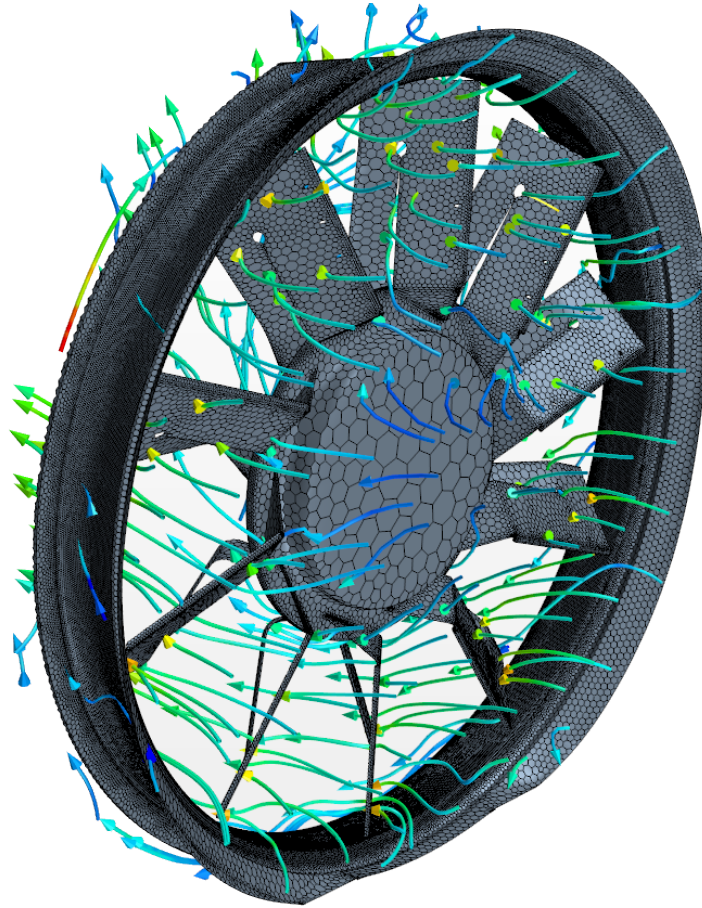




CHALMERS
UNIVERSITY OF TECHNOLOGY



An Investigation of the Performance of a Divided Fan Blade

Collaboration between Chalmers, Penn State and Volvo Group

Bachelor's thesis in Mechanical Engineering

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BACHELOR'S THESIS 2016

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Department of Product and Production Development
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2016.

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Abstract

This report comprises the product development of a radiator cooling fan, based on the patent “Divided blade rotor” [US 7396208 B1], for the sponsor Volvo Group. It’s claimed that a fan based on the patent will have better resistance to deformation, operate well with high angles of incidence and have higher efficiency to mention a few of it’s potentials.

Concepts were generated and evaluated until the project shifted focus to the important parameters because of the lack of knowledge. Because of limited resources, only three parameters were analyzed. The parameters are combined into concepts in a Taguchi array and these concepts are simulated in Star-CCM+ and tested in a wind tunnel. ANSYS simulations are made on a design of the patent. The results from simulations and tests are fairly similar and enabled optimization for two parameters; an angle of incidence of 40 degrees and number of blades of 10, which is the basis for the recommended concept. The number of holes could not be optimized because of the contradicting results from simulations and tests.

The overall performance and efficiency of the recommended concept is not equivalent to Volvo Group’s reference fan. Although some of the performances are promising, regarding the deformation, velocity and the moment, and this with only two out of nine optimized parameters. The conclusion is that this divided fan technology could be promising as an application for a radiator fan for Volvo Group trucks installation and is an interesting object for future work.

The recommendations regarding future work are to re-simulate the parameter regarding number of holes. Simulations and tests should be done using same set up for the remaining six parameters which is; size of holes, angle of split, length of split, blade geometry, transition radius and hub geometry.

This bachelor’s thesis has been carried out during the spring of 2016 as a collaboration between Chalmers University of Technology, Penn State University and Volvo Group.

Keywords: Fluid dynamics, product development, fan theory, divided fan blade, Star-CCM+, Radiator fan, Divided Blade Rotor.

Sammanfattning

Denna rapport behandlar produktutvecklingsprocessen av en radiatorfläkt till Volvo Group, som baseras på patentet "Divided blade rotor" [US 7396208 B1]. I detta patent hävdas bland annat att en fläkt designad enligt "divided fan blade teknologi" har bättre deformationsmotstånd, klarar av att drivas med en hög infallsvinkel och har högre effektivitet än konventionella fläktar.

Koncept genererades och utvärderades till den punkt då kunskap saknades. Därefter förflyttades fokus till de viktiga parametrarna. På grund av begränsade resurser valdes endast tre parametrar att analyseras. Parametrarna kombinerades till koncept i en Taguchimatrix och de nya koncepten simulerades i Star-CCM+ och testades i en vind tunnel. ANSYS beräkningar görs på en separat design av patentet. Resultaten från simuleringarna och testerna var ganska lika och möjliggjorde optimering av två av parametrarna; en infallsvinkel på 40 grader och 10 antal blad, vilket ligger till grund för det rekommenderade konceptet. Antalet hål kunde inte optimeras på grund av de motsägelsefulla resultaten mellan simuleringarna och testerna.

Den övergripande prestandan och effektiviteten på det rekommenderade konceptet är inte likvärdigt med Volvo Groups referensfläkt. Dock är några av prestandan lovande, gällande deformation, flödeshastighet och moment och detta med endast två av nio optimerade parametrar. Slutsatsen är därför att "divided fan blade teknologin" kan vara lovande att applicera i en radiatorfläkt i en Volvo Group lastbil och är intressant att fortsätta arbeta med.

Rekommendationerna gällande framtida arbete är att göra ytterligare en ny simulering för parametern gällande antal hål.

Simuleringar och tester borde göras för de återstående parametrarna med samma set-up. Parametrarna som återstår att undersöka är storlek på hål, vinkel på klyvningen, längd på klyvning, blad geometri, övergångsradi och design av navsektion.

Detta kandidatarbete har genomförts under våren 2016 som ett samarbete mellan Chalmers Tekniska Högskola, Penn State University och Volvo Group.

Nyckelord: Strömningsmekanik, produktutveckling, fläktteori, delade fläktblad, Star-CCM+, motorfläkt, Divided Blade Rotor.

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We would like to thank our supervisor Professor Mikael Enelund for his helpfulness and positivism throughout this project. We would also like to acclaim his dedication about the collaboration with Penn State University and emphasize what it has meant to the project.

We would also like to thank our supervisor Assistant Professor Jason Moore, who contributed with his energy and enthusiastic view of the project and the product development. We are grateful for the opportunity to work in a global team and the gained experience from the international collaboration.

We would like to express our gratitude to our examiner Professor Lars Almfelt for sharing his great knowledge and experience in product development. His interest in the subject is truly inspiring.

We would also like express our deepest appreciation to Volvo Group and Dr. Peter Gullberg for providing this opportunity to work in a global team and for their contributions on both information and hands on knowledge, without that this project would not have reached the point it did.

A special thanks to Volvo Group and Monica Ringvik, Director of Research & Innovation Policy at the Volvo Group, Gothenburg, Sweden, for the opportunity to gather the team at the respective University for the presentations, it has greatly improved both the project and been an unforgettable experience.

We would also like to thank Johannes Törnell for the useful help and guidance with the simulations carried out in Star-CCM+ and Hebbe-cluster

Nomenclature

AHP	Analytic Hierarchy Process
ANSA	Geometry pre-processing tool
ANSYS	Finite element analysis software used for structural analysis
CAD	Computer-Aided Design
CES	Material selection software
CFD	Computational Fluid Dynamics
CHALMERS	Chalmers University of Technology
CLUSTER	A central "super" computer dedicated to calculations and simulations
GADSL	Global Automotive Declarable Substance List
GOT	Gothenburg
ISO	International Organization for Standardization
LEARNING FACTORY	Workshop at Penn state University
MRF	Moving Reference Frame
PSU	Pennsylvania State University
PVC	Polyvinyl chloride
RBM	Rigid Body Motion
SPONSOR	Peter Gullberg, Volvo Group Gothenburg
STAR-CCM+	CFD simulation software

A	Area [m^2]
C	Fluid velocity [m/s]
D	Drag force [N]
L	Lift force [N]
ρ	Density of fluid [kg/m^3]
R	Resistance [Ω]
v	Velocity [m/s]
V	Voltage [V]
P	Power
η	Efficiency [%]
m	Mass [kg]

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1

Introduction

This section includes a general overview of the project, why it is generated and who it is generated for. It also includes limitations of the project along with the scope and objectives of the project to ensure that the results will be obtained by Volvo.

1.1 Background

During the last years it has become commonly known that human beings are contributing to the global warming [1] and that emissions from Carbone dioxide (CO₂) is one of the greatest contributors to the greenhouse effect [2]. As people become more aware about how their choices and behavior effect the coming generation an increasing demand in fuel-efficient transports have arisen. This in combination with haulage contractor's demand for fuel-efficient transports due to high oil prices give a great advantage for those manufacturers who are at the cutting edge in low fuel consumption.

In the strive to achieve this lower fuel consumption truck manufacturers, such as Volvo Group, need to improve every detail of their trucks. Improving the engine with all surrounding systems is a crucial and never ending process. To make the engine run as effective as possible, an efficient cooling system is needed. With this background, the project is to improve the design of a fan, the part of the cooling system that sucks air through the radiator. In the strive of a more efficient cooling system, the patent "Divided blade rotor" [US 7396208 B1] [3] has been presented to Volvo Group. The patent claims to significantly lower the power needed to rotate the fan. Volvo Group wants to investigate if the statement is true or not and therefore the patent will be the basis for this design project.

Volvo Group is one of the largest truck manufactures in the world with almost 110,000 employees around the globe, [4], with a manufacturing rate of over 200,000 units every year [5]. Volvo Group was founded in Gothenburg, Sweden and still have their headquarters there [6].

1.2 Initial Problem Statement

In order to cool the engine of a truck a fluid transports heat from the engine to the radiator where the fluid is cooled by air flowing through the radiator. At low vehicle speed a fan is used to suck air through the radiator to generate the air flow

needed. In order to lower the power needed to rotate the fan without changing the absolute air flow an international team from Chalmers University of Technology (Chalmers) and Penn State University (PSU) will develop a new fan design to fit a Volvo Group truck installation and investigate the developed fan with regards to air flow, efficiency, aerodynamic performance, interaction with the surrounding shroud and production cost.

1.3 Purpose of Project

The purpose of this project is to develop a fan blade design based on the patent “Divided blade rotor” [US 7396208 B1], that is applicable for a radiator cooling fan, in a Volvo Group truck installation. It also includes an investigation of its performance and a comparison against Volvo’s current fan.

1.4 Scope of Work

The project starts with a thorough research of existing designs and potential ideas from unfinished and similar work or patents, along with this the fundamentals of fan theory are researched. Concept generation to explore possible designs is described and some of those concepts are drawn in CAD-software. Further these designs are tested with computational simulations software such as ANSYS [7] and Star-CCM+ [8] and then assessed based on their performance. The impact of different parameters is also investigated by producing scaled 3D-printed prototypes of the fans for tests in wind tunnel. Aerodynamic performance is the most affecting variable on the fuel consumption for the fan design so that is a critical area for the performed research. Fluid dynamic simulations are mainly done at a computational cluster, Hebbe [9], at Chalmers using Star-CCM+.

A technical specification that states the critical limits for the design is made, these limits are based on the performance of the existing solution. There are some physical limitations that the project have to take into account, for example, size of the design, attachment and input-power.

The most promising design according to the physical testing and computational simulations will be recommended. This also results in a report containing important data such as mechanic stability of the design, the flow velocity induced by the fan and efficiency (airflow/input power).

Finally brief a cost estimation of the product is calculated under the conditions that the design will be implemented in all Volvo Group’s trucks with respect to material, production process and assembly costs.

1.4.1 Objectives

The following objectives are set out to fulfill the purpose of the project:

- Product development based on the divided fan blade technology
- Investigate the directional deformations
- Investigate the stresses in the fan blades
- Perform a lifetime analysis
- Investigate the mass flow
- Investigate the fluid velocity
- Analyze the interaction between the fan and the surrounding shroud
- Analysis of the pressure distribution on and around the fan
- Analyze the required moment to move air
- Calculate and analyze the efficiency

Moreover, the project group members are expected to learn how to work in a global product development team.

1.4.2 Deliverables

Project deliverables during project:

- Planning report along with a presentation
- Mid-term report along with a presentation
- Final project report along with a presentation
- Documentation of aerodynamic performance
- Technical specification
- Documentation of structural integrity
- Documentation of prototype testing
- Design recommendation of final concept
- CAD drawings of the recommended concept
- Manufacturing cost analysis

1.4.3 Limitations

The project is supposed to be carried out by six students; three from Chalmers and three from PSU. Chalmers students should work on the project approximately 20 hours a week each for the project and PSU students approximately 15 hours a week, as they have more classes combined with the project. Chalmers students work on the project between Jan 21, 2016 and May 27, 2016 and PSU students work on the project between Jan 11, 2016 and May 2, 2016. This limits the number of designs that can be assessed. The students have access to a prototype manufacturing lab. The computer cluster Hebbe is provided free of charge for the Chalmers students to run simulations and calculations to be able to execute a wide range of accurate test setups.

The students are not completely beginners in the topic of fluid dynamics and are able to work along with some assistance. The project group has no previous experience in Star-CCM+ but will learn by online tutorials together with assistance from

1. Introduction

the supervisors. Supervisors at Chalmers and PSU are able to assist in product development, calculations and simulations.

The project is guaranteed 2,000 SEK (220 USD) from Chalmers and 1,000 USD (9,000 SEK) from PSU, the sponsor can add funding depending on the assessment of the design and general opinion of the motivation for the funds. It is important to notice that materials and 3D-printing is free of charge at Chalmers, and therefore the lower budget.

2

Team and Project Management

Before starting generating results from a project it is important to have everything around the project clarified. In this section a preliminary economic analysis is made, the project management is being discussed together with a Gantt chart and a clarification of the deliverables that the project will result in. Thereafter the risks of the project are analyzed and ethics and environmental statements are established. Communication and coordination with sponsor are also decided in this section.

2.1 Preliminary Economic Budget

The preliminary budget can be found in Appendix A.1. The budget consists of 2,000 SEK (220 USD) provided by Chalmers and 1,000 USD (9,000 SEK) provided by PSU. The Chalmers budget will be spent on parts that the project will not be able to be provided by Chalmers. Materials for prototype and 3D-printers are free of charge at Chalmers. Computational cluster and workshop costs are excluded from the budget since it is free of charge at Chalmers. At PSU a big part of the budget will be spent on making a prototype of the design as materials and 3D-Printers are not free of charge. Some of the budget will be spent on travel, both to the local sponsor and to gather the team on one of the two sites.

2.2 Project Management

A Gantt chart is attached in Appendix A.2, where all milestones and tasks are included. Responsibility for all tasks can be rearranged during the project as the group members capabilities will show. With all of the different expertise the group possesses the outcome of this project will be fabricated with a high academic standard. Prototypes will be produced at PSU to be able to evaluate variants of the concept. The prototype will be tested in real conditions at PSU and simulations and calculations on the designs will be produced at Chalmers.

Main part of CAD-construction for tests will be produced at PSU and Chalmers will produce CAD-constructions for simulations since the group members at PSU have a great knowledge of CAD-modeling and most of the simulations will be done at Chalmers as they provide the group with a computer cluster which is made for heavy calculations. It is sufficient to know that all of the group members have knowledge in all required areas, such as strength of materials, CAD modeling, fluid

dynamics, dynamics and sustainable products etc.

Communication will be held through Adobe Connect [10], an interface platform for web meetings. All presentation, except the final presentation at Chalmers, will be held on this platform since it is both possible to show slides and discuss them at the same time and it is also a reliable system used worldwide. The final presentation at Chalmers will be held in a class room with the PSU students present in Sweden and therefore it is not necessary to have a web connected meeting. The daily contact will go through a chat service called GroupMe[11] to be able to communicate with everybody at the same time so no one miss any information.

2.3 Risk Plan and Safety

In large projects it is preferably to have a risk plan to avoid complications both within the group and external. The team has a risk management which explains how to take actions when problems arise during the project, as shown in Appendix A.3. A risk plan is made to be able to foresee problems that could occur during the project and by that eliminate the risk of it to happen and also have a fall back strategy.

First step is to identify problems that may occur during the project, important is that no problems are to small, often it is the small problems that affect the progress the most. All areas will be taken into account but problems with a link to the projects deliverables, project documents and testing will get more attention as these are critical areas for the outcome of the project.

2.3.1 Risk Analysis

With all risks stated, they were investigated and ranked upon both the impact and probability for them to happen. The probability is ranked on a scale [1 - 10] where 10 means that the probability of it to happen is very large. The impact of the risk is also ranked on a scale [1 - 10] where 10 is the worst case. To get an overall risk-level, both numbers are multiplied to get a number on a scale [1 - 100]. Risk with a high overall level should be avoided as far as possible and also have a realistic plan to take actions from when the problem is real. The overall score is ranked in three groups, “High alert” group with a score over 25, “Medium risk” with a score between 10 and 25 and the “Low risk” group with a score under 10.

14 risks were identified and distributed as follows, six in high-alert group with a maximum score of 50, five in medium risk and three at low risk. Risks that got a high-alert score mostly focus on problems that are general and may be contributing factors to a non-completed project. The output of a high risk is loss of data, unable to deliver simulations and calculations due to more complexity and time consuming than expected, also miss understanding of the task can affect the outcome in a bad way. The medium risks focus on problems within the group that will not result in a

non-completed project but still are important as the high level of the project might not hold up if the group does not work well with each other.

2.4 Ethics Statement

Volvo Group have a policy about ethics that should be followed in this project, “Key Elements Procedure 6 Corporate Social Responsibility” [12]. It mainly focus on how to take action in different situations, for example, it contains restrictions of child & forced labour, Human Rights, Discrimination and political influence within the development of new products. As we can not influence how the concept will be produced the group can not take responsibility for these factors. The group will make sure to not be influenced by third parties in exchange for personal benefits.

2.5 Environmental Statement

The new product will follow all environmental standards used by Volvo Group that focus on recycling-ability, using environmental-friendly materials and processing. Volvo Group work along with policies to develop a sustainable product, for example they always strive to reduce all harmful materials in their products by active do researches about materials. Volvo Group also take responsibility for the usage of natural resources both during development and usage [13]. To ensure that harmful chemicals or materials are not used in Volvo products they have standards for what materials that are forbidden in new products.

The project will follow these standards issued by Volvo, STD 100-0002 [14] also known as the ”black” list that contains materials that can not be used in new or existing products. STD 100-0003 [15] also known as the “grey” list that contains materials that will in the near future be in the “black” list and for that reason it should be critically considered before usage in any products. STD 100-0005 [16] also known as the “red” list and contains chemical substances that are forbidden in marketed products, marked as prohibited in GADSL. The product should achieve all specifications for ISO 14001 thus it is listed in the checklist for all developments within the Volvo Group [17]

It is important to remember that the main achievement with the project is to reduce fuel consumption for trucks, if the environmental effect of the product will increase with the new product, it should not exceed the gain due to the lower fuel consumption.

2.6 Communication and Coordination with Sponsor

The main contact with the sponsor, Peter Gullberg, at Volvo Group GOT will go through Andreas Bågfeldt at Chalmers to avoid unnecessary e-mails due to miss-

2. Team and Project Management

communication within the group. The secondary contact person for Volvo is Tyler Delk at PSU. The sponsor will receive a weekly memo of what has been accomplished and what the group will work on the next week or two. If the group have questions, it will be sent to the sponsor by e-mail or if it is urgent, the questions will be asked on phone. During the project, Volvo Group sponsored the students to travel to each university to encourage a good collaboration and dedication along with avoiding poor group spirit.

Table 2.1: Planned meetings with Volvo Group

Sort of Interaction	Date
First meeting with the sponsor	Jan 21th, 2016
Project Proposal presentation	Feb 25th, 2016
Mid-term report presentation	Apr 7th, 2016
Final Project Presentation at PSU	Apr 26th, 2016
Final Project Presentation at Chalmers	May 26th, 2016

3

Methodology

This chapter describes the methodology of the project, which is a combination of different methods composed to maximize the outcome of this project. The project can be divided into six main stages including project planning, concept generation, concept evaluation, concept refining, concept redefining and detailed design. The results from using these methods are presented in section 4-11.

3.1 Summarized Product Development Process

Data such as customer needs and technical specifications were collected from interviews and E-mails and an external search in existing products and patents was made. The problem were clarified using a black box and a sub-function diagram. Concepts were generated by brainstorming and an morphological matrix and were evaluated with an elimination matrix and Pugh's screening method. The lack of knowledge made the project shift focus to the important parameters rather than evaluating the concepts. A Taguchi array was used to create new concepts by combining parameters. The new concepts were refined by simulations in ANSYS, Star-CCM+ and tests. To validate the simulations and tests and make sure that the parameter data was accurate, one more simulation with redefined concepts containing optimized parameters was done. A final concept recommendation was made out of the results from the last simulation. A detailed design was presented with CAD drawings and a brief manufacturing plan, material selection and economic analysis. For a summarized process chart over the project approach, see figure 3.1.

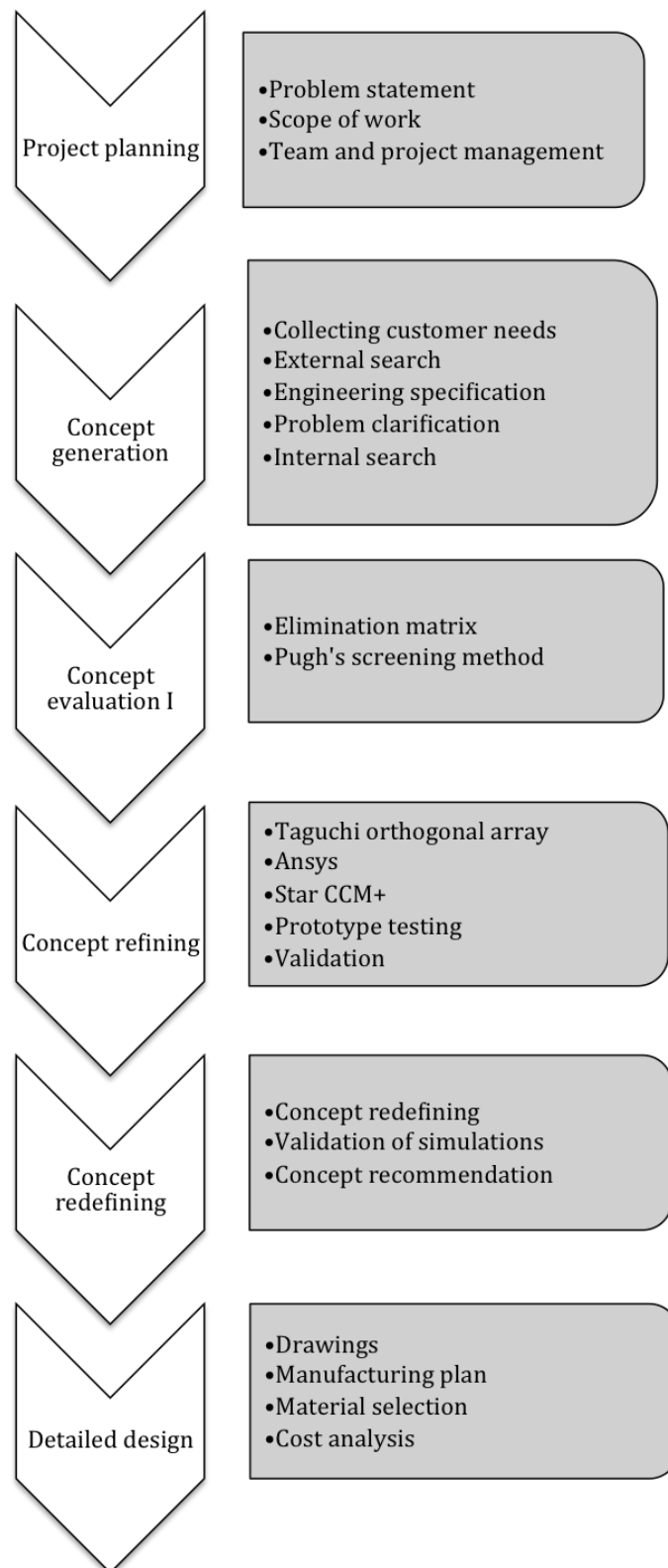


Figure 3.1: A summarized process chart over the project approach

3.2 Collecting and Weighting Customer Needs

Interviews and E-mails were the primer methods when collecting data and customer needs from the sponsor. An Analytic Hierarchy Process (AHP) was used to weight the customer needs. The AHP is a method developed by Saaty [18] and is based on pairwise comparisons creating a comparison matrix to get the relative importance of all alternatives. The alternatives are ranked on a scale from 1-9, where 1 is of equal importance and 9 is extreme importance. The importance of each alternative is then summed up and divided by the total sum to get the weight for each alternative.

3.3 Collecting Data through External Search

An external search for patents and existing products was made to get more information about similar solutions in different industries. Patent search was mainly made in Google Patents [19] which is a search engine that collects patents from different patent offices around the world. Among other these patent offices from which Google Patents collects its data are The United States Patent and Trademark Office (USPTO), the European Patent Office (EPO) and the World Intellectual Property Organization (WIPO) are only some of the patent offices included.

3.4 Collecting Data and Establishing Engineering Specification

After collecting data, an engineering specification was established. An engineering specification is a table where all specifications for the project are gathered. The specifications are measurable criterion which the final concept aims to satisfy. The specifications should be supplemented with a target value, an authentication method and a reference. Data for the engineering specification was collected through interviews and E-mails with the sponsor and by the collected data from patent findings and existing products. Some of the specifications are qualified assumptions submitted by the project group. A needs-metric's matrix was established to relate the customer needs to the specifications in the engineering specification. The needs-metric's matrix maps the customer needs to the specifications [20]. Each customer need has to be mapped to at least one specification otherwise the engineering specification is deficient and the project run the risk of not achieving the customer needs.

3.5 Black Box and Sub-function Diagram for Problem Clarification

The problem was clarified with a black box model and a sub-function diagram. The black box is a method from Pahl and Beitz [21], originally presented by Hubka and Eder[22], and is used to clarify the boundaries of a system by showing the input and the output operands of the system without describing the internal activities of

the black box. The sub-function diagram is a method by Svendsen and Hansen [23] that decompose the system hierarchically and create a function-solution tree. The main function is assigned with a solution which in turn is divided into sub-functions which also is assigned to solutions and so on.

3.6 Brainstorming and Morphological Matrix for Concept Generation

The first way to start generating concepts for this project was brainstorming. Brainstorming is not a theoretical method but a creative way to generate concepts and can be very useful to get started in a concept generation process. To create even more concepts a morphological matrix was used. The morphological matrix is a problem-solving method developed by Zwicky to find all possible solutions to a multi-dimensional problem [24]. The approach of the method is to find as many part-solutions to the sub-functions as possible. By combining one part-solution from every important sub-function a new concept is created. By combining part-solutions in this way, a very large number of concepts can be created. A lot of concepts created like this are not compatible and therefore demands a good evaluation of the concepts, both from an engineering perspective and by theoretical screening methods.

3.7 Elimination Matrix and Pugh's Screening Method for Concept Evaluation

To start evaluate the generated concepts an elimination matrix was used. The elimination matrix is a screening method by Pahl and Beitz [21] where the concepts are evaluated after their ability to fulfill the specifications of the engineering specification, see Chapter 6. If a concept does not fulfill a demand, it will be eliminated. The elimination matrix is a strong filter and might sometimes screen harder than what is reasonable for a product development project and it is therefore important to keep the engineering perspective during screening. After the first screening the evaluation continued using Pugh's screening method developed by Pugh [25]. The Pugh's screening method is a finer evaluation method, where the concepts are ranked against a reference solution in a matrix according to how well they fulfill the customer needs and specifications that is desirable for the customer to fulfill. The reference solution might be the current solution or one of the generated concepts. If the concept is better than the reference according to a criterion it is given a "+", if it is worse it is given a "-" and if it is equal it is given a "0". The values for each concept are summed up and ranked. This matrix can be iterated with different concept as reference to make sure that the result is converging. A concept with bad ranking run the risk of being rejected.

3.8 Taguchi Array for Deciding Number of Tests

At this stage more information about the important parameters was needed and the lack of knowledge made the project shift focus to the important parameters rather than continuing the evaluation of the concepts. Simulations and tests were needed and a Taguchi orthogonal array was used to make this in a structural way. The Taguchi orthogonal array is a method for minimizing the number of experiments involving multiple parameters without affecting the output information from the experiments. The method was proposed by Taguchi [26] and is based on well-defined guidelines using a special sort of arrays called orthogonal arrays. The size of the array and the number of experiments is defined after the number of independent design parameters and levels. Each independent design parameter has a combination of different levels and the number of levels must be the same for all design parameters for the array to be balanced.

3.9 ANSYS, Star-CCM+ and Testing for Concept Refining

To be able to make a qualified final concept selection, more information about the important parameters was needed. A structural analysis was made in ANSYS Mechanical which is a finite element analysis software for structural analysis developed by ANSYS Inc. Pre-processing was made in ANSA, which is a computer aided engineering tool for finite element method developed by BETA CAE Systems S.A. [27] The aerodynamic performance was simulated in Star-CCM+ which is a computational fluid dynamics software developed by CD-adapco. Tests of physical prototypes were made in a wind tunnel. The objective for the simulations and the tests was to learn more about how the parameters affected the performance of the fan blade and to optimize them. The current fan used by Volvo Group was also simulated with identical testing conditions to enable comparisons between the final concept and the current fan. The results from ANSYS, Star-CCM+ and the tests were compared against each other and describe the robustness of the simulations and the tests.

3.10 Concept Redefining

The results from the simulations and tests gave more information about the important parameters. Since this is an iterative process the concepts was redefined based on the optimized parameter data. To validate the simulations and tests and make sure that the parameter data was correct, one more simulation with the redefined concepts containing optimized parameters was done. A final concept recommendation was made based on the results from the second simulation.

3.11 Detailed Design

A detailed design was presented with drawings made in Catia which is a CAD software developed by Dassault Systèmes [28]. A brief manufacturing plan and a material selection were made together with an economic analysis. The cost analysis were made in CES EduPack which is a database of materials and process information developed by Granta [29]. CES is a short for Cambridge Engineering Selector.

4

Customer Needs Assessment

It is important to collect all the needs stated by the customer, in this case Volvo, to ensure that the project actually fulfill Volvo Group's questions. The customer needs were collected and weighted to visualize the most important needs and therefore be able to ensure that project is well performed on those areas. This is done using an Analytic hierarchy process matrices.

4.1 Gathering Customer Input

Customer needs were gathered in two ways. The first was from a meeting with the sponsor, at which the group asked the sponsor different questions to better understand the project. From these questions the team gathered customer needs based on the answers provided. The second way was from email conversations between both parties, the team asked Volvo Group questions about specific needs and what was important to the sponsor. The Volvo Group sponsor provided the team with all of the customer needs. The customer needs starting with the most important base of the AHP [30] in Table 4.1 are Power, AirFlow, Size, Noise, Durability, Weight, Cost, Safety, Efficiency and Color.

4.2 Weighting of Customer Needs

The AHP weighting came from engineering judgement and from talking with the sponsor. The sponsor was very clear that efficiency is the most important aspect of this project. The sponsor also laid out other customer needs that would be important in the design project and the needs were weighted based on earlier conversation with the sponsor. The AHP calculated the weights of each customer need. Power and Air Flow came out as the most important with a weight of .22 each. These two needs were the most important because they both have a large impact on efficiency which is the main goal of this project. Power and air flow were followed by Size, Noise, and Durability which had weights of .094, .088, and .08. These needs are still important in the project, but carry less weight than efficiency. The customer needs with the least weight are Weight, Cost, Safety, and Color with weights of .075, .075, .073, and .065 respectively. For the full AHP calculation, see Table 4.1.

Table 4.1: Analytical Hierarchy Process of the different criteria and how they depend on each other.

Criteria	Size	Noise	Durability	Color	Safety	Air Flow	Weight	Cost	Power	Total	Weight
Size	1	2	1	2	1	0.33	1	1	0.33	9.66	0.094
Noise	0.5	1	2	1	2	0.25	1	1	0.25	9	0.088
Durability	1	0.5	1	2	1	0.33	1	1	0.33	8.17	0.08
Color	0.5	1	0.5	1	1	0.33	1	1	0.33	6.66	0.065
Safety	1	0.5	1	1	1	0.5	1	1	0.5	7.5	0.073
Air Flow	3	4	3	3	2	1	3	3	1	23.01	0.22
Weight	1	1	1	1	1	0.33	1	1	0.33	7.66	0.075
Cost	1	1	1	1	1	0.33	1	1	0.33	7.67	0.075
Power	3	4	3	3	2	1	3	3	1	23	0.22
Sum										102.34	1

5

External Search

This section includes an external search of patents and existing products. During patent search, the main focus stays on the patent presented by Volvo Group. The external search of existing products describes axial fans together with a general explanation about propeller theory. Other existing products that is briefly described in this section is radial-, diagonal and contra rotating fans.

5.1 Patents

Two patents have been found to be of specific interest in the patent search, this is [US 7396208 B1] focusing on efficiency and claims to accomplish this by splitting the fan blade in two roots with a common tip and by adding holes at the leading edge. The other patent "Cross Flow Cooling Fan" [US 4364712 A] focuses on the creation of pressure difference at low tip speeds.

5.1.1 Divided Rotor Blade

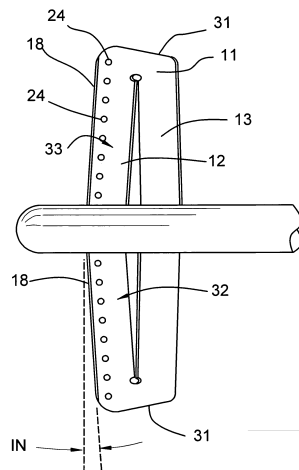


Figure 5.1: Two divided fan blades mounted on a shaft [3]

A patent of a new fan rotor blade has been presented to Volvo Group, "Divided blade rotor" [US 7396208 B1] [3]. This fan is designed with divided fan blades to give a higher efficiency than conventional blades. Very simplified, the divided rotor

blade looks like a conventional fan blade that is cut in two and creates a split with two roots that can be angled. As the blade is not cut all the way, it ends out to a common tip. The lead blade part has several holes in it that will contribute to the improved performance, see Figure 5.1.

Figure 5.2 shows three different fan blade designs included by the patent mounted on a shaft. The Figure to the left is a perspective view of a fan blade having a *bent* leading edge blade part. The Figure in the center is a perspective view of a fan blade having a *curved* leading edge blade part. The figure to the right is a perspective view of a design in which the blade parts have dissimilar angles of incidence.

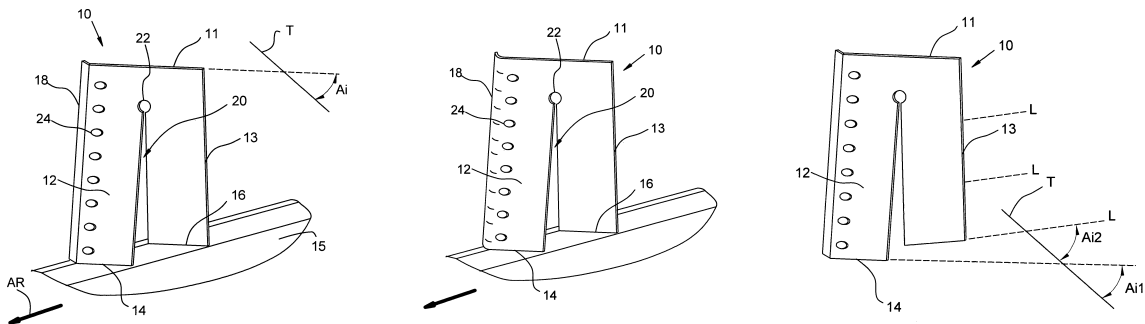


Figure 5.2: To the left is the preferred embodiment with a sharp bend for the leading edge, in the middle is an alternative embodiment with a curved leading edge and to the right is a blade with dissimilar angles of incidence [3].

There are five main purposes stated in the patent “Divided blade rotor” [US 7396208 B1]:

“A first object of the present invention is a simplified design, and improved operation, divided rotor blade that can be formed from flat sheet material.

A second object of the invention is a divided rotor blade comprising true airfoil sections in tip and root to decrease drag and increase effective lift or thrust.

A third objective of the invention is a rotor blade which can be operated effectively at supersonic tip speeds.

A fourth object of the invention a rotor blade which is resistant to cavitation, turbulence, and accelerated stalling otherwise initiated by high speed operation at a high angle of incidence.

A fifth object of the invention is a divided rotor blade with root portions having dissimilar angles of incidence.” [3]

In addition to these purposes a number of claims about the performance of a fan based on the divided rotor blade are stated in the patent. These claims are, but not limited to:

- Higher resistance to structural deformation using the same sort and amount of material
- Higher efficiency
- The port holes reduces cavitation, turbulence and delays the onset of stalling, particularly when operating at high speeds and high angles of incidence. The introduction of port holes is also supposed to significantly increase the effectiveness of the divided blade.
- If the trailing portion have a angle of incidence of preferably 5 degrees higher than that of the leading portion the net lift will be increased.
- Effective with 45 degree angle of incidence well into the range of supersonic tip speeds.

In the patent it is mentioned that the port holes at the leading edge should preferably occupy about 10 percent of the total surface area of the blade to fill the stated function but that the area may be adjusted and determined by testing for each specific application. How the holes are implemented in reference to the rest of the geometry is of great importance. As stated in the patent, “Divided blade rotor” [US 7396208 B1], description *“To reduce friction and pressure loss, the holes should be bored at an angle from the leading edge and face of the rotor blade portion, rearward to the backside.”* The angle they are bored at is the reason to why the holes are seen as ellipses in Figure 5.2.

5.1.2 Cross Flow Cooling Fan

The “Cross flow cooling fan” [US 4364712 A] [31] explains how conventional cooling system fan for vehicles is increasingly becoming smaller due to many vehicles having a smaller frontal area. This results in a higher air path resistances which forces the fan to produce higher pressures at lower tip speeds. This patent finds a solution for this by instead of using only the axial flow, it also uses the radial component of air flow. This is accomplished by using backing plates on each blade which extend downstream from the hub. Each blade is positioned in an oblique plane compared to the backing plate which is joined with its corresponding blade. This allows for the fan to combine axial thrust and centrifugal lift which generates pressure. An illustration of the patent design can be found in Figure 5.3

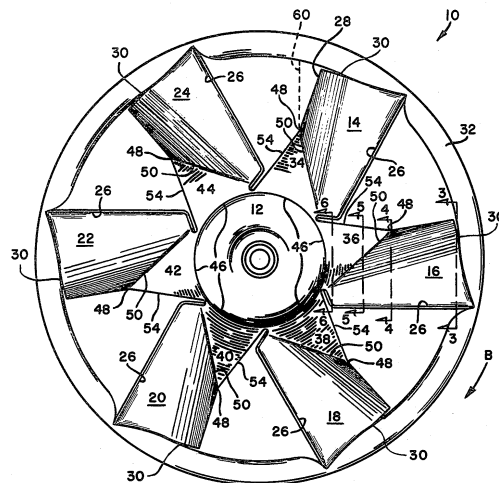


Figure 5.3: A cross flow cooling fan [31].

5.2 Existing Products

This section gives a brief description of classic airfoil and propeller design. Thereafter the most important fan types are being described, such as axial fans, radial fans and diagonal fans.

5.2.1 Axial Fan

General

The main function of an axial fan, also called propeller fan, is to transport air axially through the fan at a desirable velocity. This will result in a increased pressure at the leading edge thus create the difference in pressure that is needed for air to flow. An ducted axial fan does not change the flow direction, so air keeps flowing axially after the fan. The axial fan has many applications e.g. industrial processes, ventilation systems and cooling systems [32]. A principle sketch of an axial fan for the cooling system of an engine is illustrated in Figure 5.4. Altering angle of incidence and airfoil characteristics drastically changes the characteristics of the axial fan. The important parameters when designing a fan includes power, flow rate, pressure rise and efficiency [33], [34].

Effects of blade length and surface area

In Figure 5.5 is a chart describing the affect different surface areas on wind turbines has on efficiency with regard to the tip speed ratio, see Equation 5.1. A large surface area of the blade results in low efficiencies and low maximum tip speed, also known as the cut out speed. The range between cut in speed (the air speed at which the blades start rotating) and cut out speed are also low for a fan with large surface area. This is due to the large blade stopping fluid from passing through the swept area. A blade with the opposite characteristics is a blade with low surface area and high tip speed ratio and thus allowing large volumes of air through the swept area.

Although this figure is developed for wind turbines the same principles apply to axial fans [35].

$$\text{Tip speed ratio} = \frac{\text{Tip speed blade}}{\text{Wind speed}} \quad (5.1)$$

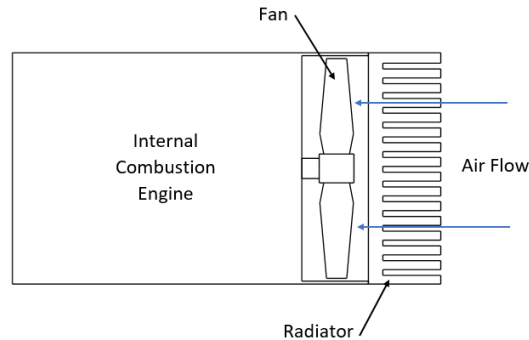


Figure 5.4: An axial fan used for cooling of engines

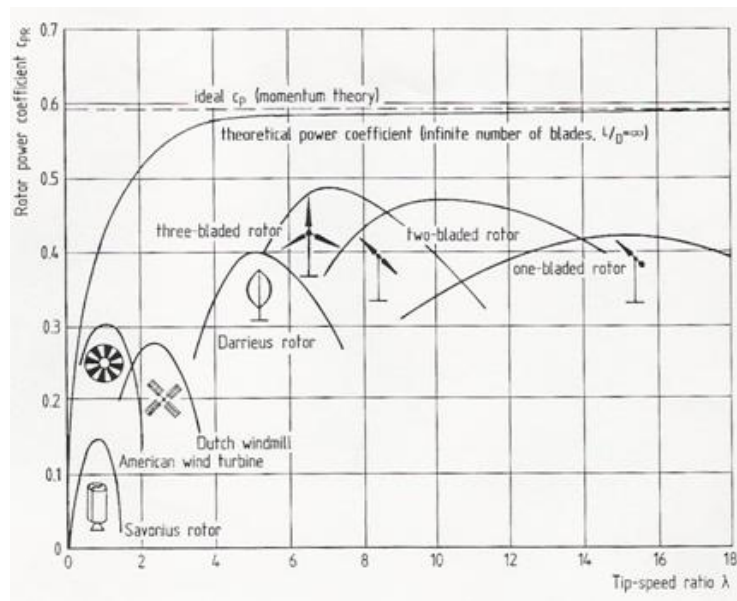


Figure 5.5: Wind turbine efficiency based on different designs [36]. Reprinted with permission.

Efficiency curve

In Figure 5.6 the relationship between pressure, efficiency and shaft power is presented. In general, a typical axial fan should be operated between points A and B. C is the point at which optimal efficiency with regards to airflow and shaft power is reached. At point D the angle of attack has reached its maximum and stalling occurs. In the E-D region the flow will not follow the blade as it was designed due to boundary layer breakaway which in turn causes the air to flow around the blade in a circular movement [37].

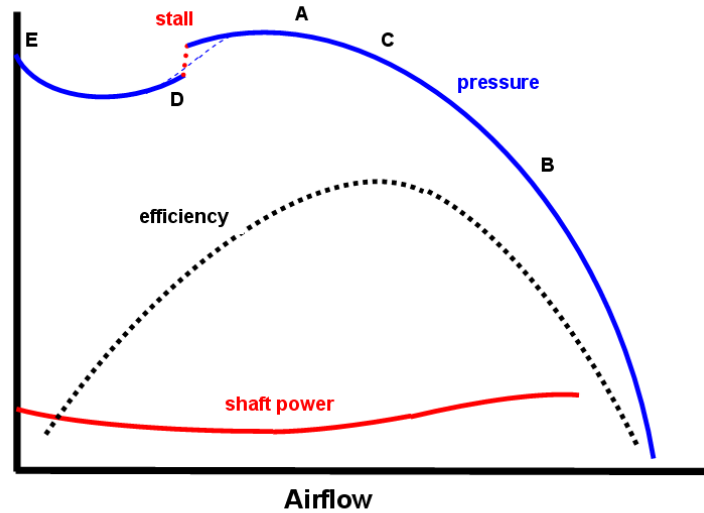


Figure 5.6: Typical performance characteristics curves for an axial fan [37]. Reprinted with permission.

Airfoil and propeller design

A rotor blade has three distinguished characteristics. The length from the rotational center to the blade tip, the width of the blade and the pitch angle. The pitch angle is the angle between the chord and the plane of rotation. If the blade at any point from the rotational center is cut between the trailing and leading edge the blades cross section, also called airfoil, will be shown.

The airfoil and pitch angle are interesting since this is what ultimately determines how the blade will perform. The most commonly used blade shape in fans is a thin curved sheet. It is basically an airfoil design with width of the blade close to zero.

In Figure 5.7 the drag coefficient C_D , the lift coefficient C_L and the relationship between them is shown. Of special interest is the stalling point, represented as "stall" in the figure, occurring at high angles of attack. Maximum lift is produced at the point of stalling, followed by a sharp decrease of lift. This again is due to boundary layer breakaway causing turbulent flow on the upper part of the airfoil. This will make the fan vibrate threatening to destroy the blades [37]. To show the relationship between the coefficients C_D or C_L and drag force (D) or lift force (L) respectively, the equations for lift and drag force are shown in Equation 5.2 and 5.3.

$$L = \rho \frac{C^2}{2} AC_L \quad (5.2)$$

$$D = \rho \frac{C^2}{2} AC_D \quad (5.3)$$

Where C is fluid velocity [m/s], D is dragforce [N], L is lift force [N] and ρ is density of the fluid [kg/m³].

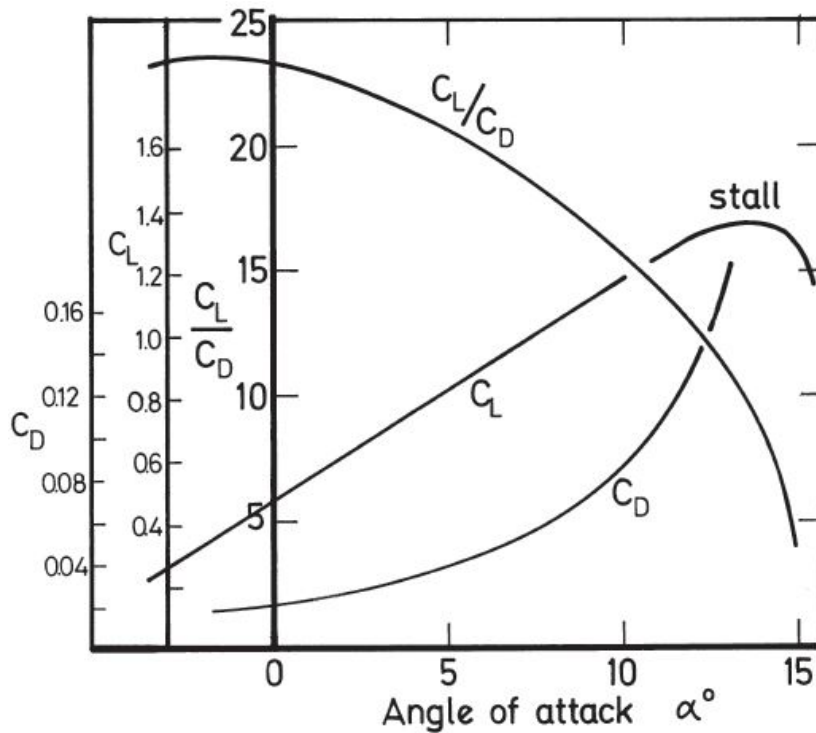


Figure 5.7: Typical behavior of lift and drag coefficients for an airfoil [37]. Reprinted with permission.

Pressure curves

The airfoil of a fan-blade has many similarities to that of an airplane. And just like the wing of an airplane creates a relative over pressure at the downwards facing surface of the wing, and a relative under pressure at the side facing upwards, so does also a fan blade. As the fan starts rotating it creates an under pressure upstream of the propeller and a over pressure downstream of the propeller. In the plane where the fan rotates there is a sudden and significant change in pressure as the fluid goes from under to over pressure [38].

5.2.2 Radial Fan

A radial fan, also called centrifugal fan, changes the direction of the flow from axial to radial. The fluid is accelerated by a rotating impeller that can be of different designs depending on the desired flow. As a result from the rotating impellers the pressure increases and forces the air against the walls of the fan until it reaches an outlet. The advantages with a radial fan is that it can take high pressures and it can be stable even when little air is entering the fan axially or when no air is leaving radially. The radial fan is the most common and there are many applications for it, e.g. air-pollution control systems, ventilation systems and many industrial systems. [33].

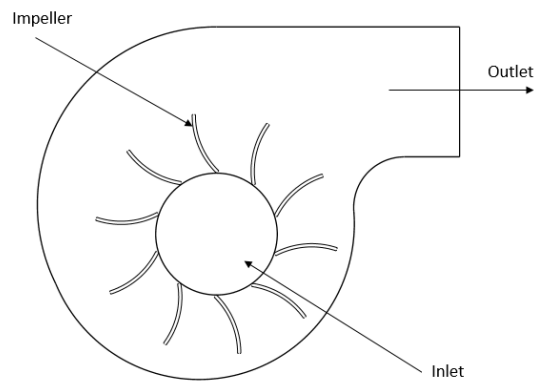


Figure 5.8: Schematic drawing of a radial fan

5.2.3 Diagonal Fan

A diagonal fan is a fan that manages air flow as a axial fan but can take higher pressure and without the counter pressure that appears in a radial fan. The air moves because of the fan impellers and the centrifugal acceleration. The diagonal fan is designed with a conical shaft with increasing diameter in the outlet to increase the circumferential speed of the blade tips and consequently the centrifugal acceleration. The conical shaft also helps to avoid vortex formation and reduce the level of noise compared to an axial fan [33], [39].

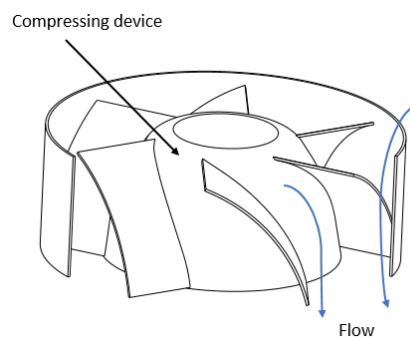


Figure 5.9: Schematic sectional view of a diagonal fan

5.2.4 Contra-Rotating Fan

Contra-rotating fans are based on standard axial fans that is placed behind each other on a shaft. The fans rotates in different directions though the stability would be disrupted as the momentum in one direction would be too great otherwise. Contra-rotating fans have a higher efficiency than conventional fans and especially in restricted amount of space as you do not need to have the same radius to accomplish the same movement of air. That works at high rotation speed as the blades are not as long as standard axial fan blades need to be and by that contribute to a more stable structure. According to T. Shigemitsu, J. Fukutomi and Y. Okabe [40] the

efficiency of a contra-rotating fan at a specific speed claims to be 44% compared to a standard axial fan at the same conditions that claims to be 35%. They also claim that the contra-rotating fan is more silent than traditional fans. The article also highlights the difficulties with this technology as it is a more complex product as you have to use some sort of transmission to get the two rotation directions. A transmission also contributes to the system's reliability and finally it contributes to a more expensive sort of fan due to the complexity.

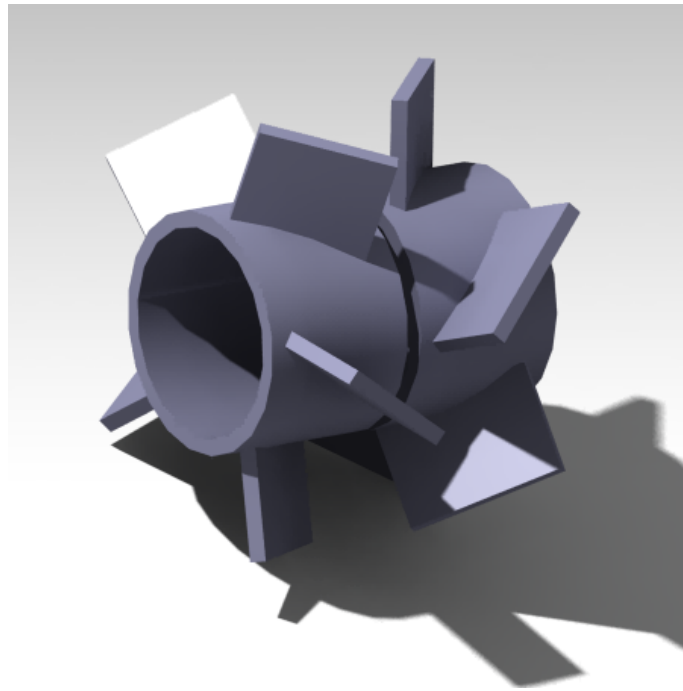


Figure 5.10: CAD rendering of a Contra-Rotating fan

6

Engineering Specification

This section includes an engineering specification that states both demands and desires specified both by the project group and by Volvo. Furthermore is a needs metric's matrix included that relates the specifications to the customer needs.

An engineering specification is established based on the collected data from customer needs in section 4 and external search in section 5. The engineering specification includes specifications with a target value, it describes if the specification is a demand or a desire, and how the specification is authenticated and gives a reference to the specification. The engineering specification is an important part of a product development project when evaluating the generated concepts and the fulfillment of the specifications and objectives of the project. The engineering specification is to be found on the next page, see Table 6.1.

6.1 Relating Specifications of Customer Needs

The customer needs are addressed through the specifications of the design. The double blade design, optimized angel of incidence, optimized air-hole specifications, diameter, thickness, and material all have a big impact on how this design will work. These specifications will be used to satisfy the customer needs. A Needs-metric's Matrix is found in Appendix B.1

Table 6.1: Initial Set of Target Value

No	Criteria	Target value	Demand/ Desire	Authentication method	Reference
1	Minimize tip vortex	NaN	Desire, 4	Simulations	Project group
2	Minimize turbulence	NaN	Desire, 4	Simulations	Project group
3	Max weight	15 kg	Desire	Weighing	Project group
4	Max deformation at operational speed	2,2684 mm	Demand	Simulations	Project group
4	Cost of manufacturing	NaN USD	Demand	Calculations	Project group
5	Ease of manufacturing	NaN	Desire		Project group
6	Life cycle	20 years	Desire, 4	Calculations/ simulations	Project group
8	Manage operational environment	Yes/no	Demand	Material selection	Project group
9.1	Fan speed	2400 RPM	Demand	Test	Project group
9.2	Fan speed	2100 RPM	Desire, 4	Test	Projekt group
10	Air flow	7 m ³	Demand	Simulations/ test	Volvo
11.1	Power input	70/30 Kw	Demand	Simulations	Volvo
11.2	Power input	40/30 Kw	Desire	Simulations	Volvo
12	Double blade design	Yes/no	Demand	Visual analysis	Volvo
13	Angle of incidence	<45 °	Demand	Design	Patent
14	Fan Radius	375 mm	Demand	Measurement	Volvo
15	Fit to existing system	Yes/no	Demand	Design	Volvo
16	Recyclable	30%	Desire, 3	Material & design analysis	Project group
18	Von Mises stress	1.7 · 10 ⁸	Demand	Simulations	Volvo
19	Drag Force	NaN	Desire	Simulations	Project Group
20	Temperature	< 80 °	Demand	Material Selection	Project Group

* NaN, Not a Number, indicates that, in lack of information, it is impossible to give a number.

7

Concept Generation and Evaluation

In this section the problem is clarified and concepts are generated with brainstorming and morphological matrix. Thereafter the concepts are evaluated with an Elimination matrix and a Pugh matrix. In the end of this section, the number of parameters that will be evaluated are narrowed down to three important ones. Number of holes, number of blades and angle of incidence.

7.1 Problem Clarification

Before starting generating concepts it is important that the problem is properly clarified so that the generated concepts are solving the real problem. Therefore a black box and a sub-function diagram are made.

7.1.1 Black Box

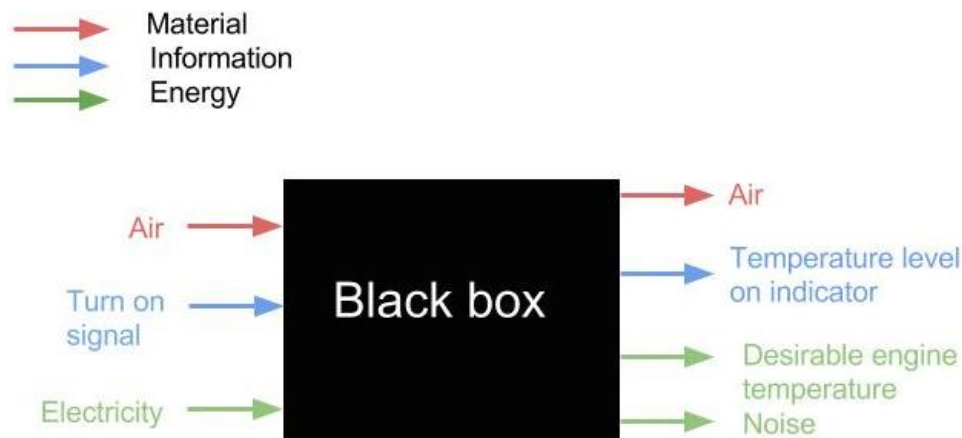


Figure 7.1: Black box model with inputs and outputs in form of material, information and energy.

A black box model shows the in- and output operands of the fan. What happens within the fan is not visualized but it is put in a black box, and that is a way to clarify the boundary of the system. The different operands are material, energy and information and are demonstrated with different colors, see Figure 7.1. The input

for the fan is material in form of air with lower velocity and pressure, energy in form of electrical energy and information in form of a turn on signal. The output consists of material in form of air with higher pressure and velocity and a desirable engine temperature, energy in form of noise and information in form of a temperature level indicator in the truck.

7.1.2 Sub-function Diagram

A sub-function diagram is made to analyze the main function and divide it into part functions with part solutions. As can be seen in Figure 7.2, the blue boxes marks the functions and the red boxes marks the part solutions.

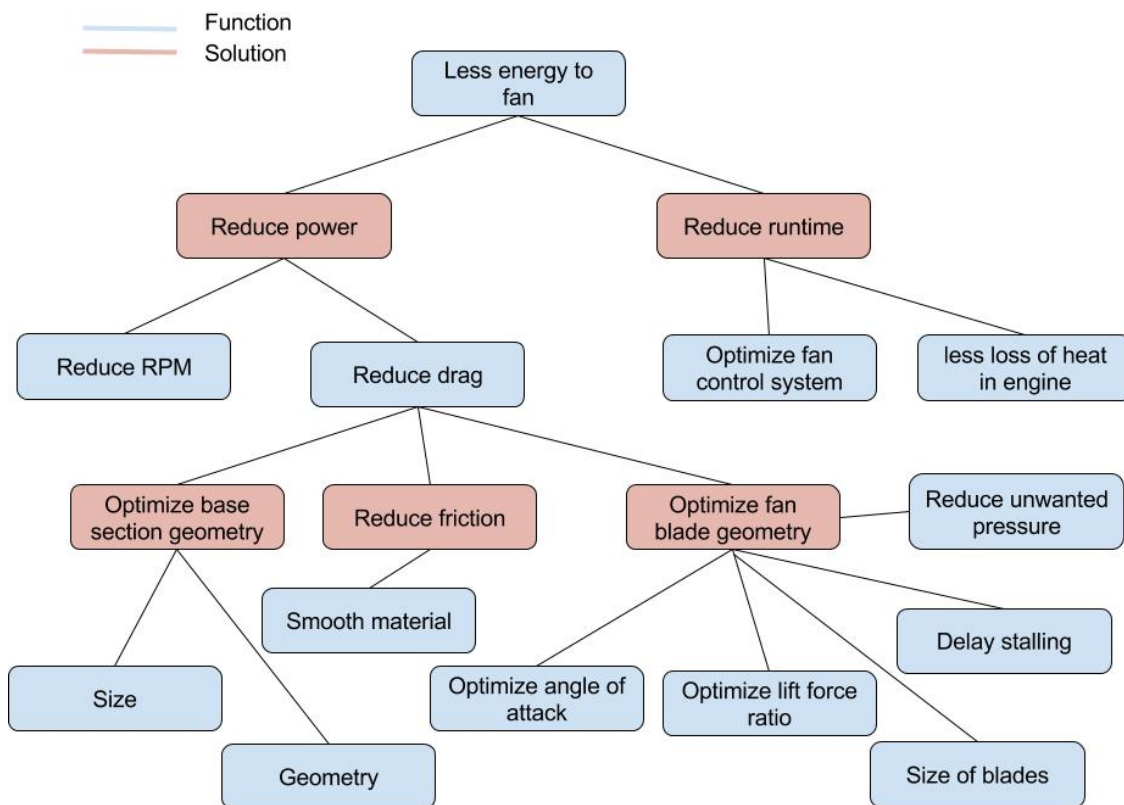


Figure 7.2: A sub-function diagram where functions are marked in blue and solutions are marked in red

7.1.3 The Important Parameters

Before generating concepts it is important to clarify the important parameters of the divided fan blade design. The important parameters are decided mainly by studying the patent [US 7396208 B1], see Section 5.1.1, but also by studying axial fan theory, see Section 5.2.1. The important parameters are shown in Figure 7.3.

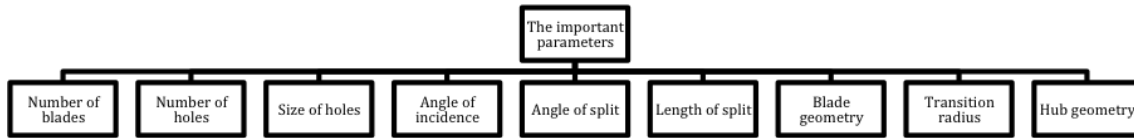


Figure 7.3: The nine most important parameters of the fan blade design

7.2 Concept Generation

When the problem is clarified it is time to start generating concepts. The methods that are used for generating concepts in this project are brainstorming and a morphological matrix.

7.2.1 Brainstorming

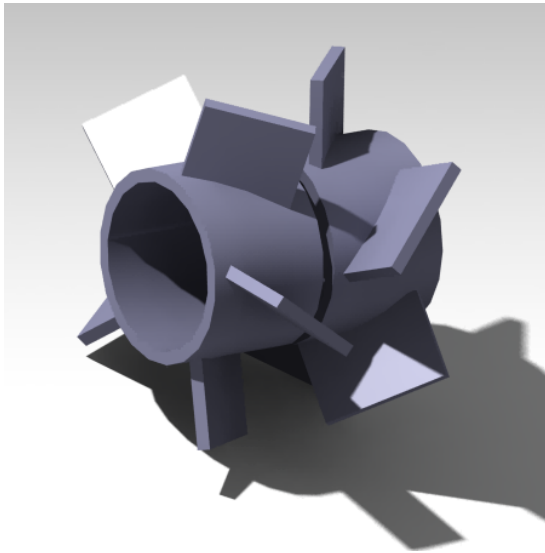
The first method to start generating concepts was brainstorming. The brainstorming was made in groups of three, with one group at Penn State and the other one at Chalmers. During the brainstorming the main focus was in being creative and not taking too much consideration to fluid and propeller theory as this may limit the outcome of the brainstorming. The brainstorming resulted in four concepts, Contra-rotating, Curvey, Bent and Rounded, see Figure 7.4. More detailed figures of the concepts can be found in Appendix C.1.

7.2.2 Morphological Matrix

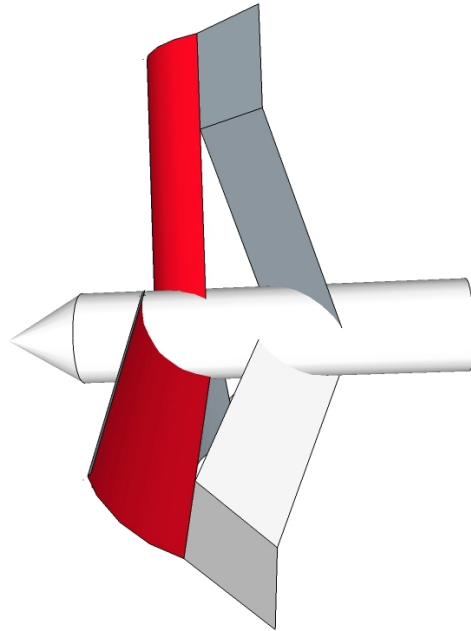
The second method used to generate concepts is a morphological matrix, which is made with more focus on fluid dynamics and propeller theory. The most important parameters of the fan was decided and can be found to the left in the matrix, see Figure 7.5. Different part solutions to these parameters is created and can be found at each row of the matrix. To generate concepts one of the part solution from every row is chosen to create a complete concept. Five different concepts are created using the morphological matrix and can be found in Appendix C.1. The concepts were named Morf 1-Morf 5.

7.3 Concept Evaluation

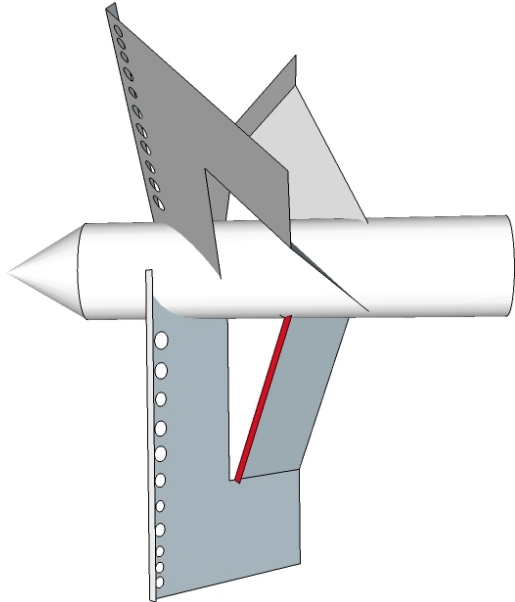
To evaluate the concepts that were generated in Section 7.2 two different evaluation methods are used. First, the concepts are analyzed in an elimination matrix to see how well they fulfill the specifications in the engineering specification, see Appendix 6.1. Second, the concepts are evaluated in a Pugh matrix, with a relative comparison of how well the concepts fulfill the desires and important specifications in the engineering specification.



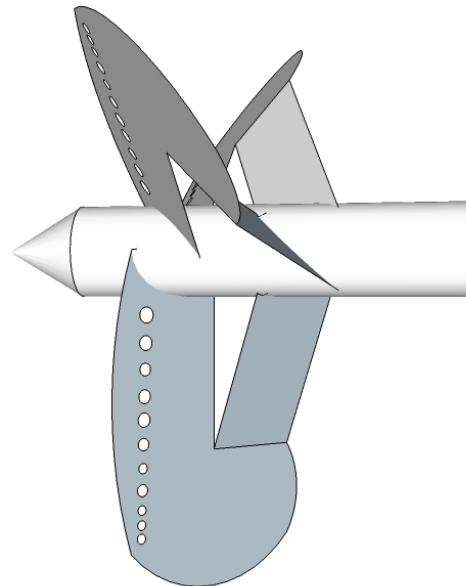
(a) Contra-Rotating Fan



(b) Curvey



(c) Bent



(d) Rounded

Figure 7.4: Concepts generated in brainstorming, Contra-rotating, Curvey, Bent and Rounded

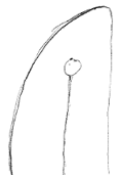
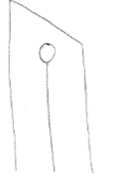
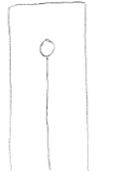
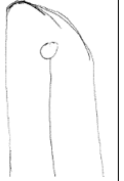
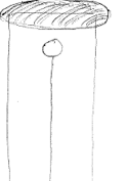



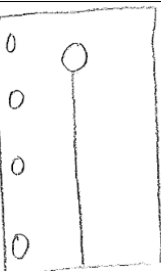
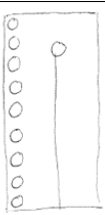
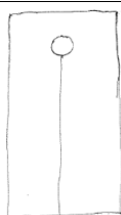




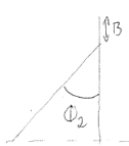


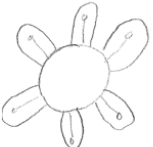




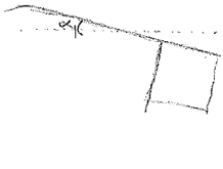


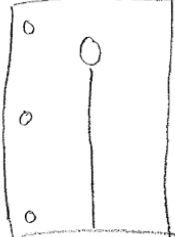
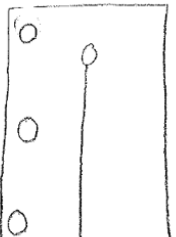
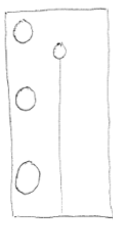
Part functions	1	2	3	4	5
A. Blade Design					
B. Transition radius leading edge-blade					
C. Number of holes					
D. Length of split between roots					
E. Angle of split between roots					
F. Number of blades					
G. Base section / Hub					
H. Angle of incidence					
I. Size of holes					

Figure 7.5: Morphological matrix, with important parameters in the column to the left and part solutions at every row

7.3.1 Elimination Matrix

The elimination matrix is the first and roughest evaluation method to screen the concepts. The concepts are put against every demand in the engineering specification, and if a concept does not fulfill one of the specifications, it will be rejected. In the elimination matrix, see Table 7.1, the generated concepts are gathered in the left column, and are evaluated after the specifications that are aligned at the first row. In the column to the right it is shown that concepts 4 and 7 are rejected because of their inability to be designed with double blades, respectively, difficulty to fit the existing system.

* *NEI stands for Not Enough Information*

Table 7.1: The elimination matrix shows that concept 5 and 7 should be rejected

Concept	Max Deformation	Manage operational environment	Fan speed	Air flow	Power input	Double blade design	Angle of incidence	Fan radius	Fit existing system	Shear stress	Von mises stress	Action
1. Curvey	YES	NEI	YES	YES	NEI	YES	YES	YES	YES	YES	YES	Keep
2. Bent	YES	NEI	YES	YES	NEI	YES	YES	YES	YES	YES	YES	Keep
3. Rounded	YES	NEI	YES	YES	NEI	YES	YES	YES	YES	YES	YES	Keep
4. Contra-rotating	YES	NEI	YES	YES	NEI	NO						Reject
5. Morf1	YES	NEI	YES	YES	NEI	YES	YES	YES	YES	YES	YES	Keep
6. Morf 2	YES	NEI	YES	YES	NEI	YES	YES	YES	NO			Reject
7. Morf 3	YES	NEI	YES	YES	NEI	YES	YES	YES	YES	YES	YES	Keep
8. Morf 4	YES	NEI	YES	YES	NEI	YES	YES	YES	YES	YES	YES	Keep
9. Morf 5	YES	NEI	YES	YES	NEI	YES	YES	YES	YES	YES	YES	Keep

7.3.2 Pugh Matrix

The remaining concepts from the elimination matrix are evaluated in a Pugh matrix. The Pugh matrix is a relative decision matrix, where concepts are evaluated after how well they fulfill the criterion compared against a chosen reference. The Pugh matrix is iterated three times to ensure that the results are converging regardless to what concept is chosen as a reference. The criterion that the concepts are evaluated against are desires and important specifications from the engineering specification. The results from the Pugh matrices are shown in Figure 7.2. One of the complete Pugh matrix with the concept Curvey as reference, see Figure 7.6. The other Pugh matrices can be found in Appendix C.2.

The results from the Pugh matrices in Figure 7.2 show that there are not a convergence for the best ranked concepts. This is probably a result from the lack of information about how the different parameters of the concepts affect the fluid. Although there is a slight convergence regarding the worst ranked concepts, where concept number 4 and 5 are ranked worst in every iteration and are therefor being rejected.

Criterion	Concepts						
	Reference, Concept 1, Curvey	2. Bent	3. Rounded	5. Morf 1	7. Morf 3	8. Morf 4	9. Morf 5
Minimize tip vortex		-	+	0	0	+	+
Minimize turbulence		-	+	-	+	+	-
Power input		+	-	+	+	+	-
Shear stress		-	0	0	-	0	-
Von Mises strain		-	0	0	-	0	-
Deformation		-	-	0	-	-	-
Number of "0"		0	2	4	1	2	0
Number of "+"		1	2	1	2	3	1
Number of "-"		5	2	1	3	1	5
Netto		-4	0	0	-1	2	-4
Ranking	2	4	2	2	3	1	4

Figure 7.6: The Pugh matrix with Curvey as reference

Table 7.2: The ranking results of the the three Pugh matrices, where the eliminated concepts are marked in red.

Ranking, Pugh 1	Ranking, Pugh 2	Ranking, Pugh 3
Curvey	Morf 4	Rounded
Morf 1	Morf 1	Curvey
Rounded	Rounded	Morf 1
Morf 4	Curvey	Morf 4
Morf 3	Morf	Morf 3
Bent	Bent	Bent
Morf 5	Morf 5	Morf 5

7.4 Shifting focus to important parameters

Except for the elimination of two insufficient concepts the Pugh's screening method resulted in discovering the lack of knowledge about the different parameters and the understanding of how they affect the properties of the generated concepts. An analysis of the parameters is required to be able to continue the evaluation of the concepts. Because of the limited resources in form of time, all parameters can not be analyzed. Three out of the nine important parameters that is assumed to have the largest impact on the fan behavior was chosen. The three parameters that is analyzed further is the number of blades, number of holes and the angle of incidence, see Figure 7.7.

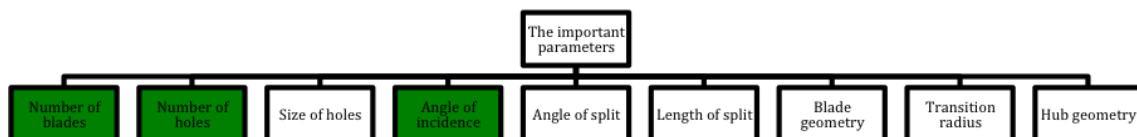


Figure 7.7: The parameters that will be further investigated is marked in green

8

Concept Refinement with ANSYS, Star-CCM+ and Tests

This section will in detail describe how the simulations in Star-CCM+ and ANSYS along with the testing procedures were executed and the results from them. Finally a series of verification test of the final design will be described.

8.1 Deciding Number of Tests with a Taguchi Orthogonal Array

There are many parameters to explore regarding the fan blade design, but only three of them will be in focus during this study; the angle of incidence, the number of port holes, and the number of blades. To find the optimum combination of these parameters, a Taguchi array is designed, see Table 8.1.

Table 8.1: Taguchi Array

Run #	Angle of Incidence (degrees)	Number of Port Holes	Number of Blades
1	15	0	4
2	15	4	8
3	15	8	12
4	30	0	8
5	30	4	12
6	30	8	4
7	45	0	12
8	45	4	4
9	45	8	8

8.1.1 Design and Manufacturing Process for Experimental Tests

Based on the Taguchi array, see Table 8.1, nine models are designed in CAD. The design of the models used in Star-CCM+ is a little bit different to the design of the models used in ANSYS and to the physical prototypes. This is because of the

dissimilar requirements for the different test types. In Star-CCM+ it is important that no fluid comes through the hub section, and it is therefore designed with a solid hub. The physical prototypes are manufactured with 3D printing, where solid sections is not preferable, both because of the characteristics of plastic but also in the matter of material savings and is therefore designed as a latticework, see Figure 8.1. For a review of the geometry of the fans tested in Star-CCM+ in this Chapter see CAD-models in Appendix D.23 and D.24. For the geometries tested in ANSYS in this Chapter see Appendix D.3.



Figure 8.1: A physical prototype manufactured with 3D-printing

8.2 Structural Analysis in ANSYS

The parameters tested in this comparative section are:

- The angle between trailing and leading root
- The length of the split separating the leading and trailing roots.

To measure how different values on a specific parameter changed the output (i.e., deformation) and if the change in output was linear to the change in parameter value, one parameter at a time were changed and tested for at least three different values with all other parameters held constant.

8.2.1 Structural Analysis Set Up

For this comparative analysis a volumetric “coarse” mesh were found to be adequate and approximately 7000 elements were created with the automatic meshing tool. The applied load were “Rotational velocity” rotating around the driving shaft at

2400 RPM. The rotation was assumed to be constant, thus the operation was set to steady state. The support was set to “Cylindrical Support” located where the shaft would have been attached. The radial constraint was set to free and both axial and tangential were set to fixed.

8.2.2 Results from Structural Analysis Comparative Section

Total Deformation: It has been possible to show that a long split between the roots stabilizes the top of the fan blade but that a long split also increases the deformation of the trailing root.

When the angle between the roots increases, the total deformation increases throughout the blade with the deformation growing faster at the trailing root. For detailed figures, see Appendix D.3

Equivalent Stress (Von Mises):

Only global stress are evaluated. Stress concentrations due to sharp edges or abrupt changes in the geometries will not be discussed or presented.

The Equivalent von mises stress remains almost constant when the length of the split is sufficiently small, but when increased to approximately 90 percent of the total length it doubles in magnitude to 684 MPa at the relief hole were the two roots are joined, see Figure D.9 in Appendix D.3.

When the angle between the roots are small, about 5 degrees, the highest stresses arise on the leading edge close to the hub. When the angle increases the maximum stress moves to the stress relief hole.

8.2.3 Discussion of Structural Analysis

The stress concentration at the relief hole becomes critical when the split of the two roots are too long. Therefore it is preferable to keep the length of this split bellow at least 85% of the total blade length.

From Section 5.2.1 it is known that the pressure will be high downstream of the fan and low upstream of the fan. This will to some extent reduce the deformation of the trailing root as the split between the roots grows longer.

8.3 Fluid Dynamics Analysis in Star-CCM+

Volvo Group’s existing fan blade design is tested along with the concept generated by the project group. The concept will be tested with different parameters according to the Taguchi array and it will thereby be able to compare the results from Star-CCM+ to the test results from wind tunnel tests of the small scale prototypes.

8.3.1 Simulation Set Up

To mimic the actual performance of the fan's performance in a actual truck installation as closely as possible, Volvo Group provided a digital mock up of their test rig along with suitable physics and meshing criteria.

Part Preparation

Since small parts, such as screws, will have a significant impact on how many nodes are created, and thereby computing time, but rarely have significant impact on the air flow, all small parts were carefully considered and valued in terms of their significance to the air flow and importance to the final result.

Most of these small parts (e.g. all screws, bolts, clamps and internal parts) were shown not to be that critical and were removed. To simplify the design further the complex design of the fan hub was replaced with a flat surface.

Even after removing small parts the complex geometry of the reference fan had to pre-processed in ANSA to ensure that no holes or overlapping faces appeared on the surface when converting the original CAD-format to a format suitable for Star-CCM+. The geometries of the generated concepts are much simpler and thus it was not necessary to prepare them in ANSA.

All simplifications have been carefully thought out to minimize the affect on the result and at the same time simplify the simulations. A render of the stripped reference CAD-model can be found in Appendix D.2.

Setting up meshing criterion

The setup of the mesh is done with both computing efficiency and robustness of the simulations in mind. This results in different meshing methods at different surfaces and volumes. The most complex and critical region in the simulation is the region closest to the fan, here called fan-region, since this is where all the induced fluid motion takes place. In the fan-region the meshing method were set to "polyhedral" with a base size of 7 mm for the comparison between the different fans. In front of the fan, here called Pressure-chamber (PC), the direction and velocity of the fluid flow are very stable except for the volume just upstream of the fan where the base size were set to 4 mm. In all other regions of the PC a simpler mesh could be used and therefore a quadratic meshing method with a base size of 40 mm was created. Just behind the fan-region the engine bay is located. In this region the flow has significant energy and the quite complex geometry of the engine bay demands a small base size to adequately describe the fluid movement. But to reduce the mesh complexity the quadratic meshing method was used with a base size of 10 mm. The fluid motion in the large tunnel surrounding the engine bay is not crucial for the fan characteristics or for the effects studied in this report and therefore a coarse quadratic meshing method with a base size of 40 mm was used. In total, this resulted in approximately 5100000 cells for the entire mesh. A side view of the mesh in the different regions can be found in Appendix D.4.1.

To couple the different regions, four interfaces along with inlets and outlets have been set up in accordance with Table 8.2.

Table 8.2: Interfaces, inlets and outlets

Interface type	Downstream region	Upstream region	Physics Value
Internal	Fan-region	PC-Region	0.02
Internal	Tunnel-region	Fan-region	0.02
Baffle	Tunnel	PC	0.02
Baffle	Fan	PC	0.02
Velocity inlet	PC	Outside simulation setup	0.746434456 m/s
Pressure outlet	Outside simulation setup	Tunnel	0 Pa

Setting Up the Physics

Two different types of simulations can be carried out. The simplest simulation, which also requires less computing time, is called “Moving Reference Frame” (MRF). The principle is to keep the fan stationary and rotate a frame/fluid around the stationary fan. The MRF method is suitable for a first assessment but is not as accurate as the more realistic method called “Rigid Body Motion” (RBM) where the mesh is rotated a predefined distance or angle for each time step and thereby inducing the fluid motion. MRF simulation is easier to implement but is not as accurate and requires extra effort to take into consideration the impact of a shroud [41].

In this project we have limited our work to the simpler MRF since the scope of the work did not give the group enough time to both learn and implement the rigid body motion set up. It would also require a lot more time to compute, which would not have been efficient when evaluating this many concepts. Importantly though the simpler version is a good and efficient method to make a first assessment of the fundamental behavior and differences, between the many and quite different concepts.

In the set up used in this work the MRF method was implemented as a frozen rotor, with only the fan-region rotating (at 2400 RPM) and since no stators have been used this has a relatively small effect to the solution. Still keeping in mind that MRF does not calculate the full effect of the shroud.

To ensure robustness in the solutions the simulations have been run until all residuals were oscillating steadily below 0.001. After having run the first set of simulations for 3000 iterations it was concluded that the concepts converged below the target value before 1000 iterations. To reduce computing time the remaining concepts were computed for 1000 iterations, see Figure D.25 in appendix.

To model the viscous layer close to walls and equipment, a viscous layer solver called “Two-Layer All y^+ Wall Treatment” has been deployed with two boundaries one in-

Table 8.3: Table shows the physics models and solvers used in the set up. Note that the Physics model and Solver at the same row don't necessarily have anything to with each other.

Physics Models	Solvers
Cell Quality Remediation	Partitioning
Constant Density	Wall distance
Exact Wall Distance	Segregated Flow
Gas (Air)	K-Epsilon Turbulence
Gradients	K-Epsilon Turbulent Viscosity
K-Epsilon Turbulence	-
Realizable K-Epsilon Two-Layer	-
Raynolds-Averaged Navier-Stokes	-
Segregated flow	-
Steady	-
Three Dimensional	-
Turbulent	-
Two-Layer All y^+ wall Treatment	-

ternal and one facing the free stream. The minimum allowable wall distance set to $1 \cdot 10^{-7}$.

In order to calculate the solution a number of different solvers have been used, a summery of them and their settings is provided in the Table 8.3. To review the settings for inlet ant outlet faces, see Table 8.2.

Setting up Reports and Plots

To draw conclusions based on the simulations a number of reports and plots have been established monitoring the performance and effects of the different concepts.

8.3.2 Results from Simulations

In this section the results from the simulations will be presented, certain attention is aimed at the three parameters number of holes, angle of incidence and number of blades. Only a sample of representative plots are shown in the text, a comprehensive set of all plots is available in Appendix D.4.2

Angle of Incidence

High angle tends to increase the magnitude of the velocity. A high angle also tends to generate mainly radial velocity, while a lower angle generates more axial velocity although this is not observable for a fan with few blades, see Figure 8.2.

Table 8.4 shows that a low angle of incidence appears to lower the required moment to rotate the fan. In general the divided fan appears to require less moment to rotate.

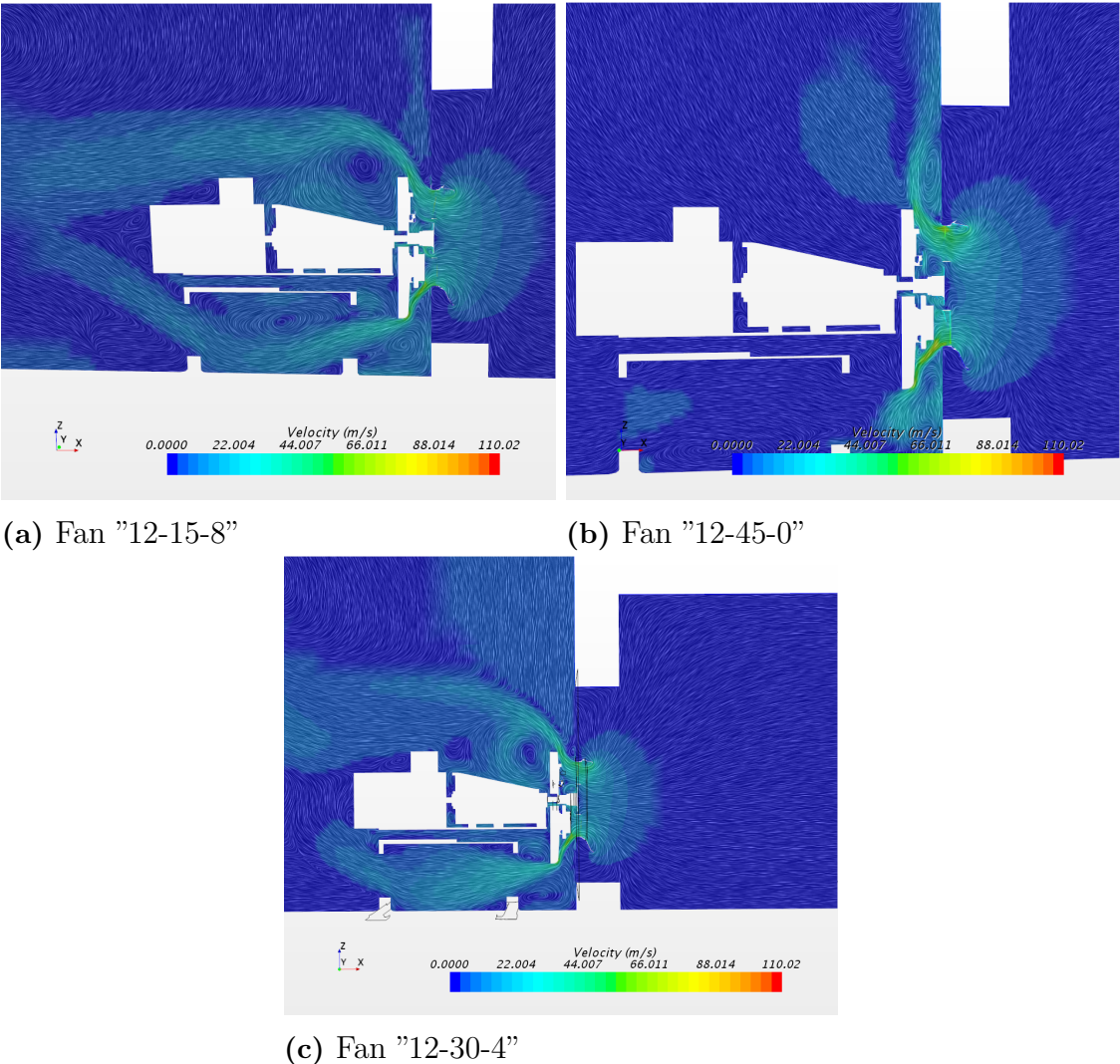
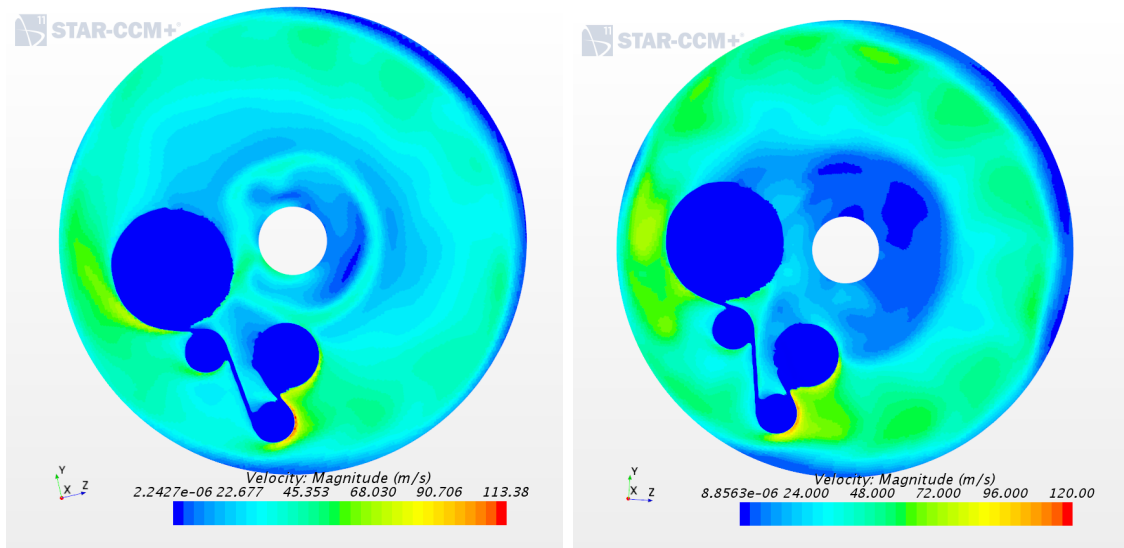
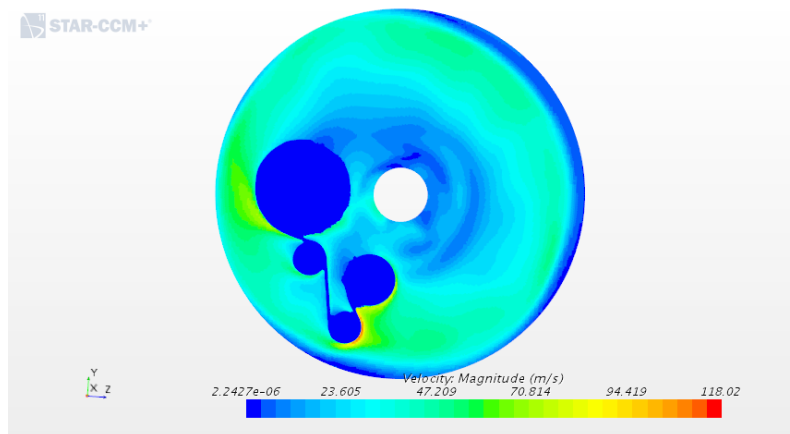


Figure 8.2: Cross section representations of the flow direction and velocity magnitude in the engine bay, used here to visualize the increasing radial velocity and increasing magnitude of the velocity as the angle of incidence increases.



(a) Fan "12-15-8"

(b) Fan "12-45-0"



(c) Fan "12-30-4"

Figure 8.3: Cross section representations visualizing flow velocity as the fluid leaves the fan-region, and the increasing velocity magnitude with higher angle of incidence.

Table 8.4: Values derived from simulations

Prototype	Moment [Nm]	Force on fan [N]	Mass flow [kg/s]
12-15-8	-7.37	-120	14.9
8-15-4	-5.41	-240	15
4-15-0	-2.26	-125	14.9
8-30-0	27.24	82.77	14.9
12.30-4	30.01	91.99	14.9
4-45-4	35.2	108.5	15
8-45-8	66.99	192.09	14.9
12-45-0	102.84	317.29	14.9
Volvo Reference	186.01	802.27	14.9

For low angles of incidence the pressure is lower behind the fan blades than in front of them. This effect disappears as the angle increases and with an angle of at least 30 degrees or higher the pressure is higher behind the fan blades than in front of them. As the angle increases the pressure at the engine just behind the fan-region also increases, see Figure 8.4.

Number of Blades

The number of blades have a large impact on the wind speed, higher speed is accomplished as fans with more blades in the design are tested, see Figure 8.5 and Appendix D.21.

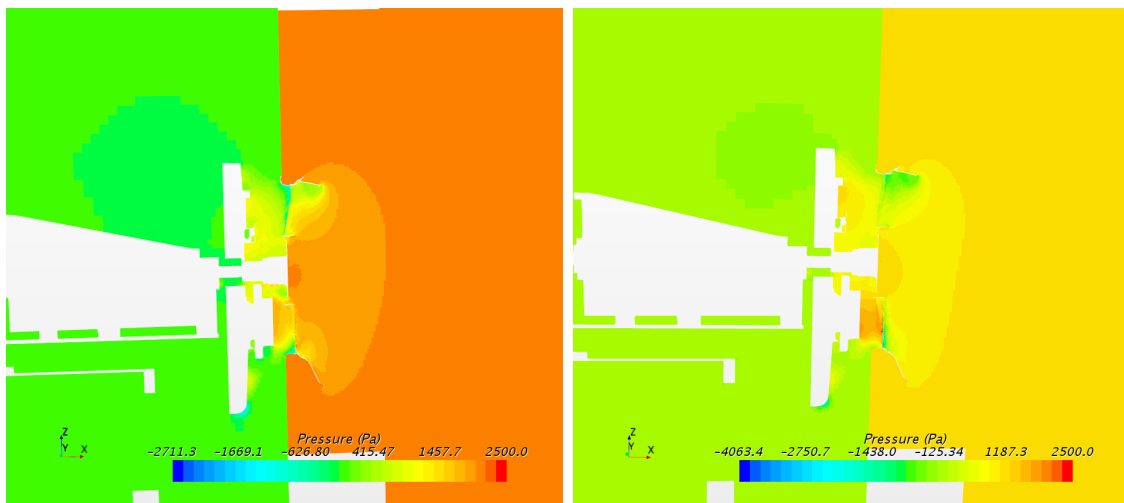
Number of Holes

The number of holes have an impact on the performance but it is not possible to see a general trend on how the performance varies based on the number of holes in the design since all designs varies in some parameters therefore it is impossible to see if it is the holes or not that contribute to the results. All results can be found in Appendix D.4.2.

8.3.3 Discussion Fluid Simulation and Recommendation

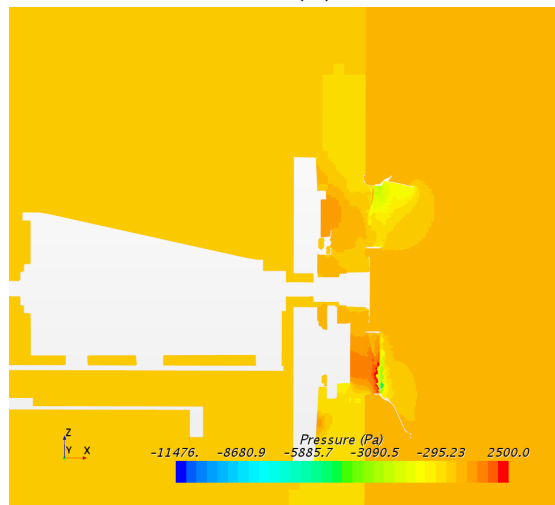
Overall

Since the approach to solve the problems and questions originally stated have been heavily focused on computer simulations which in turn rely on modelling an object by applying a mesh consisting of nodes to that object the grade of refinement and characteristics of the mesh will have a large impact on the solutions. One important thing to keep in mind when observing the plots is that when the step size between two nodes increases the energy in the flow dissipates quickly between the two nodes. The result of this is that the accuracy of the solution decreases in these coarse meshed regions and therefore the plots will be more accurate in the regions where the step size is small. The length between the nodes can be seen in Appendix D.4.1.



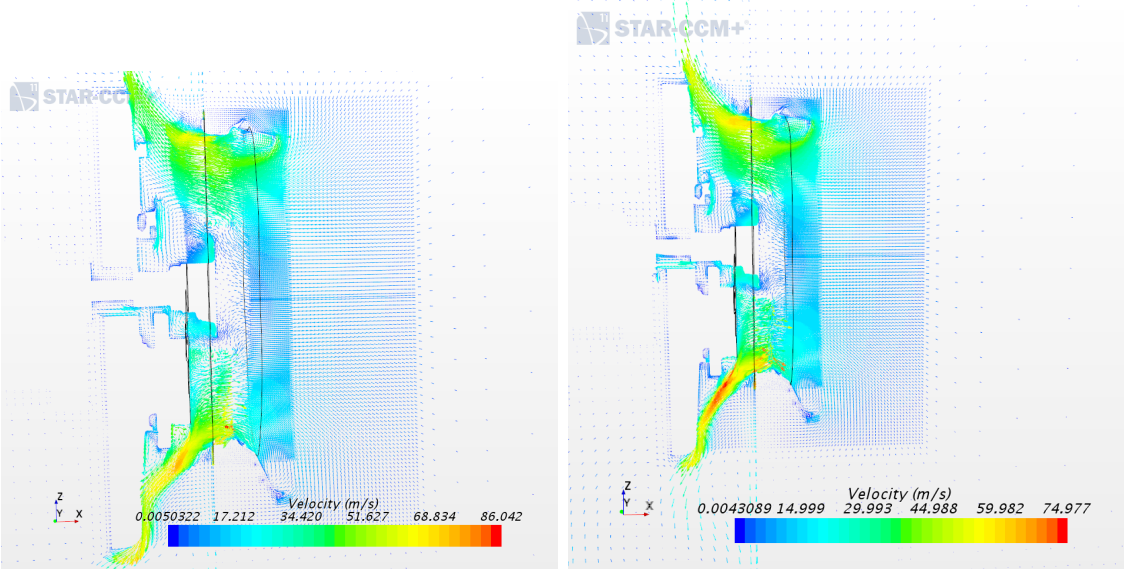
(a) Fan "12-15-8"

(b) Fan "12-30-4"



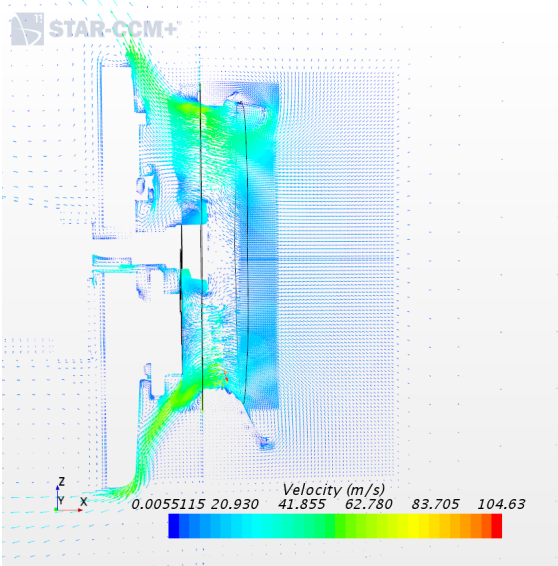
(c) Fan "12-45-0"

Figure 8.4: Pressure plots visualizing the increasing pressure against the engine block with higher angle of incidence



(a) Fan "12-45-0"

(b) Fan "8-45-8"



(c) Fan "4-45-4"

Figure 8.5: Vector plot visualizing the increasing fluid velocity after leaving the fan region with increasing number of blades.

Angle of Incidence

The fact that the pressure is higher in front of the fan blades for low angles of incidence, see Figure 8.4, could, with the knowledge that pressure in general is lower just upstream and higher just downstream from the fan blades, indicate that the fluid is flowing backwards just around the blades for angles of incidences lower than 15 degrees. This would likely be due to some unknown property of the so called trailing root however, this would be strange since the leading and trailing root in this test have the same angle of incidence.

A higher angle of incidence seems to increase the radial velocity faster than the axial velocity, see Figure 8.2 and Figure 8.3. These two observations might be explained in part by the pressure plot, which shows that the pressure against the engine bay right behind the fan-region also increases with a higher angle of incidence, especially when high angle is combined with a high number of blades. The theory to explain this is that the higher velocity out of the fan creates the high pressure against the tunnel wall and that this in turn forces the air to move up along the tunnel wall instead of backwards towards the back of the engine, and the tunnel outlet. In other words if it is important that the air moves mainly axial to cool the engine bay it would be necessary to lower the speed of the air which could be accomplished by lowering the angle of incidence. The increase in radial velocity may also in part be explained by the fact that a higher angle increases the relative area that pushes the fluid in the direction of blade movement which in this case is radial.

Number of Holes

By focusing on the velocity produced by the fan, conclusions can be drawn about the performance due to the port holes on the design. Starting to look at the plots in Figures D.27 and D.28 to investigate how the velocity changes with different parameters. First focusing on the ones with four blades. The conclusion that can be drawn is that model 4-45-4 performs best. Redoing this for each number of blades gives a result of three promising models and also an estimation of how the holes contribute to the performance. The following fans got highest results: 4-45-4, 8-30-0 and 12-30-4. This results give an estimate of a vary of 0-4 blades can optimize the performance, important to notice is that these models all have a high angle of incidence and it could be that the angle is the contributor to the results and not the holes.

Number of Blades

A high number of blades are important to take full advantage the available moment and to increase the air speed as it passes the fan but the increase of air speed does not appear to be linear.

8.4 Tests

Parallel to the simulations the concepts generated with the Taguchi array were tested in reality with a constructed wind tunnel set up.

8.4.1 Test Setup

A DC-motor is used to rotate the prototypes during testing. The DC-motor is attached to the prototypes with glue and is connected to a voltage source. The prototypes are put inside of a PVC pipe to direct the flow of the fan and to enable data collection. Data is collected with a flow calculation device, a anemometer, from the Learning Factory at Penn State. Each prototype is set to 1000 rpm, which is measured by the flash tachometer. The flow rate through the pipe is measured with a handheld anemometer. The collected data from the manometer was used to calculate the power and efficiency for each prototype.

8.4.2 Results from Tests

Calculations for the average efficiency is calculated based on equation 8.1, 8.2 and 8.3 and can then be used to calculate the efficiency for each parameter. The calculations is based on the measured values from testing, see Table 8.5. The results from calculations is in Table 8.6

$$\eta = \frac{P_{\text{OUT}}}{P_{\text{IN}}} \quad (8.1)$$

$$P_{\text{OUT}} = \frac{1}{2}\rho Av^3 \quad (8.2)$$

$$P_{\text{IN}} = \frac{V^2}{R} \quad (8.3)$$

Where η is the efficiency, P is the power, ρ is density of air, A is area of the fan, R is Resistance of the DC-Motor, v is velocity, V is voltage.

Table 8.5: Voltage and air speed at 1000 rpm

Prototype	Voltage to spin at 1000 rpm (V)	Air Speed produced at 1000 rpm (m/s)
1	7	2.1
2	7	2
3	8	1.8
4	9	3.6
5	9	4
6	8	2.4
7	11	5.6
8	9	3.7
9	10	4.4

Table 8.6: Efficiency of the nine prototypes

Prototype	Efficiency (%)
1	3.9
2	3.4
3	1.9
4	12
5	16.4
6	4.5
7	30.2
8	13
9	17.7

From the results in Table 8.6 it is possible to calculate the average efficiency for each parameter. By adding measured values from testing from each parameter. i.e. all prototypes with a 15 degrees angle is added to each other then divided by 3 to get the average. See equation 8.4

$$\text{Average Efficiency} = \frac{\text{Prototype}_{1,15deg} + \text{Prototype}_{2,15deg} + \text{Prototype}_{3,15deg}}{3} \quad (8.4)$$

The results from the calculations is showed in Table 8.7, 8.8 and 8.9 and Figure 8.6, 8.7 and 8.8. Each plot illustrate the trend and a moving reference line is also added to the graph to more clearly visualized the trend. The same procedure is carried through for the three chosen parameters; angle, number of holes and number of blades.

Table 8.7: Taguchi analysis, calculated average effience based on the angle of incidence

Angle	Average Efficiency
15	0.0307
30	0.11
45	0.203

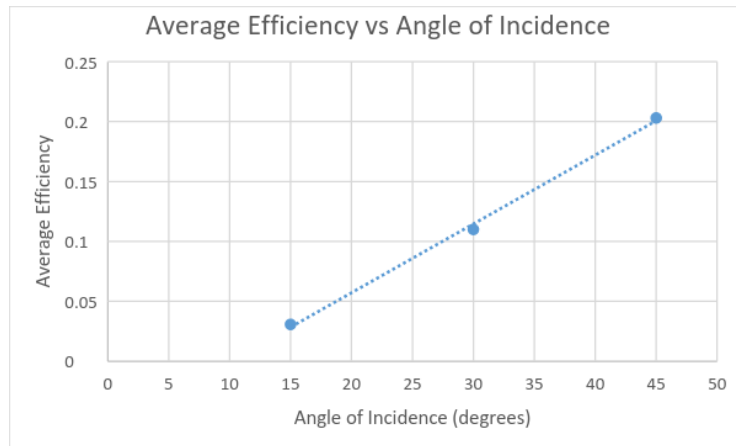


Figure 8.6: A graph showing the trend of the results given from testing the prototypes based on the angle, including a average-trendline of the results.

Table 8.8: Taguchi analysis, number of port holes

Number of Port Holes	Avarage Efficiency
0	0.154
4	0.109
8	0.0803

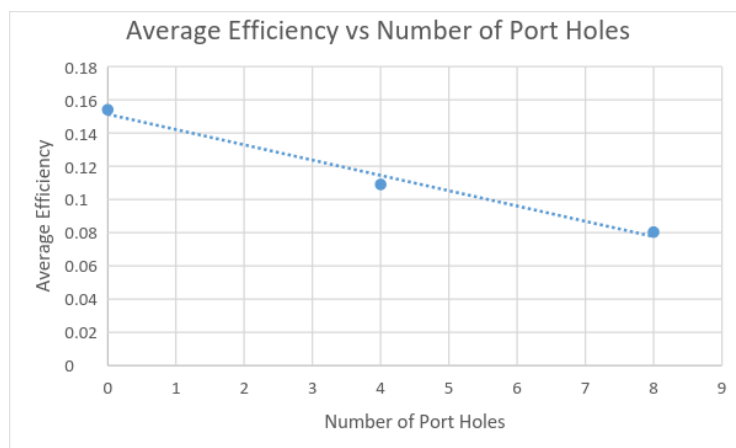


Figure 8.7: A graph showing the trend of the results given from testing the prototypes based on the number of portholes, including a average-trendline of the results.

Table 8.9: Taguchi analysis, number of blades

Number of blades	Avarage Efficiency
4	0.0713
8	0.1103
12	0.1617

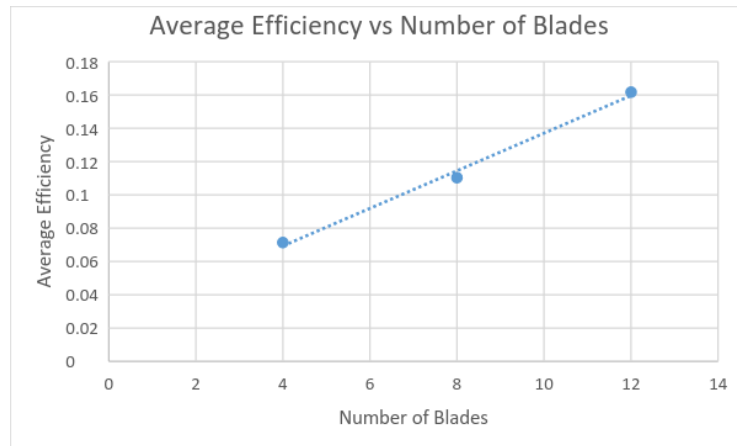


Figure 8.8: A graph showing the trend of the results given from testing the prototypes based on the number of blades, including a average-trendline of the results

8.5 Test Results Discussion

We tested nine different prototypes at 1000 rpm and obtained the efficiencies seen in Table 8.6. Based on this data and the results from the Taguchi analysis seen in Tables 8.7, 8.8 and 8.9, Prototype 7 was found to have the optimal parameters for the split blade design. From this analysis, efficiency was found to increase as angle of incidence increases as the number of blades increases. Efficiency was found to decrease as the number of port holes increases. Although the patent uses port holes, the fan is not operating at speeds for which the patent is intended, which could be a reason that they were not effective. Being only 1/4 scale and having a 30.2% efficiency, it is probably an interesting design that could result in a well performing fan in the future.

8.6 Overall Validation

Many tests and simulations have been produced and since the Taguchi model is used, the results avoid large errors due to setup errors since an average is used in the calculations. When comparing the results from testing and simulations, they do vary, but not that much. Since the results are similar to each other, the different methods validate each other. The simulations have also been produced with a finer mesh and it converges which further confirming the validity of our results. The results also confirms some of the predicted results along with the theory behind it which indicates a solid simulation- and test setup.

9

Concept Redefining and Concept Recommendation

After the first round of tests and simulations described in earlier chapters, it was still difficult to determine how port holes affects the results. Furthermore the results showed that in many cases a compromise between different designs were desirable. This chapter is based on the creation of two new designs with respect to the results given in previous chapters to test a new set of parameters that have not been tested previously and be able to determine how the holes does contribute to the performance.

9.1 Concept Redefining

The results and discussions from fluid simulations, see Sections 8.3.2 and 8.3.3, and tests, see Sections 8.4.2 and 8.5, gain new knowledge about the parameters. This optimized data about the number of holes, number of blades and angle of incidence make the concepts generated and evaluated in Chapter 7 outdated and therefore no longer interesting to go further with. Two new concepts are defined using this new knowledge gained from the refinement. The results from simulations showed that a low number of holes could be a parameter that makes the fan perform better but at the same time the tests gave the results that holes were bad for the performance. Therefore two new concepts were created, one with 0 port holes and the other one with 4 holes. All other parameters are the same on the two designs to be able to draw more specific conclusions about the holes after the next round of simulations.

9.1.1 Number of Blades

Number of blades, based on the discussions, is a large contributor to the performance and both the tests and simulations show that more blades usually give a better performance with the exception for one with 8 blades. The choice is to continue the simulations with 10 blades on both concepts and thereby also be able to use wider blades. This is a compromise between 12 and 8 blades which, according to the results, should be a high performing setup.

9.1.2 Angle of Incidence

The conclusion about the angle of incidence from the results from test and simulations is that a higher angle is advantageous in the task of moving air quicker which one of the purposes is. An angle of 45 degrees can give the effect that the fan moves the air in a radial direction instead of axial. The 45 degrees angled blades produce a high velocity but mostly in a radial direction and the 30 degrees blades produce an axial flow but not in the same speed. Thereby the angle of 40 degrees was chosen to compromise and hopefully generate a high flow velocity in axial direction.

9.1.3 Overall Design

The design is based on the existing attachment system used by Volvo where all blades are mounted on. Each blade size is optimized to use the most of the available space, this is done by measurements of the existing design used by Volvo, the portion between the leading blade and the rear blade is around 40-60 thus the first blade seems to contribute more to the performance than the rear one. All edges are rounded to minimize the point stress due to pressure on the blades and also to create a natural flow to minimize turbulence to maintain the laminar flow as far as possible. The attachment of the blades is well thought through by creating good attachment angle with large contact area in order to spread the pressure as much as possible. Beside from these changes, the other parameters are hold on the same value as earlier designs.

9.2 Structural Analysis of Redefined Concepts

Meshing

To ensure higher precision in the calculations a triangular “medium” sized volumetric mesh was generated, approximately 800 000 elements were created. For detailed mesh specification see Section 8.2.1.

Physics

The load “rotational velocity” were deployed as described in section 8.2.1. The rotation was assumed to be constant, thus the operation was set to steady state. The “Cylindrical Support” were located where the shaft would have been attached to the fan and set to fixed in all directions. A pressure load acting on the the upstream surface of the blades was applied. In addition to this a “line pressure” was applied at the leading edge of each blade if the pressure was significantly higher there than at the surface in general. The pressure applied was based on the approximate average pressure acting on the fan (see Appendix E.7c) and derived with tests described in section 9.3. The pressure was set as presented in Table 9.1. To calculate stresses and deformation the solvers “Equivalent stress (von mises)” and ”Total Deformation” were deployed. To calculate the fan’s lifetime of the the “Fatigue tool” was deployed

with stress component set to “Equivalent (von mises)” and loads set to “Zero based”. The mean stress theory was set to “SN-None”.

Table 9.1: Pressure applied by fluid flow, negative pressure indicates an upstream direction of the net force

Fan type	Mean stress on blades [Pa]	Mean stress on leading edge [Pa]
Volvo reference	-2000	0
10-40-4	-2000	-5000

9.2.1 Results from Structural Analysis of Redefined Concepts

In this section the results from the verification simulations are presented. To review plots for all tests, see Appendix E.1.

Deformation

In Table 9.2 the simulation data for total deformation is presented. Both deformations are of about the same size and quite small. In both cases and all directions the maximum deformation occurs at the blade tip.

Table 9.2: Total Deformation

Fan	Max total deformation [m]	Total deformation at tip [m]	Radial deformation at tip [m]	Axial deformation at tip [m]
Volvo reference	0.0082	0.0082	0.0048	0.00804
10-40-4	0.0081	0.0081	0.0033	0.0074

Equivalent Stress

In Table 9.3 the simulation data for the equivalent stress (von mises) is presented. The maximum stress for both fans appears at the location where the fan blades are connected to the ring that attaches to the rotating shaft. In the case of the final concept the concerned area is located to the exact point where the back of the leading root connects to the ring see Point Y in Figure 11.1. From this point the stress then spreads to big parts of the leading root of the blade. Another stress “hot spot” is at the relief hole where the leading and trailing root connect, the stress magnitude at the relief hole is approximately $3.9 \cdot 10^8$. No significant concentration of stress can be derived to the holes at the leading edge. The magnitude of the stress at the supporting trailing edge is about $1.4623 \cdot 10^8$.

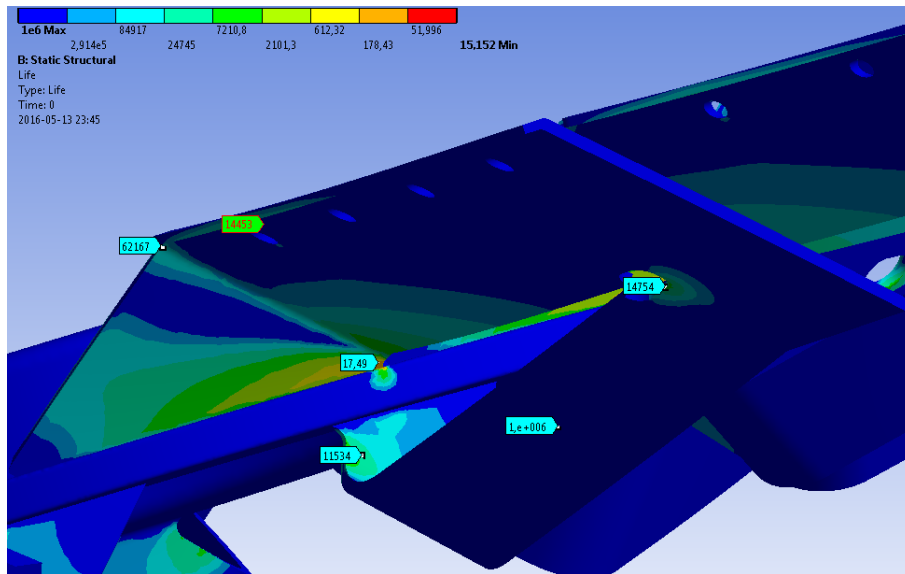


Figure 9.1: Enhanced view of life expectancy measured in cycles on the downstream surface of the final concept.

Table 9.3: Approximated global stress on the fan blades.

Fan	Stress [Pa]
volvo reference	0
10-40-4	59431

Lifetime

In Table 9.4 the range of the expected number of cycles endured by the fans are presented. In both cases the expected life is the shortest where the stress concentration is high. The entire blades for the final concept are expected to endure an "infinite" number of cycles, except for some places visible in Figure 9.1. An extra probe is added to the back of the trailing root since the shadow there makes it hard to determine to color.

Table 9.4: Lifetime

Fan	Place for longest life	Endured Cycles at blade	Place for short life	Endured Cycles at failure point
Volvo reference	Fan blades	Infinity	Connection between ring and blade stabilizer	689.07
10-40-4	Fan blades	Infinity	Connection between ring and blade	15.152

9.2.2 Discussion of Structural Performance

Only the blade with holes at the leading edge is compared to the reference fan since the two fans 10-40-4 and 10-40-0 are identical except for the holes at the leading edge. So with the exception of the characteristics added by the holes the results would have been identical.

The very low life expectancy at point Y on the final concept, see Figure 11.1, is due to the major stress concentration at this point. The main reason for this stress concentration is the many sharp edges in the local region. This is, although extreme stress values, not too damning to the concept since the concentration of stress could be avoided by improving the local geometry around the point and a improved connection to the fan-ring. The stresses in the region could be minimized further by increasing the radius at the transition between the leading root and support structure that attaches the leading root to the fan-ring. The implementation of such local improvements will not interfere significantly with the air flow and will also significantly damper the stress that spreads from Point Y to the fan blade and the support structure. It is plausible that the reduction of the stress concentration at point Y will also decrease the concentration of stress at the leading edge holes.

At the actual fan blade there are three areas of concern. These areas are

- The relief hole
- The hole at the leading edge closest to the center of rotation
- The concentration of stress where the trailing root attaches to the fan-ring.

To handle the stress concentration at the relief hole it could either be re-modeled or the radius could be increased slightly without significant effect to the air flow. The holes at the leading edge could be moved slightly towards the trailing root, but the stress concentration around these holes will probably disappear when the geometry around Point Y is improved.

The stress at the lower part of the trailing root could be reduced by increasing the width of the connecting part of the blade.

Although the pressure acting on the proposed final design is greater than the pressure acting on the reference fan the final concept performs better in all structural test. Since it is more resistant towards stress and deformation longer blades and/or higher tip speed would be possible to accomplish if requested.

9.3 Fluid Simulations of Redefined Concepts

9.3.1 Fluid Flow Setup for Redefined Concepts

For the most part the setup of the validation simulation is identical to the previous setup. For example the previously described MRF-method is used to induce fluid flow and the physics conditions are identical. The largest difference in terms of set up is the geometry of the simulated fan which in this section has been optimized to

fit the fan region and the fact that base size of the mesh in the fan-region has been decreased to better describe the geometry of the concept fan. The base-size was reduced from 7 mm to 1 mm, resulting in approximately 5600000 cells. The average velocity was calculated with the "Surface Average Report" calculating the average velocity on the interface between the fan-region and the tunnel-region. In order to calculate a more accurate solution the simulation has also been run for 5000 iterations. For a detailed guide about how the simulation was set up, see Section 8.3.1

To illustrate how the air moves through the fan-region and interacts with the fan blades the "derived parts" functions "streamline" were initialized in the fan-region.

9.3.2 Results from Fluid Simulations of Redefined Concepts

In this section the results from both the final concepts and the simulation with the reference fan are presented.

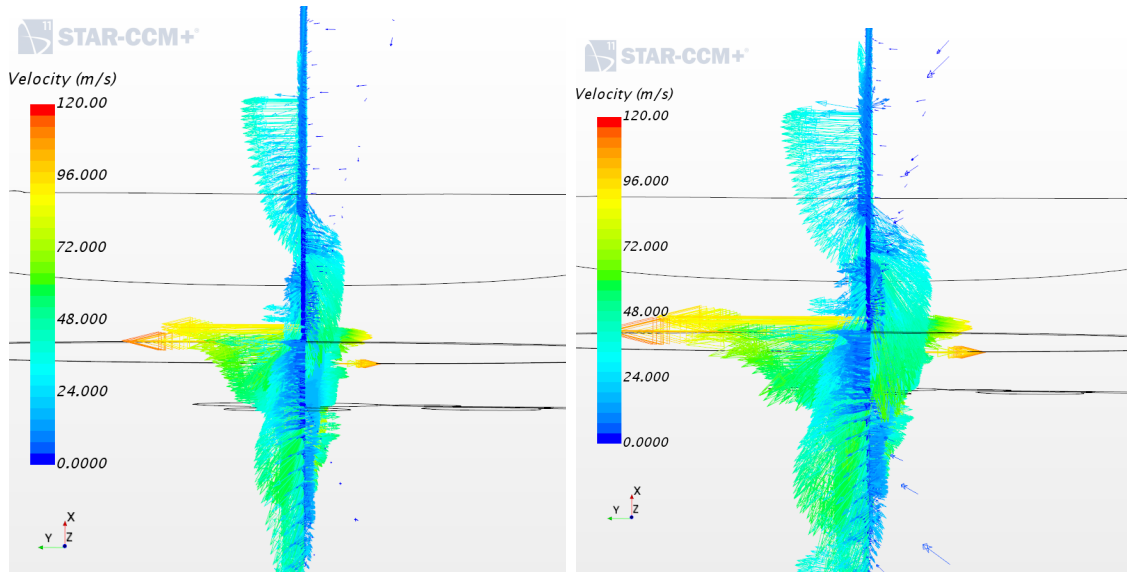
The pressure is negative upstream of both leading and trailing root, and positive downstream of both as well. The low pressure field is larger in front of the fan with holes at the leading edge. The average of the pressure in the high pressure field downstream of the fan is also lower for the fan with holes at the leading edge. In the area between the leading and trailing edge the pressure is almost the same with only minor differences. See Figure E.9 in Appendix E.2.

The final concepts generate a higher mean velocity than that of the earlier concepts, although the velocity out of the fan region is not as high as the velocity induced by the reference fan which can be seen in Figures E.10 and E.15 in Appendix E.2.

The air is moving in the same direction as the fan in the fan region, however, there is much air in rotation between the fan and the hub, see Figure E.8 in Appendix E.2.

Figure E.13 in Appendix E.2 shows that the air flow is moving backwards with quite high velocity along the engine bay for the fan with holes at the leading edge (10-40-4) while the 10-40-0 fan (the one without holes at the leading edge) generates a slower air flow that extends more radial than axial.

The fan 10-40-4 fan seems to induce more turbulence than the "10-40-0" fan. This is indicated by the length of the arrows in Figure 9.2.



(a) Fan 10-40-0

(b) Fan 10-40-4

Figure 9.2: Fan region showed from above, with arrows showing the direction of the fluid, the length of the arrow relates to the velocity in the node of origin point.

Table 9.5: Values derived from simulations

Prototype	Moment [Nm]	Force on fan [N]	Average velocity out of fan-region [m/s]	MFA minus	MFA dplus	MFA inlet
10-40-0	102.47	449.56	30.47	-10	190	189
10-40-4	101,81	624,88	30.57	-6	198	198
Volvo Reference	186.01	802.27	41.35	24	-650	-650

9.3.3 Discussion of Results from Fluid Simulation of Redefined Concepts

The same caution that applied when observing the plots that were mentioned in Section 8.3.3 also apply in this section. The final concept performs better than the one previously tested, indicating that our previous conclusions were correct. But it is important to note that the blades in the final concept are wider and therefore able to move more air. Although the new design is better than the previous it does not perform as well as the reference fan.

Two residuals were still oscillating heavily after 5000 steps but the mean is low enough to draw some conclusions. Another reason that we choose to use the results from these simulations is that overall the results are coherent with each other and theory. Although one must be carefully to draw to far reaching conclusions, this

oscillation of residuals is probably due to a velocity of 1000 m/s in a single node between the fan and the fan hub, the node where the high velocity have been removed in the presented plots.

Between the fan and the fan-hub, that is supposed to connect to the fan, there is air rotating, this occurs since it was not possible to properly connect the two parts, resulting in small area between them where fluid rotates. This effect will disappear if the two parts are connected. It is also in this area that the previously discussed 1000 m/s velocity is found.

The fan 10-40-4 performs slightly better than 10-40-0 in terms of fluid velocity, see Table 9.5, but the difference is within the margin of error especially with the oscillating residuals in mind. However 10-40-4 also seems to induce more turbulence although none of the plots derived are ideal for measuring turbulence. The cause of the small effects observed by introducing the leading edge holes could be that they are simply too small to have any significant impact with the chosen calculation method.

9.4 Concept Recommendation

The initial simulations and tests generated promising results for some of the fan designs and with this as a basis two new designs were created to test a, on beforehand, promising setup and also verify if port holes were a contributor to a well performing fan geometry or not. The results from the final simulations showed that the angle of incidence equal to 40 degrees and the number of blades equal to 10 is the best geometry evaluated in this report. The results could neither confirm or deny the impact from the port holes and thereby it is impossible to give an recommendation on that parameter. Along with the discussion in earlier sections about the results from both simulations and test this shows that this design outscore the other produced designs. Even if it does not outscore the current fan it is a interesting design and the results are promising.

Structural analysis gave the result that it does fulfill the demands, deformation and stress, by margin except some stress concentrations which can be avoided by geometrical refinement and also be able to get optimized for fluid performance without the risk of lack in structural assessment.

To summarize, the fan with an angle of 40 degrees and 10 blades is recommended and the number of port holes has to be investigated more specified to give an recommendation.

10

Proposed System Level Design

This chapter is about the overall design, explaining the most interesting parameters together with a visualization of the fan blade.

The divided fan blade design seen in Figure 10.1, is claimed to be superior to conventional blades in that it has better stall resistance, quietness, and strength; ultimately making it more efficient. The divided blade (A) alone, is not perfect in that it still has problems with cavitation and turbulence at high speeds. To alleviate these problems, port holes (B) are lined on the leading part of the blade so that air can bleed through from bottom to top. Another port hole (C) serves to reduce stress concentration where the blade splits. The leading edge (D) reduces the angle of incidence of the leading blade.

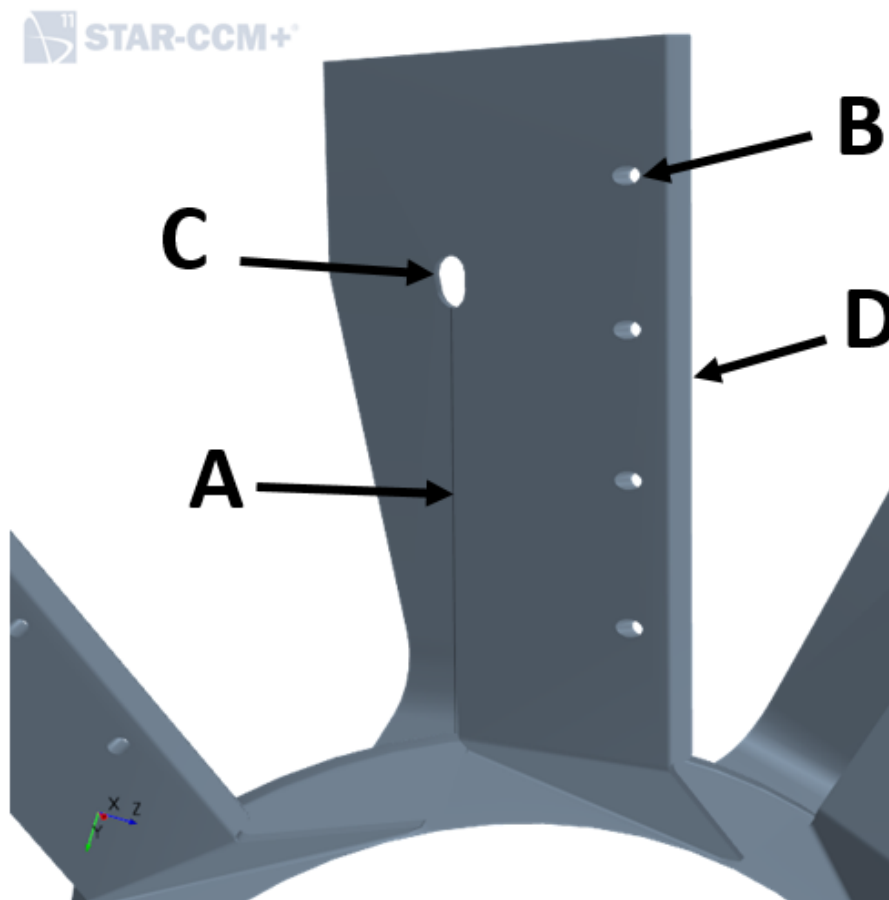


Figure 10.1: Highlighting important details on the design

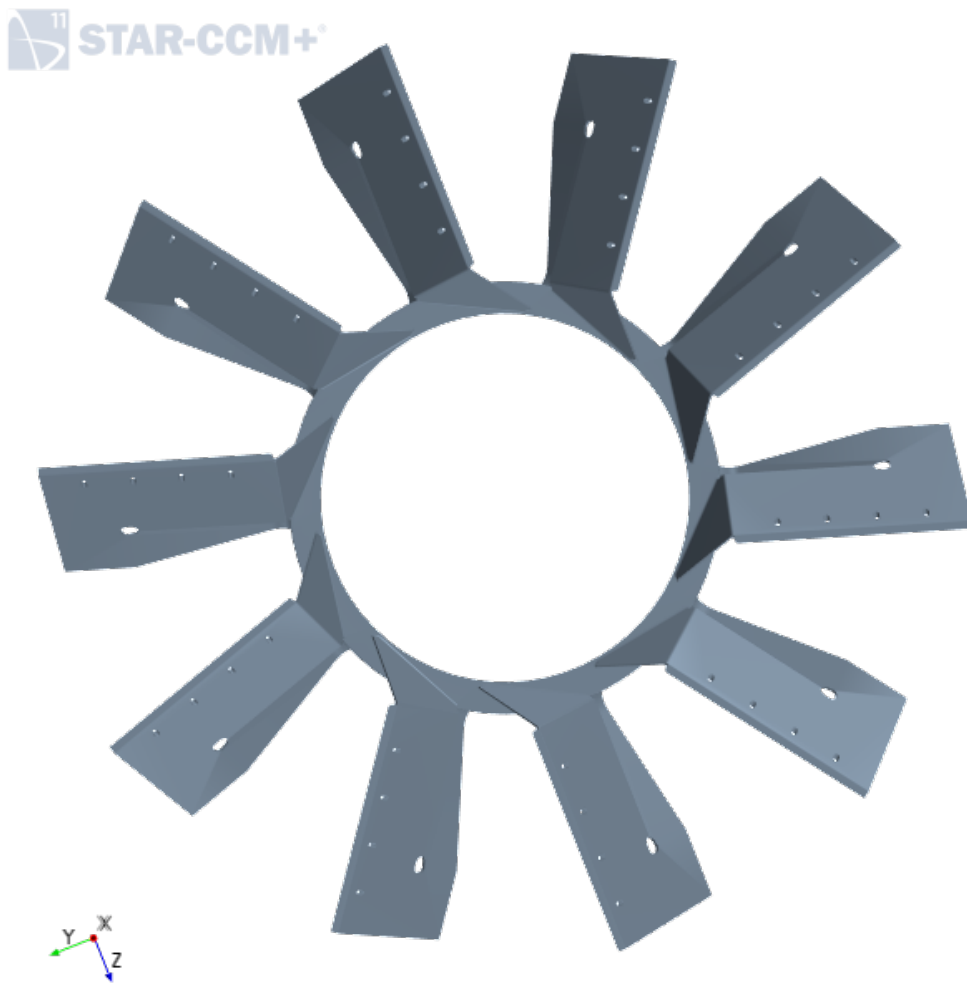


Figure 10.2: Illustrating the fan design in general

11

Detailed Design

This section is about how the final concept will be produced and manufactured, how parts will be manufactured and also how it will be assembled. Materials will be selected and discussed. Finally detailed CAD-drawings of the chosen concept will be presented to give the reader an exact explanation of the design.

11.1 CAD Drawings

In Figures 11.1 - 11.4 the details of the design are explained. To be able to illustrate the important measurements of the design, some less important parts are excluded. Rounding is not included, instead there is a global rounding of less than 3 mm. Furthermore an ISO-standard (ISO 2768-f) for tolerances is used to simplify the drawings. It is important to remember that these drawings are not made in the purpose for manufacturing thus it is made to illustrate the design in a precise way.

The design has the same base as the existing product to be able to fit it directly in to Volvo's system. This design is shown in Figures 11.1 and 11.3. Figure 11.1 also illustrates the size of the design, both inner and outer circle to ensure it fits into the shroud used in trucks manufactured by Volvo Group. Figures 11.2, 11.3 and 11.4 focus on the design of the divided blade used.

The only thing that vary this blade design with the one used in Star-CCM+ is the holes. This design has 4 holes near the leading edge and one of the designs in Star-CCM+ did not, that is the only difference.

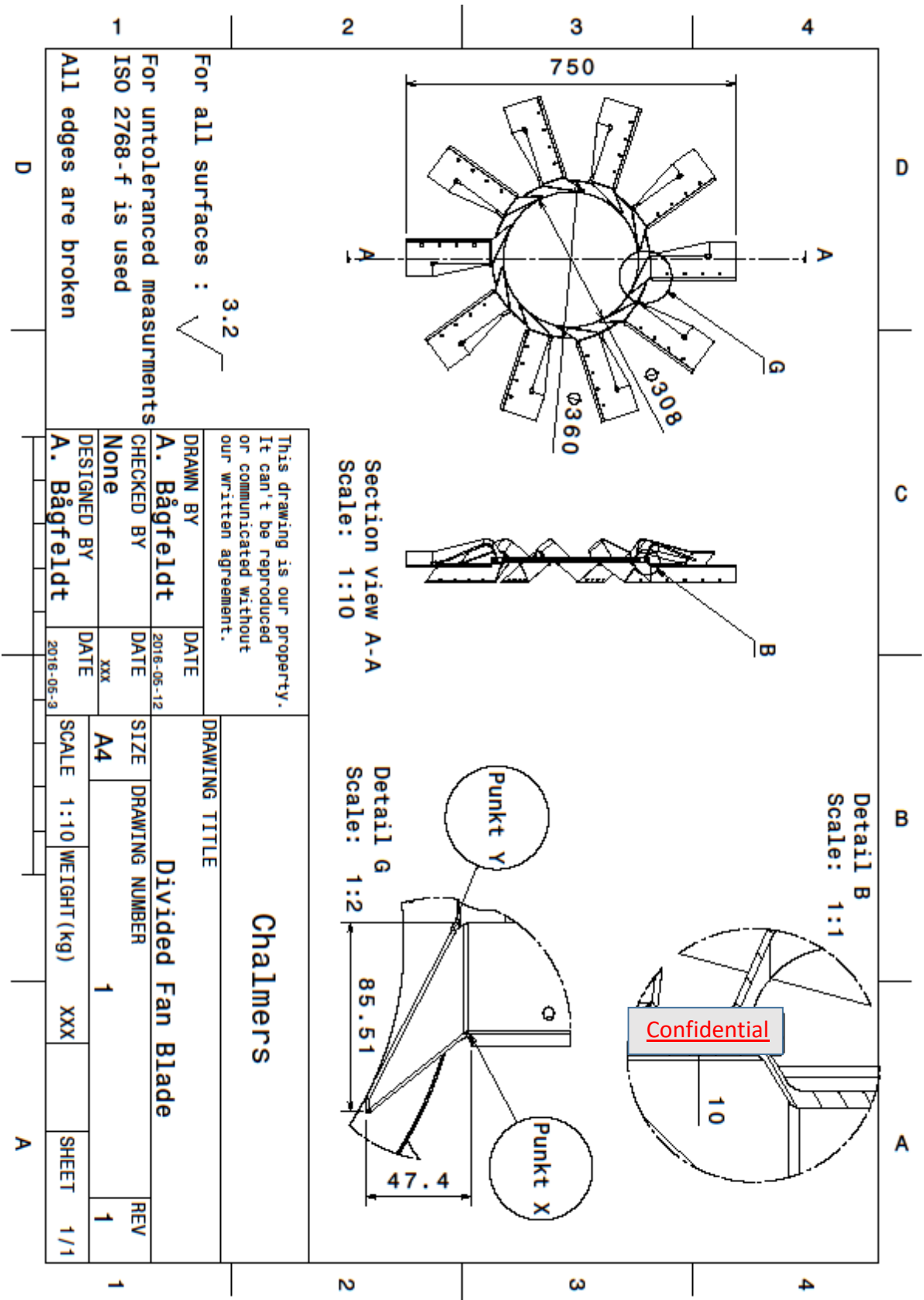


Figure 11.1: Front and detailed views of the design

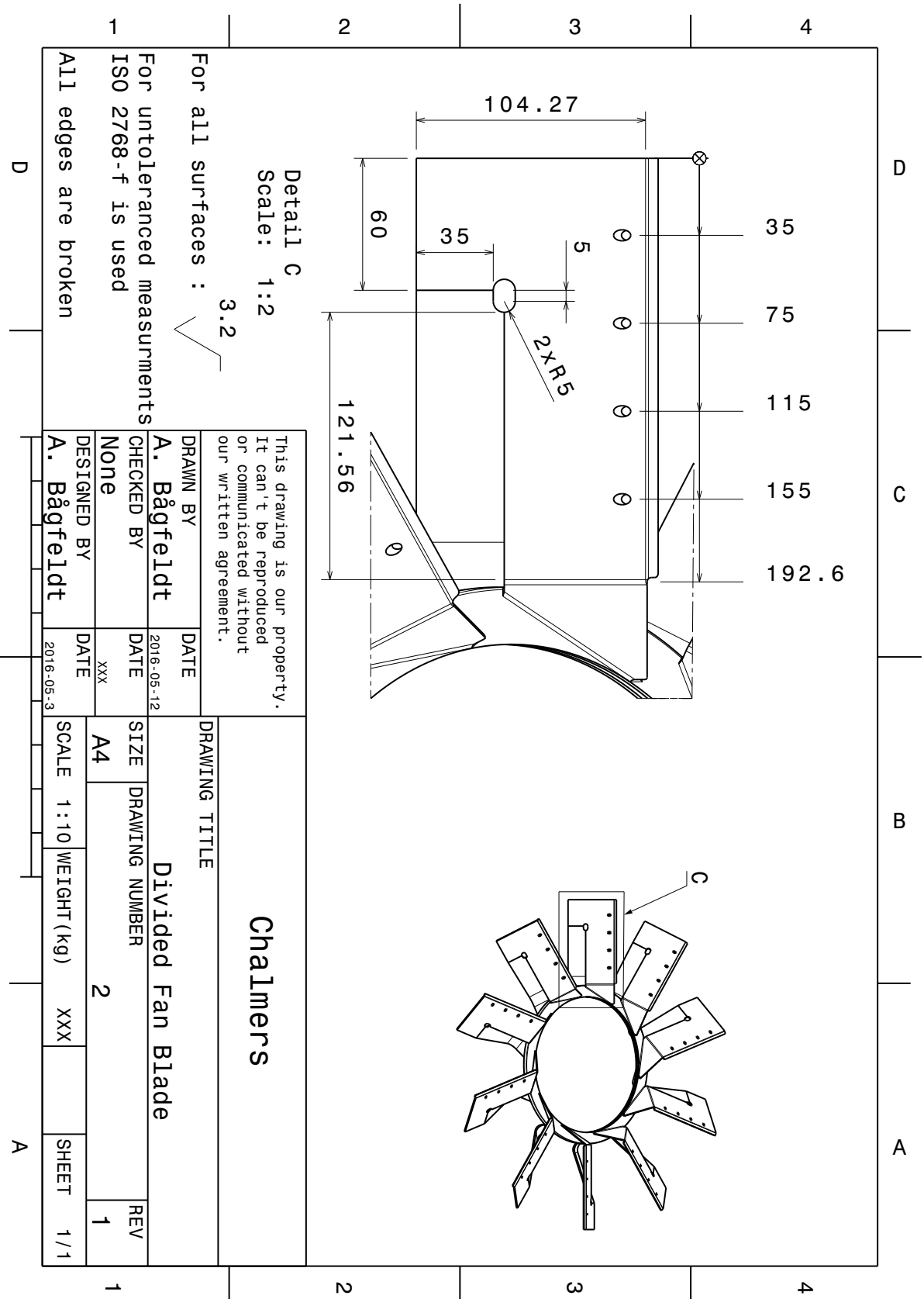


Figure 11.2: Front view of the Blade design

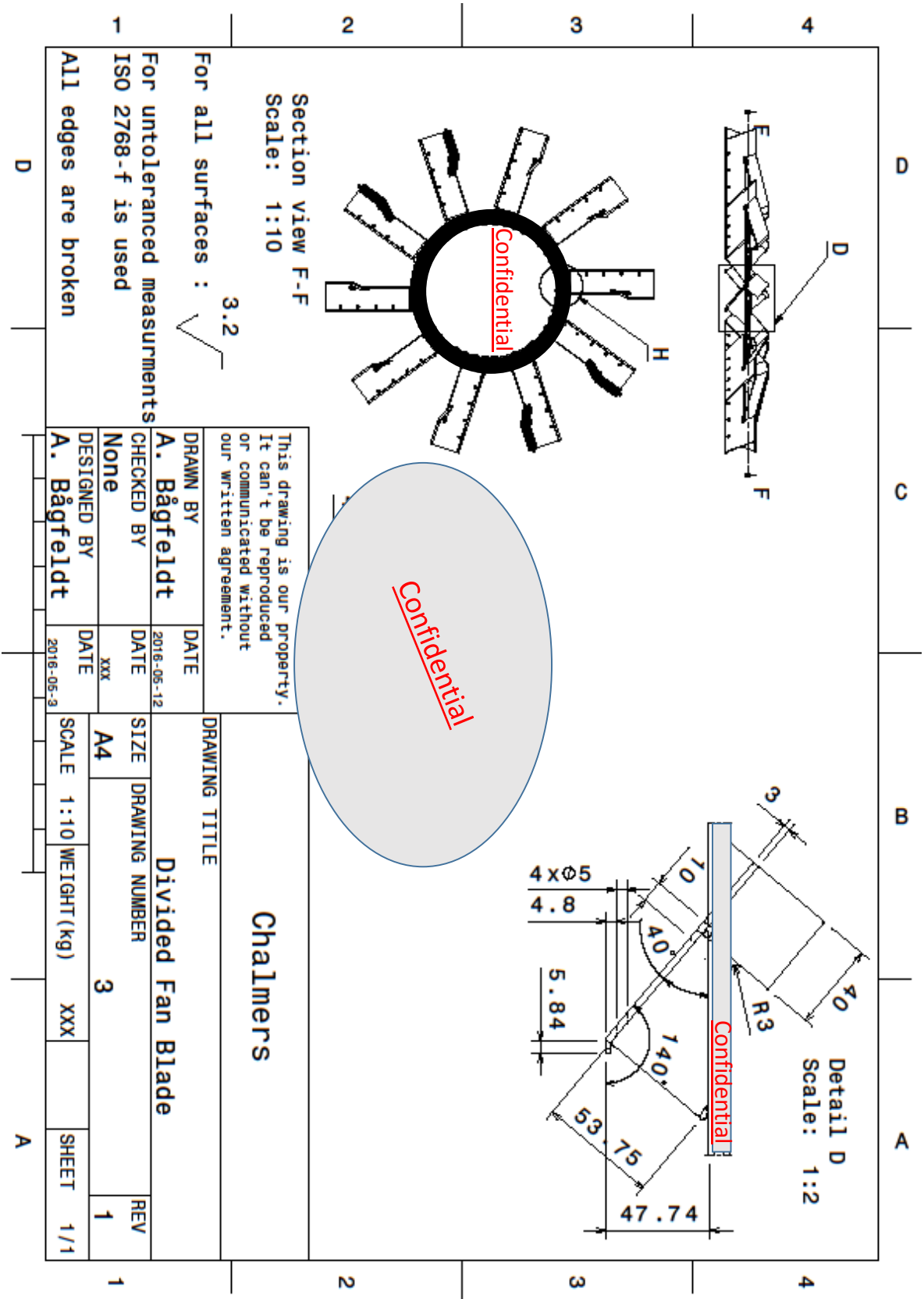


Figure 11.3: Attachment design to existing system

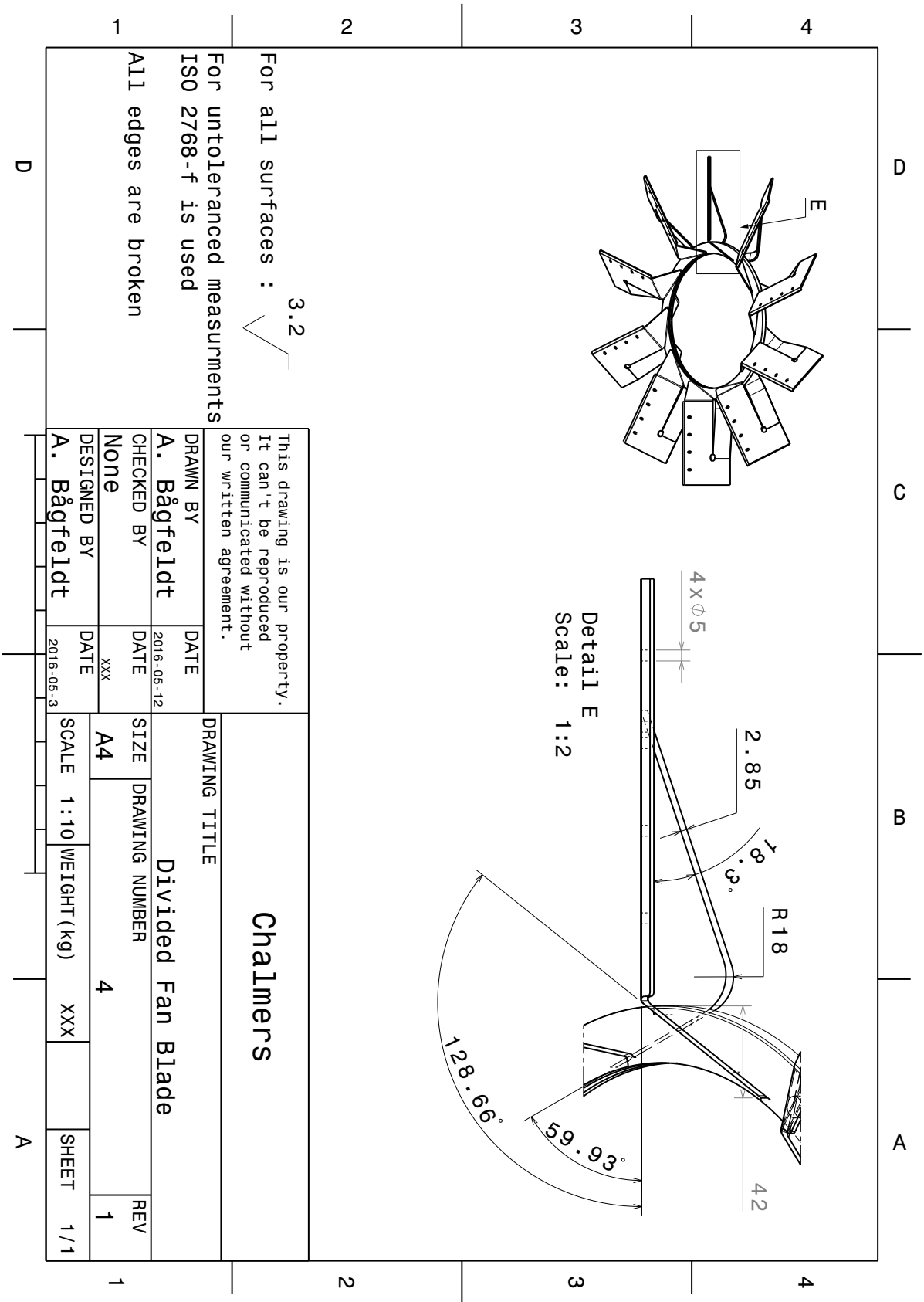


Figure 11.4: Profile view of the Blade design

11.2 Manufacturing Plan, Material Selection and Cost Analysis

This section includes a brief manufacturing and material selection plan together with a cost analysis comparing the current fan with the recommended concept with CES.

11.2.1 Material Selection

The recommendation regarding material selection is to keep the same material as for the current fan, glass fiber re-enforced polyamide, typically PA6, GF25, or GF30. The glass fiber gives the material strength but it also makes it more brittle. As the deformation in the recommended concept is less than for the current fan, especially radially, there is no need for a stronger material. Glass fiber polyamide resist sagging during manufacturing and is a good material to resist the heat from the engine [29]

11.2.2 Manufacturing Process

The recommendation regarding manufacturing process is to continue to use injection molding. The injection molding process will be slightly more difficult as the fan blade design is a more complex geometry compared to the current fan, partly because of the holes and the angled split. Even though the recommended concept is more complex than the current, injection molding is still considered the most cost effective method to manufacture this geometry.

11.2.3 Cost Analysis

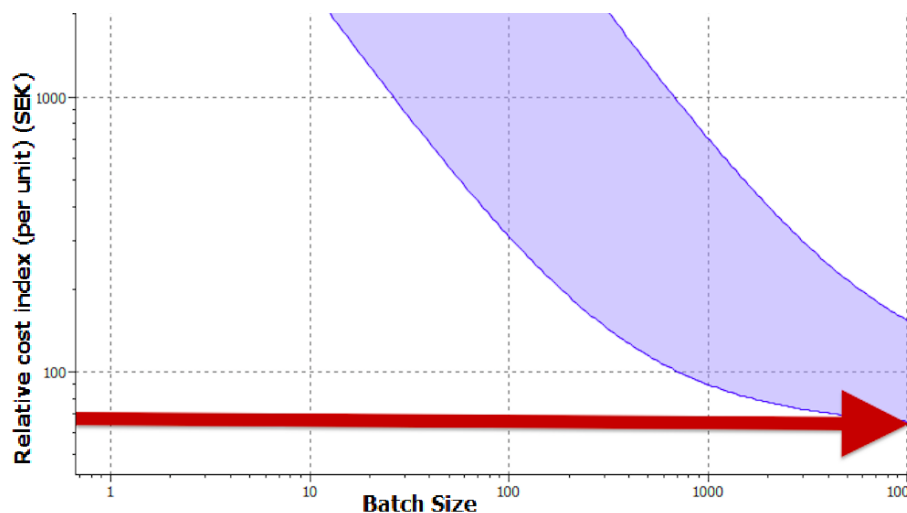
A rough manufacturing cost is calculated with CES. The base equation for the calculation in CES is Equation 11.1. An explanation to the variables can be seen in Table 11.1.

$$C_s = \frac{mC_m}{(1-f)} + \frac{C_t}{n} \left(1 + \frac{n}{n_t}\right) + \frac{1}{\dot{n}} \left(\frac{C_c}{Lt_{wo}} + \dot{C}_{oh}\right) \quad (11.1)$$

Table 11.1: Explanation of variables and constants for cost of primary shaping

Designation	Parameter	Where to find
m	Mass	From drawings + density in CES MaterialUniverse
C_m	Cost of material/kg	CES MaterialUniverse
f	Material utilization fraction	CES MaterialUniverse
C_t	Tooling cost	CES MaterialUniverse
n	Batchsize	Manufacturingplan
n_t	Tool life	CES MaterialUniverse
\dot{n}	Production rate	CES MaterialUniverse
C_c	Capital cost	CES MaterialUniverse
L	Load factor	0.6 (60%)
t_{wo}	Capital write-off time	5 years
C_{oh}	Overhead rate	500 SEK/h

Most of the input variables for the calculation is the same for both the recommended concept and the current, such as load factor of 0.6, capital write-off time of 5 years, material cost of 35 SEK/kg and a overhead rate of 500 SEK. The value of these variables is based on estimations and recommended data from CES. The only difference between the recommended and the current fan in input value is the component mass which is 1.22 kg for the recommended concept respectively 1.5 kg for the current fan. The mass is calculated by multiplying the density for PA66 with the volume for each design. The rest of the variables are decided by the CES tool and based on standard injection molding data. As the only difference between the current and the recommended concept is the mass which in turn is very small, the different plots are almost identical. Therefor only the plot for the recommended concept is showed, see Figure 11.5.

**Figure 11.5:** A zoomed CES plot describing the relative cost in respect to batch size for the recommended fan

As seen in Figure 11.5 the relative cost index is about 50 SEK at a batch size of 100,000 details for both fan designs. As the CES tool does not take the difference in tooling cost, tool life or production rate into account one can easily understand that the cost of manufacturing will be slightly more expensive for the recommended concept than the current fan because of the more complex geometry and more expensive tool needed. Exactly how much more expensive the recommended concept is cannot be decided within the limitations of this project. The recommended concept will consequently not result in any cost savings regarding manufacturing cost. Although, the recommended concept can contribute to cost savings for the costumers and therefor result in a higher costumer value and lead to higher revenues for Volvo Group.

12

Final Discussion

In this chapter will a reflection of the project and the achievements be presented. The objectives will be checked to see the fulfillment made and also a discussion about the international collaboration is included. Finally a section about the possible errors in the project group's work is presented to show what strengths and weaknesses the work has.

12.1 Methodology

The weakness of the used methodology is that the concept generation started too early in the process when the knowledge of the most important parameters was insufficient. This later forced the evaluation of the concepts to be put on hold until simulations and tests were carried out. A more efficient methodology would have been to begin with simulations and tests based on the patent “Divided rotor blade” [US 7396208 B1] in order to obtain valuable information about the parameters before starting the concept generation. If this knowledge would have been provided before the concept generation more qualified concepts would have been generated and they would be based on test and simulation data rather than assumptions. The reason this later proposed methodology was not chosen was because of early deliverables that would interfere with the simulations and tests. The strengths of the used methodology are that the early concept generation gave the project group a wide perspective of possible solutions early in the process encouraged the project group to “think outside the box” and investigate all possible parameters.

12.2 Sources of Errors in the Simulations and tests

Using the Taguchi Array to Generate Concepts

The Taguchi array is a very powerful tool to use when trying to evaluate a big range of parameters. Without running an overwhelming amount of tests. But since the analysis of the parameters is based on statistics it also requires a quite big range of variance for each parameter to show accurate results. In this project only three versions of each parameter have been tested and that could be too small of a sample for the Taguchi array to work properly.

Setting Up Meshing Criterion

Since the approach to solve the problems and questions originally stated have been heavily focused on computer simulations the meshing parameters will have a large impact on the outcome. For a detailed discussion, see section 8.3.3.

Moving Reference Frame as CFD Approach

The limitations to the approach to use a moving reference frame instead of the more accurate and realistic rigid body motion for the fluid simulations have been discussed in section 8.3.1, since this is a major source of error for this project it is recommended to review the drawbacks of the chosen method.

Faulty Conclusions from Plots

When creating plots there are primarily two things to keep in mind first it is important to be able to view the certain characteristics of a certain result while it also must be possible to efficiently compare different plots against each others. To meet both of these goals have not always been possible and therefore some of the plots describing the fan-behavior may have varying axes in order to better describe the characteristics of the tested fan. Since the evaluation of tests and results have been heavily based on the review of plots, these minor differences have shown to be difficult to fully take into account, however the results show that these minor errors have been handled effectively.

Since a computer simulation is just a model of reality that can't take everything into account a physical test was set up and executed to limit the risks and damage of faulty simulations, but also to add important data.

12.3 Project Achievement Reflection

This section will discuss the fulfillment of the objectives and purpose of the project, together with an overall discussion whether the divided fan blade is a feasible design for a radiator fan application or not .

12.3.1 Fulfillment of the Objectives

The main goal with this thesis was to develop a radiator fan for truck installation based on the “Divided Blade Rotor” patent. This has been successfully accomplished with a final concept proposal that performed very well when benchmarked against the reference fan. To prove that the final concept proposal is also feasible for mass production a preliminary study of the manufacturing cost was made. The cost analysis indicated that a fan based on the patent would be more expensive to produce than the reference fan. But we believe that the potential cost savings for customers of a more efficient fan would generate more customers and thereby increase Volvo Group's revenues.

In addition to this we also set out to investigate the certain characteristics of a fan based on the patent. Based on the test results and analyzed data presented in previous chapters we find that, with respect to the limitations of this project, the objectives connected to the goal to investigate the characteristics of a fan based on the patent "Divided Blade Rotor" have been satisfied. By the documentation and investigation of the parameters all objectives except the investigation of how the shroud and the divided fan blade interacted have been fulfilled. To use the alternative rigid body motion to fully investigate the interaction between the shroud and the divided fan blade would not have been adequate in this project as there were too many concepts to evaluate.

The final focus area of this project was to make a first assessment of whether a fan, based on the patent, could be more efficient than the conventional reference fan. From physical test it was possible to show that our best 1/4 scale divided blade prototype has an efficiency of 30.2% at 1000 rpm. Which could be compared to the reference fan's efficiency of 40%. Here it is important to notice that, in general, a small fan will have a lower efficiency than that of an identical but up-scaled fan. Further, considering the fact that only a few of the possible parameters have been optimized the result is promising. When the velocity plots of the full-scale version of this fan is compared against the same plots for the final proposal it is concluded that the final proposal is able to increase the fluid velocity even more, without increasing the moment required to rotate the fan. To reach such high efficiencies, with only there parameters investigated, we believe is argument enough to say that a fan based on the "Divided Blade Rotor" and properly fine-tuned might very well be more efficient than the reference fan. Although we have not been able to show that in this project. With this we find the objectives fulfilled.

- It has been confirmed that the divided fan blade is better at resisting deformation than the conventional reference fan. This important characteristic could be used to decrease the tip clearance which could further increase the fluid velocity.
- It has been confirmed that the divided blade operates very well at high angles of incidence.
- For blades with angle of incidences lower than at least 15 degrees the pressure is lower downstream of the fan and higher upstream. As the angle of incidence increases this pressure distribution changes and for fans with angle of incidence of 30 degrees or higher the pressure develops as could be expected, with high pressure fluid downstream of the fan and low pressure fluid upstream of the fan. The low pressure field just upstream of the blade grows as port holes are introduced.
- The global stresses in the blades are of the same magnitude, or lower than the stresses in the reference fan, the local stress concentrations we believe could be reduced by minor changes in the local geometry at those points.
- To be a viable alternative for Volvo Group the fan had to to have a life expectancy of approximately 20 years, and the preliminary calculations indicate that the divided fan blade could very well met this target value.

- The results indicate tendencies of less required moment for the the divided fan blade to move the required amount of air, see Table 9.5. However this has not been properly confirmed yet.
- In the physical tests the fans with port holes performed very poorly, this effect however has not been confirmed by the tests in STAR-CCM+ although there is some evidence that the holes create a lot of turbulence. At this point it not possible to neither confirm nor discard the claimed advantage of port holes, at least not at the type of fan we benchmarked against.
- It has not been possible to derive any reliable data about the mass flow. However the velocity plots, and Table 9.5 indicate that a fan based on the divided fan blade proposals, if properly designed, can approach the air flow velocities of the reference fan.
- It has not possible to give any viable results about how this specific fan design interacts with the shroud, due to the simulations method used.
- This thesis has not set out to research the blades performance at supersonic speeds, resistance against cavitation effects or accelerated stalling at high angles of incidence.

12.3.2 Fulfillment of the Purpose

The following purpose was stated in section 1.3:

The purpose of this project is to develop a fan blade design based on the patent “Divided blade rotor” [US 7396208 B1], that is applicable for a Volvo radiator cooling fan. It also includes an investigation of its performance and a comparison against Volvo’s current fan.

This work does fulfill the purpose, a new fan design have been developed and it fits the existing system used in Volvo trucks. The blade design is very similar to the patent in the purpose with a couple of changes in the design to fit the specific product area. The new fan design have been tested with prototypes and simulated in STAR-CCM+ and ANSYS to ensure its performance. The current fan design is also simulated with the same setup to be able to compare the newly developed design to Volvo’s current design on equal basis.

12.4 International Collaboration

One of the objectives of the project was to learn to work in a global product development team, and this has been a central part throughout the project. To begin with the start-up of the project was a bit more time consuming than for non-international collaboration teams. The general communication took more time in the beginning because of the inexperience in the technical equipment and administrative problems such as different phone numbers for different meetings, problems in accessing the communication portal among others. As soon as these things got in order, only a few communication problems remained; the distance, the language and the time

difference. These problems are unavoidable in these kinds of international collaboration teams but this has been something the project group has been aware of and continuously been working on to mitigate. One problem with the distance is that it easily divides the project team into geographical sub-groups. This is because it is easier and less time consuming to communicate face to face. Although, in order to maximize the benefits and advantages of an international project team it is important to keep the perception of being one group that is task oriented rather than divided by geographical conditions. The problem regarding language is enhanced by the distance as the use of body language is limited and cant be used in the same extent to support speech. The time difference of six hours resulted in only three common working hours(expected working hours 8am-5pm). In order to coordinate work, a good time plan and flexible communication were required. The PSU students got the opportunity to visit Chalmers and the students from Chalmers got the opportunity to visit Penn State University, both trips were sponsored by Volvo Group. This affected the project in a positive way. A personal relationship was established, which resulted in a greater understanding and respect for the team members and the project.This was also a good way to prevent and mitigate conflicts and misunderstandings. Personal strengths and weaknesses were discovered which led to a smarter allocation of tasks and resources among the team members.To maximize the outcome of the project and minimizing the problems in communication, this trip should have been arranged earlier in the project. A recommendation from the project group is to plan this trip around the delivery of the planning report.

13

Conclusion

The purpose of this project is to develop a fan blade design based on the patent "Divided blade rotor" [US 7396208 B1], that is applicable for a radiator cooling fan, in a Volvo Group truck installation. It also includes an investigation of its performance and a comparison against Volvo's current fan.

To achieve this purpose, a number of objectives were defined. As the fulfillment of these objectives also describes the fulfillment of the project achievement, a bullet list of the objective fulfillment is presented:

- A recommended concept has been developed based on the divided fan blade technology
- It has been confirmed that the divided fan blade is better at resisting deformation than the conventional reference fan with the same amount of material.
- The global stresses in the blades are of the same magnitude, or lower than the stresses in the reference fan
- The preliminary calculations for the life expectancy of the divided fan blade shows that the blade would meet the target value of 20 years.
- No reliable data about the mass flow have been calculated, but the closely connected velocity magnitude indicate that the mass flow of a fan based on the divided fan blade could match that of the reference fan if further developed.
- The velocity plots from simulating the recommended concept indicate that it approaches the air flow velocities of the reference fan.
- It is not possible to give any viable results about how this specific fan design interacts with the shroud.
- Pressure distribution for the recommended concept develops with high pressure fluid downstream of the fan and low pressure fluid upstream of the fan. The low pressure field just upstream of the blade grows as port holes are introduced.
- The results indicate tendencies of less required moment for the the divided fan blade to move the required amount of air. However this has not been properly confirmed yet.
- From physical testing it is possible to show that the best 1/4 scale divided blade prototype has an efficiency of 30.2% at 1000 rpm. This can be compared to The reference fan's efficiency of 40%.

Although not all of the objectives have been fulfilled, a new fan design have been developed and fits the existing system used in a Volvo Group truck. The blade design is based on the divided fan blade technology presented in patent "Divided rotor

blade". Two of the parameters of the recommended concept have been optimized successfully, the angle of incidence which is set to 40 degrees and the number of blades to 10. As the divided fan blade, with only 2 parameters optimized, is confirmed to resist better against deformation than the reference fan, approaches the same air flow velocity,...., there are good arguments for a continued analysis and future work of this fan design.

13.1 Future Work

The number of holes was the parameter that could not be optimized in this project because of the inconclusive results from simulations and tests, therefor this have to be further investigated with a slightly different set up.

Moreover six of the parameters still remains unanalyzed after this project and simulations and testing therefor have to be carried out using same set up to get this information in the future. When all parameters is analyzed and optimized a definite comparison against the reference fan can be made. Only then a complete conclusion regarding the the efficiency compared against the reference fan can be made. And the and of applying a divided fan blade technology into a radiator fan for a Volvo truck.

If the design proves to perform good enough, a more careful selection of materials should be done to ensure using the most preferably material available to minimize environment footprint and ease of manufacturing. A more specified cost analysis should be conducted based on both materials and manufacturing to ensure a minimized construction cost.

Finally, if the design can compete with Volvo Group's current fan on all levels, pitch the design to Volvo and advise them to implement it to their system directly.

14

Self-Assessment

This chapter is an evaluation of the project group's work and how it was able to fulfill the customer needs and also how well it did fulfill the work in general. The evaluation is based on a scale between 10-1 where 10 is perfect.

14.1 Customer Needs Assessment

The goal with this project was to develop a fan based on the divided blade rotor patent, and in that process also gather knowledge about the characteristics and behavior of a fan based on this design. With a limit in time and money all interesting parameters could not be tested within the scope of this project but it has been discussed in section 13.1 how further research and testing could be approached. Since a fan based on the proposed patent have been developed and additional information have been gathered and presented it is the groups opinion that the customer needs have been met.

The customer would preferably also receive a prototype design that could be tested against their current fan. Such a full scale prototype has not been developed but with the attached drawings the customer could easily produce such a prototype after handling the observed stress concentrations. With this full scale prototype, the rest of the customer needs will be met.

On a scale from 1 to 10 the group finds the customer needs met with a 10.

14.2 Global and Societal Needs Assessment

The team has met global and societal needs during this project as well. This also counts as a "10" on a scale of 1-10 based on what applies to this project in this category. Factors such as safety, environment, sustainability, and basic human needs have been taken into account.

For example, the structural integrity of the final prototype have been taken into account to make sure it is safe for testing as well as future production use. This will include the sustainability and life of the fan which also ties into environmental factors. The longer the life cycle of this fan, the better it is for the environment overall as less resources have to be used to continue using this product because replacements will not be necessary as often. The global and societal needs were met.

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A

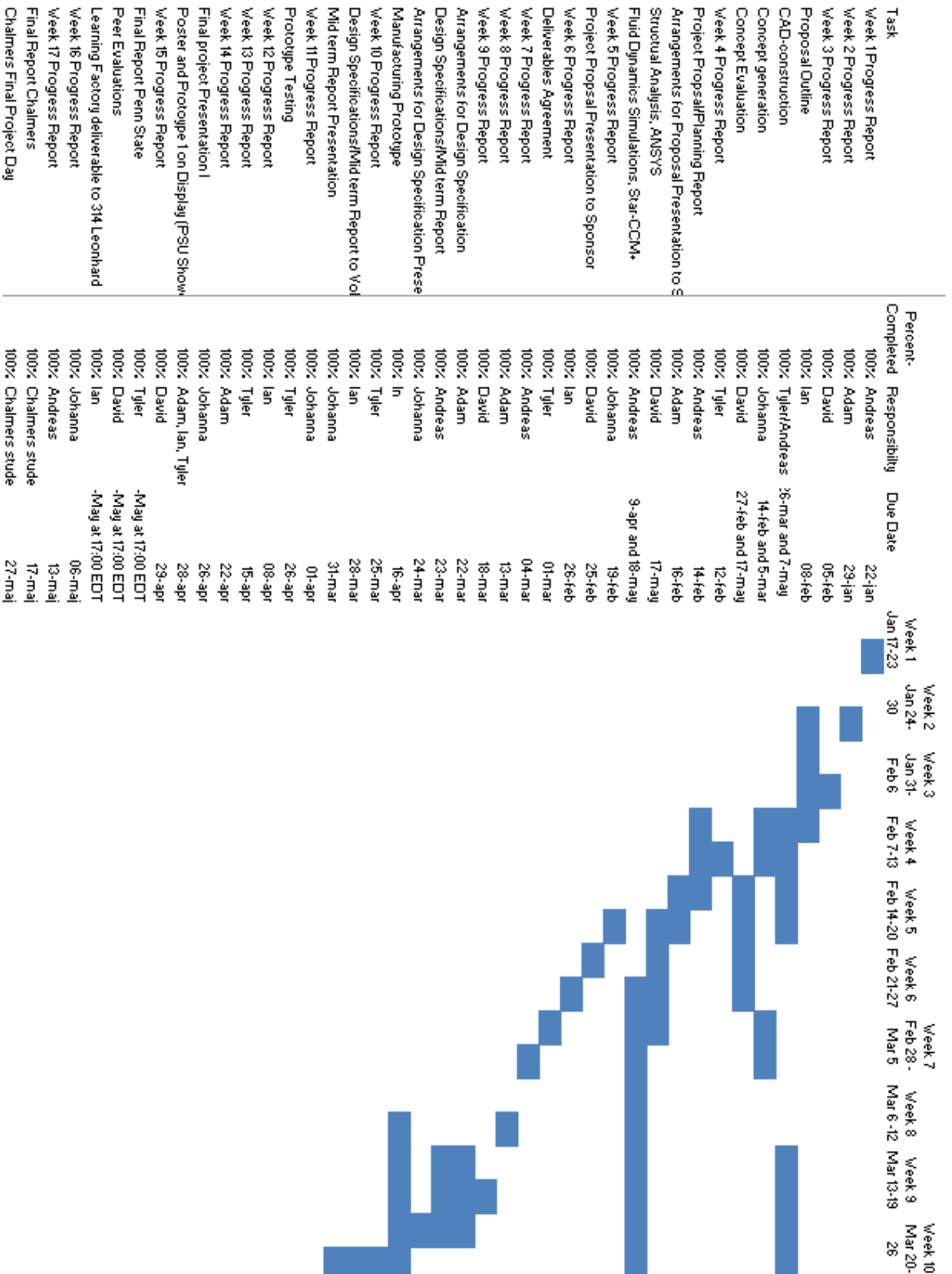
Introduction and Project
Management

A.1 Budget

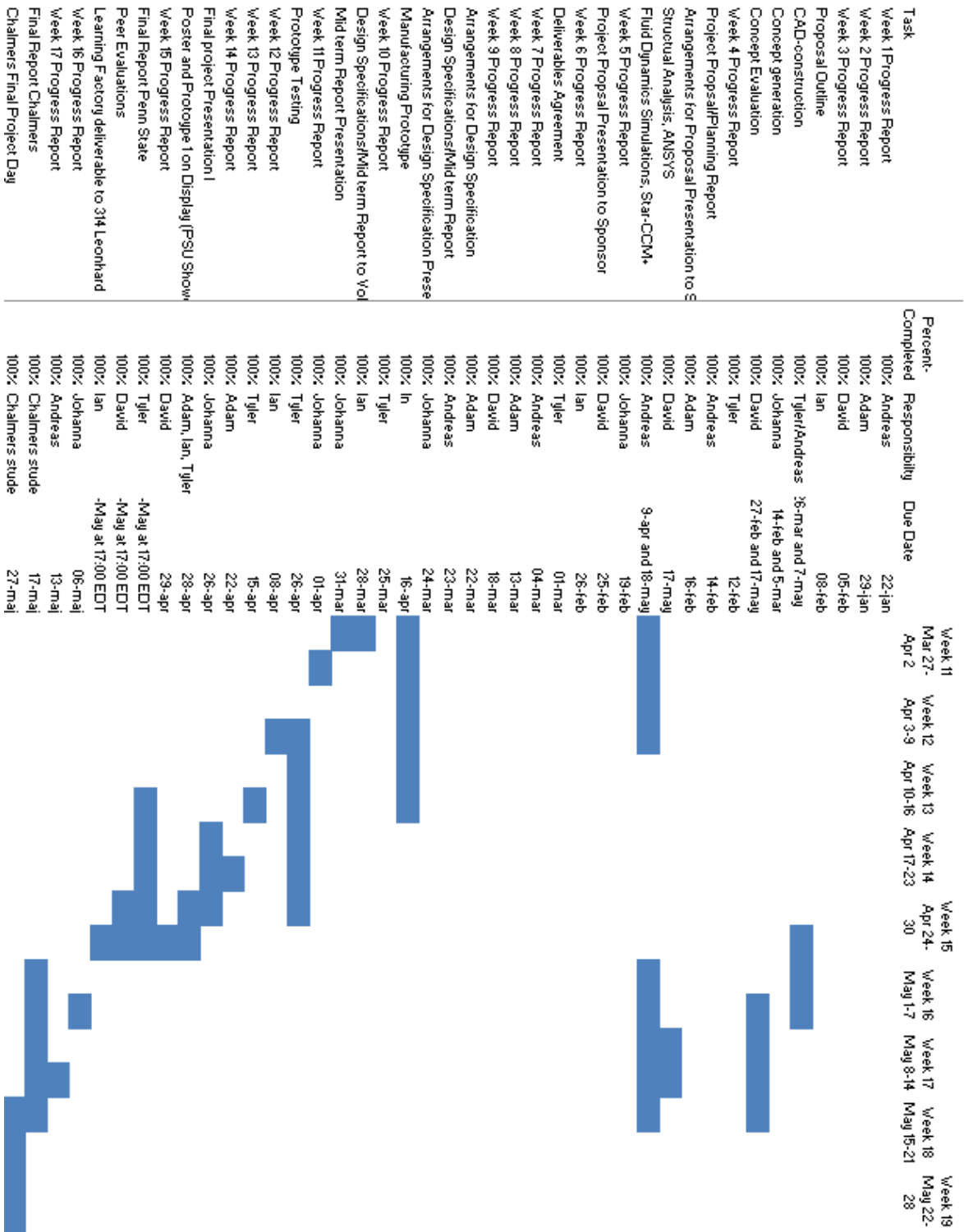
Table A.1: Budget

	Income [USD]	Outgoing [USD]	Comment
PSU Sponsoring	1,000		All materials should be included
Chalmers sponsoring	220		Materials are free of charge, amount could be reconsidered upon request
Monitor/Poster, PSU		5	
3-D Printing, PSU		250	9-10 quality downscaled 3-D printed prototypes
Prototype materials, PSU		300	Steel Sheet Metal 10 sq feet
Prototype Shipment		200	Estimated cost from USA to Sweden
Travels		100	To sponsor meeting
Special products, prototype Sweden		100	Products that Chalmers can not provide
Sum	1220	955	

A.2 Gantt Chart



A. Introduction and Project Management



A.3 Risk Analyze

Table A.2: Risk Plan

Risk	Probability	Impact	Overall	Actions to Minimize	Fall Back Strategy
Unable to deliver reports	5	10	50	<ul style="list-style-type: none"> - Good planning - Gantt chart with good structure - Weekly update - Internal deadline - Good communication - Rise a warning sign when needed to inform the team 	<ul style="list-style-type: none"> - Discuss the problem with the sponsor - Rearrange workload
Incorrect analysis and simulations	5	10	50	<ul style="list-style-type: none"> - Check one extra time before start - Begin early so it won't affect the result 	Start with simple simulations/analysis to have some results
Simulations more complex, time consuming	8	5	40	Start in good time	Begin with small simulations, at least have some results
Missunderstanding of tasks	7	5	35	If something is unclear, always ask supervisor or sponsor	
Loss of data	3	10	30	Use reliable storage	Constantly backups
Two separated groups that work one by one	6	5	30	Good planning and communication	
Lack of experience and knowledge within software's and manufacturing	5	5	25	Ask experts and supervisors for tutorials and help	Downsize the work to a level that we master
Unhealthy workload	7	3	21	<ul style="list-style-type: none"> - Realistic time management - Realistic scope of work - Even out workload if it is uneven 	Reasses what is important

A. Introduction and Project Management

Resources needed at the same time	4	4	16	- Start in time - Planning and communication	Decide whats most important
Miss understanding and long time span for answers from sponsor	3	5	15	Plan ahead and always try to be specific in all questions	
Conflicts within the group	4	3	12	- Group exercises - Well documented communication	Plan ahead
Prototype manufacturing run out of time	3	3	9	- Scale down complexity - Start in good time	Well performed drawings and CAD-models
Not able to generate enough concepts	3	3	9	Use time needed to brainstorm	
Lack of information at the generation phase	2	3	6	- Plan ahead - Ask sponsor and set a deadline to get answers by	Use the informations known and fill in as we get more information even if it is later than expected

B

Customer Needs Assessment & Engineering Specification

B.1 Needs-Metric's Matrix

Table B.1: Needs-Metric's Matrix

Product-Specification / Customer-Needs	Priority	Double Blade Design	Optimized Angel Incidence	Optimized Air-Hole Placement	Optimized Air-Hole Size	Diameter	Thickness	Material
Lower Fan Speed	5	X	X	X	X	X		
Greater Air Flow	3	X	X	X	X	X		
Lower Power Input	2					X		X
Noise Reduction	1		X			X	X	
Weight Reduction	1				X	X	X	X

C

Concept Generation and Evaluation

C.1 Generated Concepts

Concept 1, Contra-rotating part

This concept is described more in detail in section 5.2.4

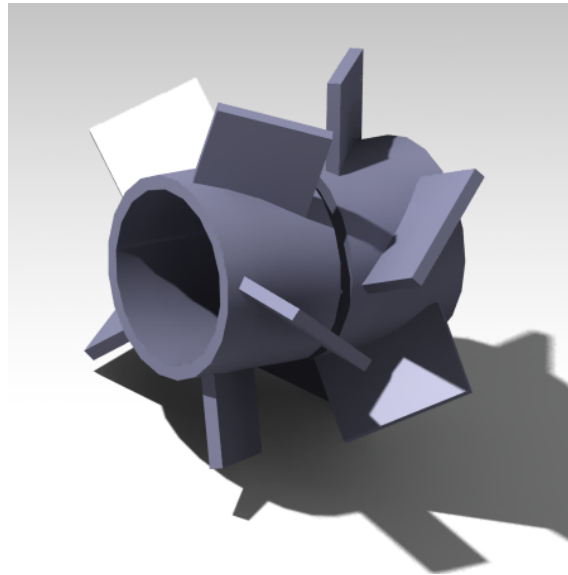


Figure C.1: CAD rendering of a Contra-Rotating fan

Concept 2, Curvey

This concept is inspired from the classic wing geometry with a slightly curved leading part, together with the divided fan blade design.

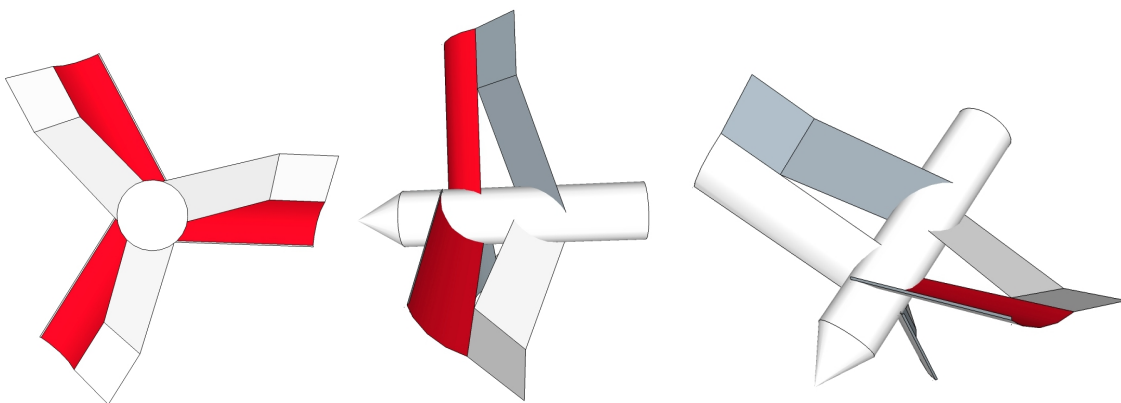


Figure C.2: Divided fan blade with curved leading part

Concept 3, Bent

In the original divided fan blade design the leading blade has a bent edge. In this concept the trailing part has a bent edge as well.

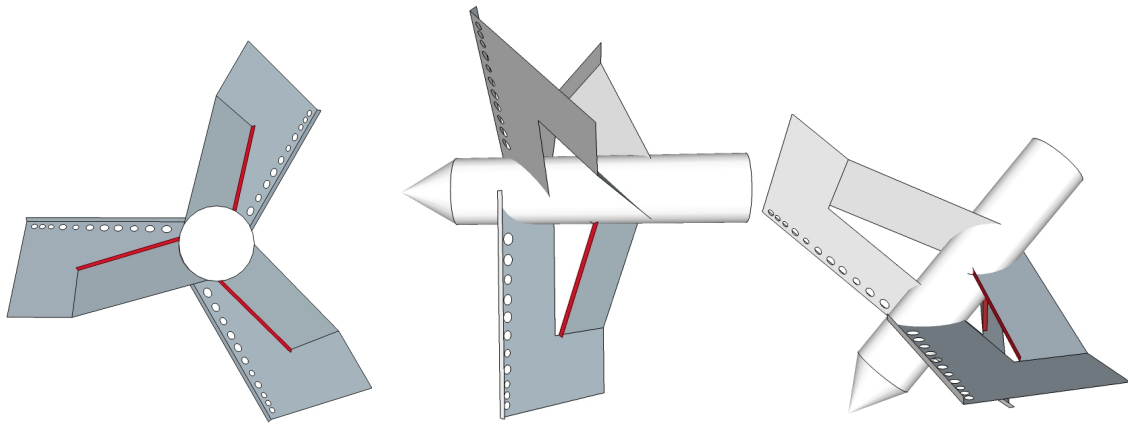


Figure C.3: Divided fan blade with bent trailing edge

Concept 4, Rounded

This concept describes the divided fan blades with rounded edges. The blades are also slightly larger than the one in the patent.

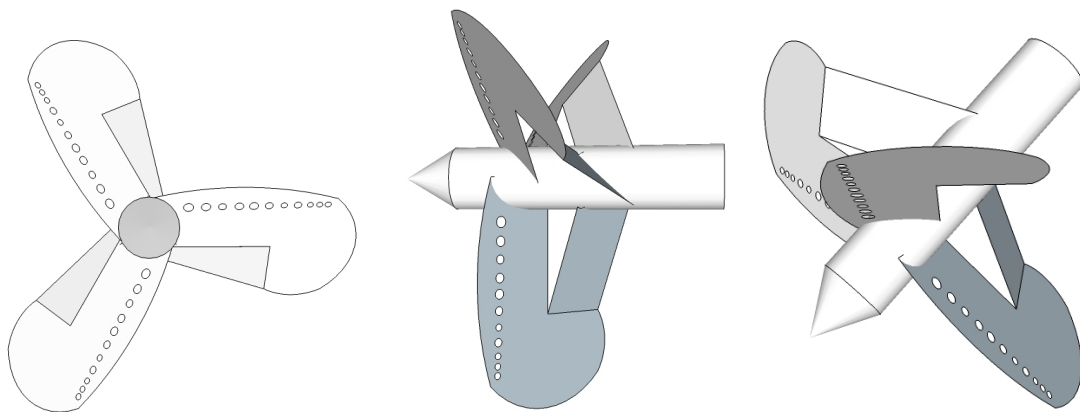


Figure C.4: Divided fan blade with rounded blades

Concept 5, Morf 1

A2+B2+C3+D2+E3+F1+G3

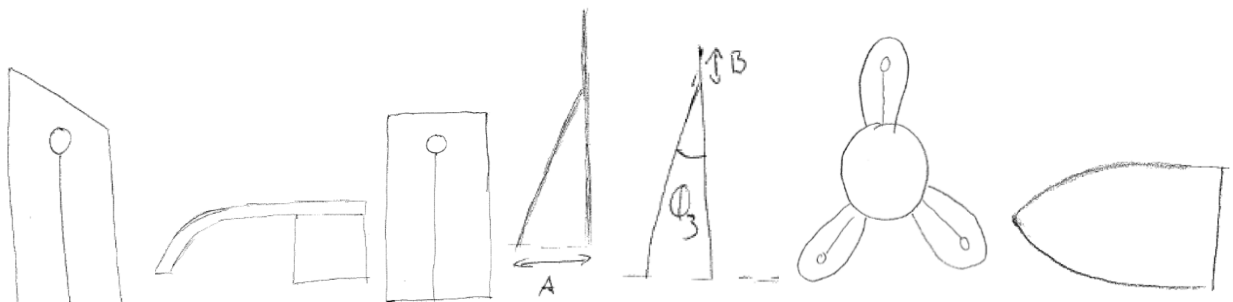


Figure C.5: Morf 1

Concept 6, Morf 2

A1+B1+C1+D1+E2+F2+G2

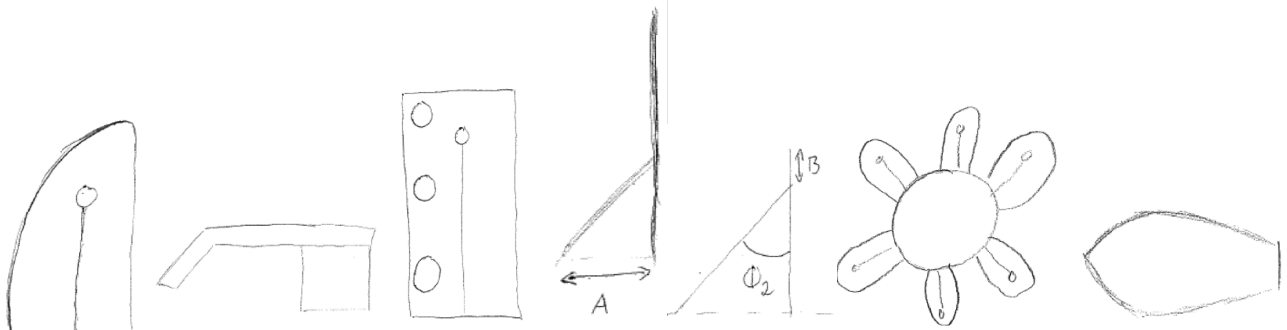


Figure C.6: Morf 2

Concept 7, Morf 3

A3+B1+C2+D2+E1+F1+G3

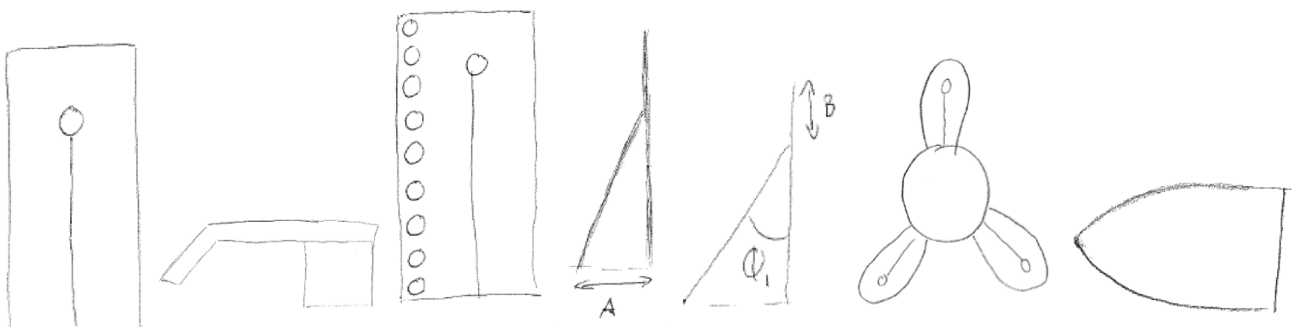


Figure C.7: Morf 3

Concept 8, Morf 4

A4+B3+C1+D3+E2+F3+G3

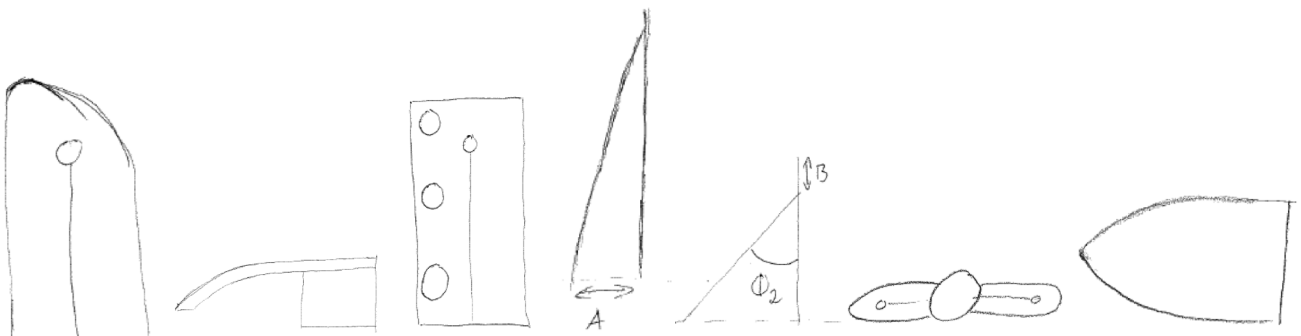


Figure C.8: Morf 4

Concept 9, Morf 5

A5+B3+C1+D2+E3+F2+G1

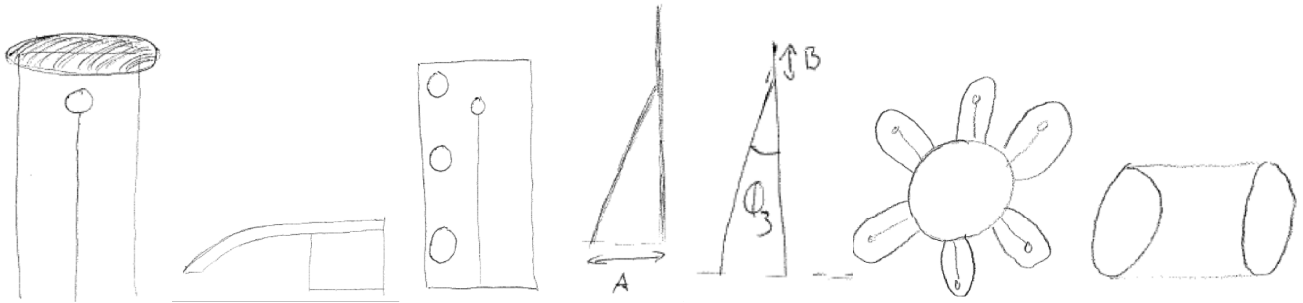


Figure C.9: Morf 5

C.2 Concept Evaluation

Criterion	Concepts						
	Reference, Concept 5, Morf 1	1. Curvey	2. Bent	3. Rounded	7. Morf 3	8. Morf 4	9. Morf 5
Minimize tip vortex		-	-	+	-	+	+
Minimize turbulence		+	-	+	0	+	-
Power input		-	-	-	+	+	-
Shear stress		+	0	0	0	-	-
Von Mises strain		+	0	0	0	-	-
Deformation		0	0	-	0	-	-
Number of "0"		1	3	2	4	0	0
Number of "+"		3	0	2	1	3	1
Number of "-"		2	3	2	1	3	5
Netto		1	-3	0	0	0	-4
Ranking	2	1	3	2	2	2	4

Figure C.10: The first Pugh matrix with Morf 1 as reference

Criterion	Concepts						
	Reference, Concept 8, Morf 4	1. Curvey	2. Bent	3. Rounded	5. Morf 1	7. Morf 3	9. Morf 5
Minimize tip vortex		-	-	-	-	-	+
Minimize turbulence		-	-	0	-	0	-
Power input		-	0	-	-	-	-
Shear stress		+	0	+	+	+	-
Von Mises strain		+	0	+	+	+	-
Deformation		+	+	+	+	0	-
Number of "0"		0	3	1	0	2	0
Number of "+"		3	1	2	3	2	1
Number of "-"		3	2	3	3	2	5
Netto		0	-1	1	0	0	-4
Ranking	2	2	3	1	2	2	5

Figure C.11: The third Pugh matrix with Morf 4 as reference

D

Concept Refinement with Ansys, Star CCM+ and Testings

D.1 CAD-model- Physical prototype

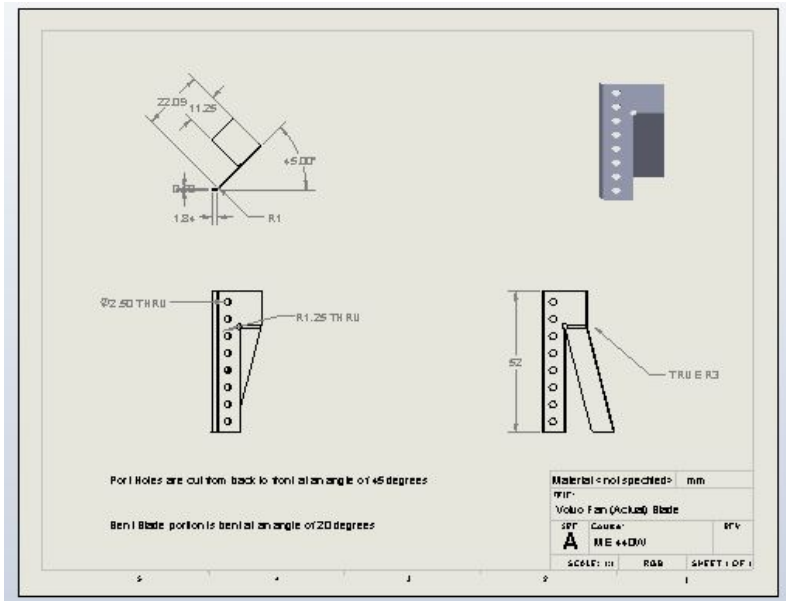


Figure D.1: A drawing of the fan blade geometry, shown in different views with measurements

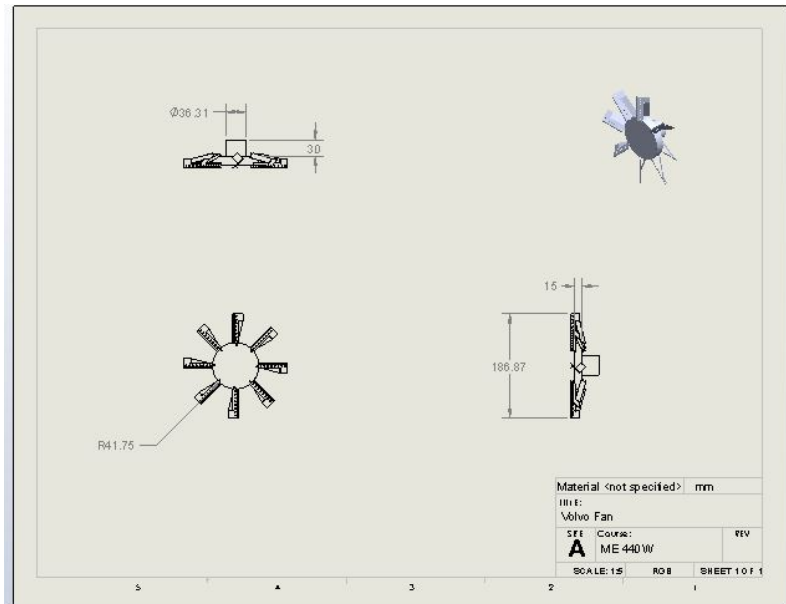


Figure D.2: A drawing of the whole fan geometry with outer measurements shown to ensure the fan to fit inside the shroud

D.2 CAD-model - Fluid Dynamics Simulation

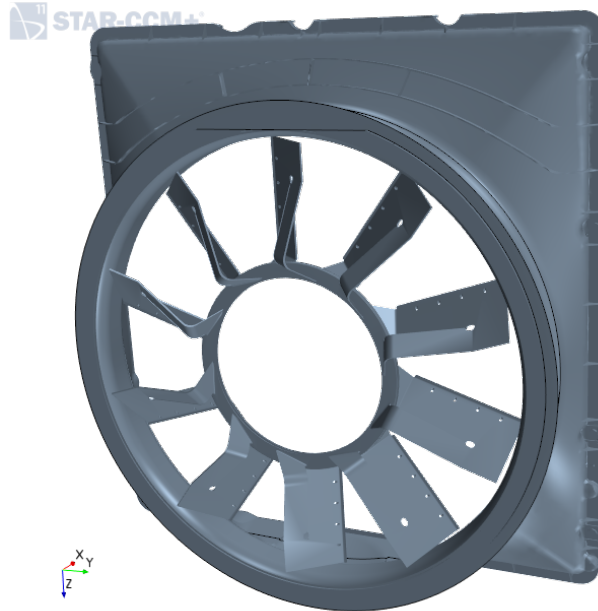


Figure D.3: Isometric view on one of the stripped down CAD-model of the developed design used in Fluid Dynamics simulations.

D.3 Finite Element Analysis

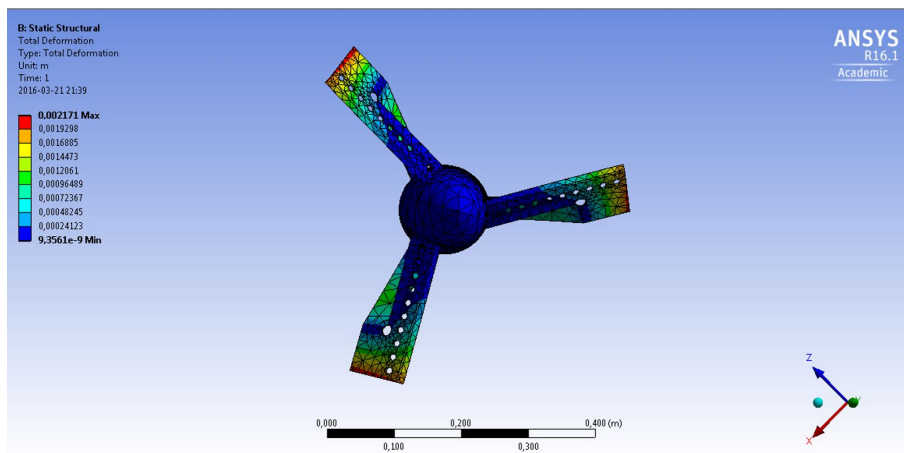


Figure D.4: Total Deformation plot for a blade of length 222mm with split of 150mm, max deformation is 0.002171 m

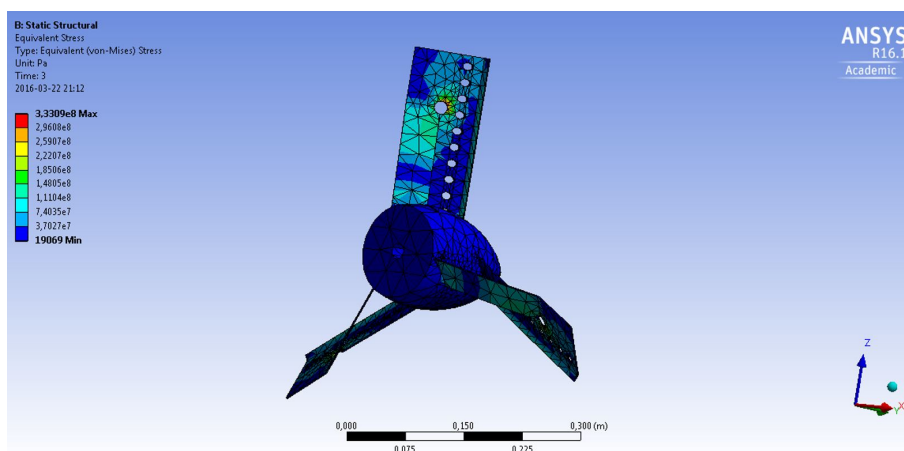


Figure D.5: Stress plot for a blade of length 222mm with split of 150mm, max stress is $3.3309 \cdot 10^8$ Pa

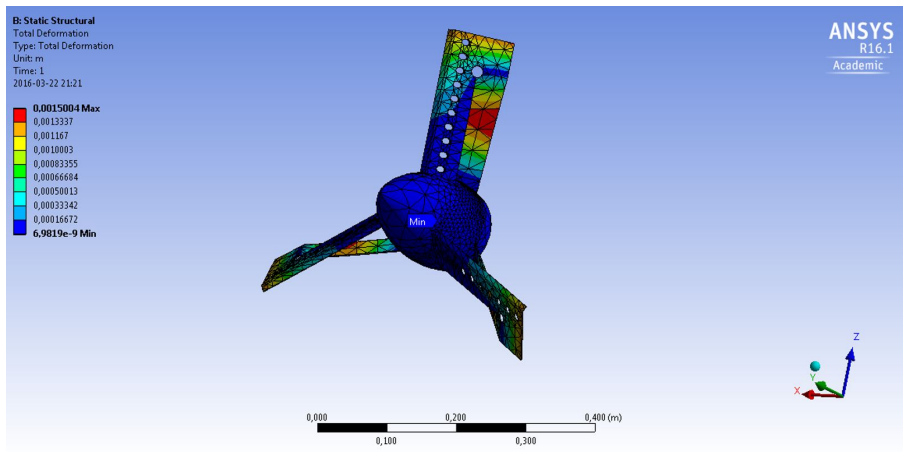


Figure D.6: Total Deformation plot for a blade of length 222mm with split of 170mm, max deformation is 0.0015004 m

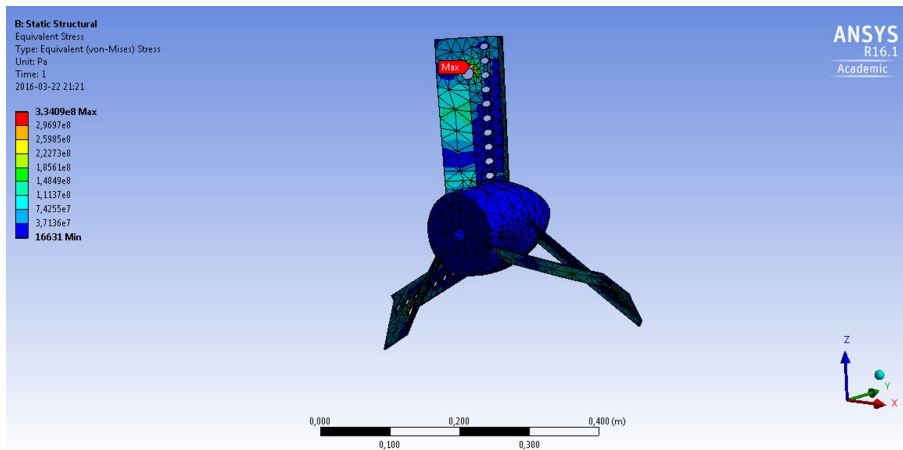


Figure D.7: Stress plot for a blade of length 222mm with split of 170mm, max stress is $3.3409 \cdot 10^8$ Pa

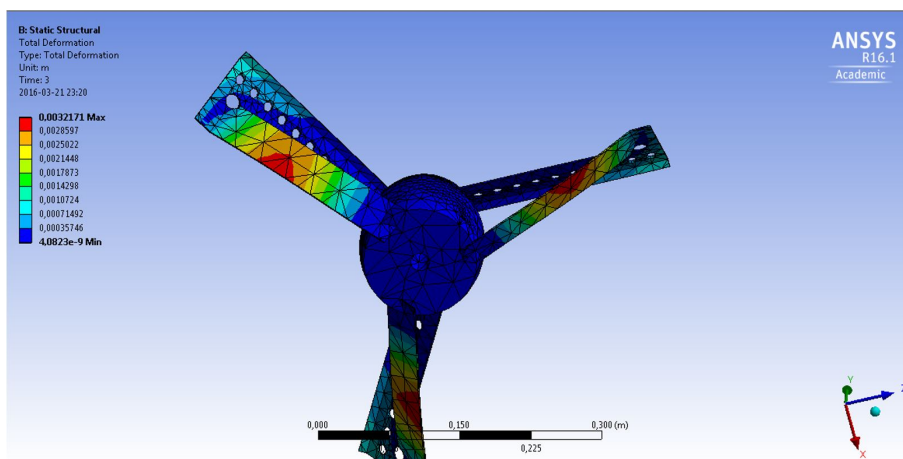


Figure D.8: Total Deformation plot for a blade of length 222mm with split of 200mm, max deformation is 0.0032171 m

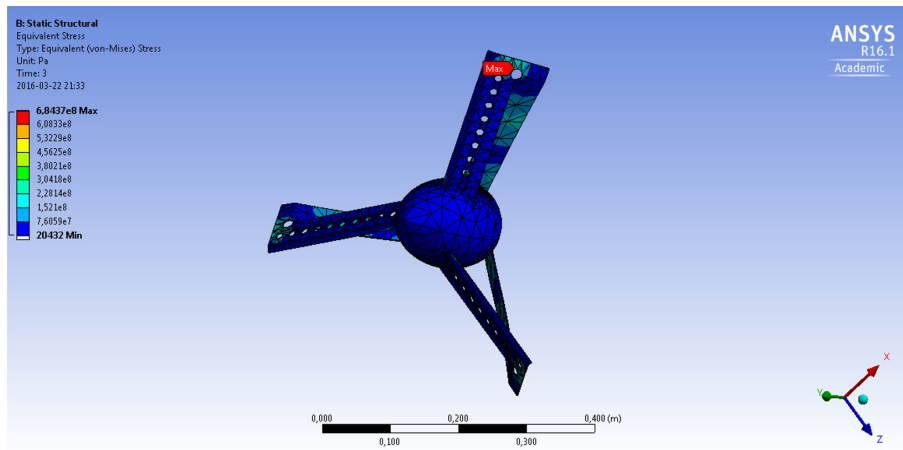


Figure D.9: Stress plot for a blade of length 222mm with split of 200mm, max stress is $6.8437 \cdot 10^8$ Pa

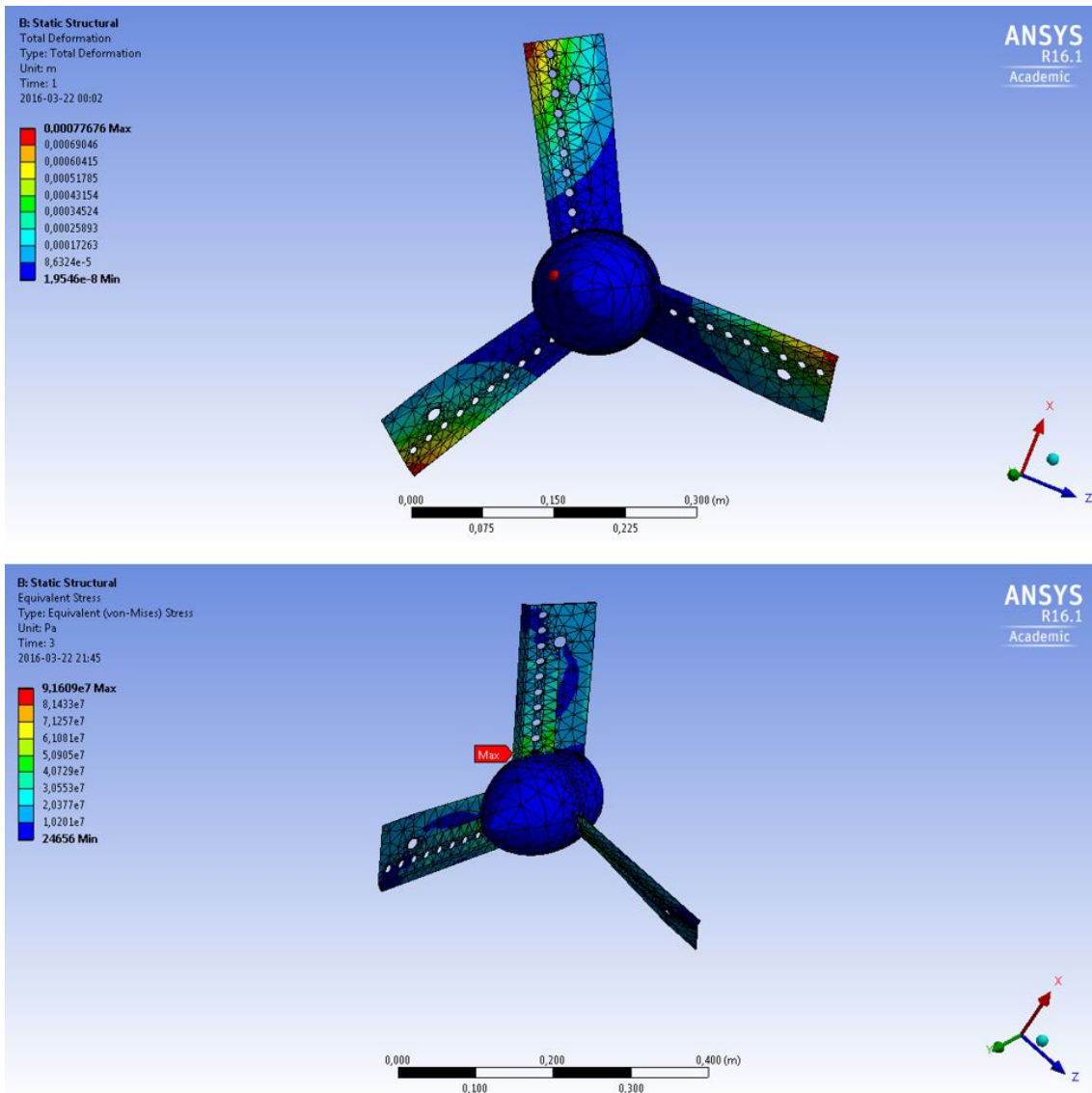


Figure D.10: Top: Total Deformation for a blade with split between roots of 5 deg, max deformation is 0.00077676 m
 Bottom: Stress plot for a blade with split between roots of 5 deg, max stress is $9.1609 \cdot 10^7$ Pa

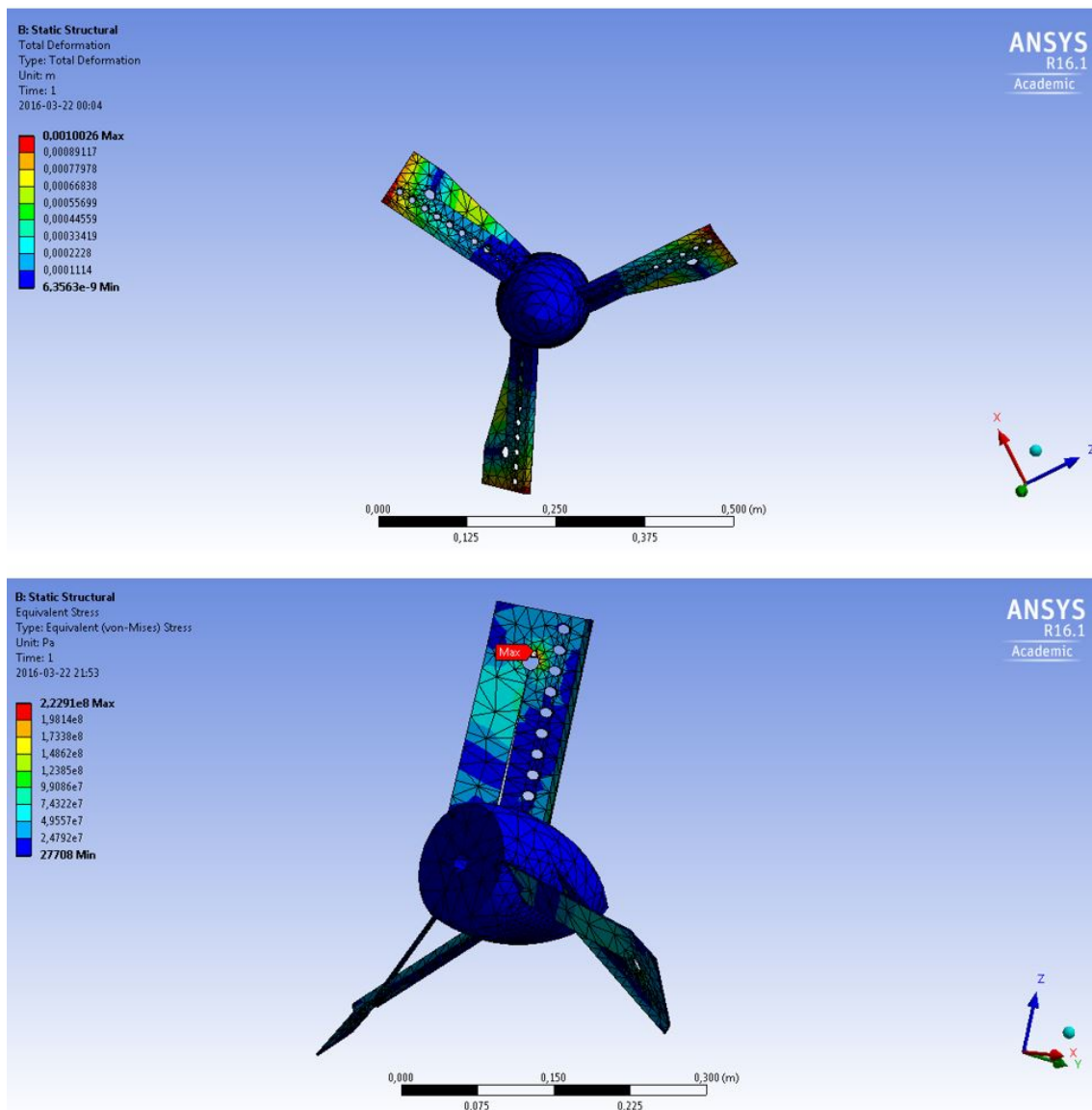


Figure D.11: Top: Total Deformation for a blade with split between roots of 17.5 deg, max deformation is 0.0010026 m
Bottom: Stress plot for a blade with split between roots of 17.5 deg, max stress is $2.2291 \cdot 10^8$ Pa

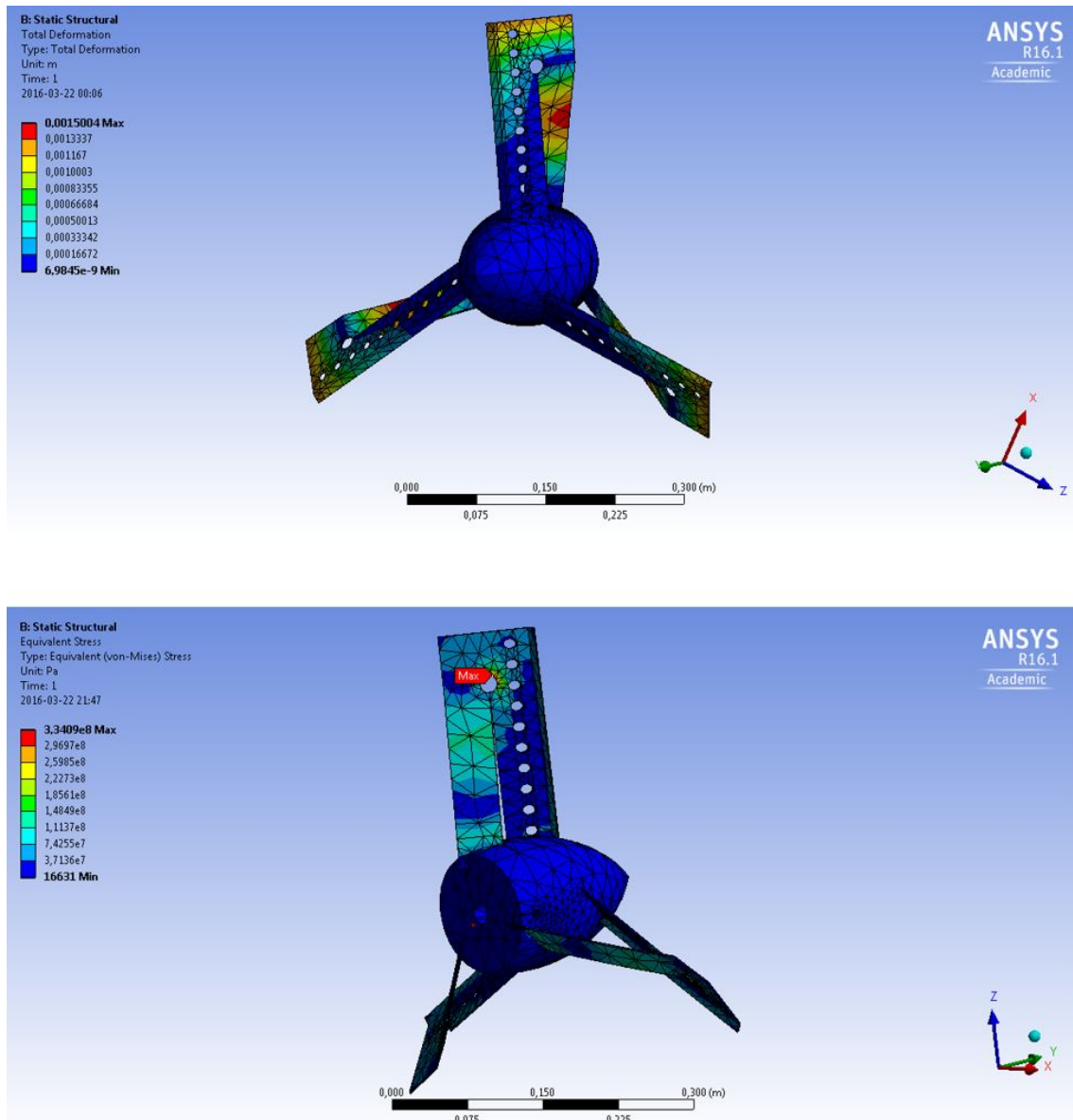


Figure D.12: Top: Total Deformation for a blade with split between roots of 25 deg, max deformation is 0.0015004 m
 Bottom: Stress plot for a blade with split between roots of 25 deg, max stress is $3.3409 \cdot 10^8$ Pa

D.4 Fluid Flow Analysis in Star-CCM+

D.4.1 Mesh for Fluid Flow

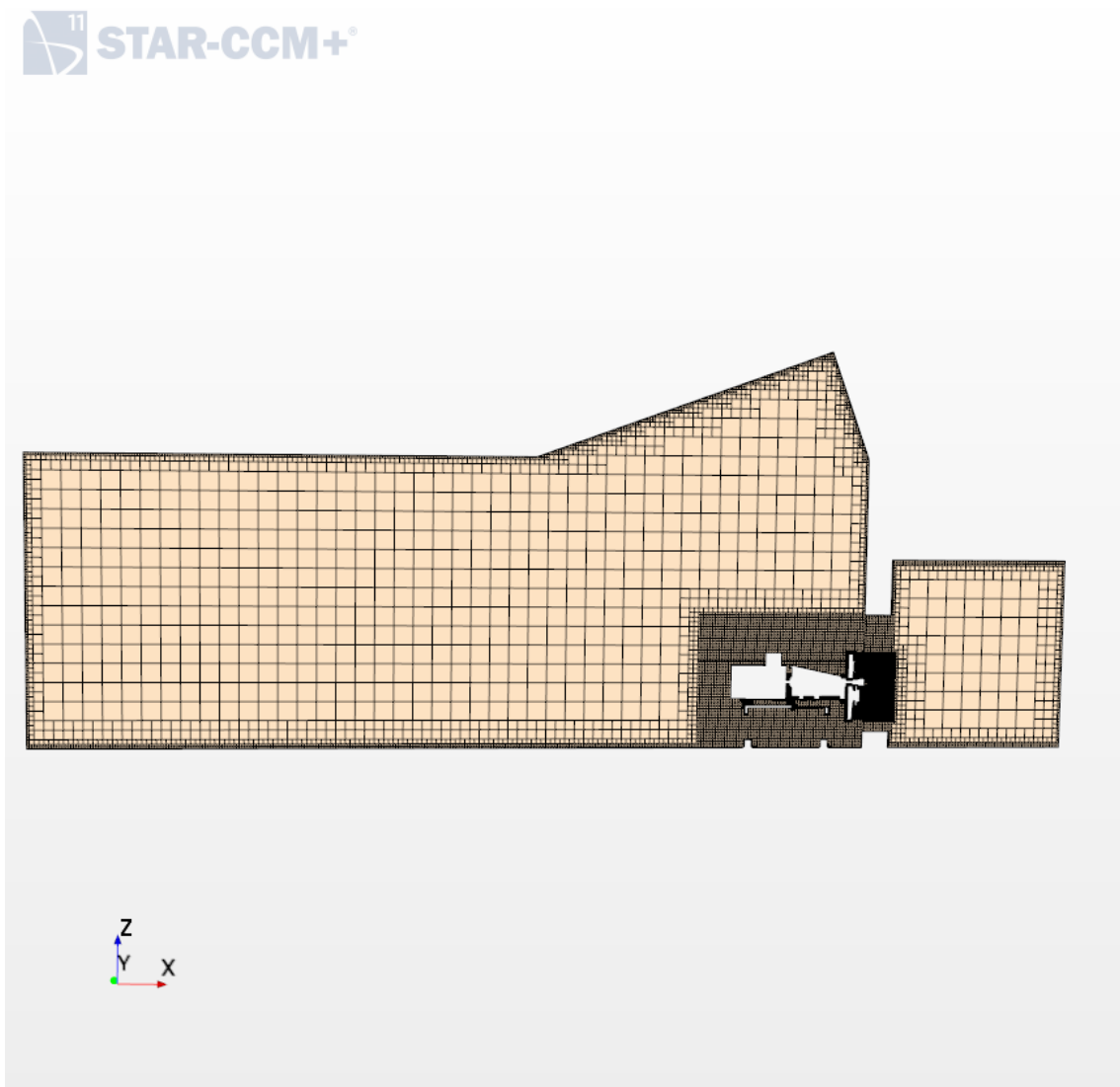


Figure D.13: Cross-section representation of the full mesh

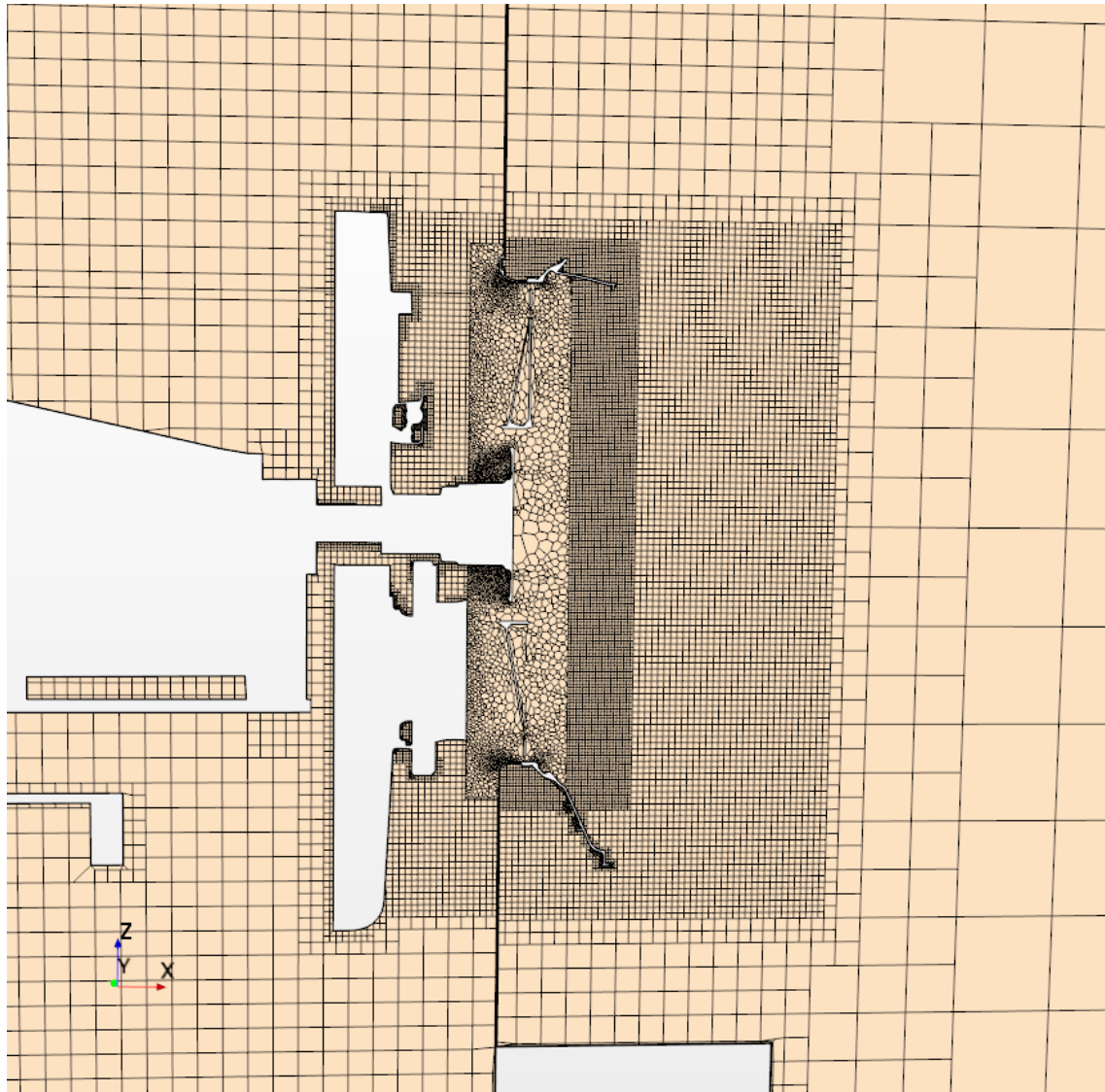


Figure D.14: Cross-section representation of the mesh in the close proximity of the fan region

D.4.2 Result Plots

D.4.2.1 Vector Velocity

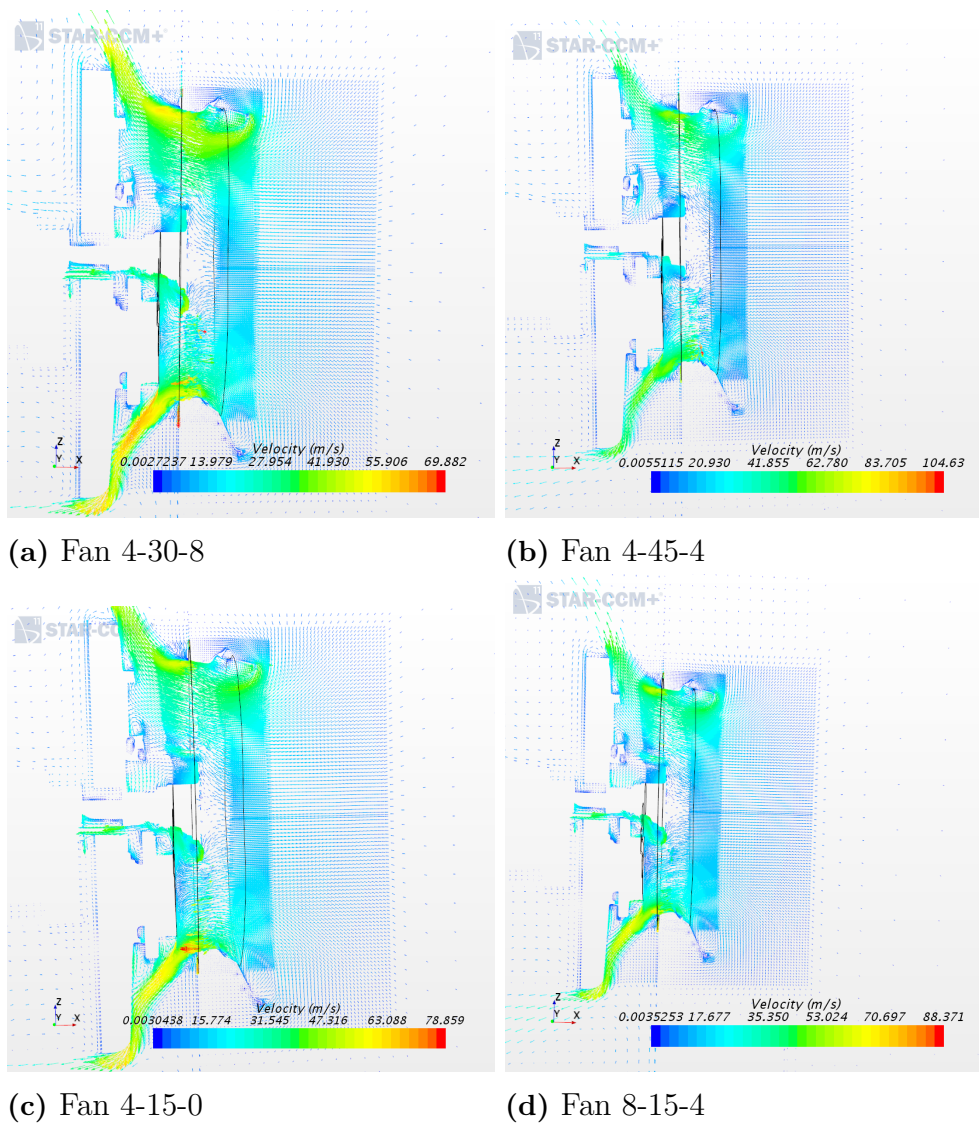
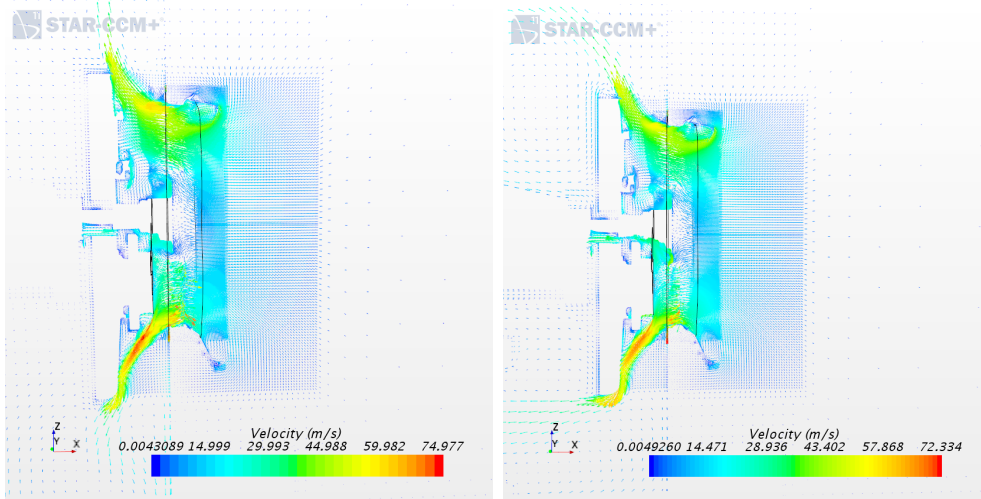
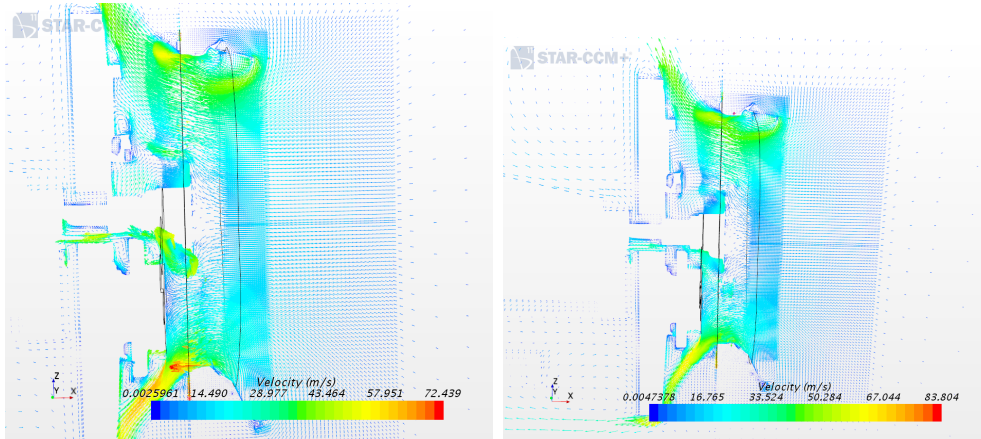


Figure D.15: Side view of the flow direction and velocity magnitude as the fluid travels through the fan region.



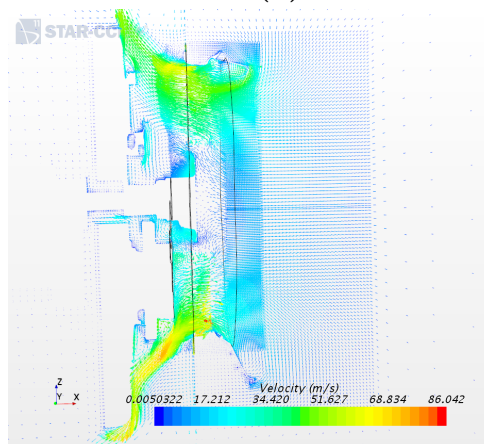
(a) Fan 8-45-8

(b) Fan 8-30-0



(c) Fan 12-15-8

(d) Fan 12-30-4



(e) Fan 12-45-0

Figure D.16: Side view of the flow direction and velocity magnitude as the fluid travels through the fan region.

D.4.2.2 Pressure scalar

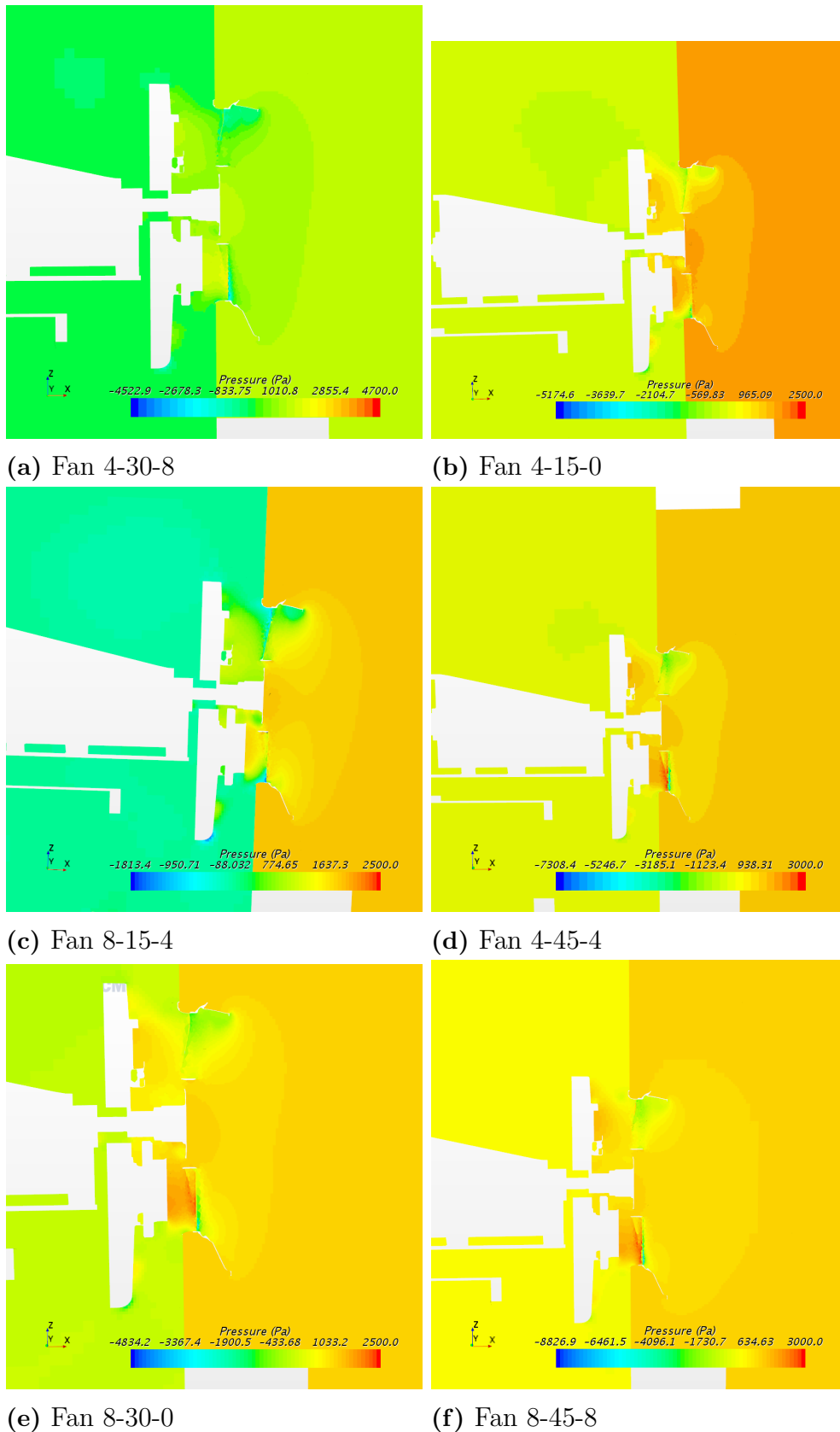


Figure D.17: Plots of the pressure in the close proximity of the fan region.

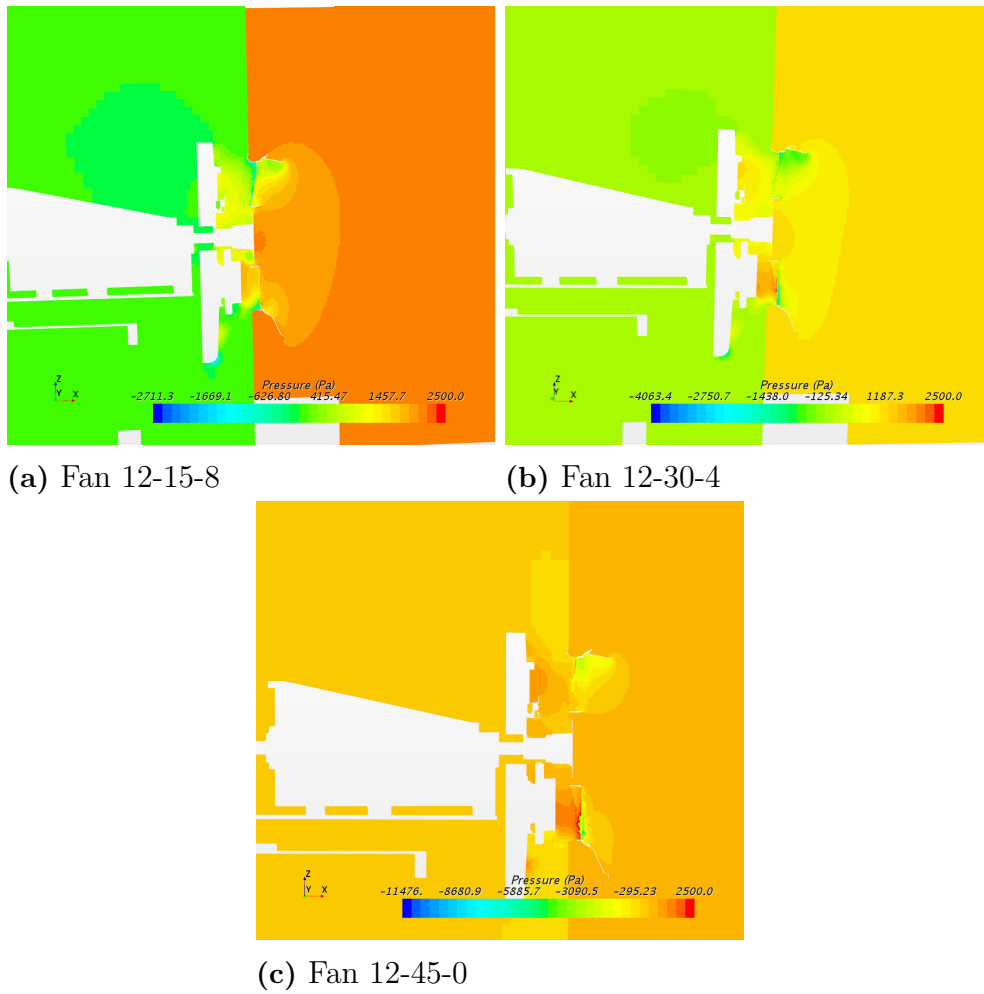


Figure D.18: Plots of the pressure in the close proximity of the fan region.

D.4.2.3 Velocity swirl

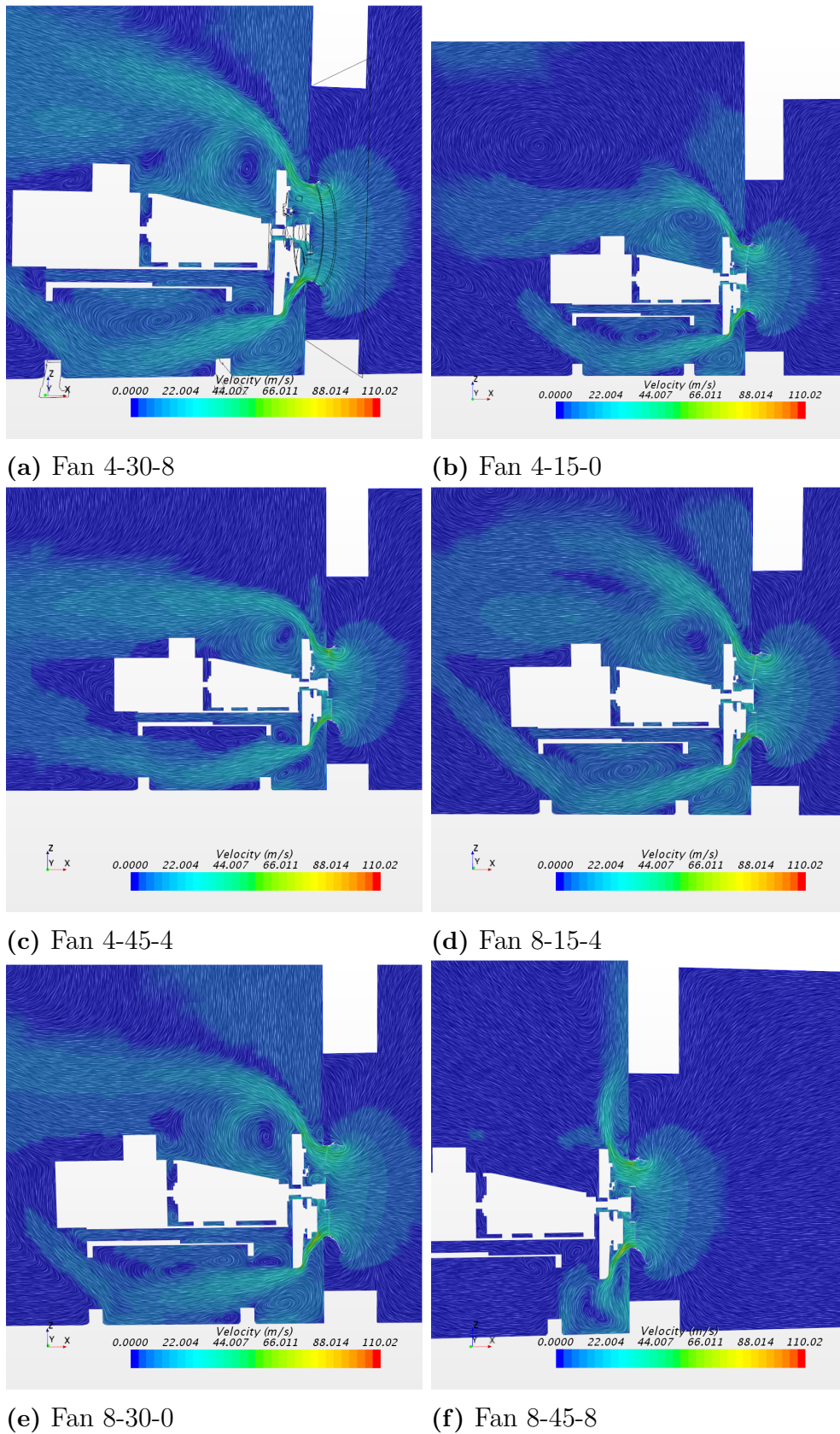


Figure D.19: Side view of the engine bay showing the velocity of air in different regions with indicative lines for flow direction.

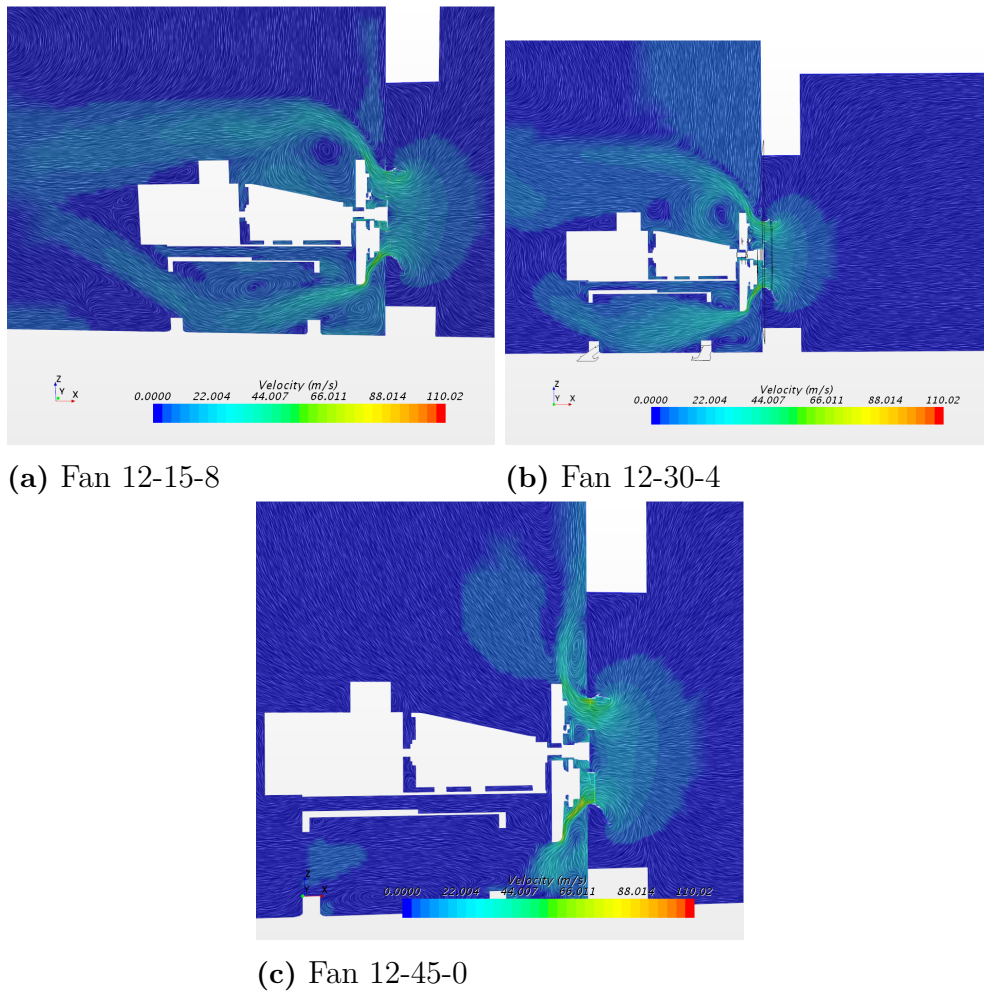


Figure D.20: Side view of the engine bay showing the velocity of air in different regions with indicative lines for flow direction.

D.4.2.4 Velocity new domain 22

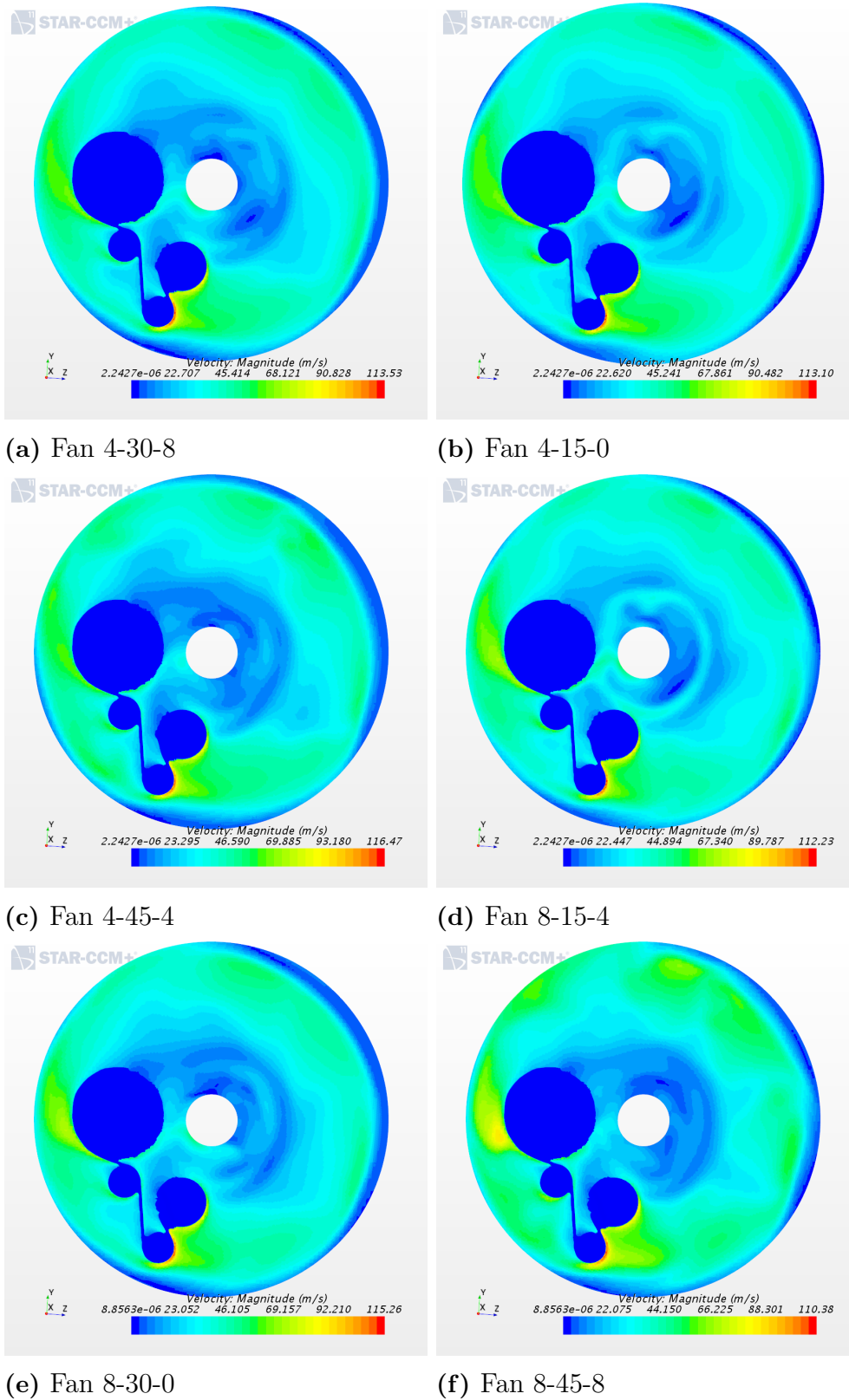
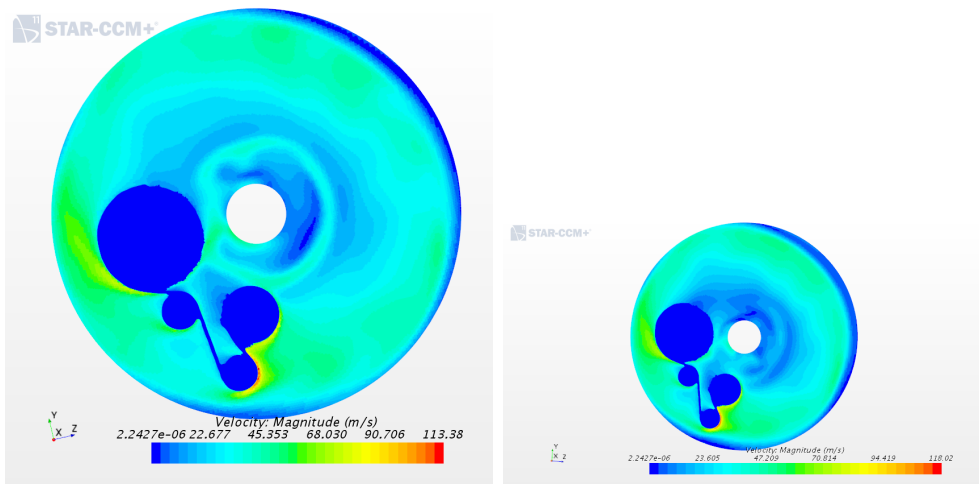
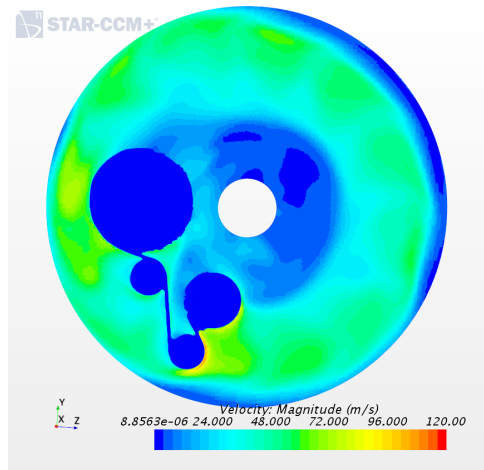


Figure D.21: Magnitude of the velocity for the fluid as it leaves the fan region.



(a) Fan 12-15-8

(b) Fan 12-30-4



(c) Fan 12-45-0

Figure D.22: Magnitude of the velocity for the fluid as it leaves the fan region.

D.4.2.5 Fan geometry

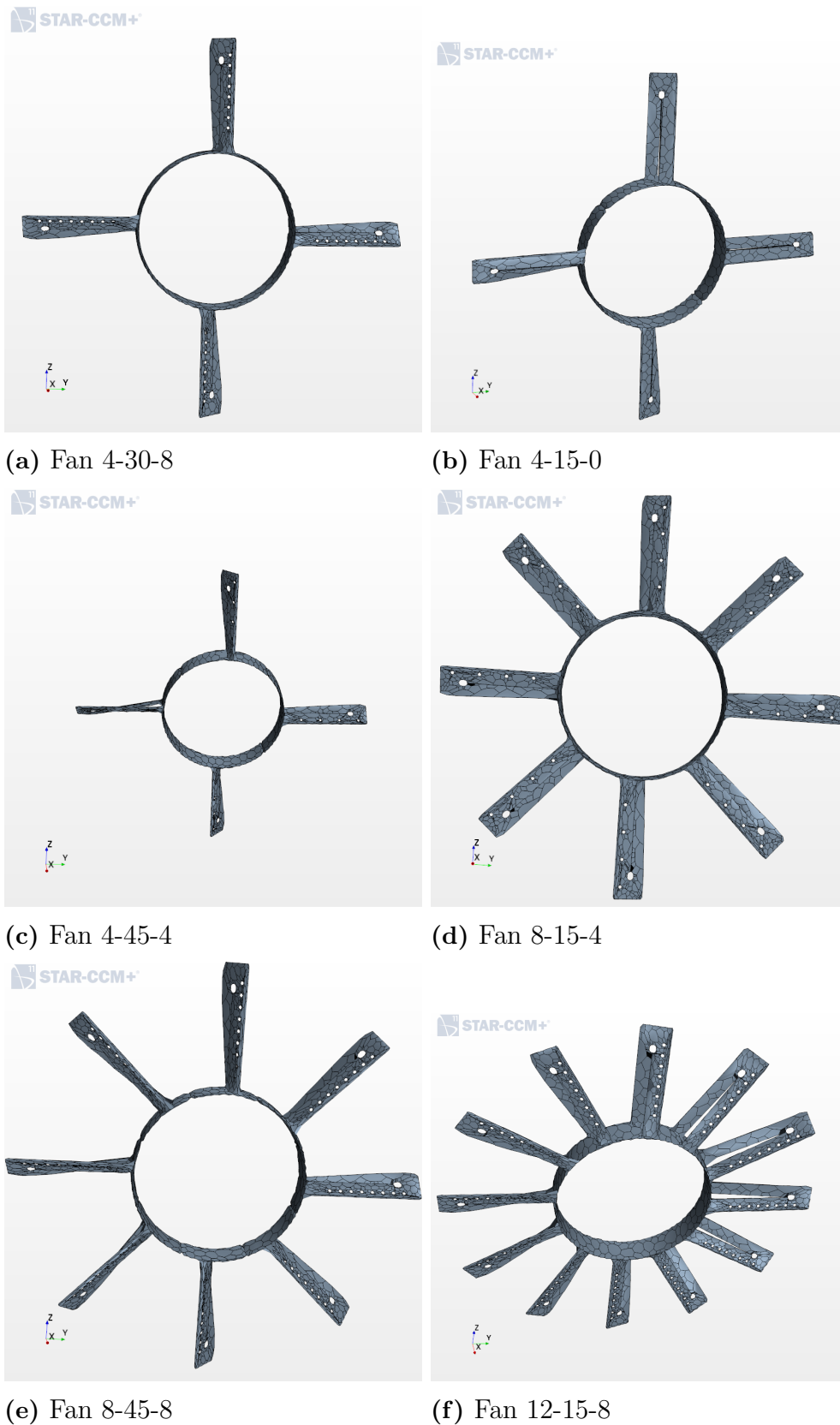


Figure D.23: Representation of Meshed geometry of the concept fans.

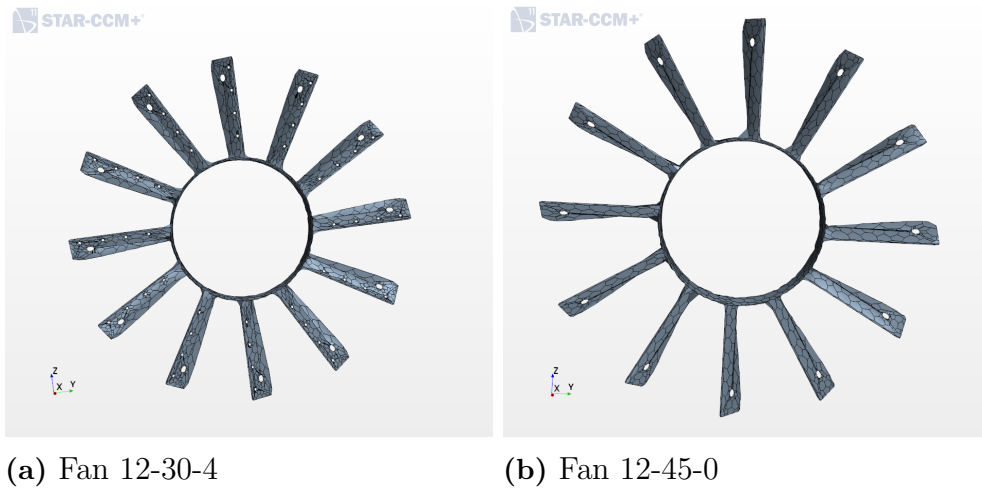
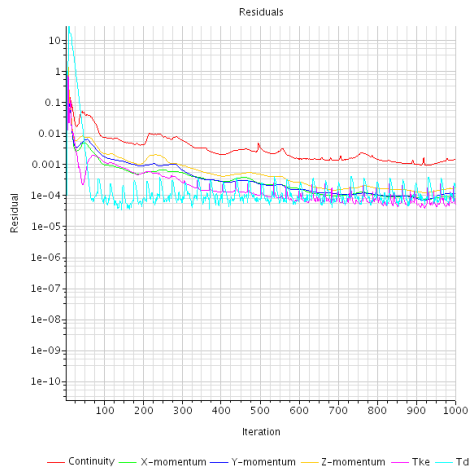
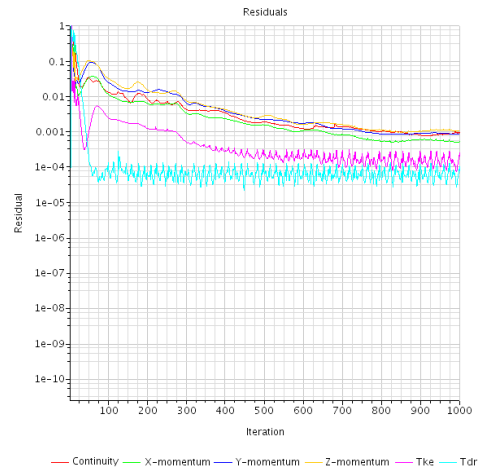


Figure D.24: Representation of Meshed geometry of the concept fans.

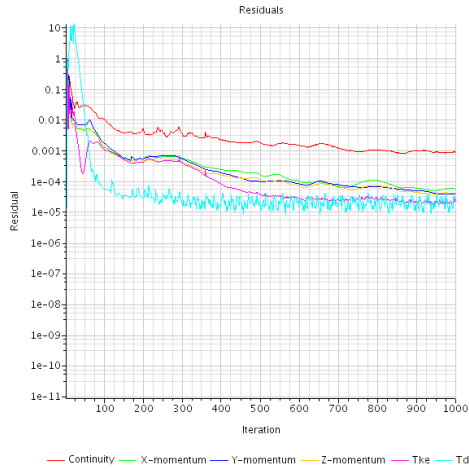
D.4.2.6 Residuals



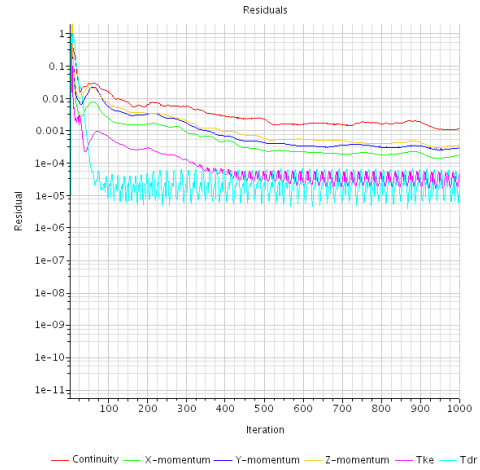
(a) Fan 4-30-8



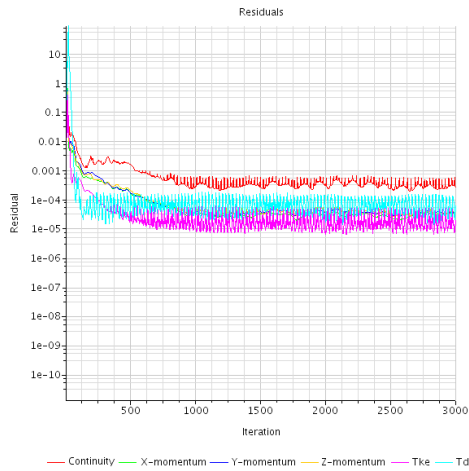
(b) Fan 4-15-0



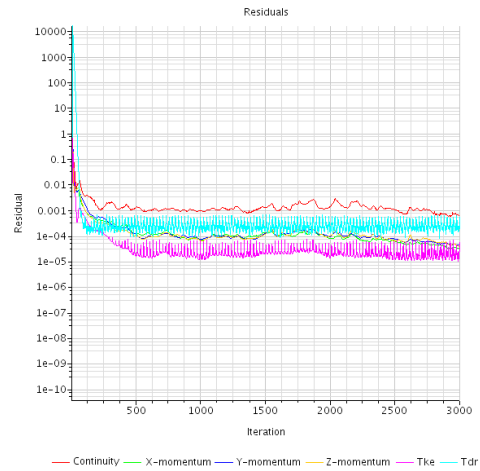
(c) Fan 4-45-8



(d) Fan 8-15-4



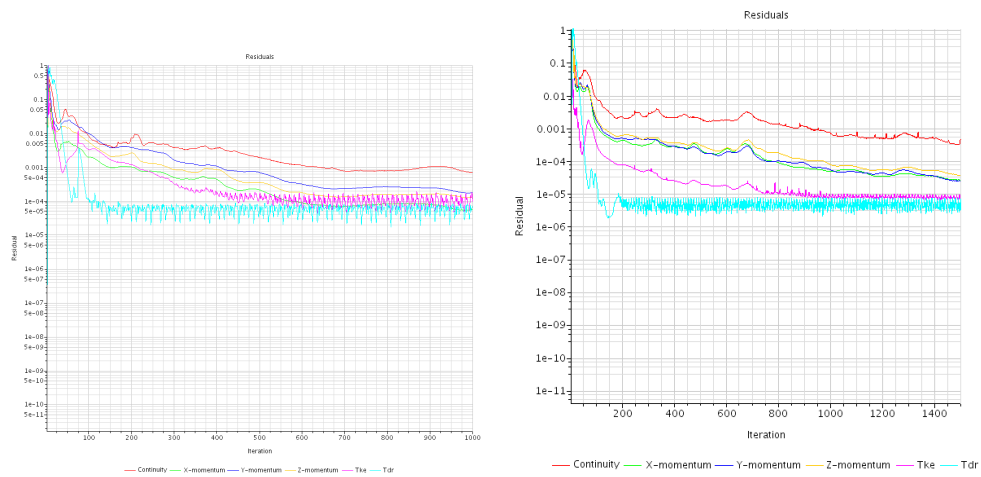
(e) Fan 8-30-0



(f) Fan 8-45-8

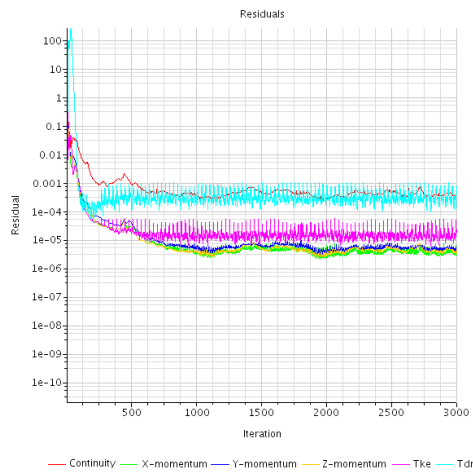
Figure D.25: The residuals from simulations in Star-CCM+.

D. Concept Refinement with Ansys, Star CCM+ and Testings



(a) Fan 12-15-8

(b) Fan 12-30-4



(c) Fan 12-45-0

Figure D.26: The residuals from simulations in Star-CCM+.

D.4.2.7 Scalar Velocity

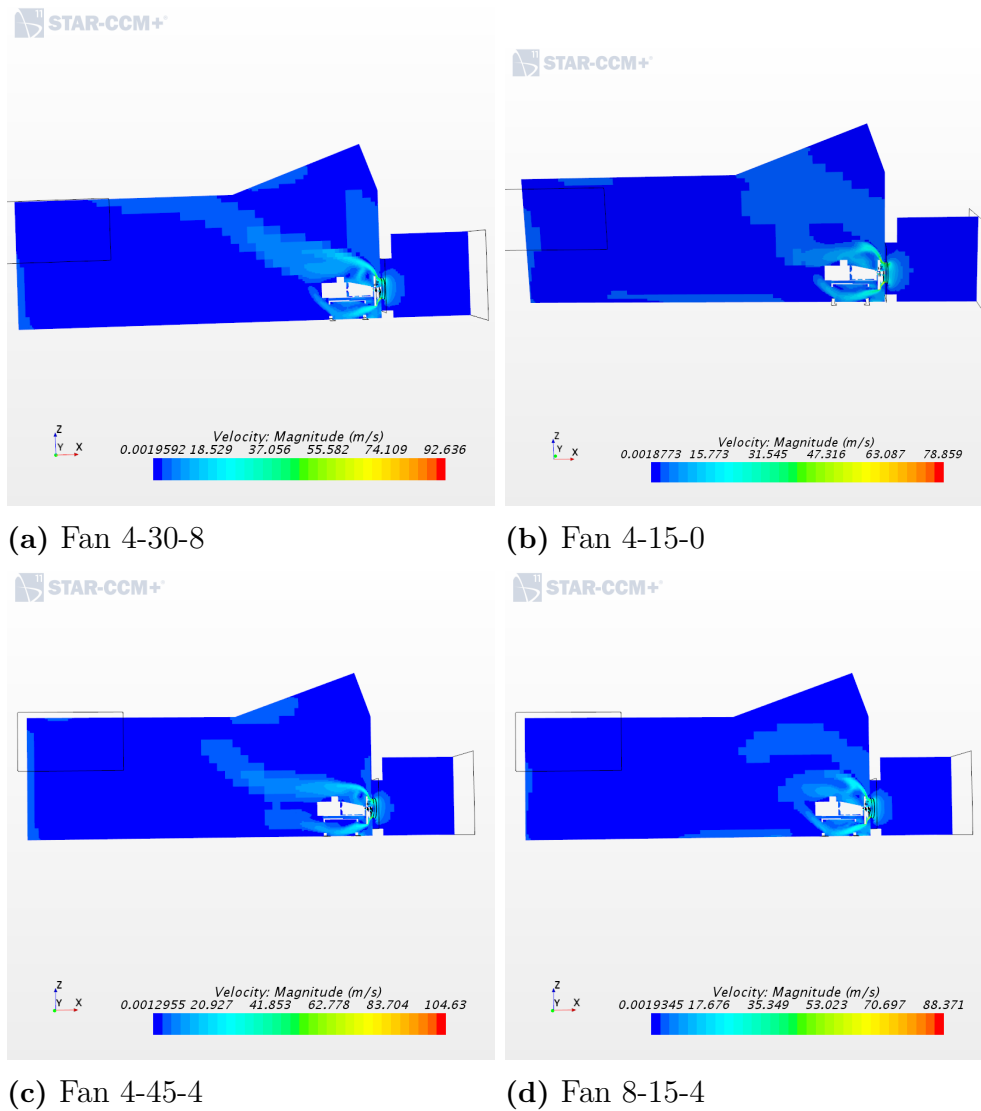


Figure D.27: Scalar plot of velocity magnitude in the entire region.

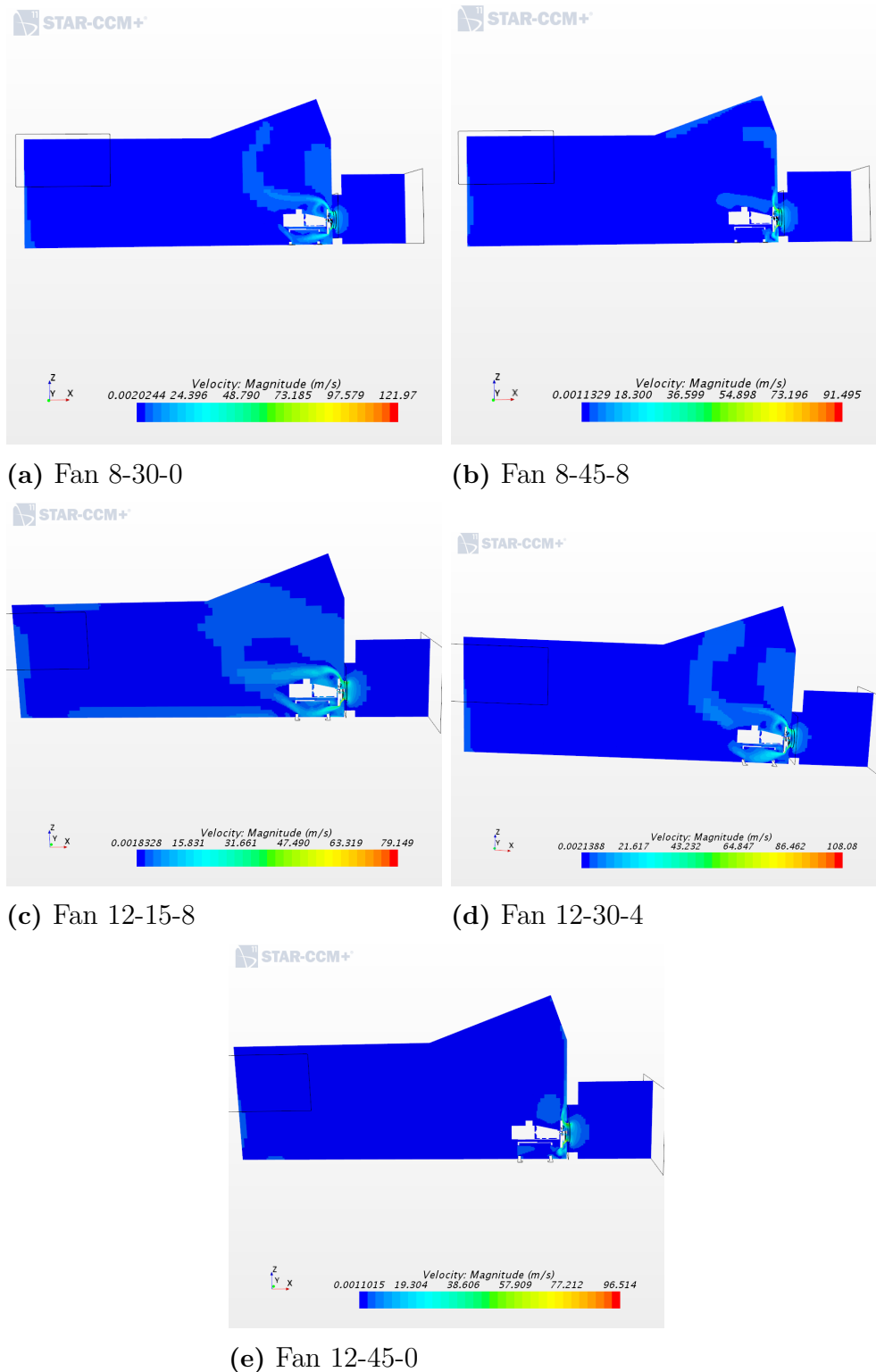


Figure D.28: Scalar plot of velocity magnitude in the entire region.

E

Concept Regeneration and Validation

E.1 Appendix for Structural Verification

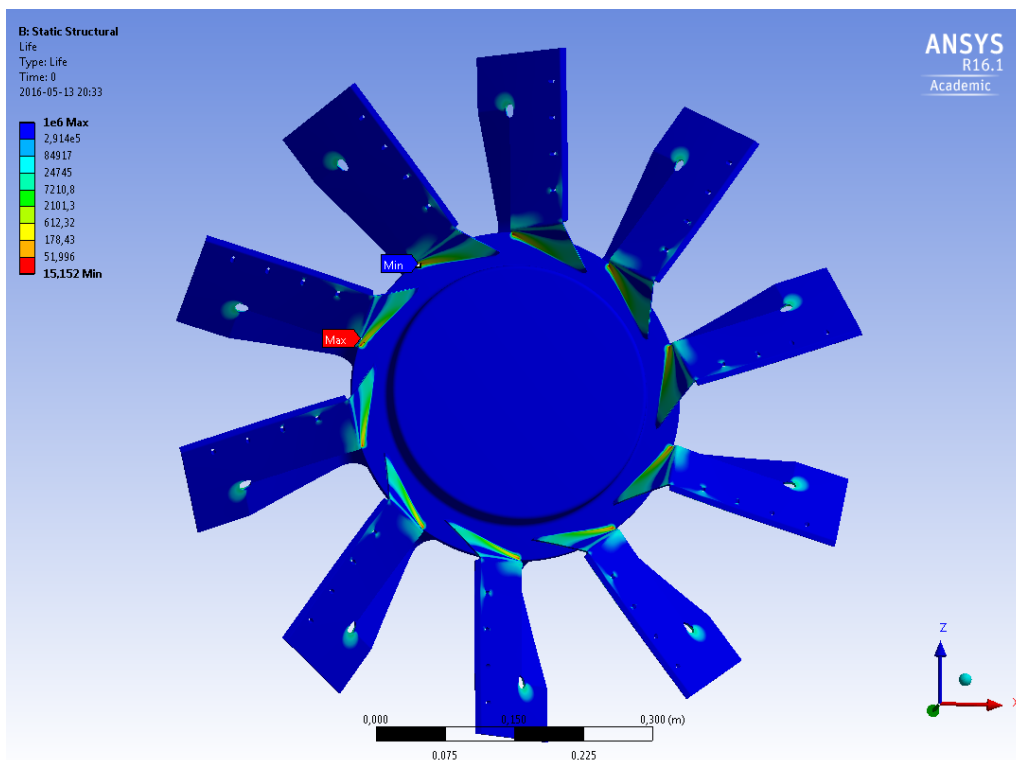


Figure E.1: Final Concept: Lifetime expectancy in cycles endured

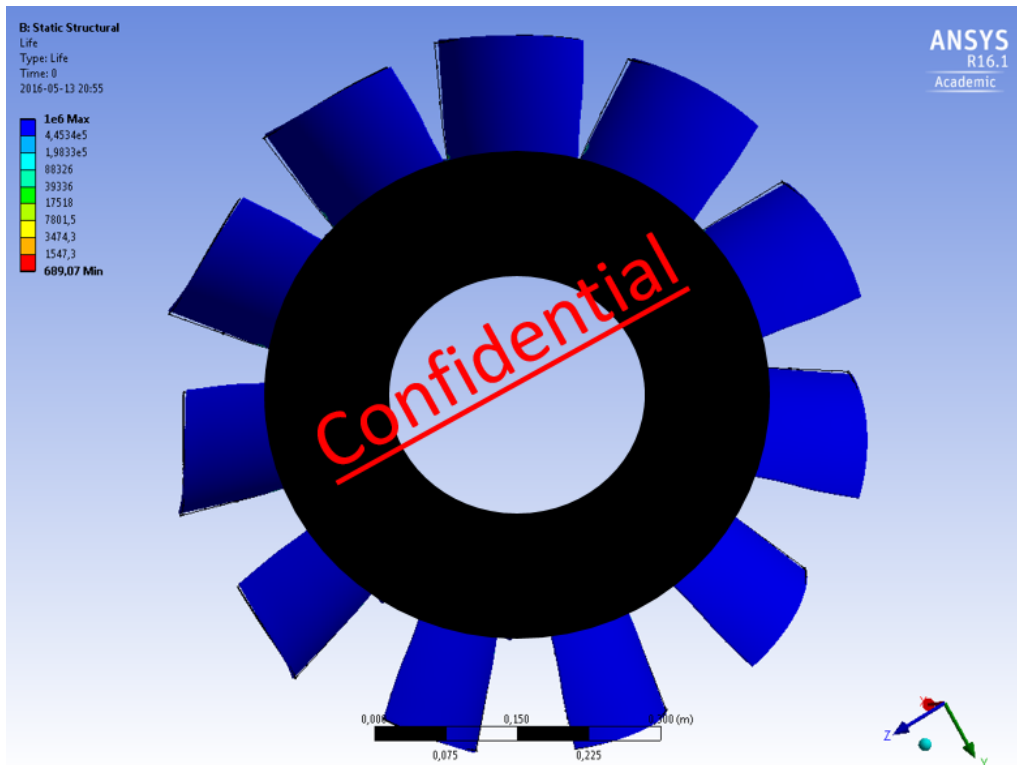


Figure E.2: Reference fan: Lifetime expectancy in cycles endured

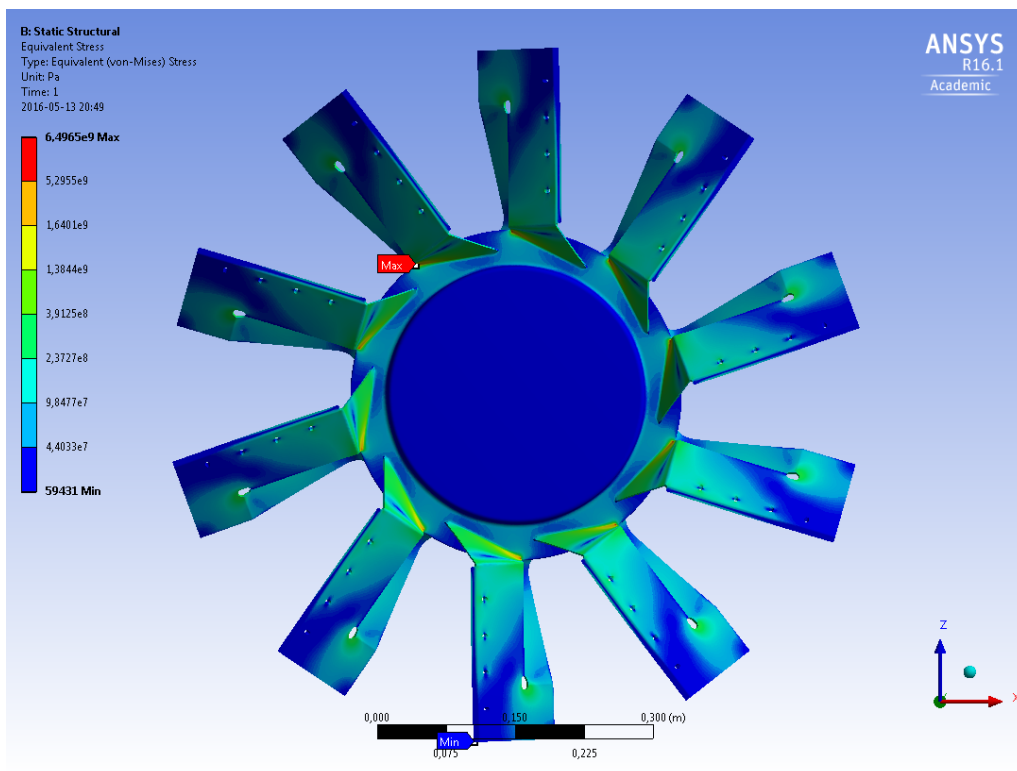


Figure E.3: Final concept: Equivalent stress

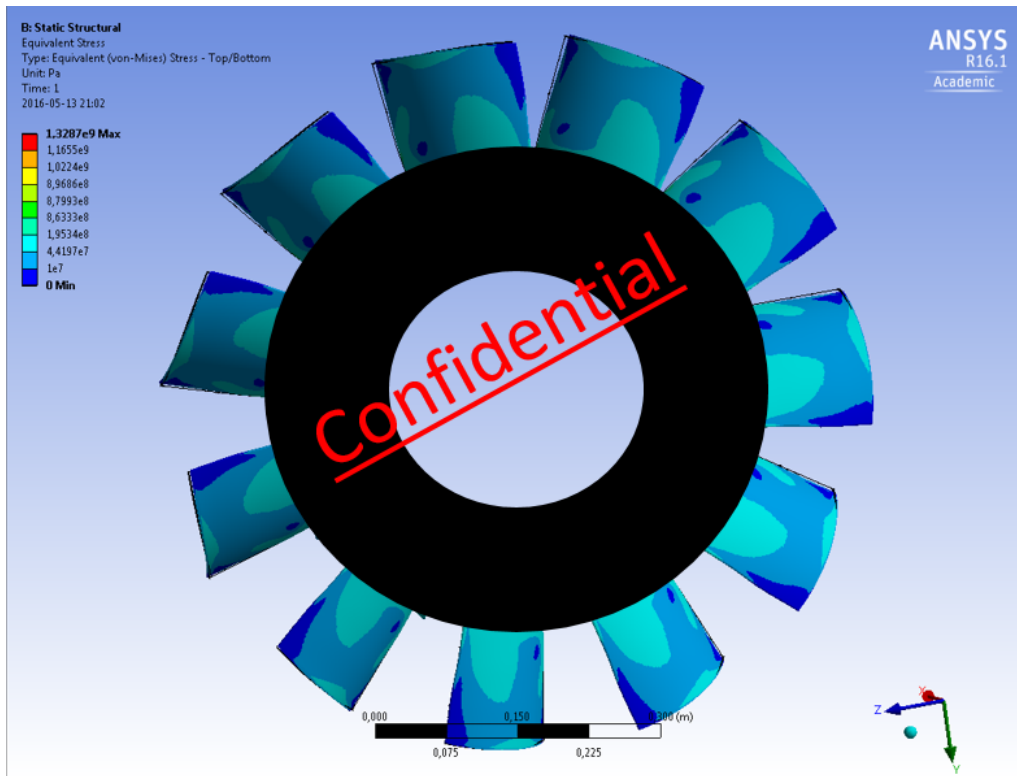


Figure E.4: Reference fan: Equivalent stress

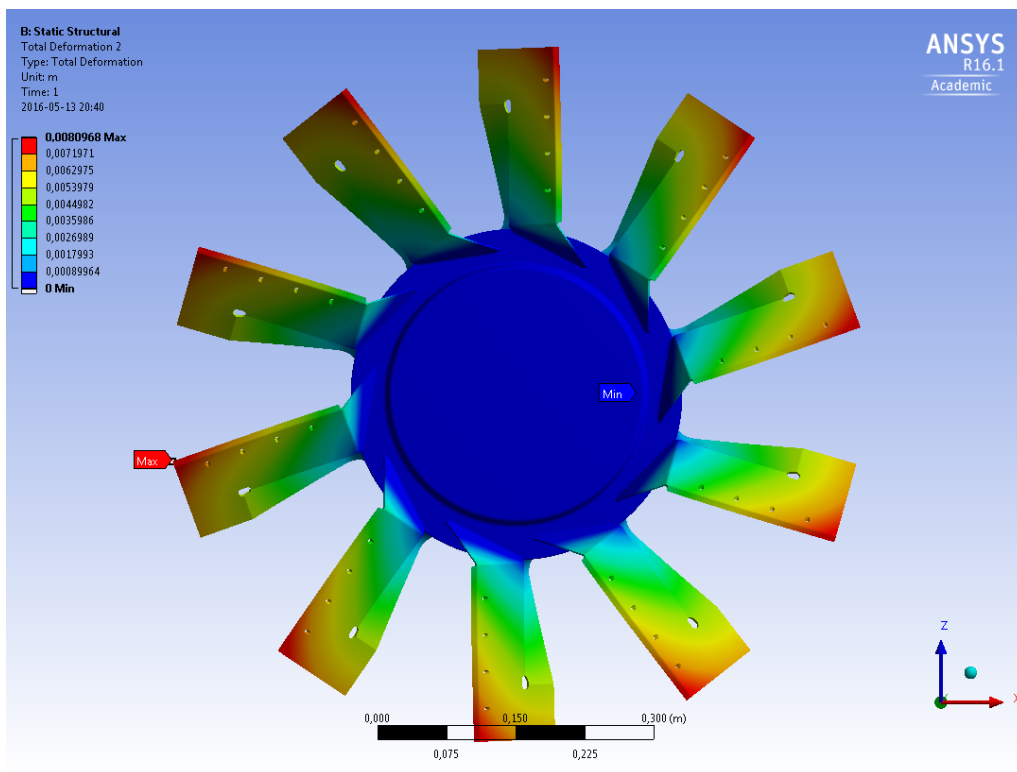


Figure E.5: Final concept: Total deformation

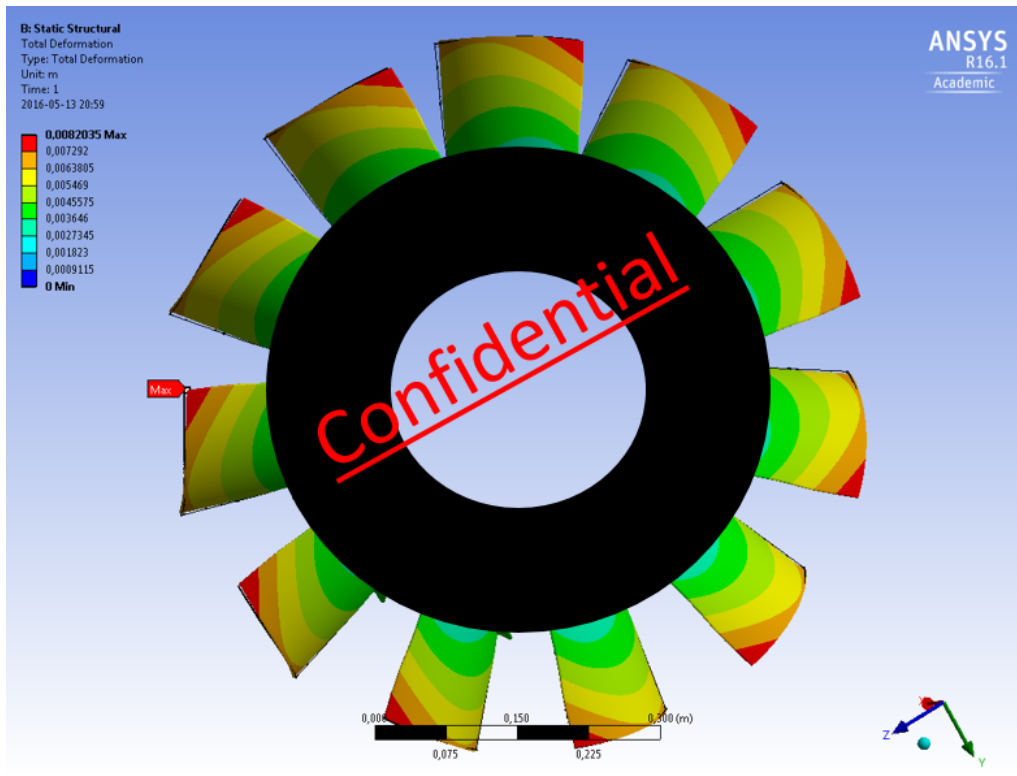
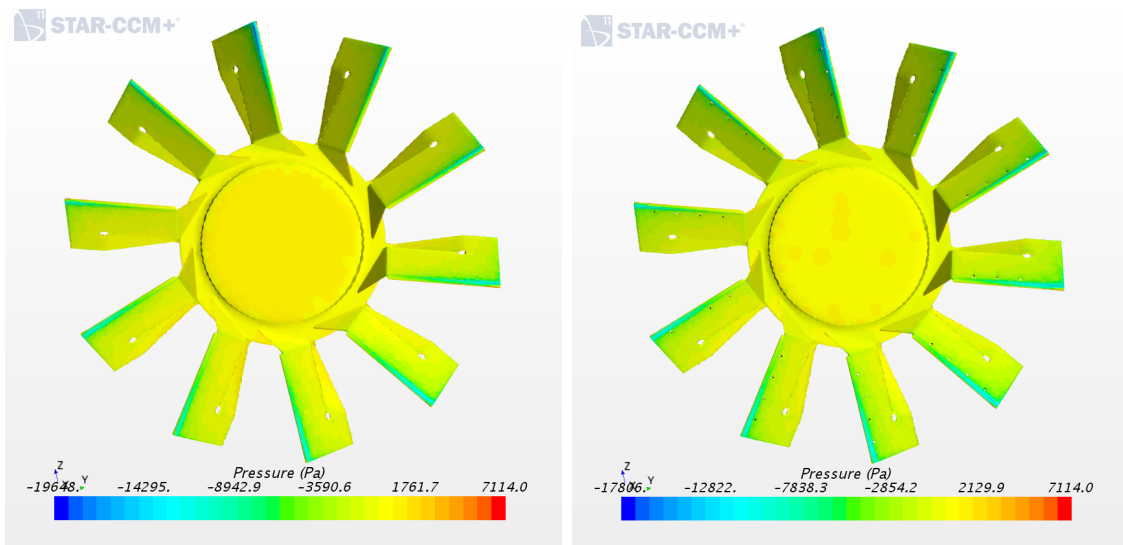


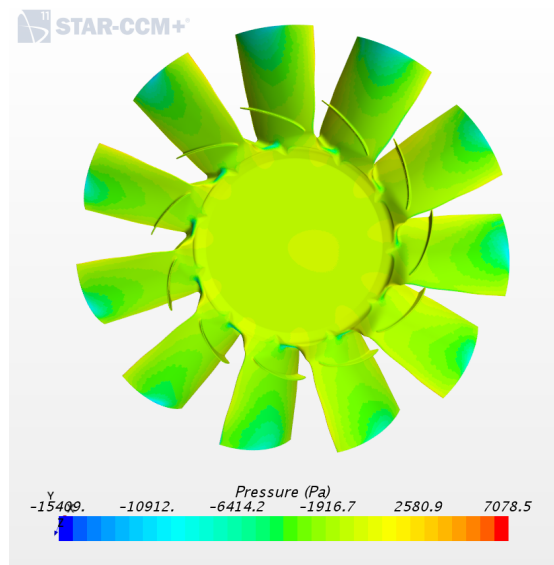
Figure E.6: Reference fan: Total deformation

E.2 Fluid flow Verification



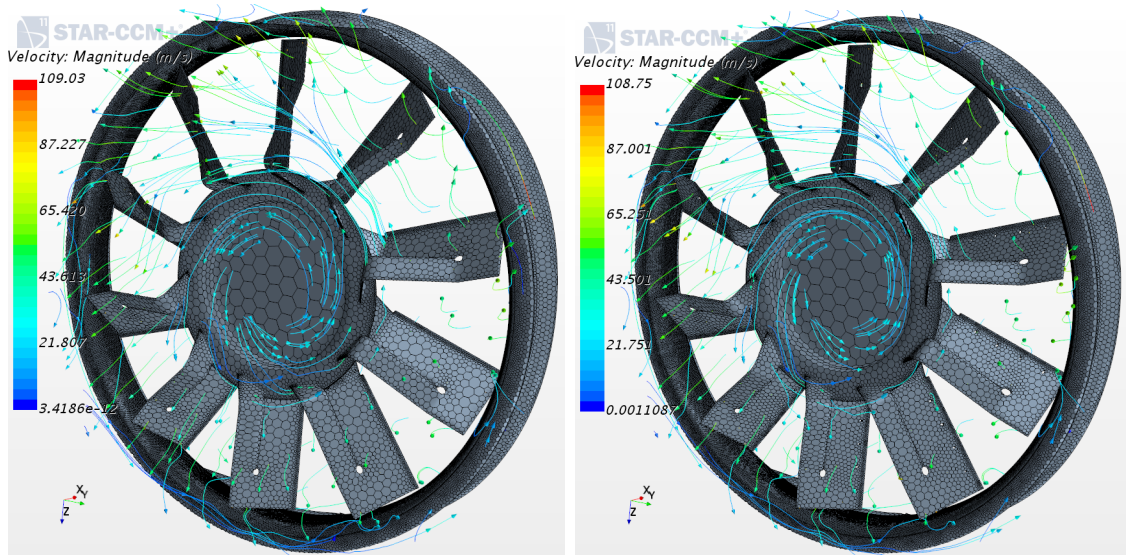
(a) Fan 10-40-0

(b) Fan 10-40-4



(c) Reference fan

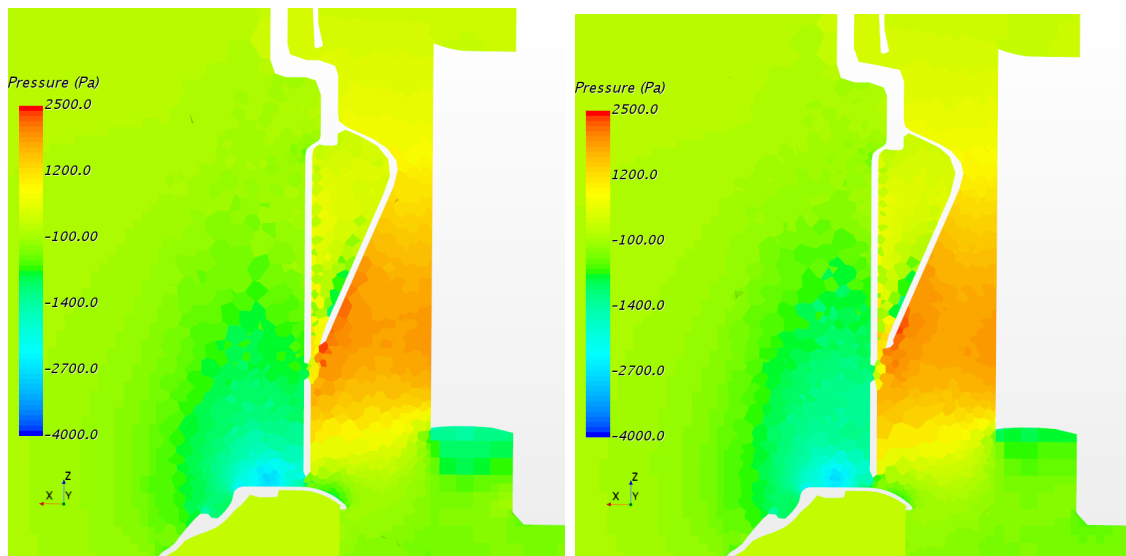
Figure E.7: Pressure on the fan blades



(a) Fan 10-40-0

(b) Fan 10-40-4

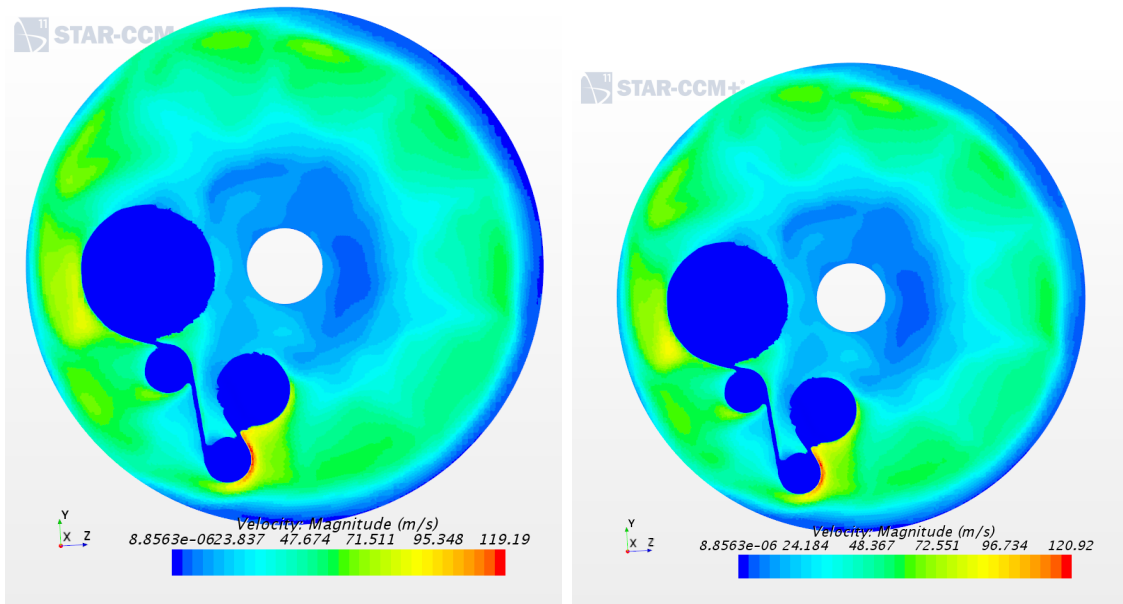
Figure E.8: Streamlines representing air flowing through the fan-region.



(a) Fan 10-40-0

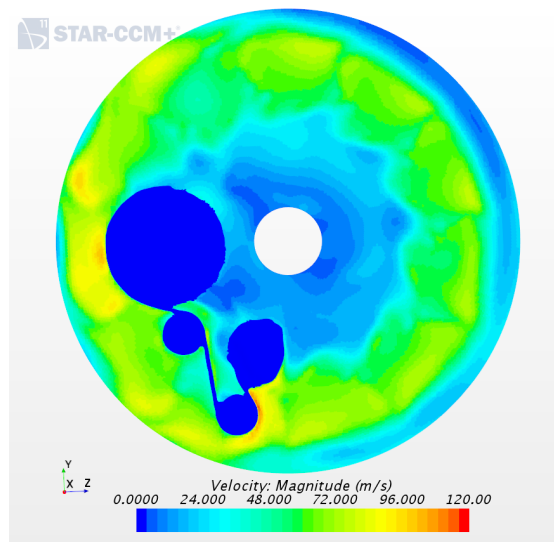
(b) Fan 10-40-4

Figure E.9: Scalar representation of the pressure field around the fan blades



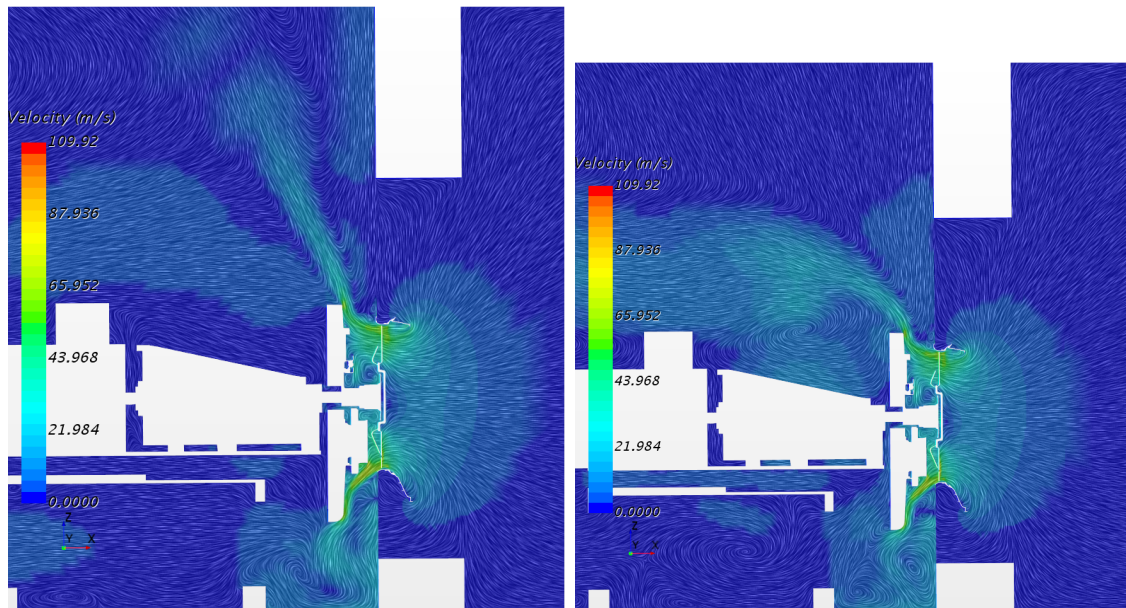
(a) Fan 10-40-0

(b) Fan 10-40-4



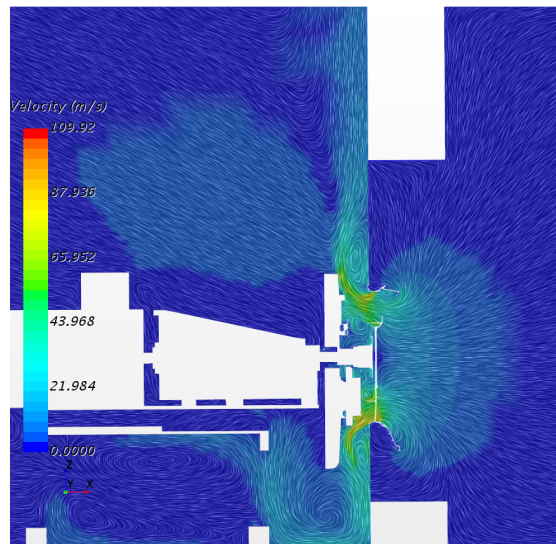
(c) Reference fan

Figure E.10: Magnitude of the velocity for the fluid as it leaves the fan-region.



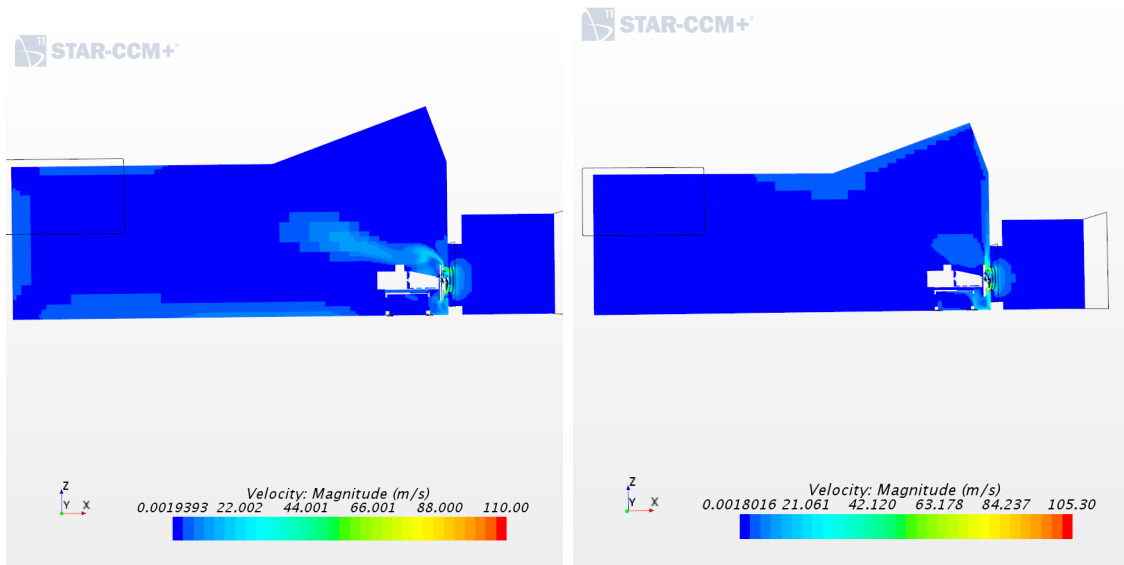
(a) Fan 10-40-0

(b) Fan 10-40-4



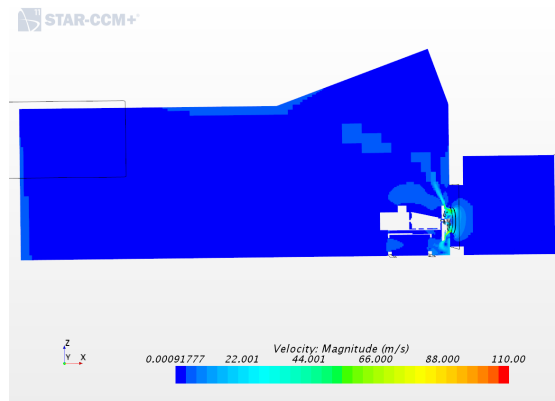
(c) Reference fan

Figure E.11: Side view of the engine bay showing the velocity of air in different regions with indicative lines for flow direction.



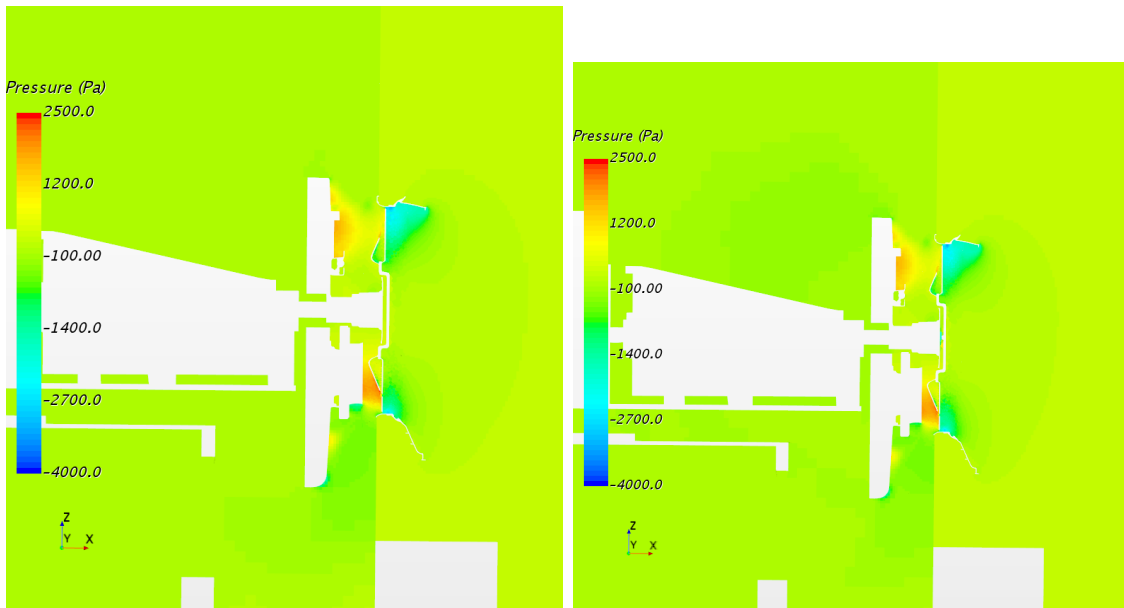
(a) Fan 10-40-4

(b) Reference fan



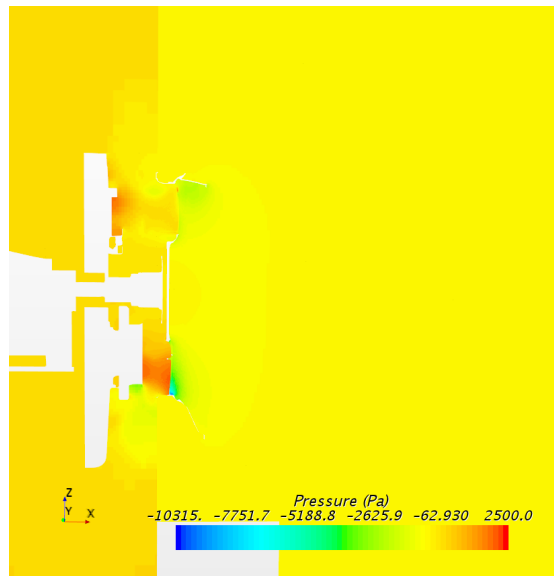
(c) Fan 10-40-0

Figure E.12: Scalar plot of velocity magnitude in the entire region.



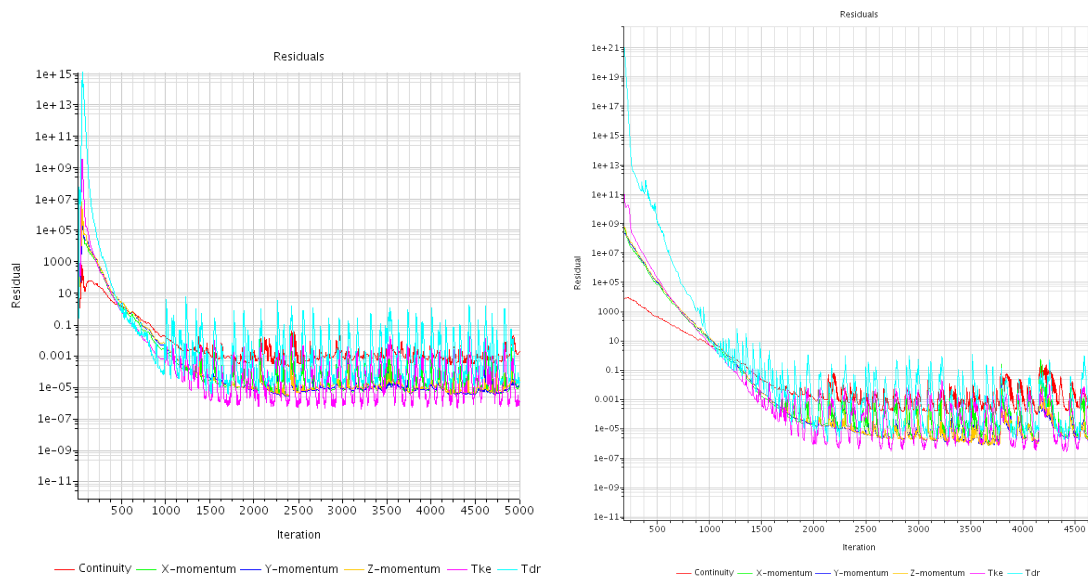
(a) Fan 10-40-0

(b) Fan 10-40-4



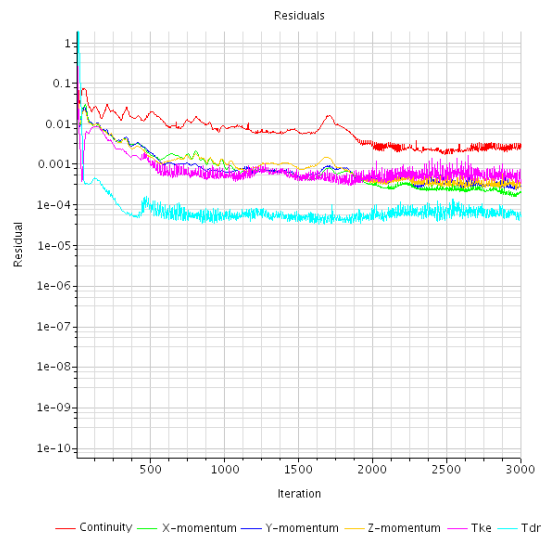
(c) Reference fan

Figure E.13: Plots of the pressure in the close proximity of the fan region.



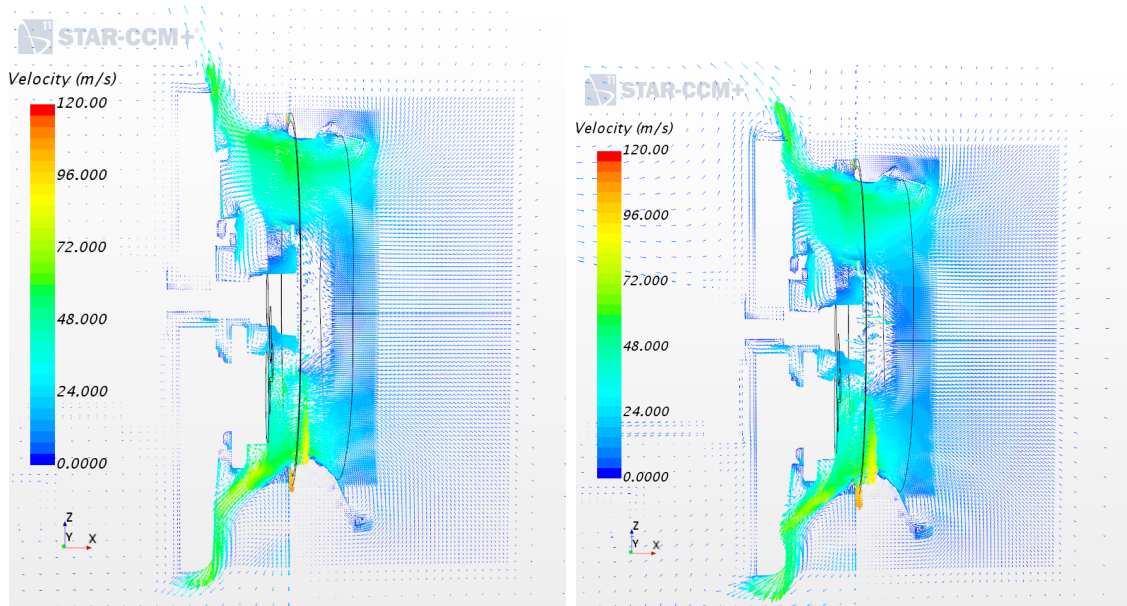
(a) Fan 10-40-0

(b) Fan 10-40-4



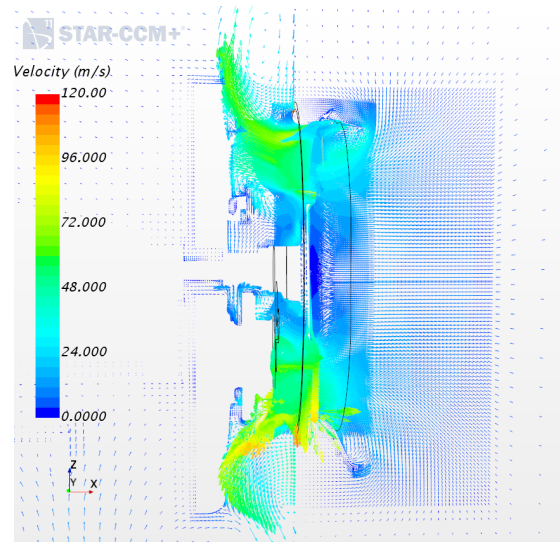
(c) Reference fan

Figure E.14: The residuals from simulations in Star-CCM+.



(a) Fan 10-40-0

(b) Fan 10-40-4



(c) Reference fan

Figure E.15: Side view of the flow direction and velocity magnitude as the fluid travels through the fan region.

Contribution Report

The contribution report is divided into a report writing part and a implementing part

Report writing:

- Executive summery: David
- Introduction: David and Andreas with assistance from Johanna
- Team and project management: Andreas
- Methodology: Johanna
- Costumer Needs Assessment: Adam
- External search
 - Divided rotor blade: Johanna with assistance from avid
 - Cross-flow cooling fan: Adam
 - Axial fan: David
 - Radial fan: Johanna
 - Diagonal fan: Johanna
 - Contra-rotating fan: Andreas
- Engineering specification: Johanna
 - Relating specifications of costumer needs: USA
- Concept generation and evaluation
 - Backbox: Johanna
 - Sub-function: Johanna, David, Tyler
 - Important parameters: Johanna
 - Concept generation: Johanna
 - Concept evaluation: Johanna
 - Shifting focus to the important parameters: Johanna
- Concept refinement with ANSYS Star och testing
 - Deciding number of tests with Taguchi Orthogonal Array: USA
 - Design and manufacturing process for experimental tests: Johanna
 - Structural Analysis in ANSYS: David
 - Fluid Analysis in Star-CCM+: David
 - Testings
 - * Testing set up: USA
 - * Testing results: Andreas
 - * Test result discussion: USA
 - Overall validation: Andreas
- Concept redefining and concept recommendation
 - Concept redefining: Andreas
 - Structural analysis of redefined concepts: David
 - Fluid simulations of redefined concepts: David
 - Concept recommendation: Andreas
- System level design: Tyler
- Detailed design
 - CAD drawings: Andreas

- Manufacturing plan, material selection and cost analysis: Johanna
- Final discussion
 - Methodology: Johanna
 - Sources of errors in simulations and testings: David
 - Project achievement:
 - * Fulfillment of project achievement: David
 - * Fulfillment of purpose: Andreas
 - International collaboration: Johanna
 - Conclusion: USA, joint effort sweden
 - future work Andreas
- Self assessment USA

Impementation:

- Introduction were carried through as a joint effort
- Team and project management were done by Andreas with some collaboration with David and Johanna for the risk evaluation.
- Methodology were done by Johanna except from the section 3.7 about the taguchi array.
- Customer needs assessment made by PSU students.
- Patent reasearch on divided rotor blae done by Johanna and David, Cross flow cooling fan made by PSU
- Reasearching existing products were made by Johanna, David and Andreas, David focusing on axial fans, Johanna on radial and diagonal fan and Andreas on contra-rotating.
- Enginerings specification were made togheter by all students and the needs matric's matrix were made by PSU students
- Concept generation and evaluation
 - Blackbox made by Johanna
 - Sub-function diagram made by David Johanna and Tylor
 - Important parameters were made by the whole group
 - Brainstorming made by the whole group
 - Morphological matrix made by David and Johanna
 - Elimination matrix made by Chalmers students
 - Pugh matrix made by Johanna
 - Shifting focus to important parameters made by PSU students
- Concept refinement with ANSYS, Star-CCM+ and Testing
 - Taguchi array made by PSU students
 - Design and manufacturing for experimental test made by Taylor. Andreas made the designs for simulations.
 - All ANSYS testing and structural analysing has been carried out by David.
 - Star-CCM+, Andreas started to learn the software, by doing tutorials and then transfer the knowledge to David to, in an effective way, be able to work together in simulations of the specific products. The analysis of the results has been made together by David and Andreas.
 - Ansa were mainly done by David with some assistance by Andreas.

- Testing were made by PSU students
- Concept redefining were based on the analysis made in previes chapters made by David, Andreas and PSU students.
- Structural analysis were made by David in ANSYS
- Fluid simulations of redined concepts were made by David and Andreas. The communication and collecting data were made by David.
- Concepts recomendation were stated by David and Andreas
- System level design made by PSU students.
- Detailed design; Cad drawing were made by Andreas, manufacturing plan, cost analysis and material selection made by Johanna
- Final discussion made in collaboration with the team. Johanna focusing on methodology and international collaboration, David focusing on sources of errors and project achivement reflection and Andreas focusing on fulfillment of the purpose.
- Conclusion made in collaboration.
- Self assessment made by PSU students with assistance from Chalmers students.

Report appearance, structure, layout were made by Andreas. This also included assisting learn the rest of the group to work in L^AT_EX. Table and Figures were mostly created by Andreas.

