Dynamic MDAO workflows, offers a promising solution. By incorporating manufacturing constraints and requirements into the design process, engineers could avoid costly design iterations and ensure that the final product can be effectively and efficiently manufactured. This proactive approach would minimise the risk of encountering manufacturing issues during the production phase, leading to significant time and cost savings. Therefore, the following main research objective was defined for this thesis:

To investigate the possibility and impact of implementing manufacturing considerations at early design stages via the integration of multiple manufacturing techniques into the MDAO workflows using a wing rib as a case study

This study will also aim to assess the influence of manufacturing on rib design by comparing the design results of a sequential process with an embedded process.

Firstly, the MDAO workflows themselves were investigated. Throughout the years, many developments have been made with a focus on improving the formulation and execution of said systems. The main tools that will be used in the study will be:

- Requirements Management Module (RMM): an innovative tool developed to improve requirements management allowing for automatic requirement compliance verification and the composition of MDAO systems based on specified requirements. It will enable the dynamic change of the MDAO workflow based on the selected production method.
- KADMOS (Knowledge- and graph-based Agile Design for Multidisciplinary Optimization System): open-source Python package developed within the AGILE framework, enhancing the process of formulating, and integrating large MDAO workflows. KADMOS analyzes the repository of tools and generates a graph-based MDAO system representation, ready for implementation into workflow execution software. It reduces the formalization process and allows for flexibility in modifying the MDAO architecture.
- Optimus PIDO (Process Integration and Design Optimization) tool: software package used for multi-domain system design and optimization, facilitating the creation and execution of MDAO workflows.
- CMDOWS: standardized workflow data exchange schema, used to reduce the number of interfaces and

enable decentralized and inter-team collaboration. By utilizing a centralized data interface, the number of links between tools can be significantly reduced.

The result will be an implementation of the Design and Engineering Engine (DEE) framework, which combines the above-mentioned tools and methodologies to automate and improve MDAO systems.

Next, different production methods and materials could be applied to the given design case for manufacturing a wing rib. In order to investigate the differences in designs based on manufacturing, one method will use aluminum alloys while the other will asses the rib design from a carbon fibre composite manufacturing perspective. For aluminum, the machining method was chosen as it allows it to have a complex and lightweight rib design while also being the method of choice in the aircraft industry. For composites, the choice is not as straightforward as the work in this direction is still ongoing. In 2015 Airbus launched a new project, Wings-of-Tomorrow (WOT), to investigate the design of a composite wing for a single-aisle aircraft of the future. As part of WOT, GKN Aerospace and Daher have both developed wing ribs using carbon fibre reinforced composited with PEEK and low-melt PAEK resin respectively. Although both were successful, they used radically different manufacturing techniques. GKN Aerospace developed a new method, similar to resin transfer moulding, while Daher made use of stamp-forming. From a design complexity and performance perspective, the production method of GKN is more interesting as it allows them to embed more complex design features in their ribs while not increasing the weight of the part with fasteners. Nevertheless, this topic needs further research and would benefit from contact with industry.

Another important element of the study is the investigation and digitisation of manufacturability aspects. For the machining production, many studies have been performed which led to the creation of tools such as ANA, DesMod, and Xometry. Furthermore, the methodology behind the inner workings of some of these tools is well documented and provides a solid basis for an in-house machining discipline creation. Additionally, it is important to consider that the availability of the aforementioned manufacturability tools presents opportunities for validating and bench-marking the developed manufacturability disciplines. For composites, such studies are yet to be performed or made publicly available. Nevertheless, general methodologies behind composite components design could be used as preliminary requirements for the composite manufacturing discipline.

Lastly, to implement the rib model itself, a systematic three-stage approach is proposed. Initially, a low-fidelity rib model comprising a main skin element with flanges serves as a starting point. This simplified model provides several advantages, including efficient workflow implementation and the ability to obtain quick results that can be validated using simple calculations. As the complexity of the model increases, with the incorporation of vertical and longitudinal stiffening elements and cut-outs, additional research into composite welding and design considerations will be required.

III

SUPPORTING WORK

1

RIB CALCULATIONS

The wing rib module, created using the ParaPy KBE software, is capable of sizing the rib design based on the required strength the design should exhibit, or compute the maximum allowable shear flow through the rib for a given design. In this chapter, the step-by-step process for rib sizing will be provided.

As mentioned in the scientific article, the methodology follows the design approach for lightly-loaded ribs defined by Sedaghati and Elsayed [33], which sizes the rib to withstand the shear stresses induced by the aerodynamic loads. Under them, the rib must neither buckle nor yield.

When the shear flow value is provided, the first step in sizing the rib is to compute the minimum web thickness required for the rib to not buckle. The relation between web thickness and shear flow is shown in Equation 1.1, where where η_s is a plasticity correction factor, C is a factor dependent on the plate boundary conditions, E is the Young's Modulus, v is the poison ratio, t is the rib thickness and h is 2/3 of the rib's overall height. With the minimum thickness found, the critical shear buckling stress can be computed using the Equation 1.2.

$$t = \sqrt[3]{\frac{12\left(1-v^2\right)}{\eta_s \pi^2 E}\left(\frac{h^2 q}{C}\right)} \qquad (1.1)$$

$$\tau_{cr} = \frac{q}{t} \qquad (1.2)$$

If the maximum shear stress based on this thickness is smaller the material yield shear stress value, then the design satisfies the no-yield requirement. Otherwise the actual material η_s parameter must be calculated (using $\eta_s = \frac{G_s}{G}$, where G is the shear modulus and G_s is the shear secant modulus), and the web thickness recomputed with the new value.

When the thickness satisfies the requirement, the critical shear stress and the height-to-thickness ratio ($\frac{h}{t}$) are used to find the ultimate allowable gross shear stresses F_o and F_s, for webs without and with web cutouts respectively. This is done using the empirical relations shown in Figure 1.1. These relations are valid for aluminum rib webs and are used to extract the hole diameter-to-height and diameter-to-spacing ratios. The ratios are then utilised to compute the actual values for lightening hole diameter and spacing.

Finally, the last step is to verify whether the net shear stresses in the web between the holes and in the vertical direction across the hole are below the below the yield shear strength of the material. This is done via Equation 1.3 and Equation 1.4 respectively. In these equations D and b are the lightening holes diameter and spacing respectively.

$$f_s = \tau_{cr}\left(\frac{h}{h-D}\right) \qquad (1.3)$$

$$f_s = \tau_{cr}\left(\frac{b}{b-D}\right) \qquad (1.4)$$

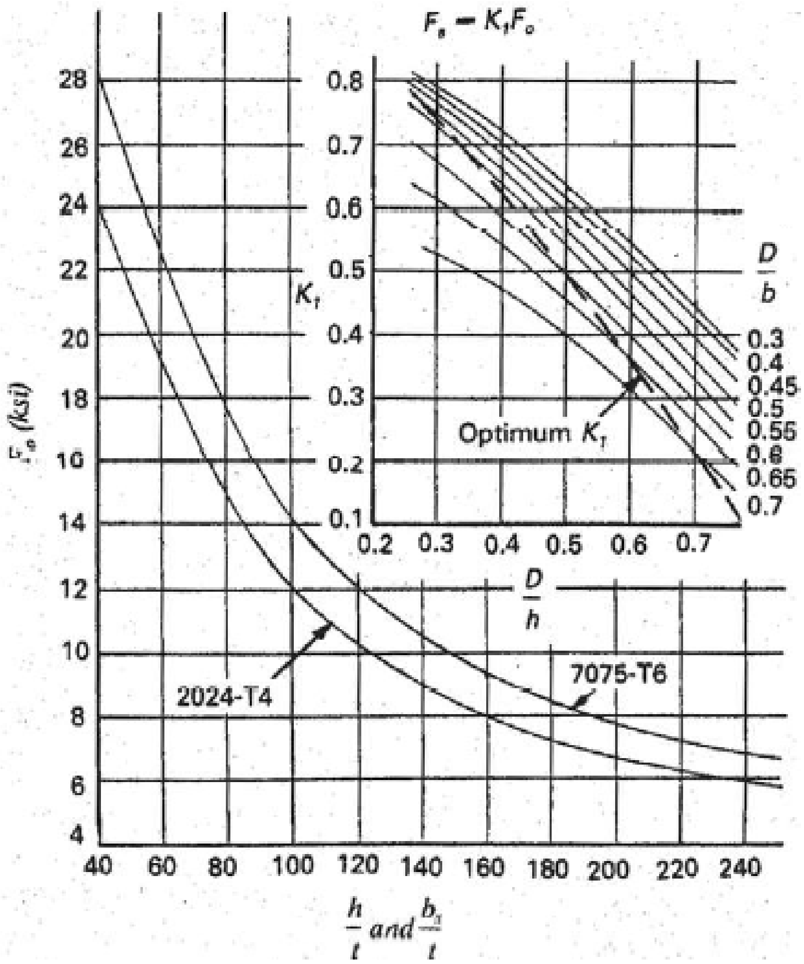


Figure 1.1: Ultimate allowable gross shear stress curve for aluminum rib webs [33]

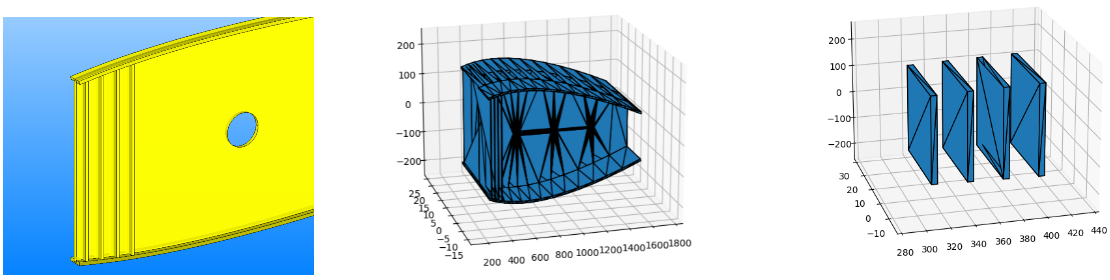
2

Machining Module Verification

The Machining Module is a self-developed tool, in the context of this research, for the purpose of assessing the accessibility criterion [39], to determine whether a design is machinable. This is done by examining the the normal vectors of each CAD surface that point in the positive or negative X-direction. Depending on the sign of the vector, the front and rear surface of each feature can be determined, and the spacing can therefore be calculated. This method only needs to store a single point per stiffener surface.

To increase the confidence in the tool's results, it is important to verify that it is capable of correctly identifying the stiffening elements within a provided rib CAD, without prior knowledge of the product. To do so, a new function was implemented which is given the stiffener thickness as an additional input. It searches and collects all the mesh points that are separated by exactly this spacing, and then sorts them by their coordinates to form individual stiffeners. Subsequently, the spacing between them is calculated. A verification can then be performed to confirm that the spacings found using the main implementation and the verification implementation are the same.

An example of such verification is presented in this chapter. Figure 2.1a illustrates the original wing rib CAD model that was constructed in the ParaPy KBE software, which is then successfully extracted by the Machining Module. For ease of visualisation, the four stiffeners present in this model are shown separately in Figure 2.1c. The task of each analysis method is to extract the stiffener points, and their results are shown in Figure 2.2.



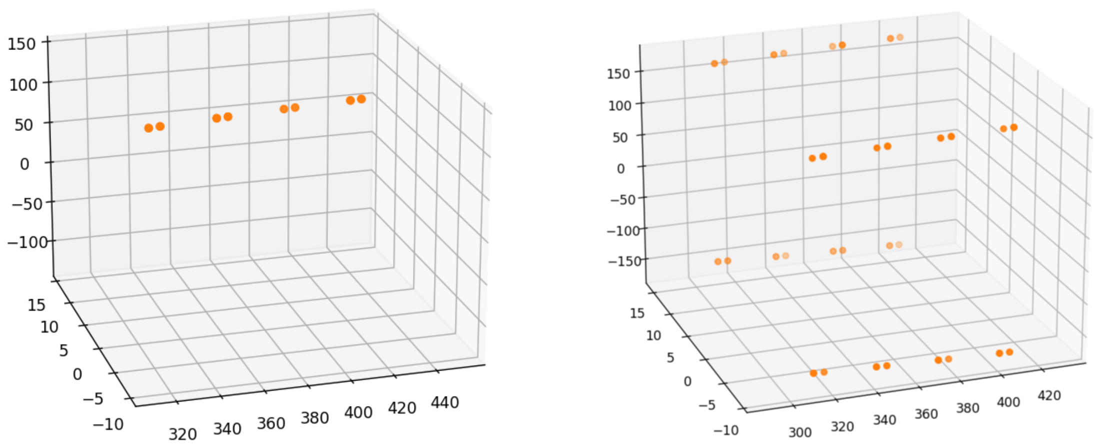
(a) Original Rib CAD in ParaPy

(b) Extracted Rib CAD with four stiffeners

(c) Isolated stiffeners from the extracted CAD model

Figure 2.1: Wing rib CAD model with four stiffeners, shown in the ParaPy app and extracted using numpy-stl package

As can be seen from Figure 2.2a and 2.2b, both methods are able to correctly identify the four stiffeners present in the CAD model. In Figure 2.2a, the original implementation extracted eight points, one for each stiffener surface that is orthogonal to the X-axis. Each pair of points represents the start and the end of a stiffener, and the distance between two pairs was found to be 25 mm. The verification method found the exact same stiffener spacing of 25 mm, and its output is shown in Figure 2.2b. As was explained above, the method stores all the points that are spaced by the value of the stiffener thickness, hence eights per each stiffeners are stored. Overall this verification was successfully performed on multiple rib models, together with a visual validation of the results, confirming the correct functioning of the Machining Module.



(a) Main method results

(b) Verification method results

Figure 2.2: Comparison of stiffening elements detection using normal vectors and using additional input

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