Design Study and Concept Development of Structural Components in a Turbofan Aero Engine

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“If everything seems under control, you’re not going fast enough.”

- Mario Andretti.
ABSTRACT

This Master Thesis was performed within Research & Technology at GKN Aerospace, Trollhättan. GKN Aerospace is participating in the Clean Sky 2 program, delivering the ICC to the UltraFan demonstrator. On this demonstrator, the split and load paths of three components in the compressor module are similar to earlier engine configurations, but GKN wanted to investigate if there are other, more efficient ways of building this structure.

The aim of this thesis was therefore to investigate if there is a more efficient architecture and design of the static components in the compressor module for the UltraFan engine. Utilizing a more efficient architecture and design GKN can, in exchange of undertaking a larger part of the engine, provide engine manufacturers a more lightweight solution. This goes accordingly with GKN’s aim to undertake a larger total share of aero engines.

The approach for concept development during this thesis has been based on a five-step concept generation method. First knowledge about different engine architectures and component designs was gathered through qualitative interviews with experts. This was followed by the creating of a simplified baseline, or reference, model based on the UltraFan compressor module. A Finite Element Analysis, FEA, of the baseline was performed which generated further understanding about the current design.

The knowledge gathered, both in the interviews and by evaluating the baseline, was used as a basis when generating concepts. Four concepts were evaluated using a screening matrix, where the concept that best satisfied the set requirements was further developed. The refined concept was then compared to the baseline, by analyzing stiffness and ovalization for both designs.

The results from the concept evaluation indicated that possible weight savings can be made, but further investigation and refinements are required to ensure fulfillment of the set stiffness and deformation requirements. A further refined version of the baseline simulation model and associated methods could be used to evaluate how different designs affect the performance in terms of weight, stiffness and ovalization.
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1 INTRODUCTION

1.1 TURBOFAN JET ENGINE

The Turbofan jet engine differs from other turbojet engines in the fact that it has a fan at the front of the engine. The fan accelerates air into two streams in the engine, the core and the bypass duct. The relationship between the mass flow through the core and the bypass is referred to as bypass ratio, BPR. The fan provides larger airflow with less difference in velocity than a comparable single stream engine, which makes the turbofan more efficient at subsonic speeds. At higher speed the aerodynamic drag has more influence and the large front area becomes a disadvantage. The majority of both medium and long-range airliners uses turbofan jet engines [1].

The key components in a turbofan engine are the fan, low-pressure rotor, high-pressure rotor, combustion chamber and nozzle. A schematic view of a two-shafted turbofan engine is shown in Figure 1.

![Figure 1. Schematic view of a turbofan engine with axial compressor [1].](image)

A jet engine with an axial compressor takes in air at the front and compresses it axially, that is in the direction of the shaft in Figure 1. The pressure of the air is increased from left to the right, this is done by one or several rotors with each rotor having multiple compressor stages. An advantage with the axial compressor is that it enables a high total compression ratio as the pressure is increased over several stages. Modern turbojet engines with high thrust force, e.g. RM12 in JAS 39 Gripen, requires such high overall compression ratio that only axial compressor are feasible [2].

After the compressor, the air enters the combustion chamber where fuel is injected. The compressed gas mix is combusted and heat is generated. The heated gas expands and accelerates in the direction of the turbine. Some of the power in the gas is then harvested by the turbine in order to drive the compressor
and fan. The remaining energy is then used in the outlet nozzle where the gas expands and accelerates further. [2]

The engine thrust force is generated according to Newton’s third law, where the accelerated gas creates a reaction force in the opposite direction. The thrust force is generated both in the core of the engine and from the fan accelerating air in the bypass duct.

1.2 GEARED TURBOFAN ARCHITECTURE

Most recently it has become clear that most aircraft manufactures are progressing towards geared fan architectures. A geared fan architecture uses a gearbox between the low pressure-shaft and the fan in order to optimize the rotational speed for both the low pressure compressor and fan. The geared fan architecture makes it possible to increase the diameter while decreasing the rotational speed of the fan. This leads to a higher bypass ratio which is desirable as it increases the efficiency while reducing the noise generated by the fan [3]. An illustration of a geared engine is displayed in Figure 2 below with different static structural components within the fan static section indicated.

The Clean Sky 2 European program, with duration 2014-2022, intends to improve air transport environmental impact and European competitiveness within the aerospace industry. The UltraFan engine family demonstrator is Rolls-Royce’s initiative within the Clean Sky 2 project. This is Rolls Royce’s first family of geared turbofan aircraft engines aimed for a thrust range from 90 to 440 kN with a fan diameter up to 3.6 meters which constitutes a major architecture change compared to their previous models. GKN Aerospace is in partnership with Rolls Royce within Clean Sky 2 regarding the UltraFan demonstrator.

![Figure 2. Geared turbofan engine [4].](image)

In the UltraFan demonstrator project, GKN have the responsibility of delivering the Intermediate Compressor Case, ICC. Connected to the ICC are the Torsion Box Rear Panel, TBRP, and Front Case, which are designed by other partners of the project [5].

1.2.1 INTERMEDIATE COMPRESSOR CASE (ICC)

The ICC, indicated with blue in Figure 2, is a main structural component in the front static core section of the engine. The ICC has many functions that vary between different engines. The ICC provides support to the main thrust bearing housing and transfer air from the intermediate pressure compressor, IPC, to the high pressure compressor, HPC, through the swan neck duct. The ICC also provides mounting for the internal gearbox and the strut at BDC will accommodate the radial drive shaft to provide drive to the Step Aside Gearbox located on the outer annulus at BDC. The struts on the ICC also provide passage to inlet, ventilation and sump of the oil system for the bearings and the internal gearbox. The ICC support the bleed air system from the IP compressor and provide mounting for bleed
1. INTRODUCTION

_valves. The bleed air system has several functions, e.g. it is used for cooling of different parts in the engine and starting and handling during operation.

1.2.2 TORSION BOX REAR PANEL (TBRP)

The TBRP, indicated with purple in Figure 2, is a structural component that provide torsional stiffness at the base of the FOGVs.

1.2.3 FAN OUTLET GUIDE VANE (FOGV)

The FOGV, indicated with red in Figure 2, is designed with respect to structural, aerodynamic performance and aeroacoustics requirements. The FOGV’s de-swirl the by-pass air coming from the fan into an axial flow, connects the engine core with the bypass duct/fan case and is required to withstand different loads in different operating conditions [6].

1.2.4 FRONT CASE

The Front Case, marked green in Figure 2, is placed between the ICC and the Front Bearing Housing, FBH. The function of the Front Case is primarily structural, where it transfers loads between the FBH, TBRP and ICC. As the Front Case surrounds the Intermediate Pressure Compressor, it is subject to containment requirements.

1.2.5 FRONT BEARING HOUSING (FBH)

The FBH, indicated with orange in Figure 2, is also a main structural component in the front static core section of the engine. The FBH has both structural and aerodynamic requirements. It has many functions that vary between different engines.

1.3 AIM AND PURPOSE

The purpose with this project is to investigate if there is an opportunity that can strengthen GKN’s position in the engine systems market. Utilizing a more efficient architecture and design GKN can, in exchange of undertaking a larger part of the engine, provide engine manufacturers a more lightweight solution. This goes accordingly with GKN’s aim to undertake a larger total share of aero engines.

The aim of this thesis is therefor to investigate if there is a more efficient architecture and design of the static components in the compressor module. In order to achieve this, the architecture of the compressor module and the different components are primarily investigated from a weight and stiffness perspective. This will be done by performing Concept Development, including a Design Study.

The Design Study will provide knowledge regarding how different designs might affect the engine performance. The study will also gather information about today’s engines in order to find advantages and disadvantages of different engine architectures. Concept Development will be done to find a new concept design without the restrictions established in the current collaboration for the UltraFan demonstrator. On this demonstrator, the split and load paths of the three components, ICC, TBRP and Front Case, are similar to earlier engine configurations, but GKN wants to investigate if there are other, more efficient ways of building this structure.

A possible implementation of the concept design is in the Notional Engine, which is GKN’s outlook of what is believed to be the next generation of aircraft engines. The Notional Engine is a theoretical design that may be used as a starting point for future product development.
1.4 LIMITATIONS

This project will primarily focus on design changes regarding the engine’s architecture in order to increase its efficiency. The major limitation for this thesis is the time span of 20 weeks, this leads to a number of subsequent simplifications and delimitations:

1. Five critical load cases are used for simulations, these load cases can be used to compare different solutions and act as a base for dimensioning of the concept.
2. The geometry used in this investigation will be simplified, i.e. bosses and weld preps will not be included. This will shorten time for pre-processing and simulations.
3. If not necessary, the number of struts on the ICC and number of vanes on the OGV/IGV will not be changed.
4. No new materials in the static compressor module will be evaluated.
2 THEORY

2.1 CONCEPT GENERATION

A product concept is an approximate description of the technology, working principles and form of a product [7]. A concept can be illustrated as a simple sketch or a rough 3D-model, usually together with a short description [7].

2.1.1 FIVE STEP METHOD

Concept generation is a relatively inexpensive part of the development phase but discovering faults in a concept late in the process can be costly. A structured approach for concept generation reduces the probability for the team to stumble upon a superior concept late in development process [7].

A structured way of generating concept is the Five Step Method, which is an organized way of generating concept. The method reduces the likelihood of costly problems and acts as a guideline for less experienced team members.

The method is based on five steps, which are illustrated in Figure 3 as a linear sequence, but the process is in most cases iterative [7]. The method includes the steps clarify the problem, search internally and externally, explore systematically and reflect on the solutions and the process.

![Figure 3. The five step concept generation method.](image)

In the first step, the problem is clarified. This is done by increasing the general understanding of the problem and if the problem is complex, dividing the problem into simpler subproblems. Problem
decomposition can be done using functional decomposition. The most important and promising subproblems for the product are then identified and the main focus is put on these areas. [7]

The second step, search externally, is usually done continually throughout the whole development process. This is done to gather knowledge about existing solutions, both by looking at competitive products and technologies related to the subproblems identified in the clarification step. Example of methods for external search is;

- Interview of lead users and experts
- Patent and literature search
- Benchmarking.

In the third step, search internally, the knowledge within the group is used to create new concepts. In order improve the internal search, or brainstorming, four guidelines are used:

1. Suspend judgment
2. Generate a lot of ideas
3. Welcome ideas that may seem infeasible
4. Use graphical and physical media

The brainstorming can be done both individually and in group. Studies has shown that individual brainstorming generates higher quality and quantity concepts compared to group sessions [7]. The group sessions are important in order to building consensus, communicate information and refining concept. Preferably individually brainstorming is done at first, with the concepts refined and discussed in group.

The fourth step, explore systematically, is done to investigate the space of possibilities by looking at combinations of subsolutions. In order to structure the investigation of possible combinations, tools as concept classifications tree or concept combination table can be used.

The concept combination matrix is used to facilitate creativity and provide structure to the development process. The table is used to combine concept for different sub-functions into overall solutions. The table consist of subproblems ordered in columns and the entries for each column are the solutions. Overall solutions is generated by combining one subsolution from each column. The combination table is also a way to make forced associations among subsolutions in order to stimulate further thinking. [7]

2.2 PUGH SCREENING

The Pugh matrix is a decision-making method, which is used to choose in a list of alternatives. The most important criteria for the decision is listed, and the alternatives are rated upon these criteria.

The matrix provides a structured and controlled approach to the concept selection process. The Pugh matrix can be used to distinguish concept worthy further investigation and concepts which are unlikely to create value. The matrix consists of a number of selection criteria on the vertical axis and concepts on the horizontal axis. The purpose is to find the concept that best satisfies the selection criteria. A baseline is chosen, against which the other concepts are rated. The concepts are rated better (+), same as (0) or worse than (-) the reference concept. The number of plus and minus are summed for each concept, and the results creates a basis for a more objective decision making.

A version of the Pugh Matrix uses weights to separate the relative importance of the selection criteria. When rating the concepts, the weight of each criteria is taken in consideration by multiplying the weight with the rating. A finalized matrix visualizes both the ability to meet the set criteria and highlights the strength and weakness for each concept.
3 METHODOLOGY

3.1 APPROACH

A schematic picture of the activities and phases in the project are shown in Figure 4. The planning was done at the beginning of the project to create structured approach for the project. The concept development phase follows the five step concept generation method, mentioned by Ulrich & Eppinger in Product design and development [7].

3.2 PLANNING

At the beginning of the project, meetings were set up with the supervisors of the project in order to establish a common ground for the thesis. A project plan was made as a steering document for the project. The project plan covered the areas, aim and purpose, approach, time plan, risk analysis and limitations.

The aim and purpose was interpreted from the project description and verified with the supervisors of the project. An approach was formulated as a broad guideline on how to fulfill the aim of the project. The approach included several questions to address during the project. A Gantt-chart was used to illustrate the time plan with the project phases and activities. The plan was updated on a regular basis to ensure that the aim is fulfilled within the time frame of the project.

Limitations for the project were defined together with the project supervisors in order to ensure that the limitations are feasible. A risk analysis was done in order to identify risks in the project. The risks was evaluated with the mini-method risk analysis. For each risk the probability of an event occurring, P, and the consequence if the event occurs, C, was graded 1 – 5. Then a risk value, R/V, was calculated as probability * consequence. For each risk a preventive action and an alternative approach was defined.

3.3 CONCEPT DEVELOPMENT

The five-step concept generation method, was used as a structured approach for concept development. The first step was to clarify the problem which requires understanding of the problem, problem
decomposition and focus on critical sub problems [7]. The second step was to search externally by studying literature and interview experts. The third step was to search internally, where concept was generated individually and in group. The fourth step was to systematically explore the concepts using a combination table. The fifth step, reflection about the solution and the process, can be read in the discussion chapter [7]. The five-step generation method, and the activities during each step is shown in Figure 5.

![Figure 5. Interpretation of the five-step generation method.](image)

### 3.3.1 CLARIFY THE PROBLEM

In order to understand the problem, the design study regarding turbofan engines in general and UltraFan specifics was done. The design challenges in this project is too complex to solve as a single problem, therefore the problem was divided into several simpler subproblems. The original problem was decomposed into the following subproblems:

1. Where should the engine mounts be positioned, e.g. on the ICC or Fan Case?
2. Which component should support the FOGV?
3. How should the FOGV be designed, e.g. vertical or diagonal?
4. Where should the thrust lugs be positioned?
5. What kind of joining should used between the each component, e.g. with bolted joint with flanges?
6. Where should the interface between each component, the split, be positioned?
7. How should the concept modules be designed?

Problem areas and knowledge about the current solution was gathered by creating and evaluating a baseline model.

#### 3.3.2 SEARCH EXTERNALLY

The design study was partially done in order to search externally for solutions related to the specified subproblems. In order to identify the existing solutions to these subproblems, experts at GKN was interviewed regarding different state of the art turbofan jet engines. By using this methodology, both problems and solutions with different architectures could be identified.
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3.3.3 SEARCH INTERNALLY

During the design study, statements regarding the design of UltraFan was categorized in different subproblems. These subproblems was used as a basis for concept generation. The problem areas defined was; Connections, Splits, Stiffness of the components ICC and TBRP. Ideas was generated within each separate area using brainstorming and mind maps.

3.3.4 EXPLORE SYSTEMATICALLY

In order to structure the concept generation, a table was created with the columns of the table corresponding to the subproblems. The entries in each column corresponded to the concepts generated to solve each subproblem. Overall solutions was then generated by combining one fragment from each column. In order to decrease the number of possible combinations, infeasible fragments should be eliminated before combining it with other fragments [7]. This process was done together with consulting from personal at GKN. The concept table, referred to as concept combination table by Ulrich, Eppinger [7] is shown in Figure 13. Multiple overall concepts were generated using this methodology.

3.4 DESIGN STUDY - INTERVIEWING

In order to gather information about how the parts are designed a descriptive design study was made. The method for the design study was qualitative interviewing. The design study consisted of interview preparation, conducting of interviews, interview compilation and assortment of gathered information.

3.4.1 INTERVIEW PREPARATION

During the interview preparation questions were formulated based on the questions addressed in the project plan, seen in appendix A. About twenty questions was formulated and placed within the categories General and Specific questions. The general questions were about the interviewee’s background, different engine architectures and opportunities for improvement. The specific questions was about engine mount and thrust lug placement, connections between components, supporting structures and load paths. One hour was set aside for each the interview and nine interviews were conducted in total.

The first interview person was chosen upon recommendations from the supervisors at GKN. At the end of each interview, the interviewed person was asked if they could recommend other persons to interview. By using this methodology, the recommended person often had complementary knowledge to the interviewee. This methodology is recommended by Ulrich, Epping at [7, p. 125],

“A good habit to develop is to always ask people consulted to suggest others who should be contacted. The best information often comes from pursuing these “second generation” leads”

The interviewee got a short introduction to our project, the aim of the interview and an invitation to a meeting. In order to get as much information as possible during the interview, the questions was send to the interviewee in advance.

Each interview was prepared with a background presentation about the project and the aim for the interview, general questions and specific questions. Cross-sections for four different architectures was brought to the meeting as a basis for discussion. The chosen cross-sections was:

- General Electric GE9x (100k, Two-shafted)
- Rolls Royce Trent XWB (84K, Three-shafted)
- Pratt & Whitney GTF (33k, Geared)
- Rolls Royce UltraFan (84K, Geared)
The engine cross-sections were chosen to cover as many differences as possible. There are major architecture differences between the engines, making it possible for the discussions to cover several areas.

3.4.2 CONDUCTION INTERVIEWS

At the start of the interview a short presentation about our project and scope was shown. This was done in order to increase the interviewed persons understanding about the purpose of the interview. All interviews were recorded, with the permission from the interviewee, in order to transcribe the results from the interview. By relying on the recording to catch the information in the conversation and only taking notes on key words for further discussion the quality of the conversation could be improved.

3.4.3 ASSORTMENT OF INFORMATION

After the interviews the recorded material was processed. The answer for each question during the interview was transcribed and discussed. The information was compiled in a document for each interview. When the material was sorted and compiled, the interviewed person was sent the material. The interviewed person was asked to verify that what had been interpreted from the interview is correct.

The information from all interviews was merged into one document, sorted by the questions. Each question was divided with headings for each interviewed person in order to assure traceability to the information source. The information was then categorized into the areas, Aero engines, EC, EM, Thrust lugs, FOGV, LSS, Module interfaces, Splits, Load paths, Weight, UltraFan, Cost and Manufacturing.

An information management document was created to track all material, both from interviews and literature. The document shows all sources available for each category.

All information that was related to the design of the UltraFan engine was sorted in a document. The information was then compiled to a table with identified problems and improvement opportunities. The statements was then categorized in areas of improvement, which was used as a basis for concept development.

3.5 DESIGN STUDY - BASELINE CREATION & FEA

Before generating and analyzing the structural components in UltraFan, a reference model, a baseline, was created. To obtain a baseline that are comparable to generated concepts, with reasonable level of complexity, simplifications of the components was done. The level of complexity differs between the available components in the fan module. The baseline acted as a reference which generated concepts in the Concept Development was compared to.

3.5.1 FRONT BEARING HOUSING

The Front Bearing Housing, FBH, has a complex geometry with a lot of bosses, small blends, stiffening ribs and interfaces. Since the design of the FBH is not part of the design space in this project, the simplification was made only to ease meshing. Problematic areas were identified and simplifications for each area was discussed. The consequence of each simplification was estimated and the model was changed.

The FBH is a very stiff component and an increase in stiffness for the stiffest component in a system are assumed to have less effect on the total system stiffness. The system can be related to as a system of springs connected in series, where an increase in stiffness for the stiffest spring has less impact on the total system. Based on this assumption, and the complex geometry of the FBH, rough simplification of the FHB was done. The simplification was done by extracting the cross-section curves at a plane where the geometry was without bosses, ribs and blends, see appendix B. The cross section was then revolved around the center axis, creating an outer and an inner segment.
The vanes connecting the inner and outer segment were also simplified. This was done by creating three cross section along the vane. Guidelines was created by connecting the cross sections at the leading and trailing edge of the vane. The geometry of the vane was then created using the swept feature. More detailed steps from the simplification is found in appendix B.

The FBH was meshed in Simcenter 12 using 3D Tetrahedral mesh with CTETRA(10) elements. The mesh was iterated using different size and settings together with mesh controls. As the geometry is cylindrical the attempt multi-block for cylinders was enabled during the 3D meshing. In order to structure the mesh further, 2D mapped mesh was used without exporting it to the solver. The 2D-mapped mesh creates a structured mesh at the surface of the polygon from which the tetrahedral mesh then is created.

3.5.2 FRONT CASE

The Front Case is a part of the design space during this project. The simple geometry of the Front Case made it unnecessary to simplify the part.

The Front Case was meshed with 3D Tetrahedral mesh, using CTETRA(10) elements. The attempt Multi-Block Cylinders function was enabled since the component is cylindrical. 2D-mapped mesh was used to organize the mesh on the inner and outer surface of the component, but was not exported to the solver. There are grooves on the inner surface of the FBH, which caused errors. This was solved by using mesh controls for edge density at the edges of the grooves.

3.5.3 FAN OUTLET GUIDE VANE

Similar to the Front Bearing Housing, the FOGVs was used as a dummy component for FEM, but was not a part of the design space for this project. Since the FOGVs wasn’t a part of the design space the simplification are made only to simplify meshing. The FOGVs were split into one FOGV, which was simplified. Since the vane of the component is long and thin with considerably uniform thickness, the geometry was simplified for 2D meshing. The outer faces of the FOGV were extracted, generating a sheet body of the FOGV. Blends between the faces were neglected and the sheet bodies were extracted and trimmed to make sharp edges instead of blends. The FOGVs are normally surrounded by a mount ring which connects the top of the FOGVs. In order to represent this mount ring in the model, the top sheet of the FOGV was extended, connecting the FOGVs directly to each other.

As the base of the FOGV would be used in contact with other component in the FEM-assembly, 3D mesh was chosen for this part. The sheet of the vane was stitched to the base and the component was meshed. The connection between the edges of the vane and the top and bottom surface of the FOGV were problematic areas to mesh since three surfaces are connecting at the same spot. In order to solve this, the surface of the vane was split and CTRIA6 elements was used at the top and bottom of the vane. The rest of the vane was meshed with CQUAD4 elements. The mesh was iterated using different mesh sizes, edge density mesh controls and mesh types.

The mesh of one FOGV was improved and then the mesh was patterned around the central axis of the component. The separate FOGVs were connected by merging the coincident nodes at the common edge of the vanes.

A modal analysis was performed for both the simplified FOGV and the original component. This was done for a single vane, since the mesh for the original model had to be very fine in order to represent the geometry. The original component was meshed using 3D Tetrahedral mesh with high resolution. Mesh controls for edge density was used to refine the mesh at the leading and trailing edge. The connection at the bottom and the top of the vane was also refined in order to not create distorted elements.
The modal analysis was done both to verify that the constrains between the 2D QUAD4, CTRIA6 and 3D Tetrahedral CTETRA (10) elements are working as expected and to calculate the eigenfrequency. The eigenfrequency is related to the stiffness and mass of the components. By evaluating the difference in eigenfrequency between the original and simplified component, an indication of the change in stiffness can be obtained.

### 3.5.4 INTERMEDIATE COMPRESSOR CASE

The ICC is a component currently designed by GKN Aerospace and is a part of the design space in this project. The simplification of the geometry at the ICC was done both to ease meshing and to simplify changes in the geometry during the concept development. Complexity that will not to be examined in the concept development are excluded in the simplified ICC.

Decisions regarding the simplification of the ICC were verified with the project supervisors at GKN. Since the project’s focus is on big architectural changes, component specific interfaces for functions as bleed valves, variable guide vanes and the gearbox were neglected. Both blends and bosses were removed in the simplified model in order to ease the meshing process.

Standard resolution was used when generating a polygon body of the ICC. The faces of the polygon body in areas with small geometric changes were misplaced, leading to not aligning edges. As this created problem in the mesh, the problematic faces were corrected manually. Instead of manually repairing the faces, a higher resolution could have been used to generate the polygon body. This option was not investigated since the manual correction eliminated the problem.

The geometry of the ICC was complex to mesh, despite the geometry simplifications. Small changes in thickness, e.g. welded supporting ribs, and vanes with small edge radius requires high local mesh resolution.

The ICC was meshed using 3D Tetrahedral mesh. To structure the mesh on certain surfaces 2D mapped mesh, without exporting the mesh to the solver, was used. The mesh was refined at the leading and trailing edge of the strut by increasing the edge density.

### 3.5.5 TORSION BOX REAR PANEL

The TBRP is a part of the design space of this project meaning that the geometry simplification is done both in order to simplify meshing and to make it easier with design changes in the concept development phase.

The simplification of the TBRP is, similar to the FBH, done by revolving the cross section around the centrum axis. The holes at the bottom part of the TBRP are not removed as they are required for piping. The small gain in mesh quality does not justify removing the holes in the baseline model.

An idealized part of the TBRP was created in order to remove unnecessary blends.

### 3.5.6 HIGH PRESSURE COMPRESSOR CASE

The high pressure compressor case is not a part of the design space during this project, but used as dummy component during the evaluation. The simple geometry of the HPC makes it unnecessary to simplify the part.

The HPC has a simple geometry and the default mesh settings created a high quality mesh. 3D Tetrahedral mesh with CTETRA (10) elements were used with automatic element sizing. Since the HPC consist of two halves, both halves was meshed separately. The halves were then connected using glue coincident mesh mating at the connecting surfaces.
3. METHODOLOGY

3.5.7 HIGH PRESSURE COMPRESSOR CASE 2 (XWB’S HPC)

In order to decrease the impact of constrains on the model, the rear end of the assembly was extended by using the HPC from the XWB. Since the Combustion Chamber Outer Casing for the UltraFan was not available, the HPC of the XWB were used as a substitute.

As the sizes of the engines are different, the HPC of the Trent XWB had to be modified. A sketch was made from the cross section. The diameter of the XWB is smaller than the Ultrafan, therefore the HPC cross-section sketch was parameterized and scaled to fit towards the UltraFan HPC flange. The cross-section was then revolved around the center axis of the component. Important features as big holes was extruded using the original model as guide. The component generated from the XWB HPC was referred to as HPC2.

The HPC2 was meshed using 3D Tetrahedral mesh with default settings, creating elements with automatic element size. The mesh was evaluated with element quality tool in Simcenter and no further refinement was done.

3.5.8 ASSEMBLY

With each component as a .prt-file, the baseline was assembled in NX12 in Assy_Baseline.prt which acted as a main assembly file where each component was positioned relative to each other using Assembly Constraints in NX12.

3.5.9 ASSEMBLY FEM

In NX12 Pre/Post an assembly FEM, Assy_Baseline_assyfem.afm, was created based upon the Assy_Baseline.prt in order to map each existing CAD component’s .fem-file to the .afm-file which made each component’s mesh positioned as the associated CAD component in Assy_Baseline.prt. By using an assembly FEM each component could be meshed in individual .fem-files which was considered as advantageous as it allowed simultaneous meshing that saved time. In the assembly FEM, 1D connections was created with RBE2 and RBE3 element spiders to represent load interfaces. An example of included objects in the assembly FEM can be seen Figure 6 below.

![Figure 6. Example hierarchy of objects included in the assembly FEM.](image)

Using an assembly FEM one component’s mesh could also be updated easily, this made it possible to work with the assembly FEM and the simulation model simultaneously as meshing. One disadvantage with separate .fem-files for each component could be that the components cannot be connected with mesh-mating, as it only works between different meshes in one .fem-file.

3.5.10 SIMULATION MODEL

A simulation model, Assy_Baseline_assyfem_sim.sim, was created in Simcenter 12 based upon Assy_Baseline_assyfem.afm in order to utilize the assembly FEM previously described. An example of included objects in the simulation model can be seen in Figure 7 below.

![Figure 7. Example of included objects in the simulation model.](image)
3. METHODOLOGY

Contacts

As displayed in Figure 7, contacts were used in the simulation model which made it possible to investigate different loads and boundary conditions with the same contact conditions. Each component’s mesh was connected by utilizing the Simulation Object Type Surface-to-Surface Gluing. This was done with the type Manual where face pairs was created by selecting one component’s flange as a Source Region and the next component’s flange as a Target Region. The dynamic behavior of the bolted joints that connects the flanges are not going to be investigated, thus gluing of the components flanges and spigots was considered as sufficient.

Constraints

As displayed in Figure 7, constraints were applied in different solutions in the simulation model, which made it possible to investigate different boundary conditions for each solution. Constraints were applied to points defined by 1D connections or surfaces of flanges. Point constraints was applied by User Defined Constraint with type SPC, selecting fixed degrees of freedom, DOF, and defining the direction. The direction was defined by either using the existing global CSYS or by creating a Cartesian CSYS based on three points. Surfaces were constrained by Fixed Constraint.

Loads

As displayed in Figure 7, loads were applied in different subcases of a solution in the simulation model. This made it possible to investigate the result of different load cases for each solution’s boundary conditions. Forces were applied by Force with type Components and entering the force magnitude in the X, Y, and Z components (Global coordinates). Moments were applied by Moment with type Components and entering the moment load magnitude of the X, Y, and Z components (Global coordinates). Translational accelerations for a component were applied by Acceleration with type Components and entering the translational acceleration of the X, Y, and Z components (Global coordinates). Rotational accelerations for a component were applied by Rotation with type Whole Model and entering the angular acceleration about a user defined vector and point.

Modal Analysis

With all components connected with glue contact, a modal analysis of the whole model was performed. The modal analysis was performed with the load interface furthest back in the model fixed. The modal analysis was done to verify that all of the components were connected to each other and that the fix constraint worked as expected.

3.5.11 APPLICATION OF BOUNDARY LOAD CASES

By consulting with personnel at GKN involved in the ongoing UltraFan ICC demonstrator project, it was chosen to investigate five critical limit loads in this thesis. The investigated limits loads were given by personnel at GKN as boundary load cases in .inp-files that are used to apply loads in the solver.
3. METHODOLOGY

ANSYS. Since NX Nastran was used as solver in this thesis, the .inp-files were opened in notepad and the different loads were inserted into an Excel sheet to enable further calculations and to ease reading. A schematic example of load extraction points displayed as red points in the sectional view of a turbofan engine can be seen Figure 8 below.

![Figure 8. Schematic example of load extraction points in a sectional view of a turbofan engine.](image)

**Creation of load interfaces - Assembly FEM**

Each load interface was defined as the load extraction points displayed in Figure 8, where the positioning of the load interfaces was done by consulting with personnel at GKN. Only the load interfaces that loads were applied to in the given boundary load cases were created. If the load extraction points were located on existing geometry, a 1D element spider between the closest edge and a center point axially in line with the load extraction point was made. The element spiders were connected to edges as the dynamic of the bolted joints in flanges were not investigated.

If the load extraction points were located on geometry that did not existed, e.g. on the bearings, a 1D element spider between an edge on existing geometry with the closest load path to the extraction point were connected to the center point axially in line with the extraction point. An example can be seen in appendix D, with the ICC’s bearings load extraction points to the left and the corresponding load interfaces as RBE2 rigid element spiders in the assembly FEM to the right. This was done as the position of each load interface has an impact on the balancing of the loads in the boundary load case and how it affect the structural components investigated. E.g. for large deformations the thrust force applied in the bearings could affect the resulting backbone bending differently depending on the bearings position along the center axis. The bearings were assumed to be relatively stiff, thus RBE2 rigid element spiders was chosen to represent the bearings. This could induce higher stress in the surrounding area than in the intrinsic case, but as the area surrounding close to the bearing was not prioritized in the evaluation, RBE2 elements was considered as sufficient.

The pins for the engine mount and thrust lugs are also assumed to be relatively stiff, thus RBE2 rigid element spiders between the center point and the lug/mount faces was chosen to represent the load interfaces located in the pin joint of the engine mounts and thrust lugs. This will not allow local deformation in the pin joint of the engine mounts and thrust lugs, but as it is not prioritized in the evaluation the RBE2 element spiders are considered as sufficient.

According to current practice in the UltraFan demonstrator project at GKN the load interface located at the rear flange of the ICC were connected to a circle between the outer and inner radius of the rear HPC2 flange. This will allow the rear flange to flex more and reduce the impact of applied boundary conditions further forward in the engine where the investigated design space is located. This load interface is
furtherly referred to as the Rear Load Interface, RLI. The RLI’s associated RBE2 element spider connected to the circle on the rear flange on the HPC2 can be seen in Figure 9 below.

![Figure 9. The Rear Load Interface’s, RLI’s, connection to a circle on the rear flange of the HPC2.](image)

**Implementation of constraints and loads – Simulation model**

With created load interfaces in the assembly FEM, constraints and loads were applied in the boundary load case simulation model. As the reaction forces for each applied boundary load case depends on the geometry, constraint were applied to represent the attachment of the engine to pylon by consulting with GKN personnel. The TL were constrained by creating a local CSYS and fix the translation in the direction of the lug. The Port EM was constrained by creating a local CSYS and fix the translation in the direction defined by the port EM’s force vector in the boundary load case. The Starboard EM was constrained in translation in global XY-direction.

An overview of included objects in the boundary load case simulation model can be seen in Table 1 below, with a hierarchy according to the example simulation model displayed in Figure 7.

<table>
<thead>
<tr>
<th>Boundary load case simulation model</th>
<th>Constraints</th>
<th>Subcases</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DOF’s fix RLI</td>
<td>TL</td>
</tr>
<tr>
<td>Solution</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FEM10</td>
<td>1,2,3,4,5,6</td>
<td>Inactive</td>
</tr>
<tr>
<td>EM1</td>
<td>1,5,6</td>
<td>Inactive</td>
</tr>
<tr>
<td>TL1</td>
<td>2,3,4,5,6</td>
<td>Active</td>
</tr>
<tr>
<td>AMOUNT1</td>
<td>5,6</td>
<td>Active</td>
</tr>
</tbody>
</table>

All of the forces, moments, translational accelerations and rotational accelerations for all five load cases were applied for each load interface, including constrained interfaces, and component in the simulation model. Loads were applied to constrained interfaces to ease further load analysis. Translational accelerations for the ICC and TBRP was applied in Simcenter 12 with the opposite sign than defined in the .inp-file. This was done as CMACEL apply a positive Y to simulate gravity acting in the negative Y direction [8]. This was verified by summation of the loads in excel where the balance of the load cases was improved with the opposite sign of the translational acceleration defined by CMACEL in the .inp-file.

**3.5.12 LOAD ANALYSIS**

By evaluating applied loads and resulting reaction forces for each boundary load case the relation to the whole engine model, which each boundary load case originates from, could be investigated.

To verify that the applied forces were consistent a summary of forces in x, y and z in Excel was done.
3. METHODOLOGY

With results from the boundary load case simulation, which can be seen in Table 1, the obtained reaction forces were compared to the forces applied in the constrained interfaces. By using this methodology, the accuracy of the constrains used in the baseline model could be evaluated.

3.5.13 OVALIZATION ANALYSIS

The ovalization, or out of roundness, is measured at the bottom edge of the front flange at the Front Case. The ovalization is evaluated as it can be related to the tip clearance of the compressor and therefore the performance of the engine.

The nodal information for all nodes at the edge is extracted to Excel, including the undeformed node coordinates and the nodal displacement. The global coordinate system was placed in the center of the undeformed engine, with the x-axis in the direction of the engine shaft, y-axis in the starboard direction and the z-axis being upwards. The deformed flange coordinates was calculated by adding the undeformed nodal coordinates with the displacements in each node.

An illustration of how the radius is defined in the deformed and undeformed model is shown in Figure 10.

![Figure 10. 2D Illustration of the front case flange ovalization.](image)

The original radius can be calculated for each node using the Pythagoras theorem in for the Z, Y-coordinates,

$$ R_1 = \sqrt{Y_{R1}^2 + Z_{R2}^2}. \tag{1} $$

In order to compute the radius for the deformed model, the coordinates of the circle center is calculated. This is done by calculating the mean coordinates of all deformed nodes at the flange. The radius in the deformed model is calculated as the distance between the center point and the edge node,

$$ R_2 = \sqrt{(X_{R2} - X_2)^2 + (Y_{R2} - Y_2)^2 + (Z_{R2} - Z_2)^2}. \tag{2} $$

The deviation in radius between the deformed and undeformed model in each node $R_{dev}$ is defined as the ovalization,

$$ R_{dev} = R_2 - R_1. \tag{3} $$

The angle from the Z-axis in the ZY-plane is calculated for each node, using the node coordinates. The results is presented as the deviation from the undeformed radius for each node around the circumference.

The peak to peak deflection is defined as the difference between the maximum positive and the maximum negative deviation from the original radius. The peak to peak deflection, $P_k$, is calculated as,
3. METHODOLOGY

\[ P_k = R_{dev,max} - R_{dev,min}. \]  

3.5.14 STIFFNESS ANALYSIS

The stiffness analysis was done at the flanges of the outer cases and the bearings in the defined design space. A one-directional load in X, Y and Z-direction was applied in one of the interfaces. This was done with constrained flanges, thrust lugs and engine mounts, referred to as amounts simulations, and with only the flanges constrained, referred to as flanges simulations. Separate simulations were run with loads applied to bearing 1, bearing 2 and the outer flanges of the design space.

An overview of included objects in the stiffness simulation model can be seen in Table 2 below, with a hierarchy according to the example simulation model displayed in Figure 7.

Table 2. Overview of the stiffness simulation model.

<table>
<thead>
<tr>
<th>Stiffness simulation model</th>
<th>Constraints</th>
<th>Subcases</th>
<th>Loaded Interface</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EM TL</td>
<td>Fix TB flange</td>
<td>Fix ICC rear flange</td>
</tr>
<tr>
<td>Bearing 2 flanges</td>
<td>Inactive</td>
<td>Active</td>
<td>Active</td>
</tr>
<tr>
<td>Bearing 2 AMOUNT</td>
<td>Active</td>
<td>Active</td>
<td>Active</td>
</tr>
<tr>
<td>Bearing 3 flanges</td>
<td>Inactive</td>
<td>Active</td>
<td>Active</td>
</tr>
<tr>
<td>Bearing 3 AMOUNT</td>
<td>Active</td>
<td>Active</td>
<td>Active</td>
</tr>
<tr>
<td>TB flanges</td>
<td>Inactive</td>
<td>Inactive</td>
<td>Inactive</td>
</tr>
<tr>
<td>TB AMOUNT</td>
<td>Active</td>
<td>Active</td>
<td>Inactive</td>
</tr>
<tr>
<td>HPC flanges</td>
<td>Inactive</td>
<td>Active</td>
<td>Inactive</td>
</tr>
<tr>
<td>HPC AMOUNT</td>
<td>Active</td>
<td>Active</td>
<td>Inactive</td>
</tr>
<tr>
<td>FC flanges</td>
<td>Inactive</td>
<td>Active</td>
<td>Active</td>
</tr>
<tr>
<td>FC AMOUNT</td>
<td>Active</td>
<td>Active</td>
<td>Active</td>
</tr>
</tbody>
</table>

With the applied stiffness load, \( F_k = 1kN \), and the measured displacement, \( d_{x,y,z} \), the stiffness for each subcase displayed in Table 2 can be calculated as

\[ K_{x,y,z} = \frac{F_k}{d_{x,y,z}}. \]

3.6 CONCEPT GENERATION & SELECTION

The knowledge from the design study was used as a basis for the concept generation. The interviews provided knowledge about state of the art engines architectures, specifics about the UltraFan and general design practices. The baseline created understanding about the current design, both strengths and weaknesses.

Concepts were generated within the design space, including Front Case, TBRP and ICC. In order to generate ideas, brainstorming in combination with mind mapping was done. Each subproblem was used as starting points for brainstorming, and branches with related solutions was created. To encourage creativity during these sessions, criticism was prohibited. Ideas was generated on all subproblem, and the most promising ideas was further developed.
3. METHODOLOGY

The UltraFan cross-section was used as a basis for concept generations of overall solutions. A template for 2D-sketches was created by removing the components in the design space from the cross-section view. The concepts were visualized by drawing new components to the cross-section, which helped to identify strengths and weakness.

The concepts generated on subproblems were combined using a concept combination table. The most promising subsolutions were identified together with the supervisors at GKN. The least interesting areas were neglected and the table was narrowed down in order to decrease the number of possible combinations. Overall solutions were generated by combining subsolutions and then presented as a 2D-sketches.

The overall concepts, generated by using brainstorming and combining subsolutions, were evaluated and compared using weighted screening. The weighted screening was used in order to separate the importance of different selection criteria. This method only compares if the concepts are better or worse than the reference, which also is advantageous since the concepts had a low level of detail.

A few important selection criteria were chosen for the evaluation process; weight, deflection and cast diameter. The selection criteria were weighted, from one to five, depending on their relative importance. The stiffness and weight of the concepts was considered as the most important criteria resulting in a weight of five. Cast diameter was identified as cost driver, making it important to consider in the concept selection but less important than the stiffness and weight. The weight of the cast diameter was set to two.

The concept which best satisfies the set requirements was further developed and referred to as Baseline 1.

3.7 CONCEPT DESIGN & FEA

The selected concept was further developed using Siemens NX. The description and 2D-sketch were interpreted and converted to 3D-models. The ICC was linked to the TBRP part and the bodies were united and modified. The Front Case was modified separately and combined with the rest of the components in an assembly.

Since the concept included big parts with complex geometry, the polygon body resolution was set to high in order to capture the face and edge curvatures. The meshing of the component was done with similar methodology as described in the Baseline Generation chapter.

The boundary load case simulation setup created for Baseline 0, previously described in chapter Application of boundary load cases, was reused and modified for Baseline 1. In the FEM assembly the Front Case, ICC and TBRP was replaced with the corresponding concept components. The design change of the Front Case removed one of the load interfaces used in the boundary load cases. The affected load was placed on the corresponding interface at Baseline 1’s Front Case, while the rest of the loads remained the same.

The load analysis for the concept was done using the same methodology as for Baseline 0, previously described in chapter Load analysis, except that only the reaction forces and moments in the solution AMOUNT1 were investigated. The ovalization of the Front Case was calculated using the same methodology as for Baseline 0, previously described in chapter Ovalization analysis. The stiffness analysis for the concept was done using the same methodology as for Baseline 0, previously described in chapter Stiffness analysis.
4 RESULTS

4.1 PLANNING

The project plan including background, aim and purpose, approach, delimitations and risk analysis is shown in appendix A.

4.2 DESIGN STUDY - BASELINE GENERATION & FEA

The geometry simplification done for the components, Front Bearing Housing, Front Case, Fan Outlet Guide Vanes, Torsion Box Rear Panel, Intermediate Compressor Case, High Pressure Compressor Case and the XWB’s Combustion Chamber Outer Casing are shown in appendix B.

Baseline 0’s assembly FEM with each component’s mesh can be seen in appendix C.

4.2.1 APPLICATION OF BOUNDARY LOADCASES

The load interfaces in Baseline 0’s assembly FEM can be seen in appendix D.

The FEA results of Baseline 0 from the FEM10 and AMOUNT1 solution, which simulation setup can be seen in Table 1, are shown in appendix E and F.

4.2.2 LOAD ANALYSIS

A comparison between the reaction forces and applied forces in the constrained thrust lugs/engine mounts for load case 5 is shown in Figure 11. The results shows how the forces in the engine mounts and thrust lugs differs from the boundary load case when being constrained, where the boundary loads was referred to as ideal.

![Figure 11. Comparison between the obtained and ideal reaction forces in the engine mounts and thrust lugs.](image)

A comparison for every load case is shown in appendix G.
4. RESULTS

4.2.3 OVALIZATION

The load case that generated most ovalization of the front flange of the Front Case, was load case 5. The ovalization of load case 5 is shown in Figure 12 with an exaggerated deformation of the Front Case to the left and the measured deflection to the right. The peak to peak deflection was calculated according to equation (4).

![Figure 12. Front Case front flange deflection.](image)

A compilation of the ovalization measured in all load cases are shown in appendix H.

4.2.4 STIFFNESS ANALYSIS

Baseline 0’s resulting displacements and calculated stiffness using equation (5) for each subcases in Table 2 can be found in appendix I. The simulation’s setup can be seen in Table 2.

4.3 CONCEPT GENERATION & SELECTION

Two concepts were generated using brainstorming on overall solutions and two concepts were generated using the concept combination table, seen in Figure 13.

![Figure 13. Concept combination table with subproblems and associated generated concepts.](image)
2-D sketches and descriptions of Concept 1-4 can be seen in appendix J. The four concepts were evaluated in a weighted screening matrix which are displayed in Table 3 below. Concept 4 is estimated to best satisfy the set requirements, leading to further development of Concept 4.

Table 3. Pugh weighted screening matrix.

<table>
<thead>
<tr>
<th>Selection Criteria</th>
<th>Weight</th>
<th>Baseline (Ref)</th>
<th>Concept 1</th>
<th>Concept 2</th>
<th>Concept 3</th>
<th>Concept 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>-5</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>Deflection</td>
<td>5</td>
<td>0</td>
<td>5</td>
<td>5</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>Cast diameter</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-2</td>
<td>-2</td>
</tr>
<tr>
<td>Net score</td>
<td>N/A</td>
<td>0</td>
<td>5</td>
<td>0</td>
<td>-2</td>
<td>8</td>
</tr>
<tr>
<td>Rank</td>
<td>N/A</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>1</td>
</tr>
</tbody>
</table>

The further developed version of Concept 4 is referred to as Baseline 1.

4.4 CONCEPT DESIGN & FEA

The weight of each component in the design space, for Baseline 0 and Baseline 1 is presented in Table 4. The decrease in weight of the ICC and Torsion Box Rear Panel are primarily due to removed flanges. The main change in the Front Case design is that it has been shortened, leading to a decreased weight. The weights are calculated with the assumption that all three components are made from Ti6-4.

Table 4. Weight comparison between the Baseline 0 and 1.

<table>
<thead>
<tr>
<th>Component</th>
<th>Decreased weight [%] Baseline 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICC &amp; TBRP</td>
<td>5 %</td>
</tr>
<tr>
<td>Front Case</td>
<td>19 %</td>
</tr>
<tr>
<td>Design Space</td>
<td>7 %</td>
</tr>
</tbody>
</table>

A bar diagram based on the data in Table 4 is shown in Figure 14.
4. RESULTS

4.4.1 OVALIZATION

The resulting ovalization generated by the load case Applied 5, for the Baseline 0 and Baseline 1 is shown in Figure 15. The resulting ovalization is bigger for the Baseline 1 than the Baseline 0. Similar results is seen for each load case, shown in appendix H.

![Figure 15. Comparison between the ovalization generated by load case 5 for Baseline 0 and Baseline 1.](image)

4.4.2 STIFFNESS ANALYSIS

Baseline 1’s resulting displacements and calculated stiffness using equation (5) for each subcases in Table 2 can be found in appendix I. In Figure 16 below the resulting stiffness of Baseline 0 and 1 with flanges constrained are displayed.

![Figure 16. Stiffness of Baseline 0 and 1 with flanges constrained.](image)

In Figure 17 below the resulting stiffness of Baseline 0 and 1 with EM, TL and flanges constrained are displayed.
Figure 17. Stiffness of Baseline 0 and 1 with EM, TL and flanges constrained.
The delimitations made during this project are mainly due to the project time frame but also due to the internal knowledge and available tools.

The concept presented shows that possible weight savings could be made, but the effect on stiffness and deformation has to be further evaluated. The results indicates that the baseline 0 is better designed to keep it roundness when being exposed to the load cases used in the ovalization analysis. However, the severity of this deformation has not been evaluated during this thesis.

The design of components in a jet engine is very complex and requires cooperation between several different disciplines. As this project focus on a region that usually is divided into separate areas, designed by different partners in the projects, the effect of changes across these boundaries are hard to predict. The effect of extensive architectural changes can be analyzed using a whole engine model but during this project no such model for this engine has been available within GKN. This has led to some subsequent delimitations, not because of lack of opportunities but rather the absence of tools to evaluate the results.

As a result of the limited project time frame, the focus during the baseline and concept evaluation has been on deformation and stiffness. The resulting stress has not been investigated since that requires high mesh quality with investigation regarding mesh convergence for each load case. This delimitation might create an evaluation method that favors concepts with high local stresses and increased fatigue. However, the deformation and stiffness are considered to be of major importance when analyzing big conceptual changes, while stresses can be dealt with when refining the concepts. This implies that the generated baseline could be used when evaluating low detail-level concepts.

The evaluation of the reaction forces suggest that the thrust lug constrains should be reconsidered, since the deviation from the boundary load case was significant. The effect of incorrectly constrained thrust lugs are hard to predict, but the uncertainty should be considered when interpreting the results.

The deformation relationship between the baseline and original model has not been investigated. This could lead to arising problems when implementing the concepts to the original design that were not considered when evaluating the concept towards the baseline.

During this project the five step concept generation method has been used. This method offered a structured approach for concept generation. The method does not specify the relative amount of time and resources that should be put into each step. In this thesis the amount of time spend on the first two steps are not proportional to the time spend in the last three steps, as the first two phases was an extensive part of the project. This has created a good foundation for concept generation with the generated knowledge from the design study. The generated knowledge is however not fully utilized during the concept generation as the search internally and systematically explore steps were strictly limited by the project time frame. However, the tools and methods generated during this thesis could possibly be implemented in future concept development.

The project has gathered knowledge regarding the engine design and created tools and methods to evaluate concepts.
The objective for the thesis was to investigate if there is a more efficient split and design of the components in the compressor module. An investigation of a different splitting scenario and design has been investigated, but as a result of the limited project time frame only one concept has been evaluated. Therefore the objective is considered to be partly met.

The purpose was to increase the understanding of how different designs could affect performance. During the Design Study knowledge regarding how different designs might affect performance was gathered. A further refined version of the Baseline simulation model and associated methods could be used to evaluate how different designs affect the performance in terms of weight, stiffness and ovalization. A redefined version could also be used when investigating design changes with low level of detail, typical for early concept evaluation, as a support in the concept selection process.

When analyzing big architectural changes, e.g. engine mounts or thrust lug positioning, the boundary load cases are not sufficient. In order to analyze this type of changes a whole engine model is also required. For the design changes evaluated in this thesis, the boundary loadcases was considered sufficient.

The concept presented indicates that relatively small changes can decrease the weight sufficiently. However, the concept should be refined in order to meet the stiffness and ovalization requirements set, based on the Baseline 0 evaluation.
As mentioned in the conclusions, a further refined version of the baseline simulation model and associated methods could be used to evaluate how different designs affect the performance in terms of weight, stiffness and ovalization. Following are some suggestions for future work:

1. To ensure that improvements in generated concepts are related to the original model, the correlation between results from the produced baseline and the original UltraFan model is required to be investigated. How the baseline’s stiffness correlates with the original models could be done by comparing with a similar stiffness analysis of the parts in the UltraFan demonstrator project. How the ovalization of the Front Case edge correlates to the performance could be examined by comparing with the LPC’s tip clearance in the whole engine model for the investigated boundary load cases.

2. In this thesis pre- and post-processing for FEA was performed manually in Simcenter 12 which is very time consuming. The resources required to perform evaluation of concepts could be reduced significantly by implementing automation.

3. Five limit load cases has been investigated in this thesis. To increase the reliability of the baseline’s evaluation, more load cases as FBO/CBO could be investigated in the baseline evaluation.

4. Strength analyses has not been performed in in this thesis. This perspective should be included in the evaluation as it demonstrates the structural integrity of the investigated components. In order to include strength evaluation the mesh of the components is required to be refined.

5. The manufacturability and cost of concepts should be addressed, as it is decisive for which concept is most interesting to further develop. Fabrication enables more in-house manufacturing and could increase the added value within GKN.

6. More concepts should be investigated. Concepts could be generated by further utilizing the gathered knowledge in the design study, investigate more combinations in the morphological matrix, iterate with evaluation of results or maybe using an alternative method, as topology optimization.

7. To further evaluate how the engine’s performance are affected by bigger changes of designs and splitting scenarios, a whole engine model should be generated. With a whole engine model backbone or carcass bending of the entire engine which are affecting the engine’s performance could be investigated. A whole engine model with overall loads is also necessary to investigate how different designs and splitting scenarios affects the entire engine.
8 REFERENCES


APPENDIX

A. INITIAL PROJECT PLAN (CONFIDENTIAL)
B. GEOMETRY SIMPLIFICATION (CONFIDENTIAL)
C. ASSEMBLY AND COMPONENT MESH (CONFIDENTIAL)
D. BASELINE 0 LOAD INTERFACES (CONFIDENTIAL)
E. BASELINE 0 FEM10 FEA RESULTS (CONFIDENTIAL)
F. BASELINE 0 AMOUNT1 FEA RESULTS (CONFIDENTIAL)
G. REACTION FORCES ANALYSIS (CONFIDENTIAL)
H. OVALIZATION ANALYSIS (CONFIDENTIAL)
I. STIFFNESS ANALYSIS (CONFIDENTIAL)
J. GENERATED CONCEPTS (CONFIDENTIAL)