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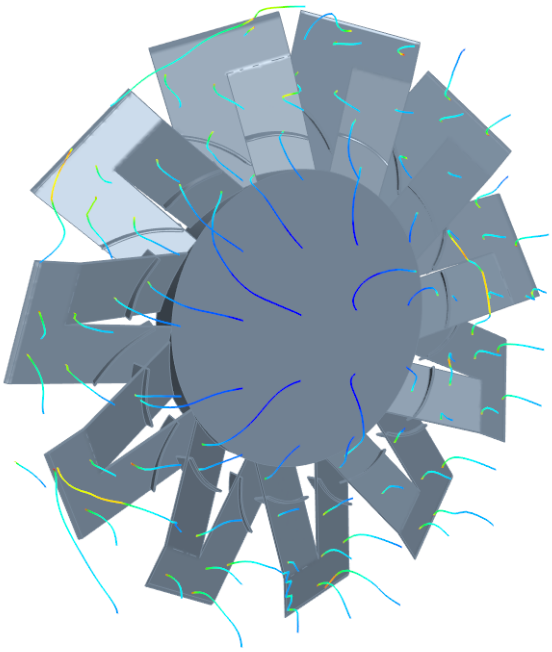

Development, Investigation and Comparison of Split Fan Blades' Performance

A collaboration between Chalmers University of Technology, Pennsylvania State University and the Volvo Group

Bachelor's thesis in Mechanical Engineering

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Department of Product and Production Development
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2017

BACHELOR’S THESIS 2017

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Cover: Illustrating the Final Concept's streamlines.

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Abstract

This report contains an investigation of the performance of a fan with split blades, based on the patent "Divided blade rotor" [US 7396208 B1]. The patent was provided by the industrial partner Volvo Group and regards a fan which claimed to allow a higher grade of efficiency.

The project started with an investigation of different patents and existing products. A black box and a sub-function diagram were made in order to establish the needs and characteristics the fan needed. From these diagrams, the project group identified seven unique design parameters that were essential for the fan. Since the investigation resulted in parameters, the most suiting method for generating concepts was design of experiment. Although, due to the time limit, the number of parameters had to be reduced to three in order get a reasonable number of concepts. Therefore, the number of generated concepts were eight.

The concepts were analysed and evaluated by their fluid dynamics performance, as well as their structural effect. Similar analyses were done on the Reference fan, supplied by Volvo Group. The parameters with the best results were combined with the Reference fan and developed into a final concept, which was analysed through simulations and compared with a similar fan containing solid blades. This made it possible to investigate the split blades' impact on the efficiency and pressure rise compared to solid blades.

The results from the simulation declared the following:

- The split blade has a higher working range than a solid blade.
- The split blade achieves a larger pressure rise.
- The split blade achieves a larger power output compared to the solid blade.
- The solid blade achieves a higher efficiency.

Hence, the design of the final concept does not have a good aerodynamics structure. There is potential to develop a better concept that could have a better efficiency due to the split blades. The recommendation is to continue the research about the split fan blade.

The bachelor's thesis has been implemented throughout the spring of 2017 as a collaboration between Chalmers University of Technology, Pennsylvania State University and Volvo Group.

Keywords: Divided Blade Rotor, Split fan blade, Volvo Group, Product development, Fluid dynamics analysis, Star-CCM+, Structural analysis, SolidWorks, Aerodynamic

Sammanfattning

Denna rapport innefattar en undersökning om prestandan för en fläkt med delade fläktblad, baserat på patentet “Divided blade rotor” [US 7396208 B1]. Patentet var tilldelat av sponsorn Volvo Group och hävdas att tillåta en högre effektivitetsgrad.

Projektet började med en undersökning av olika patent och redan existerande produkter. En black box och ett sub-function diagram gjordes för att fastställa behoven för fläkten och egenskaperna fläkten behövde. Utifrån detta tillvägagångssätt kunde projektgruppen slå fast sju parametrar som var essentiella för fläkten. Eftersom undersökningen resulterade i parametrar ansågs den mest lämpade metoden för att generera koncept vara försöksplanering. Då projektet hade en tidsgräns, behövdes antalet parametrar skalas ner till tre för att försöksplaneringmetoden skulle genererar ett resonabelt antal koncept. Slutgiltigt blev antalet genererade koncept åtta stycken.

Koncepten analyserades och utvärderades angående deras strömningsegenskaper genom simuleringar. Utöver det analyserades även bladens hållfasthet. Dessa analyser gjordes även på en referensfläkt som Volvo Group försedde projektet med. Parametrarna med bäst resultat från analyserna var kombinerade med referensfläkten och utvecklades till ett slutligt koncept med delade fläktblad. Följaktligen var detta slutgiltiga konceptet också analyserat genom simulering och jämfördes sedan med ett liknande koncept utan delade fläktblad. Detta gjorde det möjligt att undersöka de delade bladens påverkan av effekt och tryckuppbyggnad.

Resultaten från simuleringarna visade på att:

- Det delade fläktbladet är bättre för högre luftflöden än ett helt blad.
- Det delade fläktbladet uppnår en större tryckuppbyggnad.
- Det delade fläktbladet uppnår större kraft ut jämfört med ett helt blad.
- Det hela bladet uppnår högre effektivitet.

Däremot har inte det slutgiltiga konceptet en bra aerodynamisk design. På grund av detta finns det potential att utveckla ett bättre koncept med delade fläktblad för att uppnå bättre effekt. Rekommendationen är att fortsätta undersöka fläktar med delade fläktblad.

Detta kandidatarbete har utförts under våren 2017 som ett samarbete mellan Chalmers University of Technology, Pennsylvania State University och Volvo Group.

Nyckelord: Divided Blade Rotor, Delat fläktblad, Volvo Group, Produktutveckling, Strömningsmekanik, Star-CCM+, Hållfasthet, SolidWorks, Aerodynamik

Acknowledgement

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Nomenclature

AHP - Analytic Hierarchy Process
ANSA - An advanced multidisciplinary CAE pre-processing software for complete model build up
ANSYS - Finite Element Analysis Software
CAD - Computer-Aided Design
CES - Materials Selection Software
CHALMERS - Chalmers University of Technology
CLUSTER - A “supercomputer” at Chalmers utilized for simulations and calculations
DoE - Design of Experiment
FE- Finite Element
HEBBE - The name of the supercomputing cluster used at Chalmers
MATLAB - Software for mathematical and technical calculations
PSU - Pennsylvania State University
SOLIDWORKS - Software for product development processes. In this report, the Finite Element Analysis Software and Computer-Aided Design Software are used.
INDUSTRIAL PARTNER - Peter Gullberg, Volvo Group Gothenburg
STAR-CCM+ - Computational Fluid Dynamics (CFD) Simulation Software

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1. Introduction

The introduction consists of the problem presented by Volvo Group and the purpose of the project. Additionally, the project approach is introduced by a summary of the methodology used to accomplish the purpose as well as the objectives and limitations of the project. It also embodies the team and project management including a risk plan along with an ethics and environmental statement.

1.1 Background

Since globalization is increasing each day, there is a growing reliance on transportation. Because of this, more fuel is consumed and there is a bigger impact on the emission of carbon dioxide contributing to global warming. In addition, oil prices have recently been increasing radically. With this in mind, the importance of the developing resource-effective transportation is essential since the climate change affects the whole world. Global warming leads to numerous problems and to alter this negative trend, a change is necessary.

Volvo Group is a Swedish truck manufacturing company with headquarters in Gothenburg. They have production in 18 countries, 100,000 employees and last year, net sales of approximately SEK 313 billion (35 billion USD) in total [1]. As one of the largest truck manufacturers in the world, Volvo Group has realized the significance of taking care of the environment and is taking action. One approach toward reducing the dangerous emissions is to develop resource-effective transportation methods which can be done by optimizing every part of truck engines. Through a cooling system, the efficiency of a truck engine can increase and consequently the transportation will consume less fuel. This will contribute to less emissions getting released into our atmosphere. Volvo Group has presented the patent "Divided blade rotor" [US 7396208 B1] [2] which contains a fan with split blades that is presumed to considerably reduce the fan power and achieve an efficient cooling system. The aim with this project is consequently to investigate whether the split fan blade actually results in a more efficient design or not.

1.2 Initial Problem Statement

A cooling system is needed in internal combustion engines of a truck in order to remove the heat that is produced during the process. A fluid is used to transfer the heat from the engine to the radiator. The heat entering the radiator will be cooled down by air flowing through a fan, in order prevent it to overheat. The fan is mainly used during lower vehicle speeds [3]. A new design of a fan that will reduce the rotation power using the same absolute air flow, will be developed by an international team including students from Chalmers University of Technology (Chalmers) and Pennsylvania State University (PSU). The fan will be generated considering air flow rate, efficiency, pressure rise, safety and production cost, and it will furthermore fit a Volvo Group truck installation.

1.3 Purpose of Project

The purpose of the project is to investigate and develop a fan containing split blades, based on patent US 7396208 B1 [2]. A fan with split blades will be developed and compared with a standard fan provided by Volvo Group. The main objective is to investigate the possibility of achieving a better efficiency with split rather than solid fan blades.

1.4 Project Approach

The project began with a study of the previous work on the application of divided fan blades in truck engines [4]. The project group investigated the provided patent [2] and thereafter, more existing patents and similar solutions were studied. Additionally, the members of the group enhanced their understanding about fans in general.

When a sufficient investigation was complete, plans to run a preliminary Computational Fluid Dynamics (CFD) simulation in Star-CCM+, which is a software developed by CD-adapco [5], were made. In the simulations, the Computer-Aided Designs (CAD) files provided by Peter Gullberg at Volvo Group were used. This allowed for a baseline of the current product's capabilities to be compared with future simulated tests. It also ensured that the modifications made to the existing model were beneficial.

To limit the project and make certain that the purpose is fulfilled, the customer needs and an engineering specification were set. They included a fan with efficiency over 42 %, a static pressure rise above 2000 Pa and a fan power below 35 kW. More customer desires that were acknowledged was to lower cost, maintain safety and a fan rotational speed of 2400 rpm, air flow rate at 4-8 m^3/s, ease of installation and life of 20 years. Furthermore, to ensure that the concepts met the desires, constant contact with the industrial partner at Volvo Group was kept throughout the project. Once the specifications were originated, the concept generation process initiated by getting an overview of the problem. An investigation about engine theory was done and in addition, a black box and a sub-function diagram were created. The black box includes the flow of inputs and outputs that the concept needs to operate. The product's functions and solutions are demonstrated in the sub-function diagram.

Once the diagrams were made, the project group explored design parameters that the concept should consist of and the result was seven different various design parameters. When the parameters were generated, the project group chose to use a strategic concept generation due to the time limit. Therefore, the method design of experiment, abbreviated DoE, was used [6]. The method creates a number of concepts due to the number of different parameters. When using three parameters, the method generates eight different concepts. Executing simulations and calculations of eight concepts was considered possible within the time limit and therefore, the project group decided to investigate three parameters.

The initial quantity of design parameters exceeded the desired number and therefore, a reduction among the parameters had to be done. Once the parameters were down to three, which was accomplished by talking to experts and doing investigations, the DoE could be used. Because of the limit regarding three parameters, the DoE resulted in a matrix with the shape of a cube. Each corner of the cube constitutes a concept, containing a unique combination of the three parameters. In this case, parameters that the concept contains set the axes *(x, y, z-axis)* [6].

To clarify which value of each parameter that had the most beneficial impact, eight concepts were tested through simulations. First, each concept had to be drawn in the software SolidWorks [7], which is a Computer-Aided Design Software abbreviated CAD. Second, analyses of the aerodynamics of the blade using computational a fluid dynamics software called Star-CCM+ was performed. These simulations were calculated at a supercomputing cluster called Hebbe [8]. The results from Star-CCM+ were illustrated through different scenes and fan curves which presented data of pressure, power usage and efficiency. Third, the concepts blades were analysed using a Finite Element (FE) Analysis Software, SolidWorks [9], to investigate their stresses and deformation.

Finally, the concepts were evaluated and compared to each other. The parameters which most significantly fulfilled the customer's desires were combined with the Reference fan and the outcome was considered the final concept. The final concept was simulated in Star-CCM+ as well as analysed using the Finite Element Analysis Software, ANSYS [10], to see how the stresses affected the concepts blades and its safety. To get more knowledge about how the split blades affect the results, a similar comparing fan with solid blades was created and simulated.

Consequently, the project contained five simulations of each concept generated from DoE, the final fan, a comparing fan and of the existing fan, which were a total of 55 simulations. Once a design was finalized, a scale model of the final concept was made using 3D printing. Additionally, a material selection, a manufacturing plan and a cost estimation were done on the final concept. A flow chart over the work is illustrated in Figure 1.

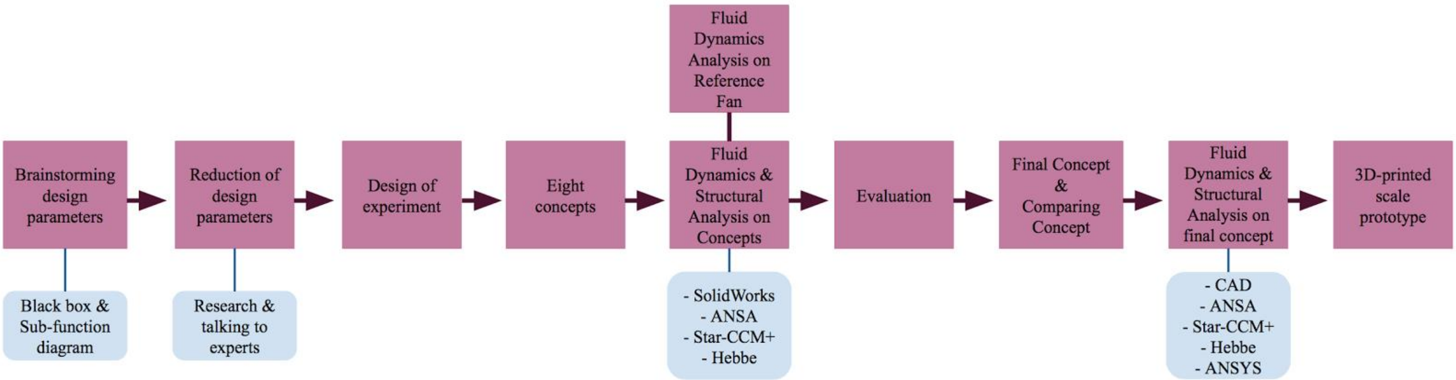


Figure 1: A flow chart over the project's work.

1.4.1 Objectives

In order to get a structural approach of the work that was needed to accomplish the purpose of the project, a list of objectives was done. These objectives are stated below:

• Product development based on the patent.
• Investigate the developed concepts efficiency.
• Investigate the developed concepts pressure rise.
• Investigate the developed concepts power usage.
• Investigate the stresses on the concepts blades.
• Analyse the different concepts performance regarding their efficiency, pressure rise and power usage.
• Develop a final concept.
• Analyse the final concept.
• A comparison between a fan with split blades and a fan with solid blades

The project's developed fan blade should preferably require ease of installation and a low manufacturing cost. Furthermore, the project's purpose for the participating students was to develop as engineers and get used to working in an international product development team.

1.4.2 Limitations

General limitations of the project consisted of the number of members, time, money and knowledge. The number of members working on the project were three students from Chalmers and three from PSU. The students from PSU worked on the project between January 9th 2017 and May 2nd 2017, and the Chalmers students worked on the project between January 17th 2017 and May 24th 2017. The students from Chalmers worked approximately 20 hours a week with the project, while the PSU students worked about 15 hours a week since they had more classes combined with the project. The time restrictions limited the number of concepts that could be generated and simulated.

The project's budget was provided from Chalmers and PSU, a total of approximately 1220 USD (11000 SEK). Chalmers contributed with 220 USD (2000 SEK) and PSU contributed with 1000 USD (9000 SEK). PSU provided with larger funds since it was expensive to develop the prototype. Chalmers contributed with use of a 3D printer, the computational cluster (Hebbe) and material free of charge, hence the lower budget contribution.

The project group was able to carry out the purpose of the project since all students had knowledge about fluid dynamics and product development and the supervisors assisted when support was needed. However, the students were beginners at Star-CCM+ and ANSA, and had to use online tutorials to get familiar with the software as well as getting assistance from the supervisors.

The time limit of the project only allowed for three parameters to be investigated. Additionally, the used method only generated eight concepts due to the number of parameters. Furthermore, the method could not be iterated and therefore the parameters could not be optimized. Every demand and desire that the sponsor declared in the Engineering Specification could not be evaluated because of the time limit. For example, it was not possible to execute a Life Cycle Analysis to determine the life of 20 years for the final concept.

1.5 Team and Project Management

In order to accomplish the purpose and get the desired results, the team and project management had to be defined. This includes the project group's general form, the project's risks and also its ethics and environmental aim. Consequently, a good structure and an advantageous collaboration could be achieved.

1.5.1 Project Management

Since the purpose of this project was to investigate and develop a split fan blade, various calculations and simulations were made. This procedure was essential in order to find a solution that can accomplish all the required credentials that Volvo Group had. Models in CAD of each concept were made and sent to Chalmers to perform CFD tests. The FE-analyses was executed at PSU on varying blade types.

The members of the project group had knowledge about mechanics, machining, fluid dynamics, heat transfer, stress/strain analyses, testing and CAD programming which all were skills demanded to complete the task. Since the students lived in different countries and had different schedules, the majority of the work and meetings were mainly performed in two groups, one per school. The groups had constant contact throughout the entire project, mainly through web meetings using Skype [11]. Skype was also used for all presentations. For daily communication, the project group utilized Google Hangouts [12], a group chat including all group members. Furthermore, to achieve more structure and to ensure that the deadlines would be reached, a Gantt Chart [13] was established, see Appendix A.

In order to prevent miscommunication, the contact with the industrial partner Peter Gullberg at Volvo Group Gothenburg, was primarily maintained by Mikaela Collijn at Chalmers. Ben Sparango at PSU was the point of contact with Sam McLaughlin at Volvo Group North America.

1.5.2 Risk Plan and Safety

In any project, there will be risks. To minimize these, a risk plan including both teams and industrial partner was formed. The purpose of the risk plan was to foresee the obstacles that could occur during the project as early as possible and thereby minimize the encountered problems.

The identification of risks mainly focused on the outcome and aims of the project. Additionally, other important risk factors such as environment, safety and resources were considered. An evaluation of the team’s efforts, as well as those of the industrial partner was also included in the risk identification. The risk analysis was based on a rating of the incident’s impact and probability, see the rating in Appendix B.

The risks that were considered critical are found in Appendix C. The level of a risk was also included, along with ways to prevent these risks from occurring. These actions were more or less drastic depending on the level of the risk. The greatest risks were conflicts within the project group and missed deadlines. To avoid the former, an open channel of communication was kept throughout the project. For the later, a Gantt chart was used and time was well managed.

1.5.3 Ethics Statement

It is important to keep moral principles in mind while developing and producing a new product. Every effort to prevent patent infringement was made and all work was acknowledged. Credit was given where credit was due. Non-Disclosure Agreements and Intellectual Property Agreements were signed by all members of the project group. General principles included complying with laws and regulations of the U.S. and Sweden, as well as demonstrating and promoting responsible business practices. All financial transactions from the project were properly reported in accordance with generally accepted accounting principles. By adhering to the fair competition practices, the team members ensured that they were not exchanging information or entering agreements with other competitors, customers, or suppliers outside of Volvo Group. It was also important that resources were used efficiently, so as to minimize material and energy waste.

1.5.4 Environmental Statement

The aim of the project was to reduce a truck’s fuel consumption with a more effective fan. If the aim was reached, it was important that the choice of material and manufacturing process did not affect, or even impair, the achieved environmental savings. The team strived for a sustainable development and this was an essential part of the project. Additionally, eco-friendly and energy-efficient manufacturing processes was a priority. The new product aimed for a life length of approximately 20 years. The project served for minimizing the product’s environmental impact during the lifespan.

2. Implementation and Result

This chapter is divided in two parts. The first part, Part I, includes the product development process that was used to be able to start generating concepts. The generated concepts were consequently analysed and a final concept was developed. Part II contains different analyses of the final concept and a comparison concept which was developed. Therefore, a discussion about the results and the split fan blade's performance contra the solid blade's performance was done. The part also consists of a material selection for the developed fan, manufacturing plan and cost estimation of the final concept.

2.1 Part I: Product Development Process

To be able to begin the product development process, the project group executed an external search and made an engineering specification based on the customer's needs. Next, the problem was clarified and the design parameters needed for the design of experiment method were set. The concepts were then generated and evaluated by performing fluid dynamics- and structural analyses on each one of them as well as the reference fan. Finally, a discussion was made to decide which parameters that would be developed further into a final concept.

2.1.1 External Search

To get more comprehension about fans in general, an investigation of patents and existing products were carried out. The search was necessary since it gave the project group knowledge about how fans operates in general and also gave inspiration about how a fan can be developed. This was used later on during the concept generation.

2.1.1.1 External Search of Patents

The first investigated patent was the "Divided blade rotor" [US 7,396,208 B1] patent provided by Volvo Group. Since the project's purpose was based on this patent, it had the primary focus during the external search. The patent contains a blade that is split into two blades with separated roots. The design is supposed to result in a more efficient fan. The second found patent is the "Split blade radial fan" [US 6,435,828 B1]. It contains a lot of blades and is expected to increase the efficiency by generating both radial- and axial flow at the tip of the blade [14].

Patent: Divided Blade Rotor

The patent "Divided blade rotor" [US 7,396,208 B1] is based on a new design of a rotor fan blade, see Figure 2. This design allows a higher grade of efficiency. By starting from a standard fan, the blade is split in two diverging blades with respective roots which are separated from each other. The air, which is the operating medium, flows through the gap which is formed between the blade portion and through the holes in the lead blade portion. [2]

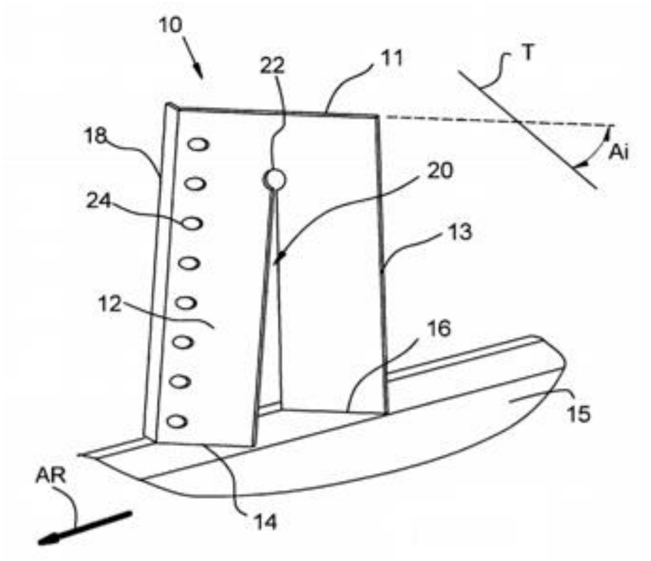


Figure 2: The design of a fan according to the patent: Divided blade rotor [US 7,396,208 B1].

Patent: Split Blade Radial Fan

The “Split blade radial fan” [US 6,435,828 B1] patent contains a plurality of blades which are configured to induce radial flow adjacent the trailing edge of the blade, see Figure 3. It is also configured to induce both radial- and axial flow near the base end of the blade. Increased ability for the fan to draw air in axially is accomplished by orienting the chord-line of the blades near the hub of the fan at an angle relative to the axis of the hub. The fan also makes use of an annular ring joining the trailing edges of the blades. The ring has axially opposite sides that taper toward each other as the ring extends radially inward. It then acts like a diverter to channel air to axially opposite sides of an annular obstruction in the flow path of air being exhausted from the fan, thereby further increasing the fan’s efficiency. [14]

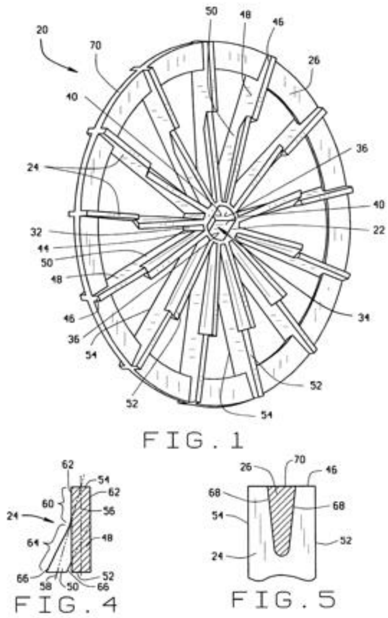


Figure 3: The design of a fan according to the patent: Split blade radial fan [US 6,435,828 B1].

2.1.1.2 External Search of Existing Products

The three most common types of fans were established. These are axial fan, radial fan and diagonal fan. The air in the axial fan has an orientation along the axis. The radial fan has blades and air flowing in the opposite, the radial, direction. The last one, diagonal fan, is a combination of the previously mentioned fans.

Existing Product: Axial Fan

The blades in an axial-flow fan are mostly formed as wing profiles and work by moving air along the axis of the fan, see Figure 4. It looks like a propeller and is often used when the space in the radial direction is restricted. Cooling systems often use axial fans since they allow large volume flows and also low pressure increase. To avoid high levels of sound, the radial fan can only work in a fairly limited pressure range. [15] and [16]

Figure 4: The design of an Axial fan with air moving along the axis [17].

Existing Product: Radial Fan

Radial fans are the most commonly used ones, their blades are straight in the radial direction and this makes the fan useful for gases contaminated with particles, see Figure 5. The rotating impeller, which is placed in a shell-shaped capsule, moves the air stream and the centrifugal force causes pressure and velocity to increase. An advantage with these fans are that they can work under high temperatures and high pressurized conditions. [15] and [16]

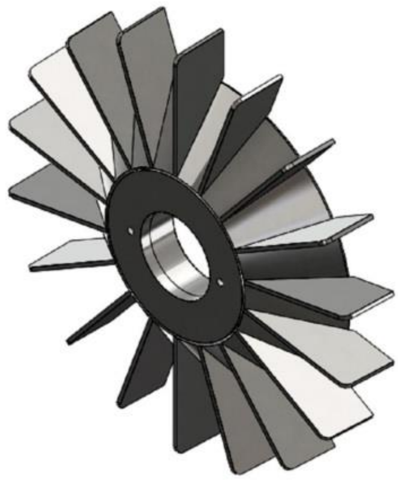


Figure 5: The design of a Radial fan with air moving in a radial direction [18].

Existing Product: Diagonal Fan
The diagonal fan consists of a conical rotor hub, which prevents vortex formation and significantly reduces noise. The fans take a position between the axial and radial fans and they allow a similar air flow as the axial fans while achieving a higher static pressure, see Figure 6. In the inlet area, the cross-section is small and the diameter increases gradually. This shape of a fan contributes to a higher circumferential speed of the blade tips, meaning a higher centrifugal acceleration. [16]

Figure 6: The design of a Diagonal fan with air flowing in a similar way as the axial fan [19].

2.1.2 Customer Needs Assessment

To ensure that the final concept satisfies the customer needs, a gathering of Volvo Group's input was done. As a result, the customer needs were established and also a request of the simulations to be presented by fan curves was stated. Furthermore, an Analytic Hierarchy Process matrix distinguished how the customer needs importance affect one another in order to rank the needs due to importance.

2.1.2.1 Gathering Customer Input

Based on earlier work within the subject [4], a partial list of customer needs was established. Additional inputs were gathered through a meeting and an interview with the industrial partner. The outcome from the interview was a wish for more simulations on the new fan blade. Evaluation of the fan's capacity was done by fan curves; an example of a fan curve can be seen in Figure 7 [20]. Through the simulations, similar curves were created over the course of the project to show the performance of the concepts.

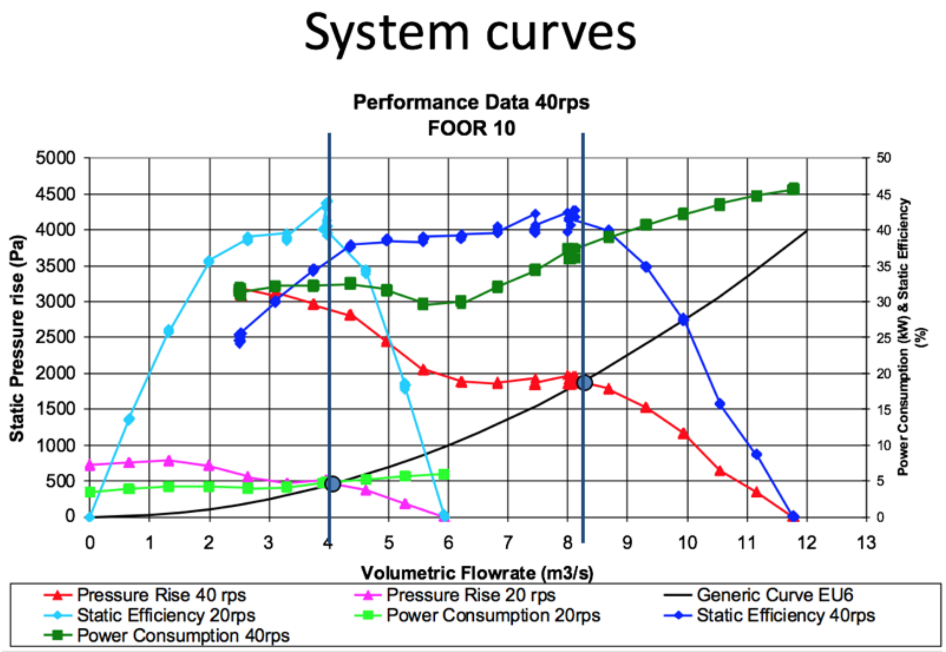


Figure 7: An example of a fan curve provided by Volvo Group, visualising the fan's pressure rise, efficiency and power consumption. The unit rps stands for revolutions per second.

The two vertical (grey) lines in Figure 7 define the interval of the volumetric flowrate in which the concepts were tested. Each concept was simulated with five different volumetric flowrates, shown in Figure 7 and are 4, 5, 6, 7 and 8 m^3/s. The pressure rise, moment and efficiency of the fans were calculated during the simulations. The different concepts results were then compared to each other and to the Reference fan in order to see which concept had the best performance. The concept with the best results was investigated and developed further.

2.1.2.2 Weighting of Customer Needs

The customer's primary established needs were a fan power below 35 kW, a desired efficiency above 42 % and a static pressure rise over 2000 Pa for the fan. The other set up desires were parameters such as the fan's diameter (750 mm), a desire to produce the volumetric flow rate at 8 m^3/s and a fan rotational speed at 2400 rpm. According to the customer, the fan could be exposed to approximately a temperature of 87° Celsius and at failure, it could experience temperatures as high as 112° Celsius. The remaining desires provided by the customer were to maintain safety and to maintain or lower the mass. It was also important that the concept had a life of 20 years, ease of installation and to lower cost.

As seen in Table 1, the project group aimed for ten customer needs to be fulfilled. These were an integral to the design of the fan in ways such as emissions, repair (if needed), operation and consumer needs.

Table 1: The 10 customer needs that the project needs to fulfil

Efficiency
Fan power
Static pressure rise
Size
Volumetric flow rate
Rotational speed
Safety
Mass
Durability
Cost

The project group made an Analytic Hierarchy Process, shortened AHP, to evaluate the importance of each customer need compared to each other, see Appendix D [21]. The AHP was made regarding the importance of the different needs according to the customer. The top three needs based on this matrix were, in chronological order, efficiency, fan power and static pressure rise.

2.1.3 Engineering Specification

To establish which aims the final product needed to fulfil, an engineering specification was created, see Appendix E. From the external search, section 2.1.1, establishing target specification, section 2.1.3.1, and the customer needs, section 2.1.2, the characteristics which the product needed in order to achieve the aims of the final product were determined. It contains the different function criteria including if they are a demand or desire, authentication method, target value and their reference.

2.1.3.1 Establishing Target Specifications

Specifications were generated through contact with the industrial partner and from the customer needs, section 2.1.2. They were made to identify the needs that the project group would focus on and can be seen in Table 2.

Table 2: The project's target specifications generated from the customer needs

Target Specification	Value
Power Input	<35kW
Efficiency	>42%
Static pressure rise	>2000 Pa
Fan rotation speed	2400 rpm
Material	Polyamide
Temperature Interval	87-112 °C
Diameter	750 mm
Life	20 years
Volumetric Flow Rate	4-8 m^3/s
Fit to existing system	Keep the base section geometry

2.1.4 Concept Development

Firstly, the problem was clarified by establishing a black box and a sub-function diagram. Consequently, it was possible to start the concept generation by exploring parameters that the final concept should consist of. The three most important design parameters were then distinguished and used to generate concepts in the design of experiment method.

2.1.4.1 Problem Clarification

The problem clarification began with investigating the engine theory and continued with executing a black box and a sub-function diagram. It was of great value to understand what the problem was in order to find a solution.

Engine Theory

In internal combustion engines, a cooling system is needed to remove the remaining fuel energy that is produced in the combustion process. This energy is rejected as heat. The cooling system consists of a single loop water system where the working fluid is antifreeze, water and either ethylene glycol or propylene glycol. The water pump sends the coolant to the engine block and then to the head. The warm coolant will then flow through the intake manifold in order to heat up even more to assist in vaporizing the fuel. The coolant will then flow into the radiator to reject the heat. The heat entering the radiator can cause the radiator to overheat, especially if the vehicle is not moving, so fans are added to cool the radiator. Since the fan is directly connected to the crankshaft of the engine, the fan will be circulating the air as long as the engine is running to help in the rejection of heat. A split fan blade allows for a longer lifespan of each fan blade, as it divides the forces due to drag and circular motion between two parts as opposed to a singular blade. [3]

Black Box

Flows of energy, material and information that the concept needed to process and how they are connected is presented in the black box, as seen in Figure 8. The black box made it easier to get a clear picture of the concepts' inputs and outputs, without having any information about the internal system. In this case, the inputs involved energy in form of electricity and air flowing in with a low pressure and velocity. It also contained information about when the truck is started in form of a turn on signal. The outputs from the fan-system were desirable temperature of the engine together with noise, velocity, air with a higher pressure and information about the engine temperature. [13]

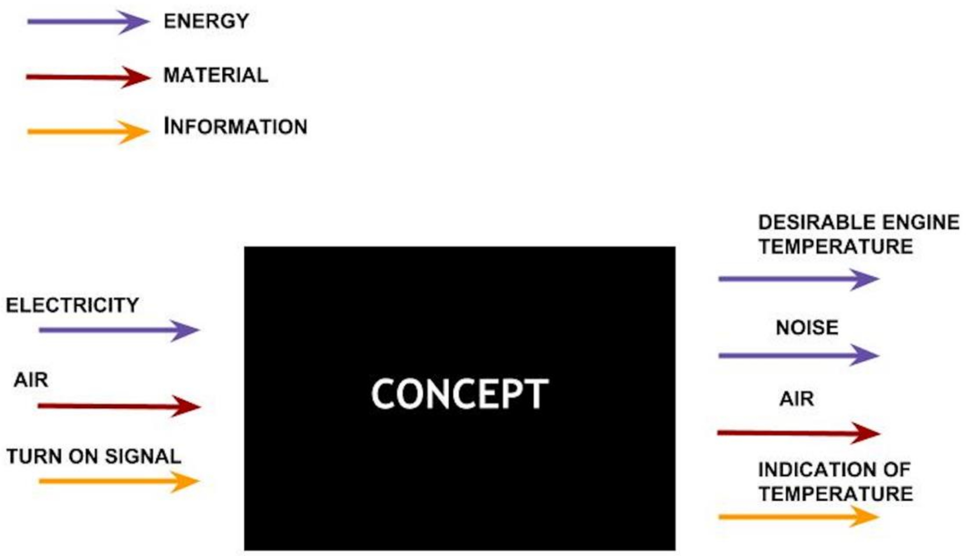


Figure 8: Black Box Diagram with the different flows in the system. The purple arrow shows the energy flow, red is the material flow and information is demonstrated with an orange arrow.

Sub-function Diagram

Once the essential flows were clarified, a sub-function diagram was created in order to illustrate the product's function and the solution needed for the main purpose, see Figure 9. The top of the diagram contains the most important function and is thereafter divided into sub-functions with individual solutions. The diagram was overall based on earlier work that has been done within this subject. [13]

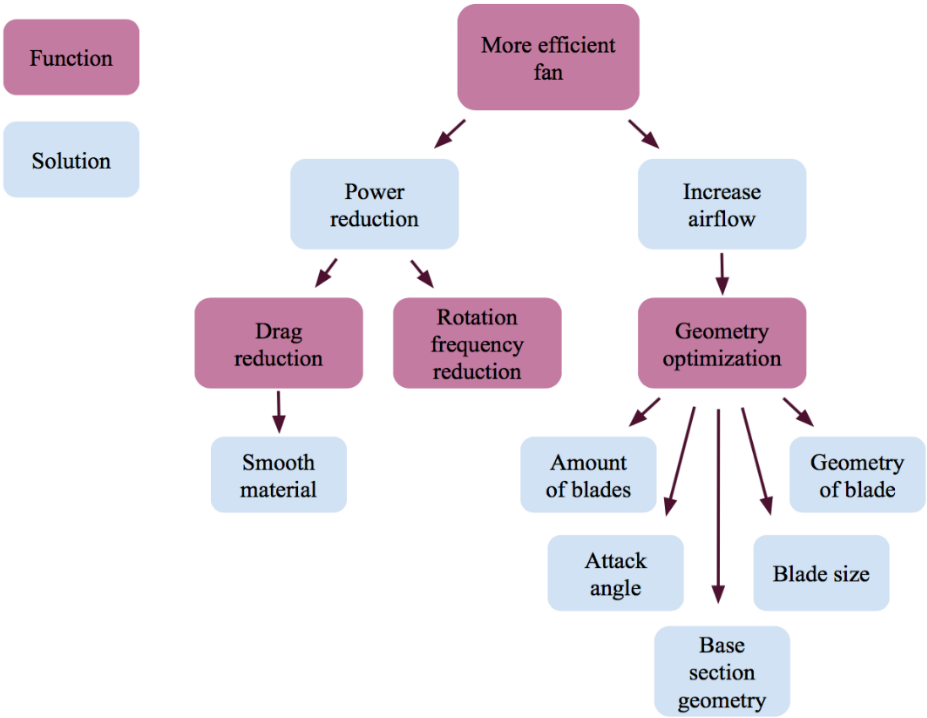


Figure 9: Sub-function diagram showing the product's functions and solutions needed for the main purpose.

2.1.4.2 Concept Generation

The concept generation started with exploring different design parameters that the fan should have. The exploration was based on the earlier steps in the problem clarification such as the black box and sub-function diagram. The seven parameters along with their importance towards the development of the fan are listed below:

- Number of blades. How many blades would the fan contain of?
- Attack angle. At which angle of the torso would the blade accomplish optimal air flow?
- Base section geometry. What shape is most optimal for the aerodynamic?
- Length of split. How long could the split between the roots be? This was measured in percent of the blades total length.
- Number of holes on one blade. Would the holes affect the air flow?
- Angle of split between the roots. How wide could the split be?
- Geometry of blade. Which blade geometry was creating the best air flow?

Thereafter, the concepts were developed by the method design of experiment [6], abbreviated DoE, and the first generation of concepts were evaluated through simulations. When this was executed, the results were compared to each other and the parameters of the best performing concept was applied on the Reference fan and developed further as the final concept.

Important Parameters of Concept

Since the project was restricted by time, the project group had to limit the study of design parameters. Due to the limit, the parameters had to be reduced from seven to three in order to get a reasonable number of concepts generated by the method DoE. To be able to scale down the parameters to the most important ones, the project group researched and talked to experts.

The parameters that finally got reduced were the geometry of the blade, base section geometry, the attack angle and the number of holes in one blade. Firstly, the project group decided to keep the current base geometry, since it would facilitate the manufacturing process. Secondly, since a demand for the DoE method was that the parameters had two comparative values, the geometry of the blades was disregarded. Due to the unavailability to choose two values within a comparative interval, the parameter was therefore removed. Straight blades were used instead, in order to get an equal comparison between the generated concepts. Thirdly, the attack angle was reduced since it is possible to calculate the optimal attack angle and use it for all concepts [22], see the attack angle in Appendix F.

By studying the previous work [4], more information about how the number of holes affect the fan's performance could be established. The conclusion about the number of holes was that they most likely do not contribute to the results that they achieved, instead it depended on the high angle of incidence. In addition to this, the project group talked to the adjunct Chalmers professor and mechanical engineer at GKN Group, Anders Lundbladh. According to him, the number of holes only have a significant impact when the fan is started, at least when it comes to fans for jet engines [23]. Consequently, the project group determined that a study of a blade with holes would be unnecessary for the project and therefore number of holes were set to zero and the parameter was disdained.

The parameters that were considered most interesting and that will be used for further investigation and concept generation were the number of blades, length of split and angle of split between the roots. Based on recommendations from the earlier research within this field [4], the number of blades should be investigated. Furthermore, the number of blades are interesting because it affects both the moment needed to run the fan and also the airspeed and therefore the parameter was kept. Next, the length of split was regarded as a significant parameter to retain since the length is connected to the projected area of the fan. To make a fan as efficient as possible, it is important to increase the projected area which is the reason why the parameter should be investigated more. Last, the angle of split between the roots is also associated with the projected area and will therefore neither be reduced.

Design of Experiment Method

The method called design of experiment was used to make the research as time effective and strategic as possible. As mentioned before, when using three parameters to investigate the DoE method generates a cube. With the chosen parameters, the cube contains eight different concepts, this can be seen in Figure 10 The eight corners of the cube represent different combinations of parameters that turn into concepts. The main purpose of DoE was to strategically evaluate the impact of every parameter and the impact of the different parameters combined. Additionally, the DoE method was limited within this project to use just three parameters, due to not generate too many concepts. This because of the limited time for evaluation of the concepts. [6]

To set up the design of experiment matrix, the values of the different axis needed to be determined. First, the interval of number of blades given from the industrial partner was between 7 and 13 blades. To ease the interpretation of the result, the parameter regarding the number of blades would be alternated between 9 and 11 in order to see whether the optimal number would need to increase or decrease. The length of the split, measured from the bottom of the blade, was set by a percentage of the total length of the blade where the blade length remained constant. The values were set between 75% and 85% of the total length of the blade. Finally, the angle of the split would be measured between the two roots as shown in Figure 11c. The angle was alternated between 5 and 15 degrees.

These three parameters were set as the axis for the cube as seen in Figure 10. Consequently, the DoE was implemented and the results of each corner generated the following concepts:

1. 5°+9+75%
2. 5°+11+75%
3. 5°+11+85%
4. 5°+9+85%
5. 15°+9+85%
6. 15°+9+75%
7. 15°+11+75%
8. 15°+11+85%

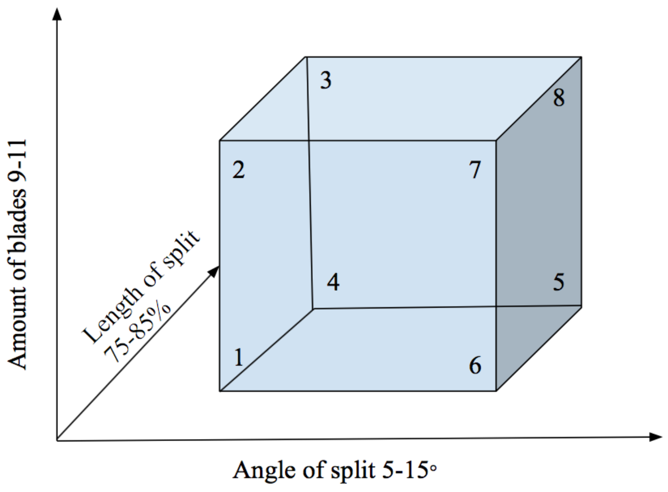


Figure 10: The DoE matrix used for generating concepts. The axis represents the three parameters; length of split, number of blades and angle of split.

The eight concepts above are combinations of the three parameters and their altered values. To see which combinations that were most efficient and that should be developed further, the concepts were evaluated with respect to efficiency, pressure rise and power usage.

2.1.5 Concept Evaluation and Results

Different simulations were made on the reference fan and the generated concepts. Simulations in SolidWorks [9] showed the strength of the fan, while simulations in Star-CCM+ [5] visually showed how the flow and pressure changes around the fan. Star-CCM+ gave results of the pressure rise and the moment which were used to calculate the power input, power usage and efficiency for numerous air flows. The concepts results were subsequently evaluated and the altered benefits and disadvantages each concept were stated.

2.1.5.1 System Level Design of Concepts

The different concepts were evaluated by CFD-simulations and FE-analyses and in order to do this, they had to be modelled in CAD. The parts of the CAD-assembly, see Figure 11, were drafted using SolidWorks [7] first.

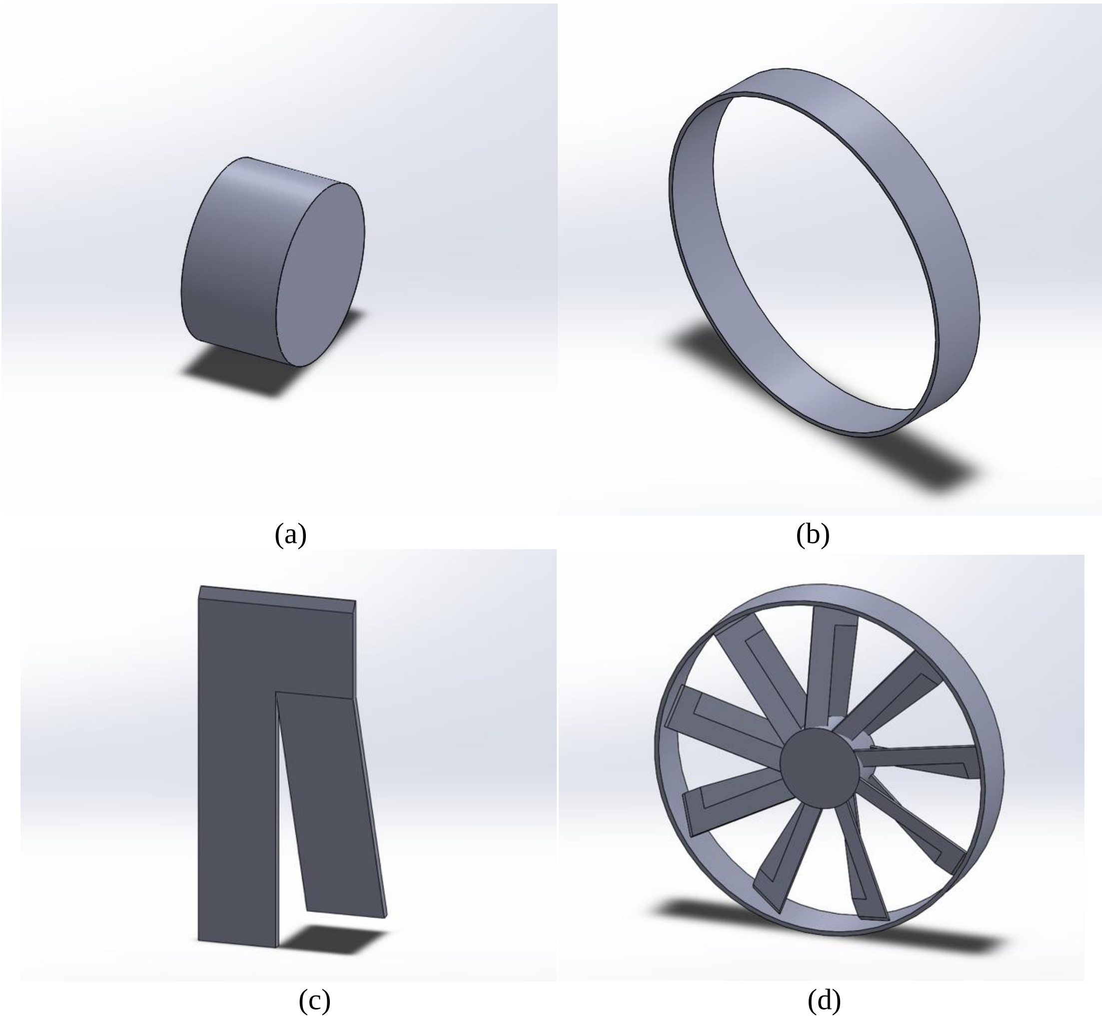


Figure 11: The components of the assembly drawn in CAD: the hub (a), outer housing (b), blade (c) and (d) the assembly.

A hub was created to allow for the attachment of the blades. The hub was simplified down to a solid disk for analysis of air flow and stresses. The outside housing was created purely for aesthetics and to ensure a fit for the actual implication of the entire assembly. The blade was then drafted in SolidWorks following the parameters that were designated to be tested.

Finally, an assembly was created to put all the individual parts into one complete system. During the assembly process, the hub and housing were mated concentrically to ensure that the hub was located in the centre of the housing. The blades were then inserted and rotated about the *y-axis* in order to mate them to the hub at the designated attack angle of 23.78° degrees. A circular pattern was made in order to easily change the number of blades to coincide with the parameters of the concepts. This process was repeated until all eight concepts were completely drafted.

2.1.5.2 Structural Analyses of the Concepts

Finite Element Analyses (FE-analyses) were performed on the CAD models. The analyses were primarily used to determine the safety through the analyses of the stresses and stress concentration. This analyse was only performed on four different blades, see Table 3. If the fan fails, it will most likely be at the tip of the split or at the connection to the hub. The housing will not be the point of failure due to larger amount of material and it is therefore not included in the simulations.

The FE-analyses was done solely on the blade in the software SolidWorks, where the base of the blade had a fixed support boundary condition. This condition is equivalent with the blades fixed attachment to the hub and is represented by the green arrows shown in Figure 12. The pressure on the front and back of the blade was determined by the pressure differences from the CFD analyses results, see section 2.1.5.4, regarding the Reference fan. This pressure is indicated by the red arrows in Figure 12. The pressure was applied normal to a plane at 23.78° from the front plane to simulate the attack angle. This allowed the pressure to be applied to the blades at the angle which it would actually be in the engine compartment. The calculations of these forces can be seen in Appendix G.

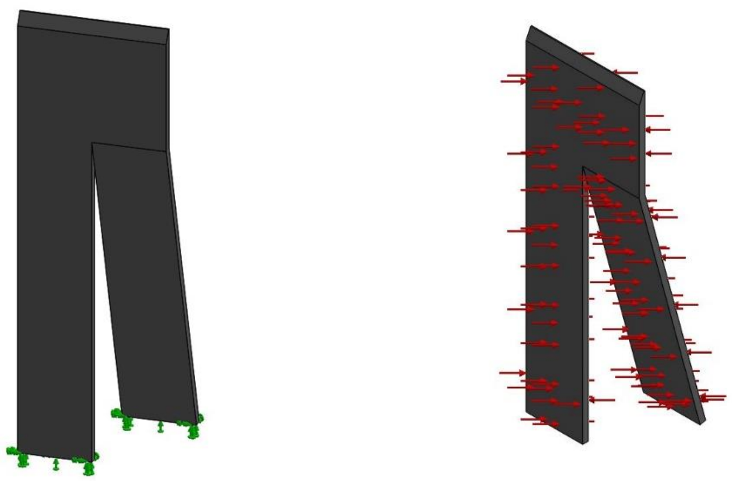


Figure 12: The boundary conditions (left) and pressure (right), used to complete the Finite Element Analyses in SolidWorks on the different blade types.

Structural Analyses Results of the Concepts

From the eight generated concepts, there are four different blade types. Each of the blade types are a combination of the parameters length of split and angle of split. The four different blade types were named SFB 1-4, were SFB stands for "Split Fan Blade". The different concepts, their parameters and the results are shown in the Table 3.

Table 3: The different blade types' parameters and their respectively result from the structural analyses.

Blade Number	Angle of Split (°)	Length of Split (%)	Displacement (mm)	Stress (MPa)
SFB 2	5	75	8.8	12
SFB 3	5	85	9.2	11
SFB 5	15	75	0.85	4.4
SFB 6	15	85	1.2	3.6

The results of the displacements on combination 1, which has a split of 75% and an angle of 15° can be seen in Figure 13. The computed effective stress was well below the yield strength of the final material which is 9.5 GPa. The full stress distribution, including a zoomed view of the largest effective von-Mises stress concentration, are shown in Figure 14. The maximum stress on the blade was 3.7 MPa, which is acceptable. As expected, the largest stress occurs at the split of the blade and at the connection to the hub. These could be alleviated by rounding off the tip of the split and utilizing fillets at the point of connection with the hub.

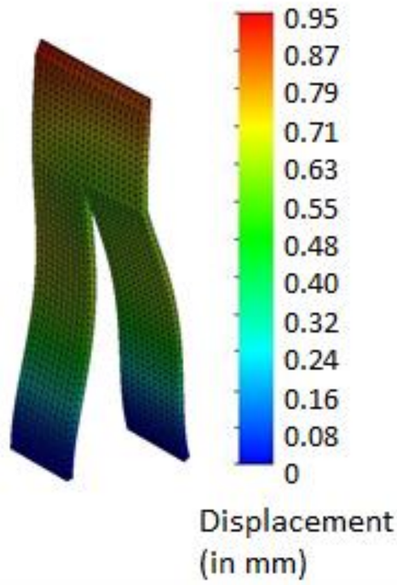


Figure 13: The displacement distribution from the structural analysis of the first combination with a split of 75% and an angle of 15°.

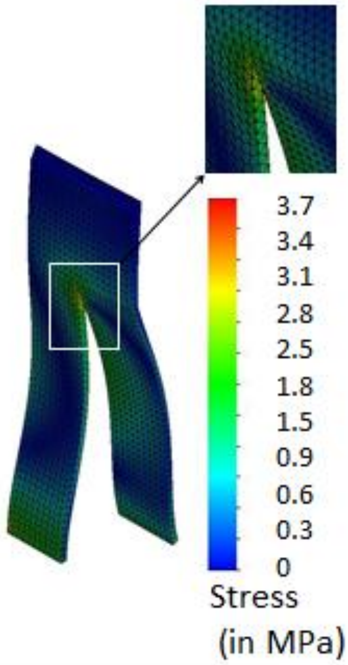


Figure 14: The stress distribution the first combination with a split of 75% and an angle of 15°. The largest effective von-Mises stress concentration is at the split, and the connection to the hub, as expected.

2.1.5.3 Fluid Dynamics Analyses of the Reference Fan and the Concepts

On each of the eight CAD models as well as the Reference fan and the final concept, Computational Fluid Dynamics (CFD) was performed. The concepts were tested to judge the efficiency, pressure rise and power usage of each design. The results were documented, and the results for the eight concepts were evaluated to determine which combination of parameters that had the best performance during the simulations.

By using a prepared simulation file distributed by the industrial partner, the different concepts could be analysed. The file contained a test rig which is similar to how the fan operates in a truck. The original file contained Volvo Group's original fan, which was the first fan analysed for comparison. The simulations on the Reference fan made it possible for the project group to get familiar with the software for the continuous work. In order to make the simulation file work for the different generated concepts, a pre-mesh of the concepts had to be made in ANSA, an advanced multidisciplinary CAE pre-processing software for complete model build up [24]. The meshed concepts were thereafter imported as one region with all boundary conditions into the simulation file and replaced the original fan. When the fan was translated to the accurate position, a volume mesh was made. The simulations were done in steady state, meaning having a moving reference frame. In order to calculate the power usage and the input power, the moment and the pressure rise of the fan between the inlet and outlet were especially interesting. Therefore, before running the simulations, some settings for the outcome reports were needed.

In order to reach convergence, the simulations were iterated 2000 times and the mesh contained around 5 million cells. For a normal computer, these simulations would have taken a long time, therefore the files were uploaded to the supercomputer Hebbe [8]. When the simulations were done, the results were downloaded from Hebbe. From the outcome reports, the moment and pressure rise were documented in an Excel file in order to execute the calculations of the fan's efficiency, Appendix H. The residuals were checked, see Appendix I, after every simulation to be sure that the simulation had reached convergence.

Fans in general have different optimal working ranges but the project's concepts will only be simulated with five different air flows q. These were defined in the inlet and had values between 4-8 m^3/s. This means that the concepts might not perform as good as they could if they were in their actual optimized working range. The interval 4-8 m^3/s will be referred to as the working range later on. The air thereafter flowed through the fan and out through the outlet. The pressure rise p was calculated between the inlet and the outlet and the moment was calculated on the hub and the fan. With the rotational speed ω constant at 2400 rpm, equals 251 rad/s, and the moment M given from the simulations, the power input P_{in} was calculated, see Equation 2.1. The power usage P_{out} was calculated through the air flow, q, and the pressure rise, p, which also was given from the simulations, see Equation 2.2. The efficiency η of the fan was thereafter calculated by dividing P_{out} with P_{in}, Equation 2.3.

$$P_{\text{in}} = \omega \cdot M \tag{2.1}$$

$$P_{\text{out}} = q \cdot p \tag{2.2}$$

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}} \tag{2.3}$$

Every fan had five air flows analysed and the results of the power usage, pressure rise and efficiency were compiled in graphs. These were made in MATLAB [25] and used for comparison of the different concepts. Although, since the simulations were time consuming, only five different values of air flows were sufficient.

Four different scenes were created in the post-simulation process, and they made it possible to analyse the fan's performance and ease the comparison of the eight concepts. The four created scenes were:

- Volume mesh, see Appendix J
- Streamlines, see Appendix K
- Pressure rise, see Appendix L
- Backflow, see Appendix M

The volume mesh scene enables the ability to see the accuracy of the mesh and emphasizes the fairness of the simulations. The scenes displaying the streamlines and the pressure rise illustrates how the air flow behaves and affects by the fan. Finally, the scene illustrating the backflow made it possible to determine how the air streams through the fan. The blue areas in Figure 15 symbolizes air flowing in the wrong direction through the Reference fan, which represents the backflow. Moreover, the backflow scenes of each concept are found in their respectively sections in the report. This phenomenon is important to take in consideration thus it highly affects the pressure rise and thereby the fan's efficiency.

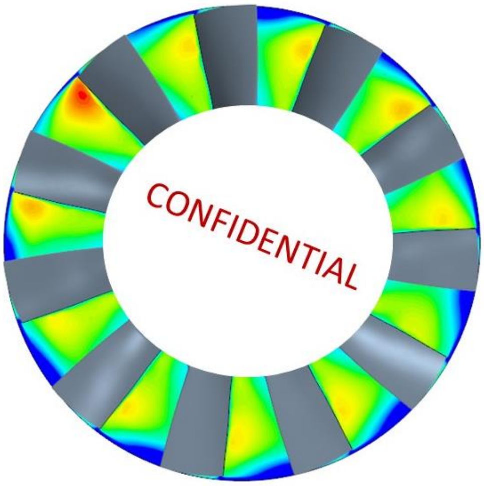


Figure 15: Illustration of the Reference fan's backflow, the blue area shows the backflow.

2.1.5.4 Reference Fan

A Reference fan was given by Volvo Group and the aim was to outperform the result from the analyses on the Reference fan with a final concept.

Fluid Dynamics Analyses Results of the Reference Fan

CFD analyses were made, using the software Star-CCM+, on the reference fan. As mentioned in section 2.1.5.3, the efficiency, the pressure rise and the power usage were investigated by the CFD analyses and compared to the air flow rate at the rotational speed of 2400 rpm, according to the Engineering specification, see Appendix E. The results that were calculated in MATLAB are presented in Figures 16 and 17.

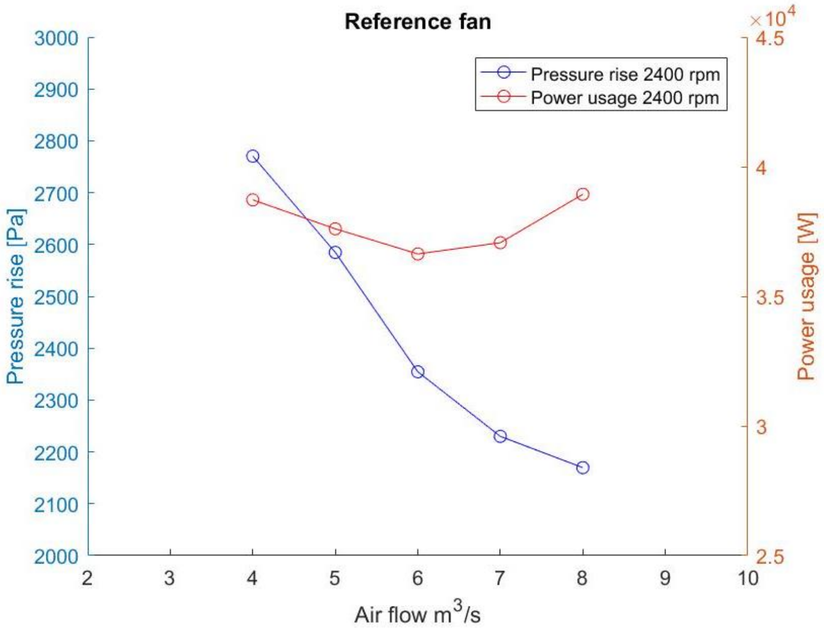


Figure 16: The fan curves are illustrating the pressure rise and power usage of the Reference fan. The graph is based on the results from the CFD analyse

s.

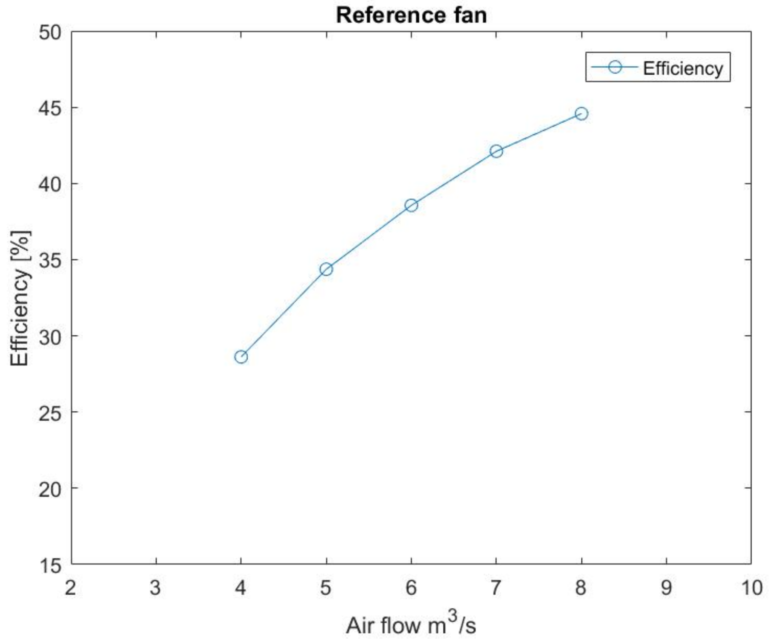


Figure 17: A graph illustrating the efficiency of the Reference Fan.

By analysing the efficiency curve, illustrated in Figure 17, it is obvious that the overall efficiency of the Reference fan is increasing. This means that the fan was run within its working range [20]. In Figure 18, it is possible to observe the pressure rise between the front- and backside of the fan. The figure also presents the results from a simulation with the air flow 6 m^3/s. The direction and the velocity of the air flow is illustrated by the streamlines in Appendix K.

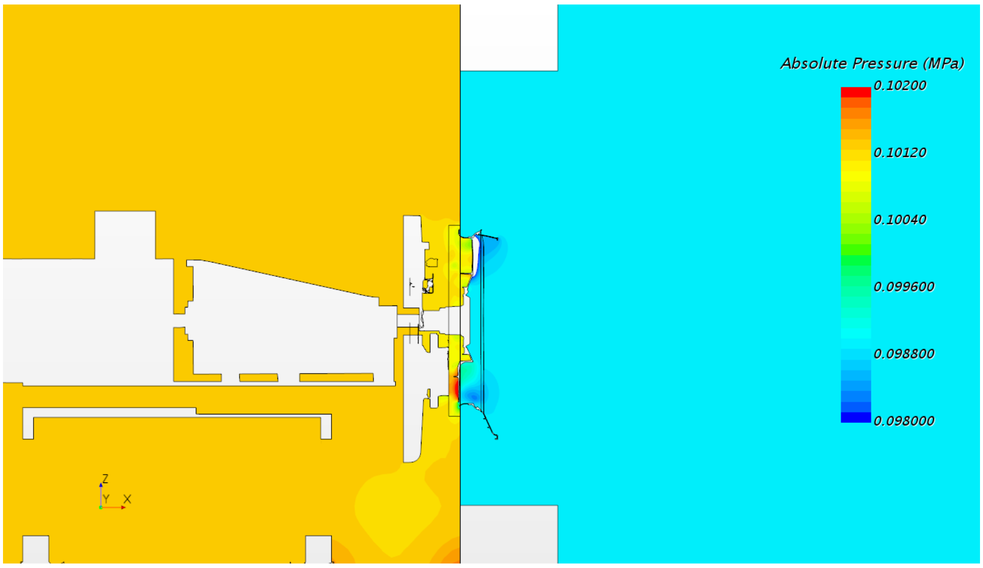


Figure 18: The pressure rise between the front- and backside of the reference fan in a simulation with air flow of 6 m³/s.

2.1.5.5 Presentation of Concept 1

The first concept, called Concept 1, contained the combination of 9 blades, 75% and 5°. This means that the concept contains nine blades, the length of split is 75% of the blade and the angle of split it 5°. Concept 1 can be seen in Figure 19.

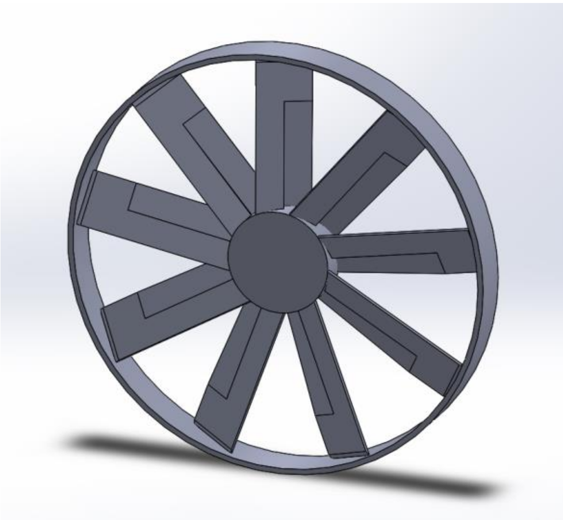


Figure 19: Concept 1 which contains nine blades, 75% length of split and 5° angle of split.

Fluid Dynamics Analyses Results of Concept 1

As the scene in Figure 20 shows, Concept 1 has a lot of backflow close to the hub, but almost not any near the blades. According to the efficiency drop in the fan curve in Figure 21, the fan is not in the optimal working range. Out of the examined air flows, the maximum efficiency that Concept 1 has is at 6 m^3/s and is the value 30.8%.

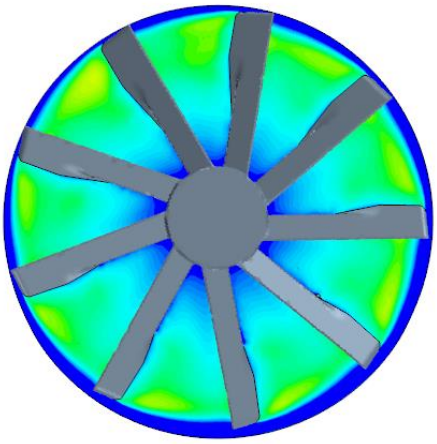


Figure 20: Illustration of Concept 1 at the air flow 6 m³/s . The blue area represents the backflow. There is a lot of backflow close to the hub.

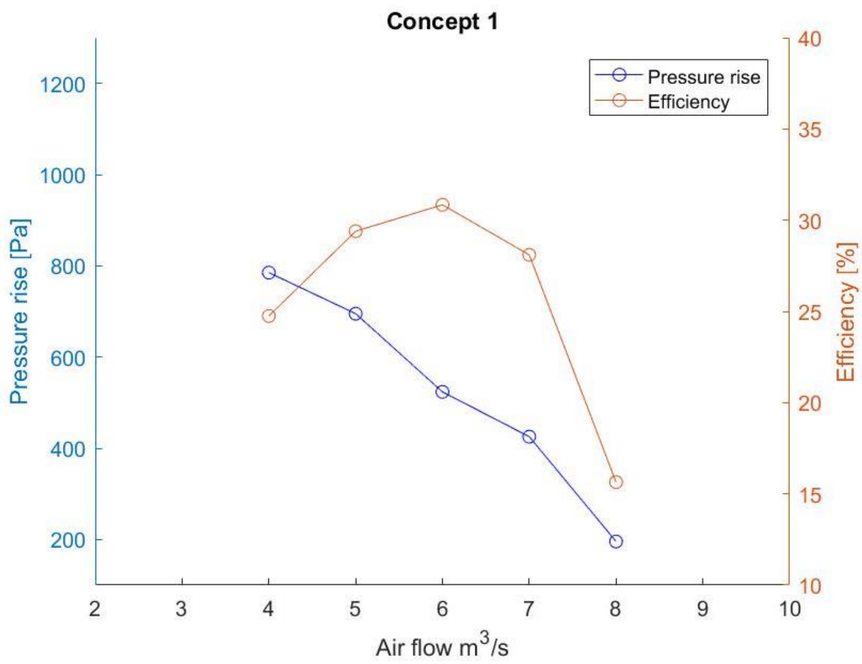


Figure 21: Fan curves illustrating pressure rise and efficiency of Concept 1.

2.1.5.6 Presentation of Concept 2

The second concept, called Concept 2, contained the combination of 11 blades, 75% and 5°. This means that the concept contains eleven blades, the length of split is 75% of the blade and the angle of split it 5°, see Figure 22.

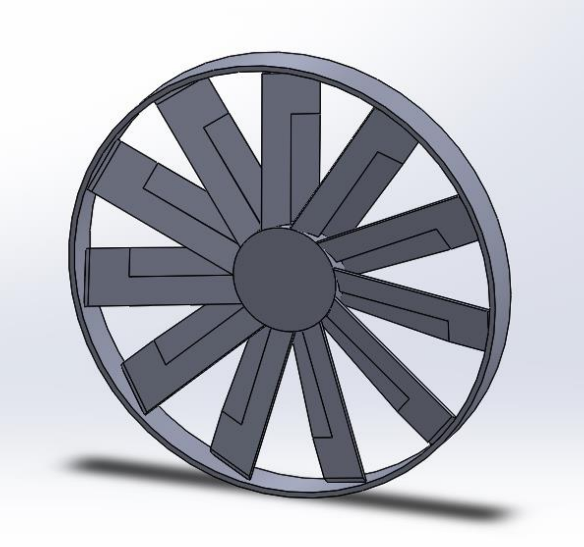


Figure 22: Concept 2 which contains eleven blades, 75% length of split and 5° angle of split.

Fluid Dynamics Analyses Results of Concept 2

As the scene in Figure 23 shows, Concept 2 does not have quite as much backflow close to the hub compared to Concept 1. There is almost no backflow near the blades, which contributes to the conclusion that the backflow near the hub is dependent of how many blades the concept contains of. Another conclusion that could be made is that the backflow near the blades are according to either the length of split or angle of split.

Pursuant to the fan curve, Figure 24, the fan is in the optimal working range for the fan in the end. The maximum efficiency that Concept 2 has is at the air flow 6 m^3/s and is the value 33.4%.

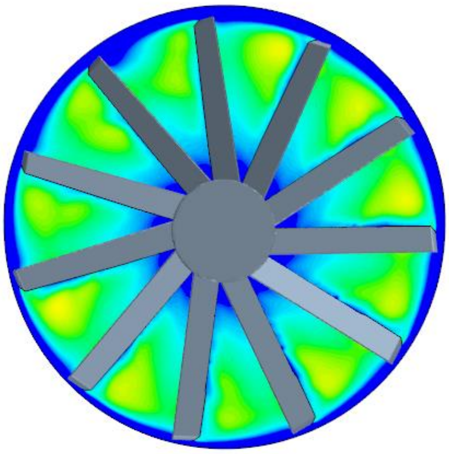


Figure 23: Illustration of Concept 2 at the air flow 6 m^3/s. There is not as much backflow close to the hub, compared to Concept 1.

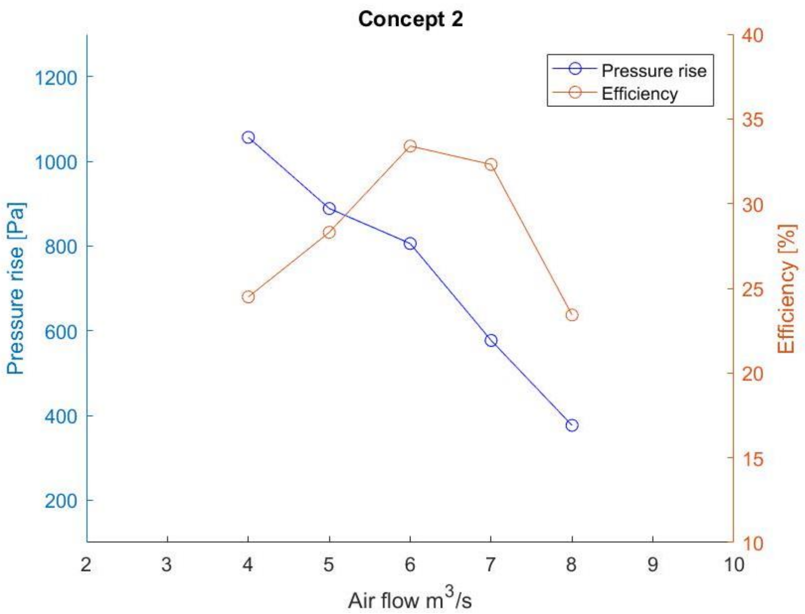


Figure 24: Fan curves illustrating pressure rise and efficiency of Concept 2.

2.1.5.7 Presentation of Concept 3

The third concept, called Concept 3, contained the combination of 11 blades, 85% and 5°. This means that the concept contains eleven blades, the length of split is 85% of the blade and the angle of split it 5°, see Figure 25.

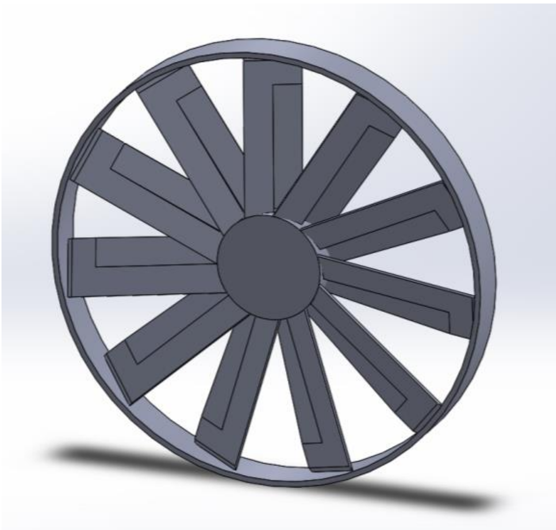


Figure 25: Concept 3 which contains eleven blades, 85% length of split and 5° angle of split.

Fluid Dynamics Analyses Results of Concept 3

As the scene in Figure 26 shows, Concept 3 does not have a lot of backflow close to the hub which strengthens the conclusion that it is dependent on the number of blades. The backflow is also reduced near the blades and the conclusion is thereby that it depends on the angle of split rather than the length of split.

According to the fast drop of efficiency that is plotted in the fan curve, Figure 27, the fan is not in the optimal working range for the fan. The maximum efficiency that Concept 3 achieves in the given interval is at the air flow 6 m^3/s and is the value 29.2%.

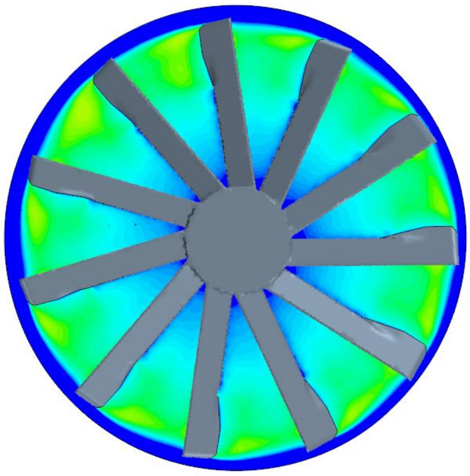


Figure 26: Illustration of Concept 3 at the air flow 6 m^3/s . There is not a lot of backflow close to the hub. Notice the blue ring around the fan.

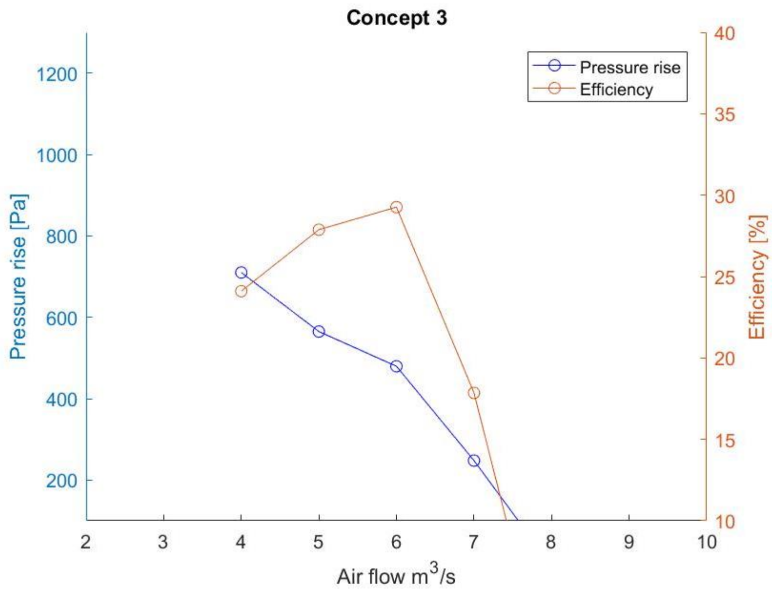


Figure 27: Fan curves illustrating pressure rise and efficiency of Concept 3.

2.1.5.8 Presentation of Concept 4

The fourth concept, called Concept 4, contained the combination of 9 blades, 85% and 5°. This means that the concept contains nine blades, the length of split is 85% of the blade and the angle of split is 5°, see Figure 28.

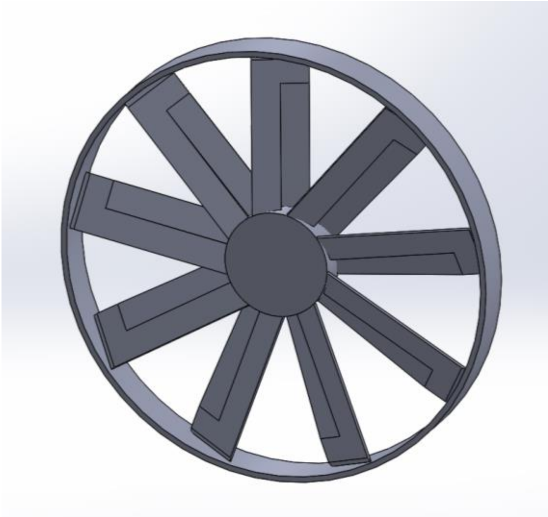


Figure 28: Concept 4 which contains nine blades, 85% length of split and 5° angle of split.

Fluid Dynamics Analyses Results of Concept 4

As the scene in Figure 29 shows, Concept 4 has more backflow close to the hub than Concept 2 and 3, the concepts which also consists of a larger number of blades. There is not much backflow near the blades, which contributes to emphasizing the assumption that this kind of backflow is dependent on the angle of split.

Pursuant to the efficiency in the fan curve, Figure 30, the fan is in the optimal working range for the fan. The maximum efficiency that Concept 4 achieves is at the air flow 6 m^3/s and has the value 29.4%.

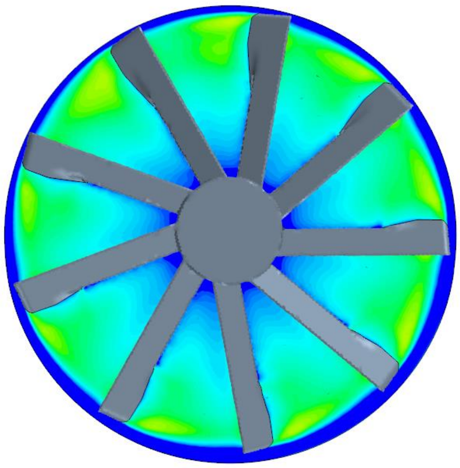


Figure 29: Illustration of Concept 4 at the air flow 6 m^3/s . The blue area represents the backflow. Compared to Concept 2 and 3, there is more backflow close to the hub on Concept 4. Notice the blue ring around the concept.

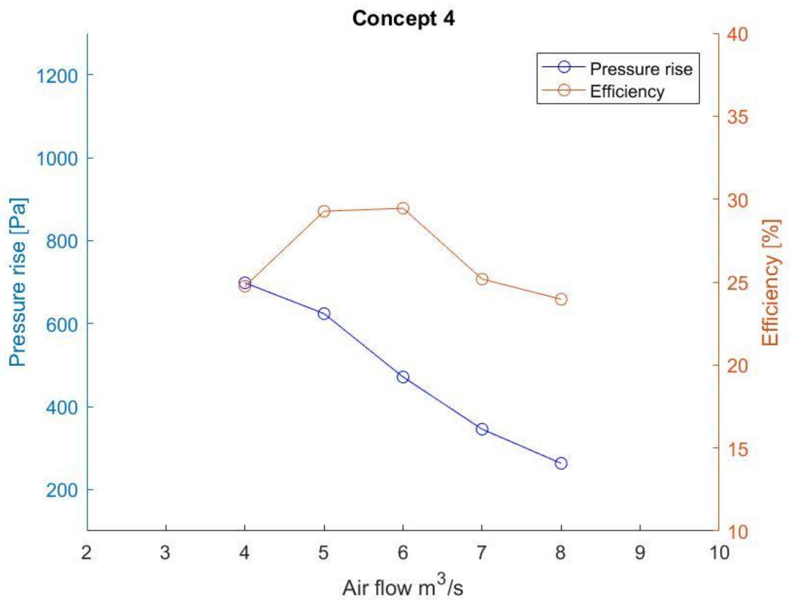


Figure 30: Fan curves illustrating pressure rise and efficiency of Concept 4.

2.1.5.9 Presentation of Concept 5

The fifth concept, called Concept 5, contained the combination of 9 blades, 85% and 15°. This means that the concept contains nine blades, the length of split is 85% of the blade and the angle of split it 15°, see Figure 31.

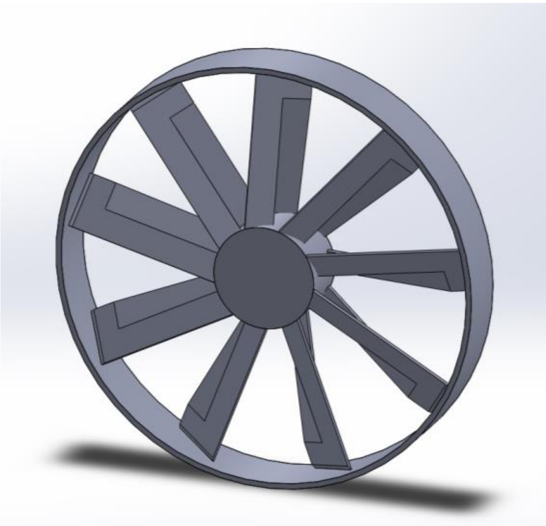


Figure 31: Concept 5 which contains nine blades, 85% length of split and 15° angle of split.

Fluid Dynamics Analyses Results of Concept 5

Concept 5 is the first fan analysed with the parameter of 15° angle between the split. The interesting thing about this parameter is the possible effect of the backflow. As seen in Figure 32, a blue area can be detected at the top of the split. A wider angle can be contributing to a greater backflow of air. On the other hand, Concept 5 is one of the best concepts that is consisting of nine blades according to the pressure rise, see Figure 33. Concerning the efficiency of Concept 5, it has a higher value compared to the other nine bladed concepts.

The air flow range of 4-8 m^3/s seems to be a good working range for the concepts thus it reaches its maximal efficiency of 28.8% at 7 m^3/s, see Figure 33 and Appendix H.

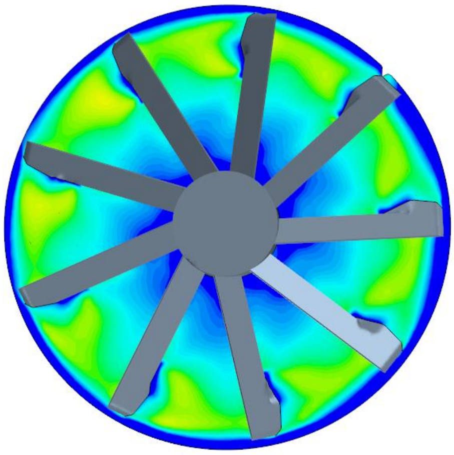


Figure 32: Illustration of Concept 5 at the air flow 6 m^3/s . The blue area represents the backflow. There is a lot of backflow close to the hub.

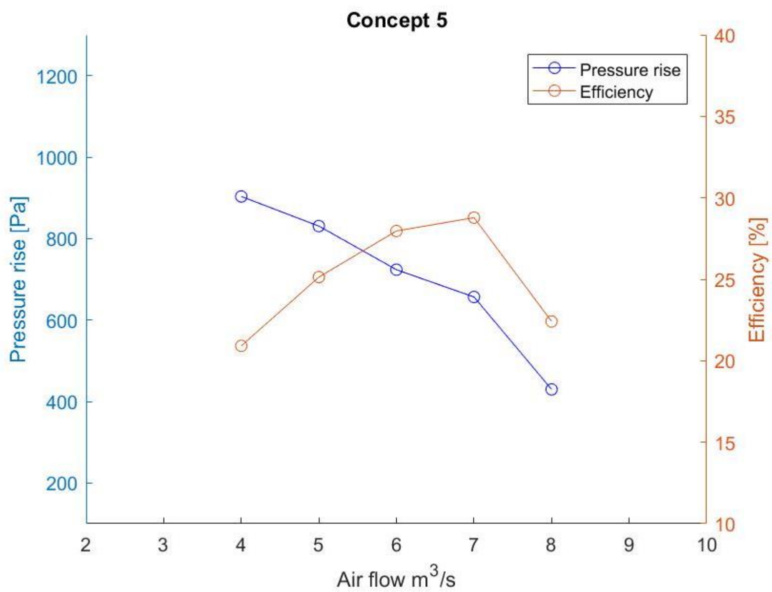


Figure 33: Fan curves illustrating pressure rise and efficiency of Concept 5.

2.1.5.10 Presentation of Concept 6

The sixth concept, called Concept 6, contained the combination of 9 blades, 75% and 15°. This means that the concept contains nine blades, the length of split is 75% of the blade and the angle of split it 15°, see Figure 34.

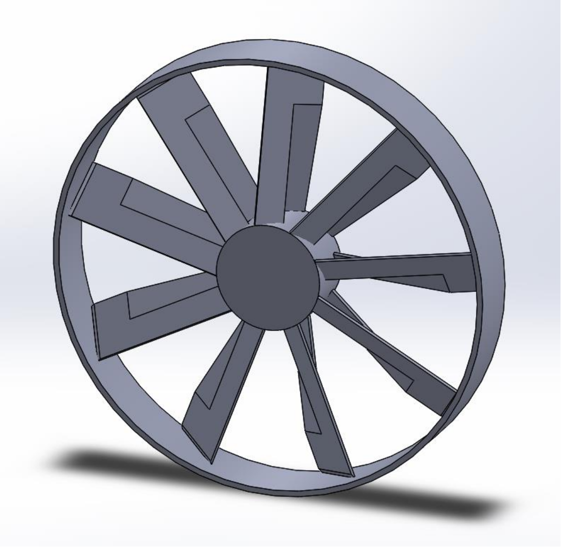


Figure 34: Concept 6 which contains nine blades, 75% length of split and 15° angle of split.

Fluid Dynamics Analyses Results of Concept 6

Concept 6 and Concept 5 are quite similar; the only difference is the parameter concerning the length of the split. As seen in Figure 35, Concept 6 has the same backflow as Concept 5 at the tip of the split. Although, Concept 6 is able to reach a much higher pressure rise, see Figure 36. Concept 6's efficiency is moderate but reaches its maximum at 28.3% within the air flow range of 4-8 m^3/s, see Appendix H.

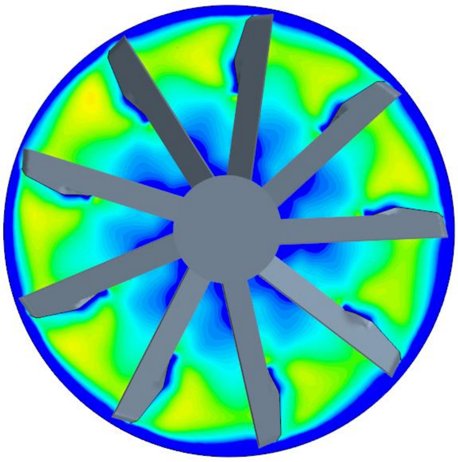


Figure 35: Illustration of Concept 6 at the air flow 6 m^3/s . The blue area represents the backflow. There is a lot of backflow close to the hub alike Concept 5.

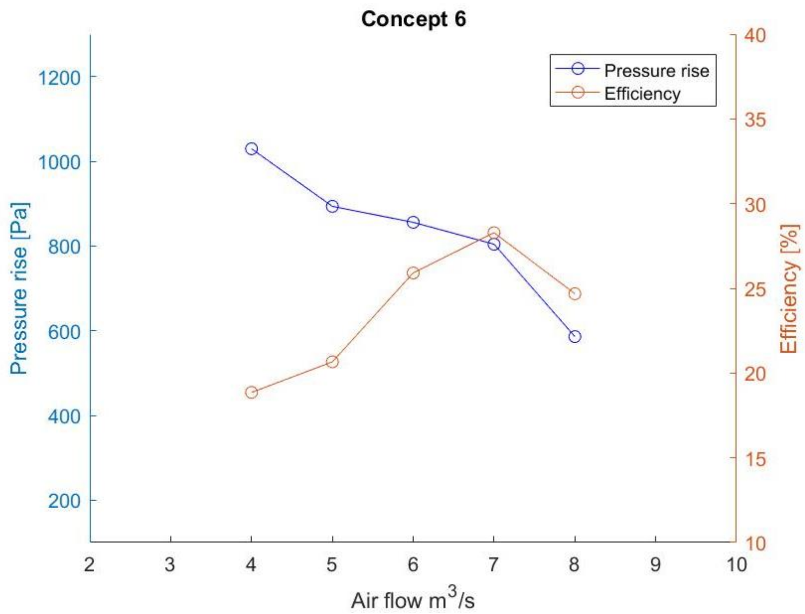


Figure 36: Fan curves illustrating pressure rise and efficiency of Concept 6.

2.1.5.11 Presentation of Concept 7

The seventh concept, called Concept 7, contained the combination of 11 blades, 75% and 15°. This means that the concept contains eleven blades, the length of split is 75% of the blade and the angle of split it 15°, see Figure 37.

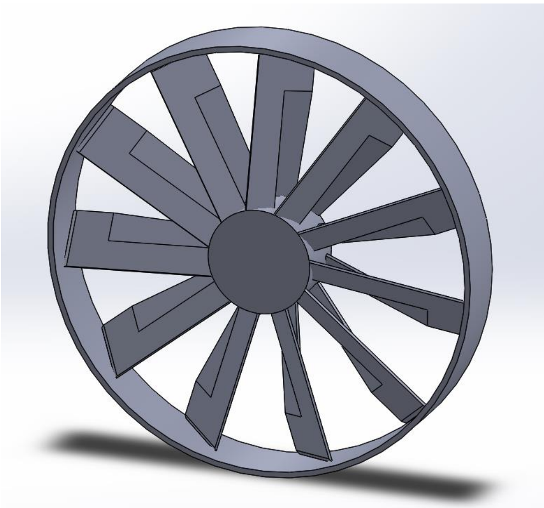


Figure 37: Concept 7 which contains eleven blades, 75% length of split and 15° angle of split.

Fluid Dynamics Analyses Results of Concept 7

Concept 7 is one of the best generated concepts according to the pressure rise and the efficiency. According to Figure 38, the greater number of blades decrease the backflow around the hub. This is most likely one of the reasons that Concept 7 has a higher pressure rise. Although, Concept 7 also has the blue area at the tip of the split which indicates backflow. Notable for Concept 7 is the steady drop of pressure against increasing air flow, see Figure 39. The figure also shows that the efficiency is increasing over the entire working range of air flow. The conclusion is that Concept 7 possibly can achieve a higher efficiency with a greater air flow, if the blade can handle higher stress that comes with greater air flow. Highest efficiency for Concept 7 is 29.6% at 8 m^3/s according to the results from the simulations, see Appendix H.

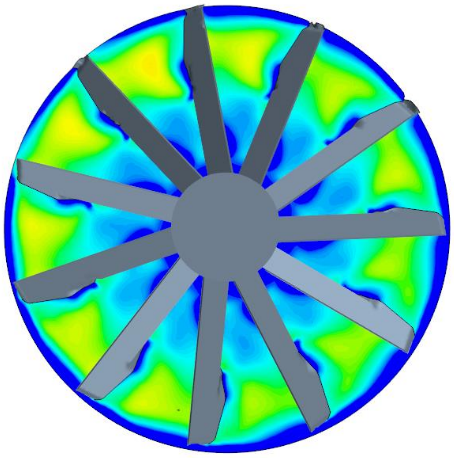


Figure 38: Illustration of Concept 7 at the air flow 6 m^3/s . The blue area represents the backflow. There is a lot of backflow close to the split.

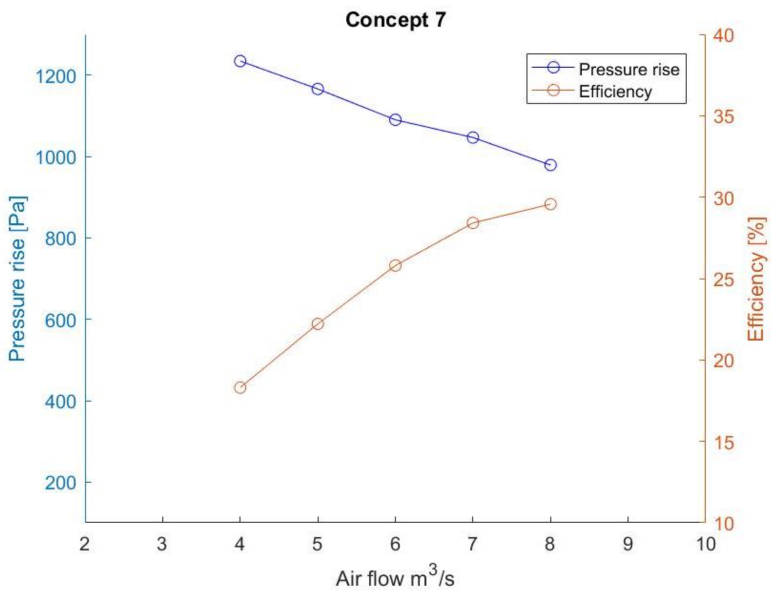


Figure 39: Fan curves illustrating pressure rise and efficiency of Concept 7.

2.1.5.12 Presentation of Concept 8

The eighth concept, called Concept 8, contained the combination of 11 blades, 85% and 15°. This means that the concept contains eleven blades, the length of split is 85% of the blade and the angle of split it 15°, see Figure 40.

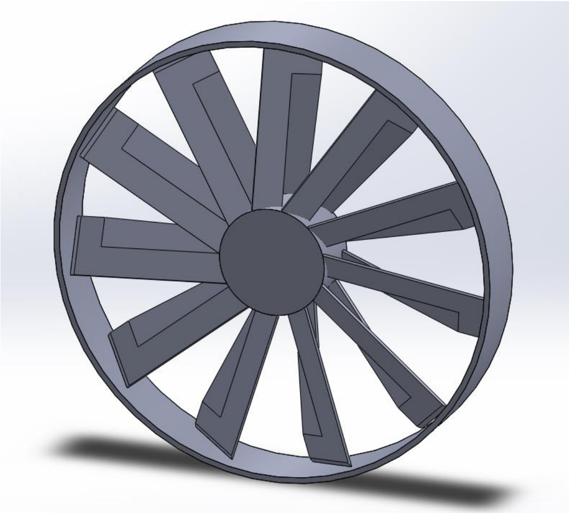


Figure 40: Concept 8 which contains eleven blades, 85% length of split and 15° angle of split.

Fluid Dynamics Analyses Results of Concept 8

Alike Concept 7, Concept 8 is also one of the best generated concepts according to pressure rise and efficiency. It is one of the concepts which has the most backflow, see Figure 41, since the number of blades affects the flow around the hub. However, the length of the split seems to be affecting the backflow at the tip of the split thus the blue area is smaller for Concept 8 compared to Concept 7.

The efficiency of Concept 8, illustrated in Figure 42, is overall increasing like Concept 7. Therefore, it is also possible for Concept 8 to generate a better efficiency in a greater working range if the blades can hold the stress from a greater air flow. Although, the pressure rise of Concept 8 varies more within the working range, which indicates that the pressure rise is about to drop and is in that way affecting the efficiency fast. Consequently, it is not likely to expect a much higher efficiency for Concept 8. The highest efficiency is 30.6% at 8 m^3/s according to the results from the simulations, see Appendix H.

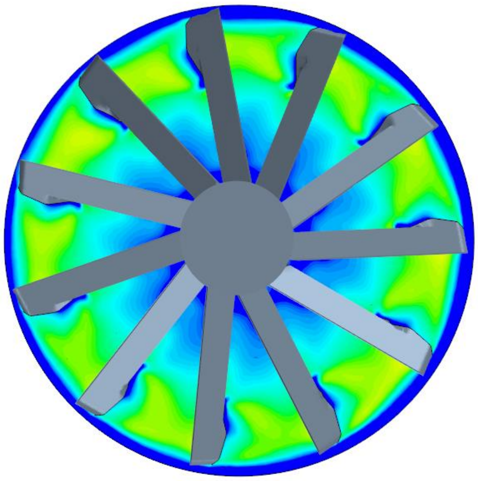


Figure 41: Illustration of Concept 8 at the air flow 6 m³/s . The blue area represents the backflow. The backflow is alike Concept 7.

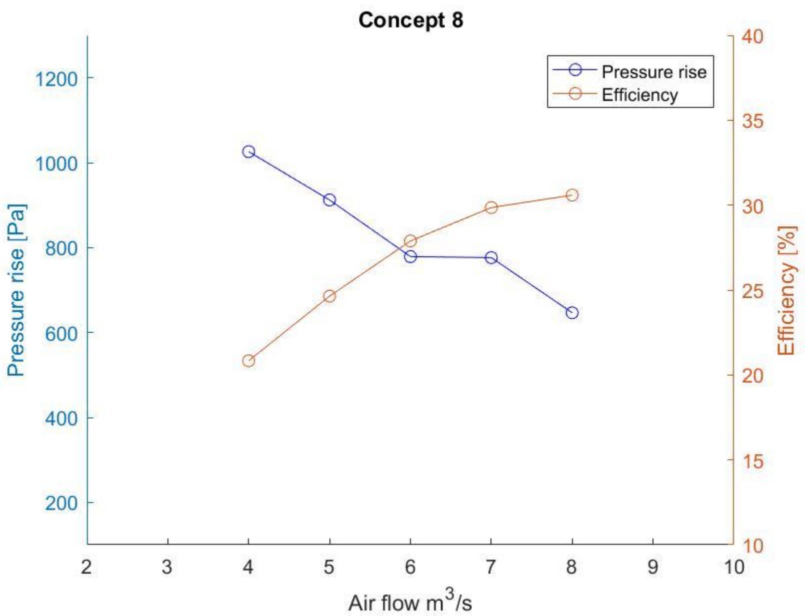


Figure 42: Fan curves illustrating pressure rise and efficiency of Concept 8.

2.1.6 Concept Discussion

To complete the separate analyses of the concepts in the previous chapters, a complementary analysis was made according to the DoE method [6]. The analysis was made to clarify which design parameters that have the greatest impact on the pressure rise, the results are illustrated in Table 4. The different values of the pressure rise in Table 4 can be found in Appendix H, with the rest of the results from the simulations. By sorting the concepts parameters by either pluses or minuses, depending on the concepts position in the DoE cube, it is possible to calculate the parameters' affect [6]. The sum of the pressure rise, for each parameter combination, resulted in their estimated affect. This analysis could also be made with focus on the efficiency but it was considered superfluous in this case thus the efficiency is dependent of the pressure rise.

Table 4: Analysis of the design parameters' impact on the pressure rise. The results show which parameters that were most important according to the DoE method.

Concept	1. Amount of blades	2. Length of split	3. Angle	1x2	1x3	2x3	1x2x3	Pressure rise at 6m^3/s
1	-	-	-	+	+	+	-	523.5
2	+	-	-	-	-	+	+	805.8
3	+	+	-	+	-	-	-	479.6
4	-	+	-	-	+	-	+	471.1
5	-	+	+	-	-	+	-	723.5
6	-	-	+	+	-	-	+	855.8
7	+	-	+	-	-	-	-	1046.5
8	+	+	+	+	+	+	+	778.8
Estimated effect	134.2	-194.65	281.15	-102.3	-106.55	-5.35	34.6	

The analysis of the DoE resulted in the split of the angle being the most important parameter and second important were the number of blades, see Table 4. The length of the split resulted in not having a significant impact according to the DoE, but it was regarded important from the FE-analyses. According to the analysis, the length of split parameter should be set to 75% in order to not break due to stress, see section 2.1.1.2. Table 4 also shows that the estimated effect of the combined parameters is not noteworthy in comparison to the parameters affect alone. To sum up, as specified from the DoE a wide angle and a great number of blades were the most important parameters and the FE-analyses declared the value for the length of split.

From the separate analyses of each concept, it was clarified that none of the concepts achieved the same pressure rise nor efficiency as the Reference fan. Although, there were some sources of errors in the CFD analyses that could have affected the performance of the concepts. For example, when analysing the backflow, it is possible to detect a blue ring around every concept. This blue ring indicates backflow due to the poorly fitting of the fan in the fan ring. Because of the need to manually translate the fan to the accurate place in the test rig, it was not possible to achieve a perfect placing of the fan. This affected the mesh since the fan and the fan ring grew together if the blades were too close to the fan ring. To avoid this problem, the fan needed to be scaled down. Therefore, there was no other solution than to allow a greater backflow around the outer edge of the fan. The downside of this problem was the probable effect the backflow had on the pressure rise. Consequently, the concepts pressure rise and efficiency could possibly be greater if the mesh and placement could be optimized.

To reach a conclusion about the parameters of the final concept, a final analysis of the fan curves was made. By comparing the graphs of the efficiency and the pressure rise for all concepts, it was possible to detect which concepts that stands out. As seen in Figure 43, Concept 2 reaches the highest efficiency, but it also peaks within the working range. If it on the other hand is the similarity between the concepts and the Reference fan's efficiency that is interesting, it can be established that Concept 7 and Concept 8 appear to have a resembling incline as the Reference fan.

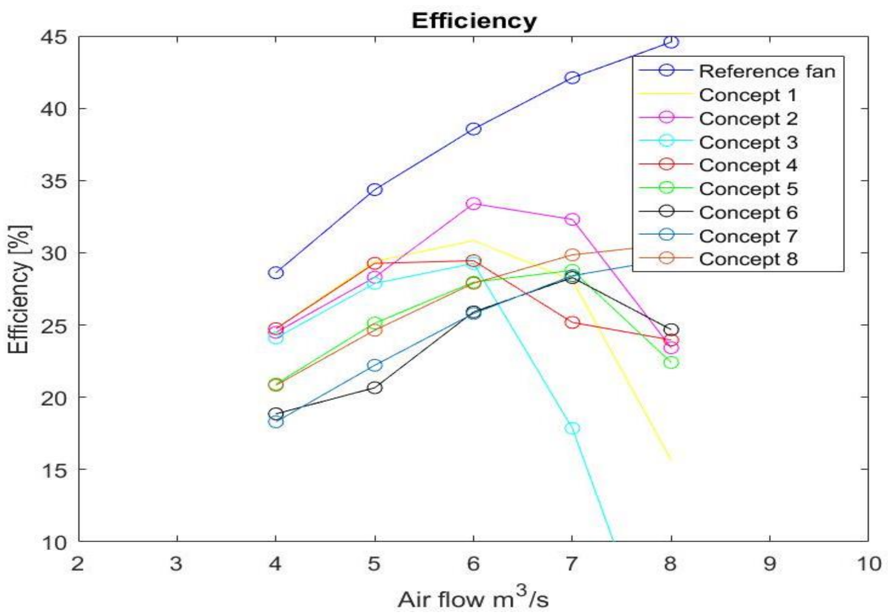


Figure 43: A comparison of the Reference fan's and the different concepts' efficiency.

Finally, in the comparison between the concepts pressure rise as seen Figure 44, it can be determined that Concept 7 stands out. It reaches almost a 200 Pa higher pressure rise than the other concepts regardless the inlet of air flow. Although, regarding to the engineering specification, see Appendix E, a target value of a pressure rise of 2000 Pa was declared. Hence the efficiency is depending on the pressure rise and the moment of the fan, it is relevant to prioritize a greater pressure rise above the efficiency.

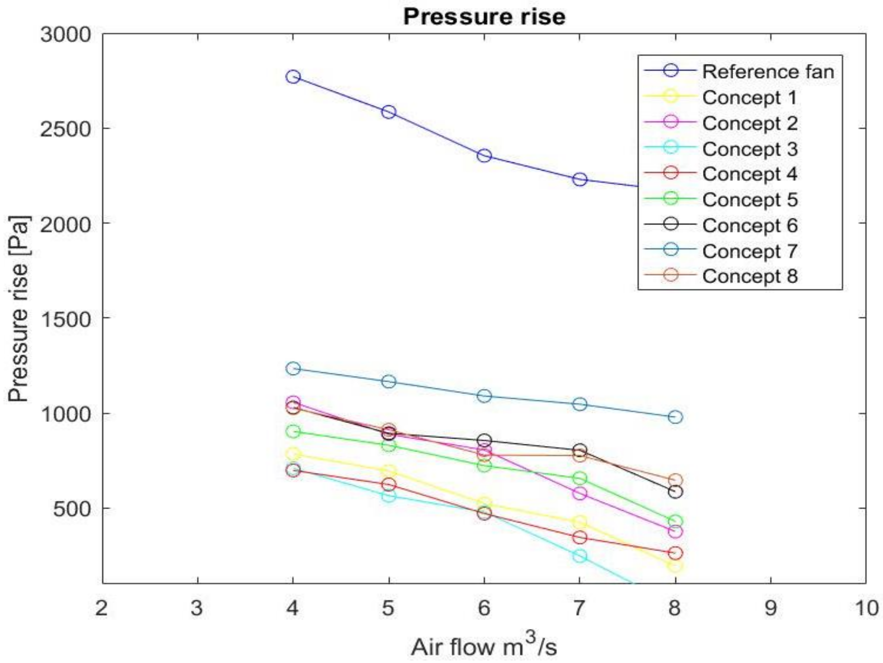


Figure 44: A comparison of the Reference fan's and the different concepts' pressure rise.

The conclusion of the comparison regarding the concepts efficiency and pressure rise, the DoE- and the FE-analyses resulted in the parameters of Concept 7 being the best performing parameters. By getting back to the DoE, it was now possible to draw an arrow within the DoE box to detect in which direction the parameters of the final concept should aim, see Figure 45. The result was a fan with 11 blades, a split angle of 15° and a split length of 75% of the blade length.

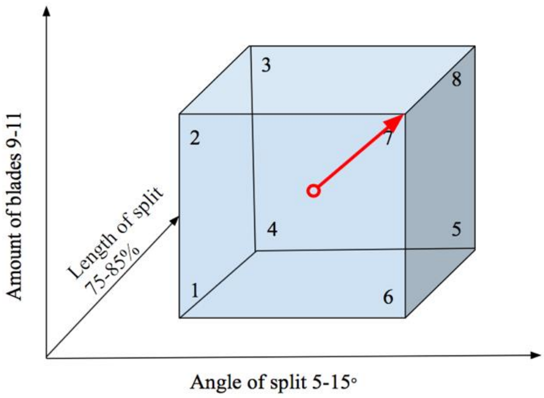


Figure 45: An illustration of the direction the parameters in the final concept should aim for. The result was a fan with eleven blades, 75% of the blade length and a 15° split of angle.

2.2 Part II: Analyses of the Final Concept and an Evaluation of Split Fan Blades

The parameters that were considered the best according to the simulations in Part I were developed further in a concept called the Final Concept. It is based on the Reference fan, which was provided by Volvo Group but the fan blades were split and the parameters of Concept 7 were applied. The Final Concept was modelled in CAD and due to the complexity of the Reference fan, it was not possible to retain the entire original design of the Reference fan. Therefore, it is a compromise between the Reference fan and Concept 7. Additionally, a concept similar to the Final Concept but with solid blades was created and simulated in order to determine the split blade’s influences. This concept is called the Comparison Concept. The Final Concept and the Comparison Concept was analysed regarding fluid dynamics. The Final Concept was also evaluated through structural analyses. These analyses were used to evaluate the impact of split blades. Next, the detailed design was presented including a CAD drawing, a manufacturing plan, material selection and a cost analysis of the Final Concept.

2.2.1 Analyses of the Final Concept

The Final Concept was a compromise between the Reference fan and Concept 7 since it was not possible to directly apply the parameters from Concept 7 on the Reference fan. Due to the complexity of the Reference fan, some adjustments such as the blade shape were necessary. The CAD of the Final Concept can be seen in Figure 46. The Final Concept contained the parameters eleven blades, a 15° angle split and 75% split of the blade.

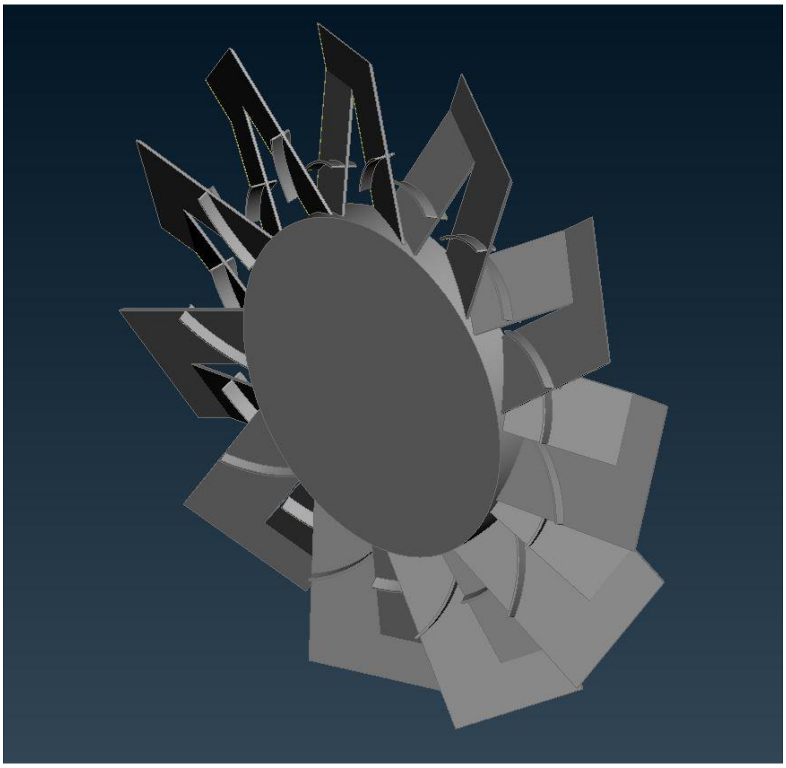


Figure 46: CAD of the Final concept which contained the parameters eleven blades, a 15° angle split and 75% split of the blade. The Final Concept was adjusted to get a more alike structure as the Reference fan.

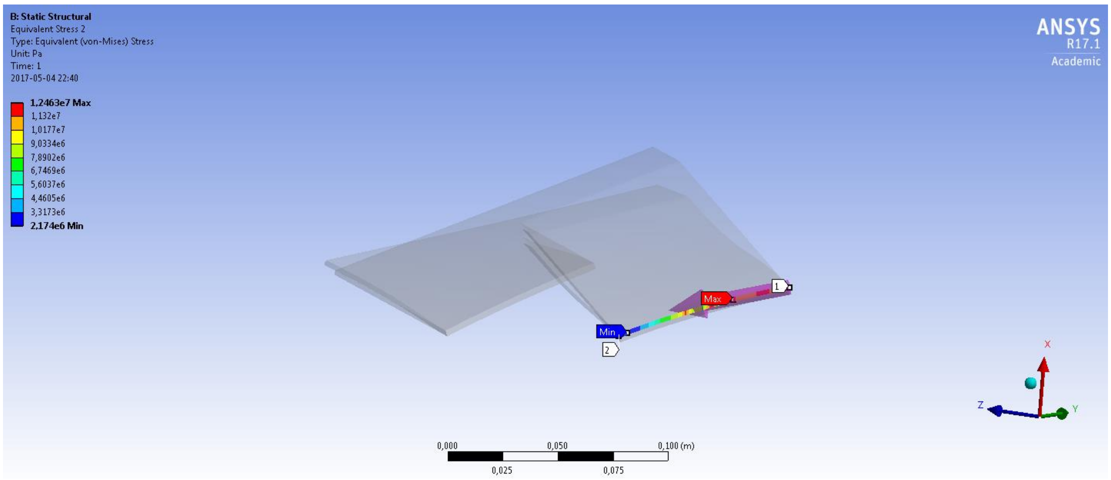
Fluid Dynamics Analyses of the Final Concept

The Final Concept was made in CAD using the software SolidWorks [7]. Before importing the concept into Star-CCM+ [5], it was meshed in ANSA [24]. Thereafter, the concept exchanged the original fan by being translated to the accurate position in the test rig. The fan and the hub were surface wrapped together using a seed point, and afterwards a volume mesh with the accuracy of approximately 5 million cells was made in order to be able to run the simulation. They were thereafter uploaded to the computational cluster Hebbe [8]. The simulations were made in the same way as for the previous concepts. The input of air flow was between of 4-8 m^3/s and the rotational speed was 2400 rpm. The CFD simulations gave results of the pressure rise between the inlet and outlet and the moment of the fan and the hub. The efficiency was calculated and plotted together with the reference fan for analysis and comparison in section 2.2.2.

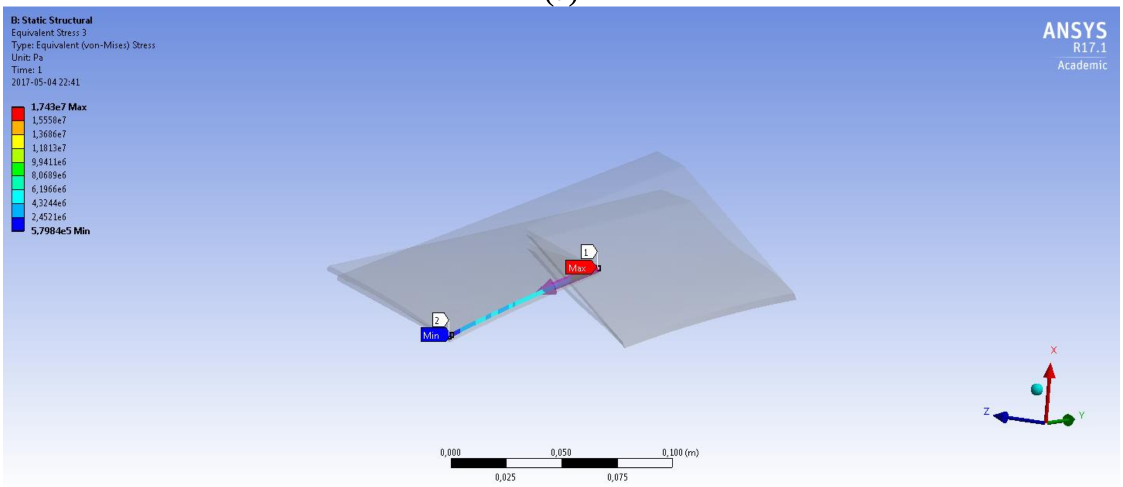
Structural Analyses of the Final Concept

The structural analyses for the final concept was done in the software ANSYS [10]. To begin with, one blade was cut out of the final concept and meshed in ANSA. Thereafter, the setup for the FE-analyses in ANSYS contained a fixed support at the curved edges of the blade, the ones that are connected to the hub, and a net pressure of 1100 Pa, see Figures 47, 48 and 49. The pressure was chosen since the maximum pressure rise for the Final Concept was around 1000 Pa. Furthermore, it had a rotational speed of 251 rad/s around the *x-axis* and a fine mesh in order to reach convergence. The material had properties of the chosen material in 2.1.4.2, PA6. The system was in steady state.

The effective von-Mises stresses [27] were calculated on both the two curved edges as well as on the solid blade. To get the stress on the edges, two paths were made. These effective von Mises stresses turned out to be 12.5 MPa on the right edge and 17.4 MPa on the left one, see Figure 47 (a) and (b). On the solid blade, Figure 48, the effective von-Mises stresses were between 0.033-10.4 MPa. The maximum was at 46.8 MPa, but it is only a stress concentration where the blade is split. This would in reality result in plasticity which smoothen the stresses. In conclusion, the stresses on the blade were not too high and are acceptable. As mentioned in section 2.1.5.2 the stresses can be alleviated by rounding off the tip of the split and utilizing fillets at the point of connection with the hub.



(a)



(b)

Figure 47: The von-Mises stress on the two edges, (a) and (b), on a blade of the Final Concept. The von-Mises stresses on the edges of the blade are not too high and therefore acceptable. The max value is 12.463 MPa for (a) and 17.43 MPa for (b)

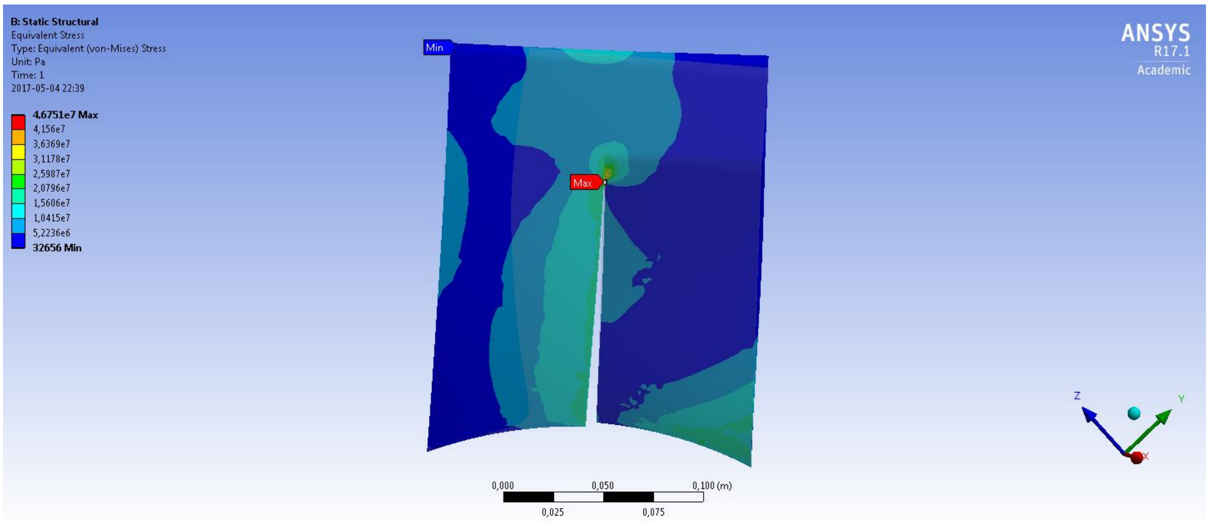


Figure 48: The von-Mises stress on a blade of the Final Concept. The stresses are not too high for the whole blade either. The max value is 46.75 MPa.

The total deformation can be seen in Figure 49. It had a maximum at one top edge of the blade with a deformation of 6.74 mm. Hence, the deformation on the Final Concept's blades is quite small.

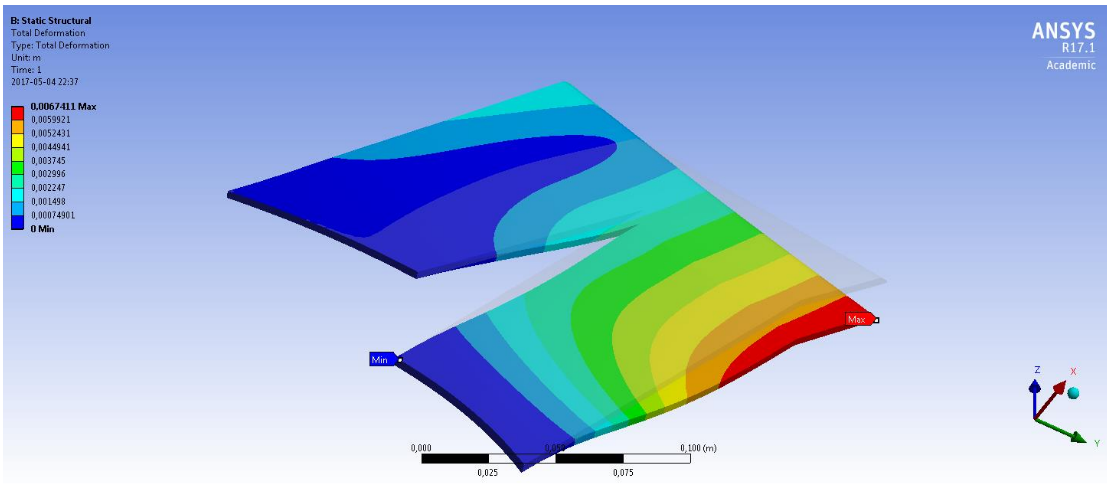


Figure 49: The total deformation on a blade of the Final Concept. The simulation shows that the total deformation on the blades are rather small. The max deformation is 6.74 mm.

The equivalent plastic strain on the blade was insignificant. The blade only has locally high stresses focused to a very small area around the split. This is why the plastic strain have not been taken into account.

2.2.2 Final Concept Discussion

Regarding the CFD analyses, the Final Concept did not achieve the expected pressure rise and efficiency. In comparison to the Reference fan, the Final Concept's efficiency does not increase within the working range, see Figure 50. Instead, the efficiency peaks at 32,07 % with the air flow 6 m^3/s. The CFD showed that the Final Concept still has backflow around the hub and in the splits, which can be seen in Figure 51. However, there is not much backflow around the outer edge of the fan which possibly contributed beneficially to the fans pressure rise, see Figure 52. As mentioned before, the backflow affects the pressure rise and thereby also the efficiency, and this can be a factor to the low pressure rise and efficiency. All of the simulations results can be seen in Appendix H and O.

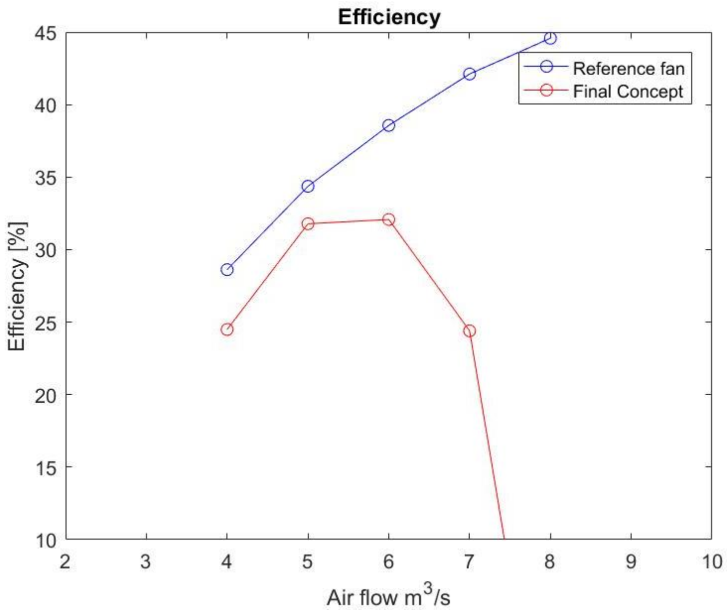


Figure 50: A comparison of the Reference fan's and the Final Concept's efficiency.

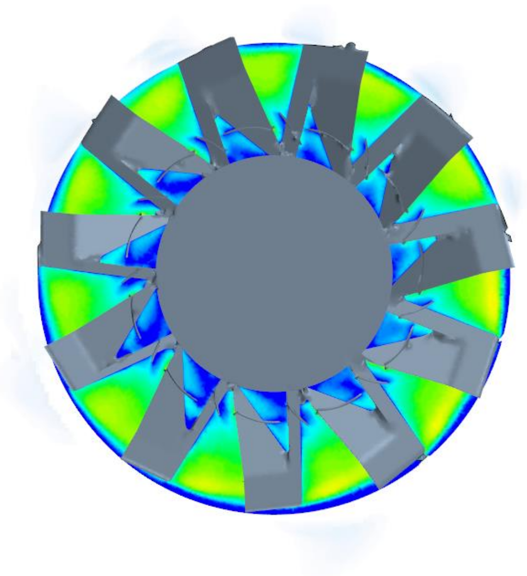


Figure 51: Demonstration of the backflow at 6 m^3/s of the Final Concept. There is still backflow around the hub and the splits. Though, around the outer edge of the fan there is not much backflow.

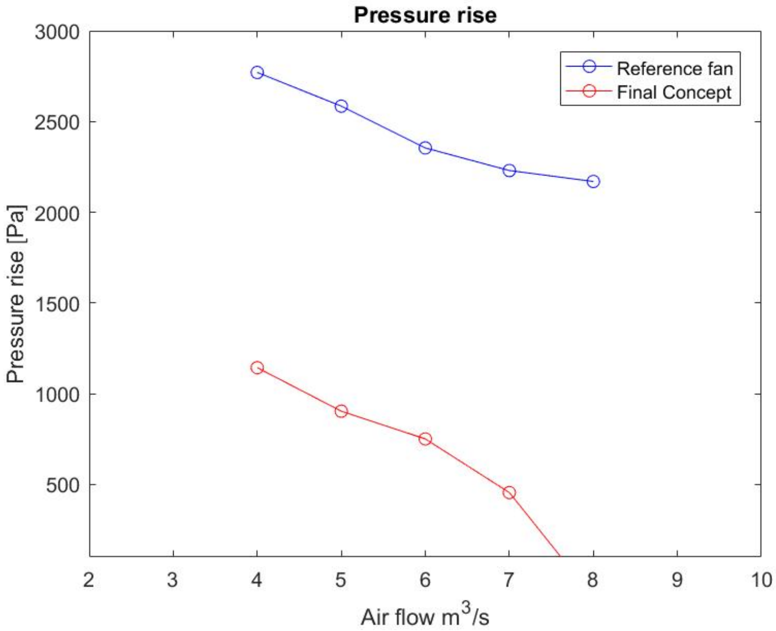


Figure 52: A comparison of the Reference fan's and the Final Concept's pressure rise.

One reason why the Final Concept's performance is inferior to the Reference fan was mainly because of the differences in the blade shape. The Reference fan has streamlined blades, while the Final Concept has straight blades with sharp edges, due to that it was not possible to apply the parameters directly without changing the blade shape. Moreover, the curve of the blade that the Reference fan has close to the hub was instead substituted with a larger hub. Unfortunately, all these differences affect the results in a way that makes it impossible to determine the split blades impact on the fan by comparing the Final Concept to the Reference fan. Therefore, a new concept was made and evaluated in order to establish how a split blade actually impacts the fan's performance. This was necessary because the Reference fan's streamlined shaped blades affected the results and the comparison between the concepts was therefore not equal.

2.2.3 Split Blade Comparison

A concept was made for comparing a split and a solid blade. It had the same hub size as the Final Concept and also straight blades with the same parameters, see Figure 53. This gave a more equal comparison between a solid and a split blade concerning the pressure rise and efficiency. The Comparison Concept, as well as the Final Concept, had the same attack angle as the previous concepts. By using the same angle for all developed concepts, the comparison between the concepts is more equal and the impact that the parameters makes will not change due to the angle. The results of the simulations can be seen in Appendix P.

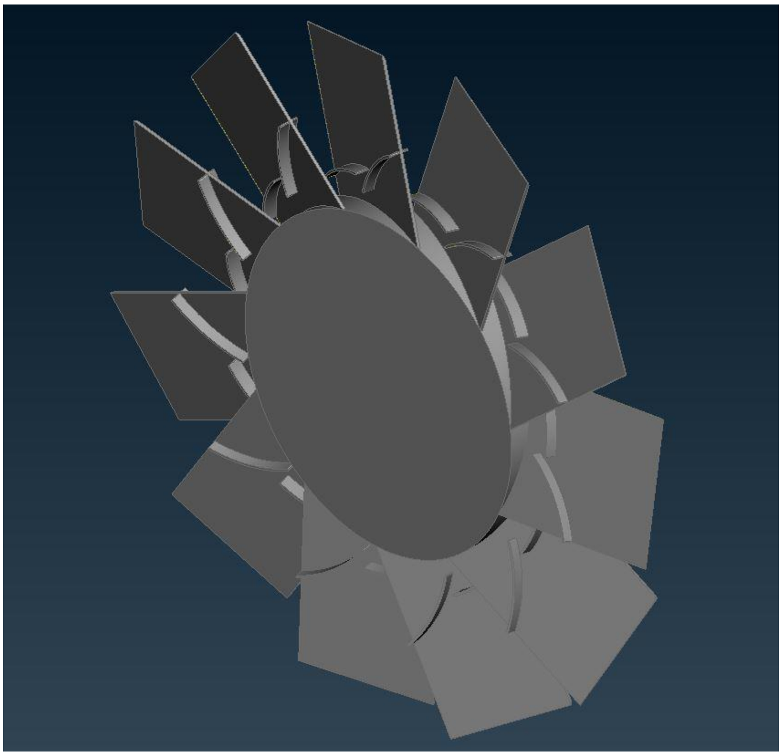


Figure 53: The Comparison Concept with eleven solid blades. The Comparison Concept, like the Final Concept, has a similar structure as the Reference fan.

The results from the Comparison Concept was acceptable for the air flow 4 m^3/s, thereafter it dropped fast and was very low. This is because, according to the blue line in Figure 54 (system curves), the fan is not in its working range. The Comparison Concept reached zero efficiency, which means that there is no pressure rise and this occurs when the fan repels the air. Although, the Comparison Concept reached a higher efficiency than the Final Concept before it dropped. Nevertheless, it is not easy to conclude whether or not a solid blade is better than a split blade. If the pressure rise is considered, it is clear to say that the Final Concept with split blades performs much better, see Figure 55. If the results from the simulations are analysed, see Appendix H, it can be determined that the moment is much larger for the split blade than for the solid blade. Since the moment is incident to the efficiency, there is the larger pressure rise and yet worse efficiency compared to the Comparison Concept. To sum up to a conclusion, it can be declared that a fan with a solid blade has a lower working range but a better efficiency than a split blade. However, the split blades achieve a larger pressure rise during the same circumstances.

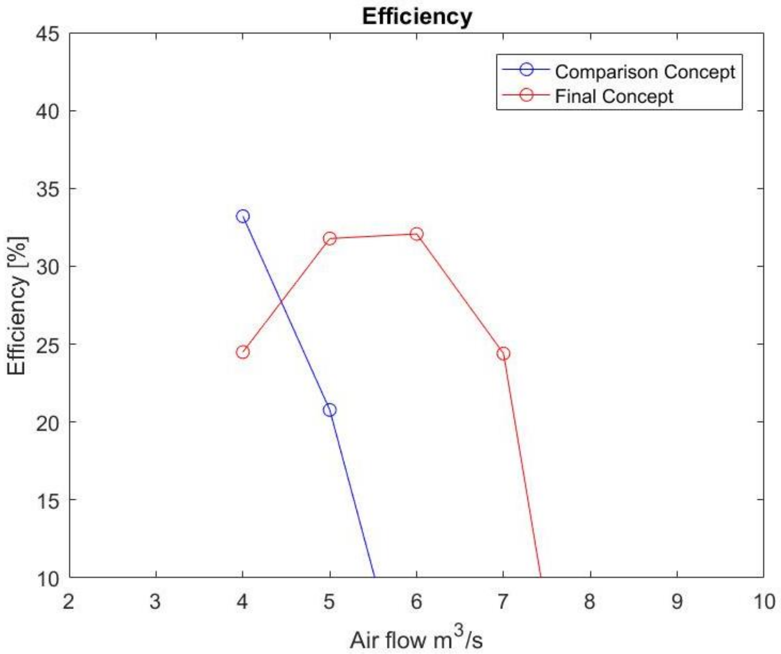


Figure 54: A comparison of the Reference fan's and the Comparison concept's efficiency.

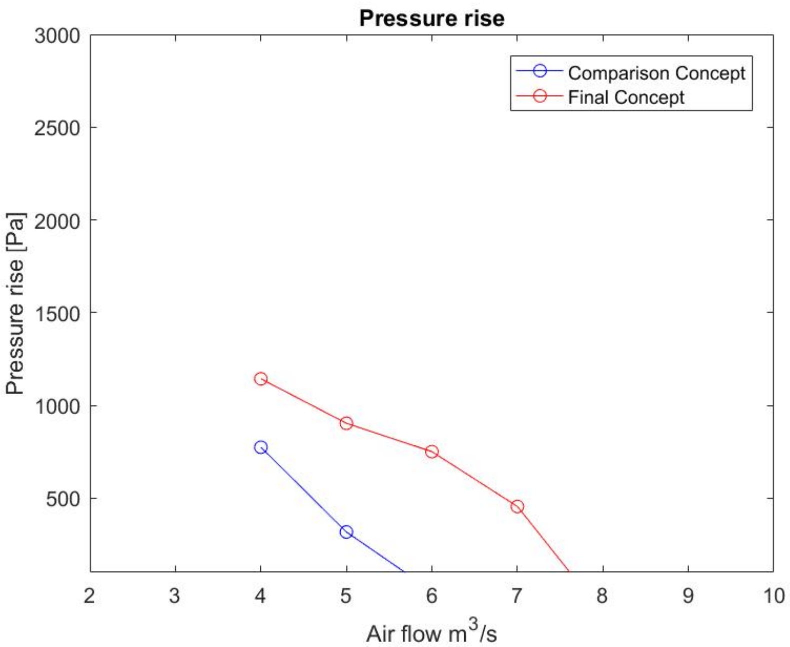


Figure 55: A comparison of the Reference fan's and the Comparison concept's pressure rise.

2.2.4 Detailed Design of the Final Concept

A detailed design with a CAD drawing [28] will be presented to envision the Final Concept. Additionally, it will include a plan of which material the product will consist of and how it will be produced and manufactured.

2.2.4.1 CAD Drawing of the Final Concept

Due to the Final Concept's poorly performance, the CAD drawing is not detailed enough for manufacturing of the fan. The CAD drawing was only made for visualising the shape of the Final Concept, see Figure 56.

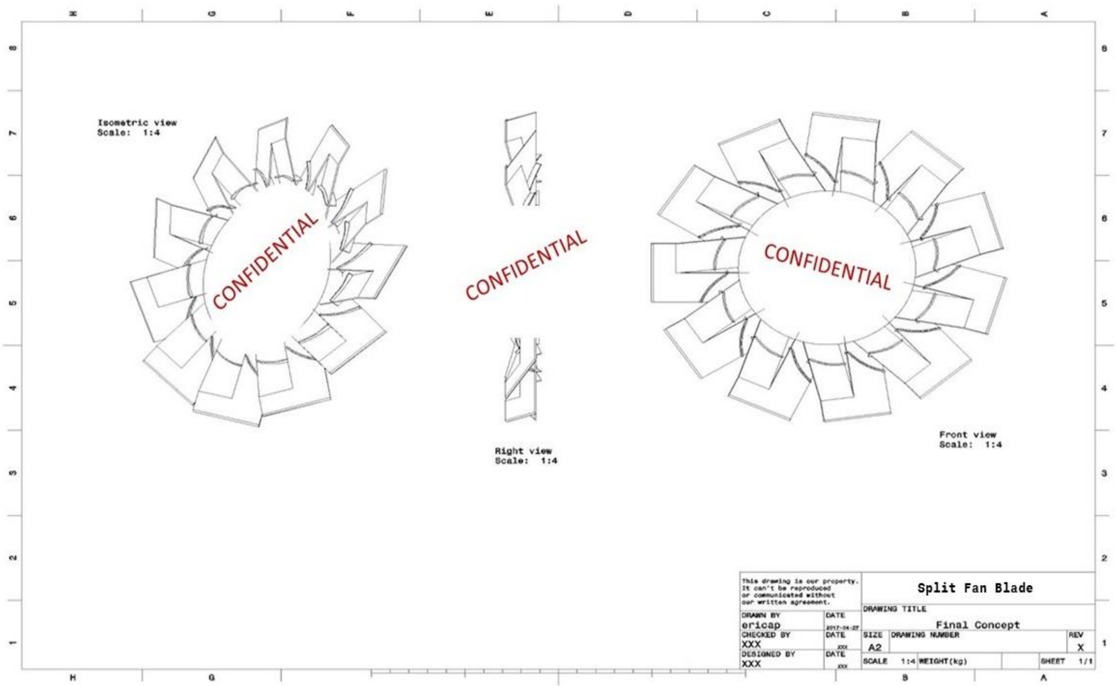


Figure 56: A CAD drawing of the Final Concept showing the shape of the hub and the blades.

The Final Concept consists of the same central hub as the Reference fan because of the ease of installation to the already existing system in a Volvo truck. The Reference fan has a more streamlined base geometry of the blades than the Final Concept does, since the Final Concept has straight blades over the entire projected area.

2.2.4.2 Material Selection of the Final Concept

The material that Volvo Group currently uses for the Reference fan is glass fibre reinforced polyamide. The material has high strength, good heat resistance and withstands sagging during manufacturing, but the glass fibre also contributes to a more brittle material. The deformation in the Final Concept did not exceed the customer needs, Appendix E, which is why the project group decided to keep the material since a stronger material is not necessary. PA6 GF25 was chosen for manufacturing of the fan. The focus has not been to find the optimal material for this kind of a fan with split blades since it is still in the development process. The results from the fan would have to be better in order to be able to make an analyse about which material that would be beneficial for the fan. When the fan develops further, the stresses and strains might affect the blades differently and another material might be necessary.

2.2.4.3 Manufacturing Plan of the Final Concept

The recommendation of manufacturing process will be to keep the existing, which means injection moulding. Even though the final concept has a more complicated design than the Reference fan, injection moulding will be possible. It is especially the split of the blade that will complicate the manufacturing process, but it will anyhow be possible to use injection moulding. Additionally, injection moulding is compatible with the material PA6 GF25 according to CES [29].

2.2.4.4 Cost Analysis of the Final Concept

To get an overview of what the manufacturing cost would be for the Final Concept, CES, a Materials Selection Software was used [29]. The software applied the Equation 2.4 to calculate the cost. The variables and their values are illustrated in Table 5.

$$C_s = \frac{m \cdot C_m}{1-f} + \frac{C_t}{n} \cdot \left(1 + \frac{n}{n_t}\right) + \frac{1}{\dot{n}} \cdot \left(\frac{C_c}{L \cdot t_{wo}} + \dot{C}_{oh}\right) \tag{2.4}$$

Table 5: Variables and values used for calculating the manufacturing cost.

Variables	Parameter	Value/Source
t_{wo}	Capital Write-off Time	5 years
m	Component Mass	3 kg
L	Load Factor	0.5
C_m	Material Cost	35 SEK/kg
$\dot{C}_{oh}$	Overhead Rate	1300 SEK/hr
C_c	Capital Cost	CESMaterialUniverse
C_t	Tooling Cost	CESMaterialUniverse
f	Material Utilization Fraction	CESMaterialUniverse
n	Batchsize	Manufacturing Plan
n_t	Tool Life	CESMaterialUniverse
$\dot{n}$	Production Rate	CESMaterialUniverse

PA6 was chosen as the material and injection moulding as the process which, according to CES, is a very good method for shaping thermoplastics. This resulted in data recommendations from CES such as a capital write-off time of 5 years, a load factor of 0.5, material cost of 35 SEK/kg and an overhead rate of approximately 1300 SEK/hr that was needed for Equation 2.4. The remaining variables that were required are standard for the selected process and were calculated by the CES tool. The result of the manufacturing cost for the Final Concept can be seen in Figure 57. The result for the Reference fan was roughly the same, the only difference is that the mass of the Final Concept is 3 kg which is around twice as much compared to the Reference fan's mass but this did not have a major effect on the cost.

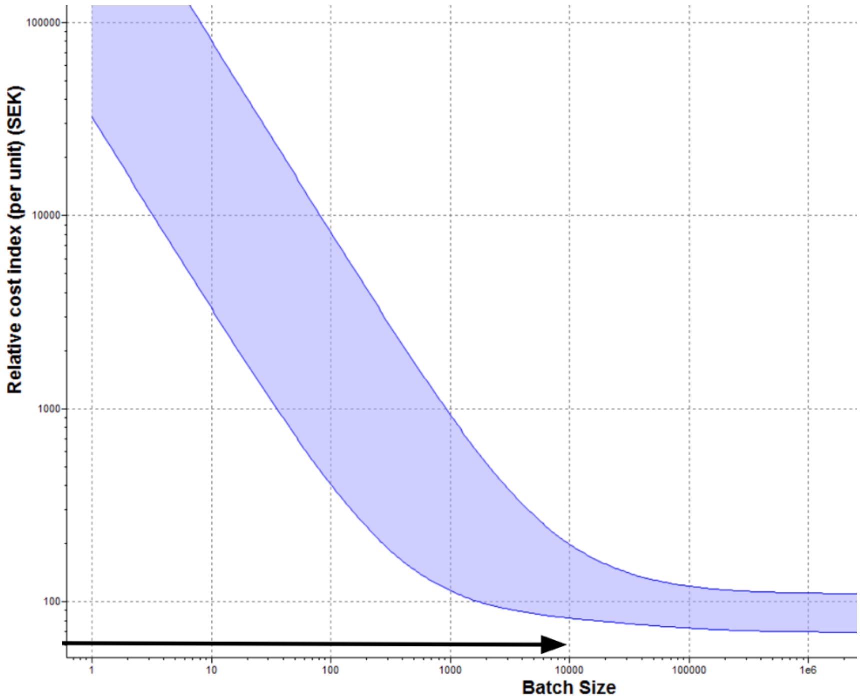


Figure 57: Zoomed picture of the relative cost index in SEK per batch size calculated in CES. The relative cost index per unit is around 55-60 SEK with a batch size of 10000.

The result is only an approximation of the manufacturing cost and a more precise estimation cannot be done within the limitations of this project. Figure 57 demonstrates that the relative cost index per unit is around 55-60 SEK with a batch size of 10000. However, since Equation 2.4 does not take the geometry into account, the relative cost index seems to be lower than it actually is. The geometry of the Final Concept is much more complex than the geometry of the reference fan due to the split blades. This complicates the production process as well as the production rate and more complex and expensive tools are needed and therefore the manufacturing cost for Volvo Group will increase instead. On the contrary, a fan with split blades could turn out to be more efficient and consequently result in more savings and a higher customer value.

3. Final Discussion

The final discussion consists of a discussion of the overall project. The methodology and its benefits and disadvantages for this project will be examined. Additionally, the sources of errors and how they affected the results will be described. Finally, a reflection about the project’s achievement as well as a consideration about the international collaboration will be done.

3.1 Discussion of the Methodology

The project began with stating the initial problem and the purpose of the project. This gave a good start to the project, since the goal was clarified and the project group knew what to strive for. Thereafter, an external search was executed to make the group aware of what inventions that exists and thereby prevent patent infringement. When the members of the group were aware of existing products, a customer needs assessment was made. This included gathering customer input and weighting of customer needs, which was made by talking to Volvo Group and using the gained information from the research in the area. A deeper study about fans in general could have been made, as well as research about fan blades. The project group did not have much knowledge about what benefits the performance of the fan nor which parts of the fan that contributes to a higher pressure rise. Thus, the first step of searching for existing products and information about fans in general could have been more profound, it would have been beneficial for the project.

The concept development part started off with research about engines and thereafter making a black box and a sub function diagram in order to obtain the important parameters. These were later utilized in the design of experiment method that was used in the project. The benefits of using the DoE method was that it generated eight different concepts, which included one of the two values each parameter had. The limited amount of the generated concepts was beneficial with the projects time limit in mind. The disadvantages that DoE brought with it was that the parameters had to be reduced to three. The number of important parameters, according to the project group, were seven from the beginning. Reducing them made the variety of investigated parameters limited and the variety of different concepts quite small. However, the DoE method made it possible to base the project on scientific ground by the strategic concept generation.

In the CFD simulations the tests were run equivalent, which was good since the comparison between the concepts thereby was equal. Since every concept was run with the same air flows and test rig, their circumstances were quite similar. Therefore, the assumption of which parameters that had the best effect on the pressure rise could be considered correct. The number of cells that the volume mesh contained has also been checked. The number of cells has been between 4,5 to 5 million cells for every concept. The precision and accuracy are therefore the same for every concept, which also gives equality in the comparison.

Additionally, a disadvantage of the methodology which highly affected the outcome of the results was the design of the Final Concept. Due to the difficulties of applying the parameters directly onto the elaborate shape of the Reference fan, it was not possible to achieve the desired results. Hence the Final Concept did not have streamlined blades, a new concept with solid blades had to be made and analysed to be able to compare and establish results about split blades impact.

3.2 Sources of Errors in the Simulations and Tests

The FE-analyses had a fine mesh and a nonlinear model. This made the analyses' results reliable. Additionally, a convergence test was made to establish the accuracy of the result.

In the CFD analyses there were some error sources that could have affected the results. Because of the different angle of the split, two different methods for meshing were needed. For the concepts with a greater angle of split, a surface wrap was necessary to integrate the fan with the hub. The surface wrap affected the surface mesh and therefore the four first and four last different concepts could not be meshed with the same precision. For example, the fan sometimes collided with the fan ring when the surface mesh was applied on the four last concepts. This caused the different concepts to have different quality meshes, and these differences could affect the results since the air flow around the fan is dependant of the fan's surface.

Another error source is that the fan had to be translated manually in Star-CCM+, so the different concepts were not in the exact same position. In order to achieve maximum precision in positioning of the fan, coordinate systems on each fan was made. The different positions of the fans could then be seen in coordinates, and the fan could be translated to almost the same place as the Reference fan. This course of action made the position of the fan as centred as possible. Although, an error source is still that when translating the fans, the origin was not always the Reference fan and therefore some concepts were more dislocated than others. When placing the fan in the fan ring, the size needed to be adjusted so that the blades did not collide with the ring and therefore, the different concepts had a slightly varying diameter. The differences were small, only a couple of millimetres, but they existed. This affected the results by air flowing backwards at the tip of each blade in the simulations. This phenomenon can be seen in Appendix M and is an error source for the pressure rise of the developed concepts.

3.3 Project Achievement Reflection

The project achievement includes a reflection about which objectives, that were set in the beginning, the project has attained and how well the purpose was fulfilled.

3.3.1 Evaluation of the Fulfilment of the Objectives

The different objectives that the project had can be seen in section 1.4.1. These have all gotten fulfilled throughout the project. The project development originated from the patent about the split fan blade. The concepts were made in CAD to be able to make FE-analyses and CFD simulations on them. When the concepts were simulated, the pressure rise, efficiency and power usages were calculated through the simulations and the stresses on the blades were calculated through the FE-analyses. The results were later gathered and analysed to see which parameters that were the most beneficial when developing a split fan blade. Thereafter, they were combined with the Reference fan and from this, the Final Concept was made. It was analysed in the same way as the concepts, and the results were thereafter compared with a fan called the Comparison Concept. It had the same parameters and blade shape as the Final Concept, except that it consisted of solid blades. A comparison between the Final Concept and the Comparison Concept was therefore more equal and shows the real impact of a split blade.

3.3.2 Evaluation of the Fulfilment of the Purpose

The purpose with the project read:

"The purpose of the project is to investigate and develop a fan containing split blades, based on patent US 7396208 B1 [2]. A fan with split blades will be developed and compared with a standard fan provided by Volvo Group. The main objective is to investigate the possibility of achieving a better efficiency with split rather than solid fan blades."

A fan with split blades was developed through concept generation, simulations and evaluations. It was also compared to a standard fan provided by Volvo Group. The efficiency of the Reference fan provided by Volvo Group had an efficiency of 42 %, which the developed concept never exceeded. The answer to the main objective of the purpose is thereby no and according to the simulations, it is not possible to achieve a better efficiency with split fan blades. Moreover, this was not a fair comparison due to the Final Concepts lack of aerodynamic characteristics. Although, when comparing the developed Final Concept to a similar fan without the split, the overall efficiency was better with the split blade. Its efficiency curve is more stable, whilst the efficiency of the comparing fan was 33 % at the air flow 4 m^3/s. Thereafter it drops very fast, which is a sign that the comparison fan is on the outer edge of its working range at the air flow 4 m^3/s, and thereafter it is outside of its range. The results comparison to this fan is thereby not reliable in the aspect that a split blade is better than a solid one.

3.4 Discussion of the International Collaboration

A main part of the project was the international collaboration. This has been educative for all members of the project group and has affected the project in both positive and negative ways.

For instance, it has been complicated to work the same hours due to the six-hour time difference. Therefore, the work has been divided between the schools, the PSU students have been responsible for the CAD and the structural analyses and the Chalmers students have been in charge of the product development and the CFD analyses. Because of this division of responsibilities, it has been very important to have continuous contact between all members. Additionally, the distance and the languages have affected the project in a way of making it more time consuming.

The project group had a scheduled meeting every week for updating both supervisors and other group members of the ongoing process. Although, in the beginning of the project, it was hard to establish a useful way of contacting each other except for Skype. Therefore, after the first start-up weeks, the group had uninterrupted contact with each other through a group chat. The benefits of working this way is that the group members learned about the importance of expressing themselves so all the group members understand.

The possibility to visit each other had a very positive contribution to the project. By getting to know each other, a personal relationship was created. This helped the project group to get a better understanding and respect for each other. From the point where the group met in real life and got to know each other on a personal level, the project continued on more smoothly. The Chalmers students visited PSU in the end of March, around the time to hand in the midterm report. The PSU students visited Chalmers after they graduated to attend the Chalmers presentation at the end of May. Both of the trips were sponsored by Volvo Group.

4. Conclusion of the Project

In the conclusion part, the results and achievements throughout the project will be presented in sections about the impact of the split blades and the future work within the subject.

4.1 The Impact of Split Blades

The project group came to a conclusion regarding the impact of the split blade due to the comparison between the Final Concept and the Comparison Concept. From the comparison between two identical fans, besides the split blade, it can be established that:

- The split blade has a higher working range than a solid blade.
- The split blade achieves a larger pressure rise.
- The split blade achieves a larger power output compared to the solid blade.
- The solid blade achieves a higher efficiency.

Even though the solid blade achieves a better efficiency, it is clear to say that the split blade has potential to perform better in higher ranges of air flows. Moreover, the pressure rise is significantly larger for the split blade than for the solid blade. Thus the dependency between the efficiency and pressure rise, it cannot be stated that the solid blade performs better even though it has a higher efficiency.

Additionally, an evaluation of the three parameters values that were investigated during the project was made. The conclusion regarding the values of the parameters were:

- Length of split should not exceed 75% of the blade length due to the stresses according to the structural analyses.
- Number of blades should be 11 blades according to the CFD analyses and the increasing of pressure.
- The angle of the split should be 15 degrees according to the CFD analyses due to the increasing of pressure.

The Final Concept with the chosen parameter values, is illustrated with streamlines in Figure 58. The parameters are not optimized in any way because of the time limit of the project. However, due the project’s analyses, these are the best values for the parameters. Furthermore, the evaluation of the DoE resulted in the parameter regarding the length of split not being important considering the performance of the fan. Although, the project’s conclusion is to iterate the DoE with the chosen parameters and also investigate different parameters in the future work.

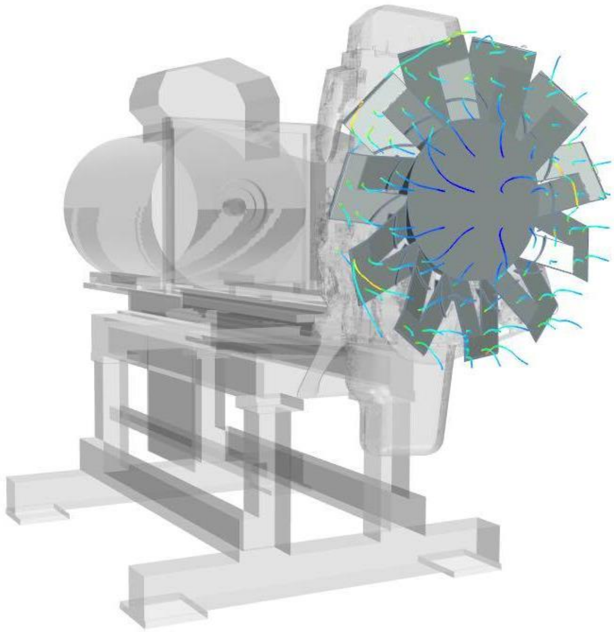


Figure 58: The Final Concept implemented in the engine within the simulation file. The streamlines are illustrated as ribbons showing the velocity of the air.

All of the evaluations of the parameters and the impact of the split fan blades are based on the results in Appendix H, O and P. In conclusion, due to the results of this project, it is possible to conclude that the solid blade reaches a greater efficiency. However, the split blade achieves a greater pressure rise and working range.

4.2 Future Work Within the Subject

The future work should start with applying the parameters of Concept 7 on the Reference fans complex incurvation to see the real effect of the parameters and a split blade. Thereafter, an iteration of the parameters with more specified values according to the DoE and simulation results should be made. Through this, a better interval can be chosen when selecting the parameters for analysing and evaluating the next generation of concepts. Once the simulations are done and the results analysed, yet another iteration can be made if the results is not satisfactory. If the results are good, the best parameters can be applied to the Reference fan's streamlined blades and later their results can get compared.

Better methods for comparing the results would be recommended and also more similar concepts. Since half of the concepts had to get surface wrapped in Star-CCM+ and the other half did not, the mesh quality between the concepts was very varying. That affected some of the concepts to be scaled down, which was to their disadvantage since their projected area got smaller. Another thing to develop is the blade shape of a split blade by examining the scenes from the CFD simulations. By doing that, it is possible to detect where the backflow emerges and where the air flows slowly. From analysing the pictures, a blade shape which is beneficial for a split blade can be developed.

The different parameters that were eliminated in the beginning of the project due to the DoE can also be investigated. These were parameters that the group thought was important and therefore they could be interesting to look further into. The material choice would also be of interest to investigate and develop. There was no focus in finding the ideal material for this kind of fan due to the time limit and poor results from the fan. If another material is chosen, maybe the length of split or angle of split could be even greater without the risk of the blades breaking due to stress.

In the patent, there were holes in the blades as well. The group decided not to have holes in the blades because when they were examined in the report [4], they only had a negative contribution to the pressure rise. Although, the fan was not in the optimal design and the holes could be of interest if they are placed accurately on the blade.

5. Self-Assessment

The self-assessment consists of an evaluation of how the customer, global and societal needs were met and fulfilled. The customer needs included the purpose of the project as well as the target specification. Furthermore, the global and societal assessment embraces requirements that affect the users and the entire world. The different needs achievement was evaluated on a range from 1-10 with 1 being the lowest and 10 being the highest.

5.1 Customer Needs Assessment

The goal was to investigate and develop a fan with split blades, based on the patent US 7396208 B1 [2]. Additionally, it was to gain more understanding about how a fan with a split blade design could raise the pressure and efficiency. The customer, Volvo Group, desired a lot of results and simulations of the different concepts. Therefore, the project group focused more on getting results from different simulations, rather than generating many new concepts. Because of this focus, the project has results about the parameters impact and has also suggested ways for Volvo Group to continue the work.

The target specification, which can be seen in Table 2, mentions different specifications that were goals during the project. The aim to reach an efficiency over 42% and a pressure rise over 2000 Pa were not equalled.

On a scale from 1-10, the customer needs met with an 8.

5.2 Global and Societal Needs Assessment

During the project's process, both global and societal needs have always been made allowances for. This includes needs such as environmental, sustainability and fundamental human demands. For example, since one of the aims was to find a fan with a higher efficiency, the project has focused on the long-term goal of less fuel consumption. Also, while selecting material and manufacturing process, environmental and sustainability requirements have been taking into account.

On a scale from 1-10, the project group finds the global and societal needs met with a 10.

6. Recommendations

The outcome of this project is for Volvo Group not to replace their existing fan with the Final Concept, see Figure 59, due to the results of the project. Although, the recommendation will be to continue the development and the research of a split fan blade. The project group sees potential to develop a better concept with split blades if more streamlined blades will be used. If the project continues, there are many more parameters to investigate. Furthermore, above all, there is a great chance to develop a better fan if the project's focus were more on the aerodynamics design.

Even though none of the concept reached the customer needs of 42% efficiency and a 2000 Pa pressure rise, the project has resulted in some conclusions about the impact of a split blade. These conclusions read:

- The split blade has a higher working range than a solid blade.
- The split blade achieves a larger pressure rise.
- The split blade achieves a larger power output compared to the solid blade.
- The solid blade achieves a higher efficiency.

The main influence that has been determined is the greater pressure rise and the higher working range compared to an identical fan without split blades. This conclusion could be established due to identical simulations of two fans within the software Star-CCM+. They were equal on every point besides that one had split blades and one had solid blades. Therefore, the group will emphasize the accuracy of this assessment. Hence, the recommendation to Volvo Group is to continue the research about the split fan blade.

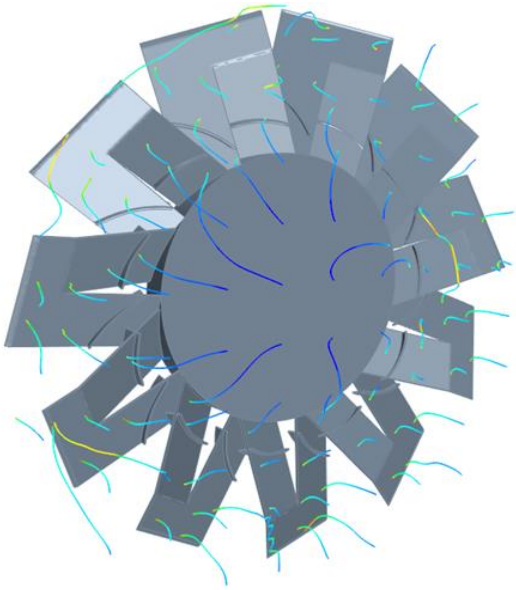


Figure 59: The Final Concept with split blades. The streamlines are illustrated as ribbons showing the velocity of the air.

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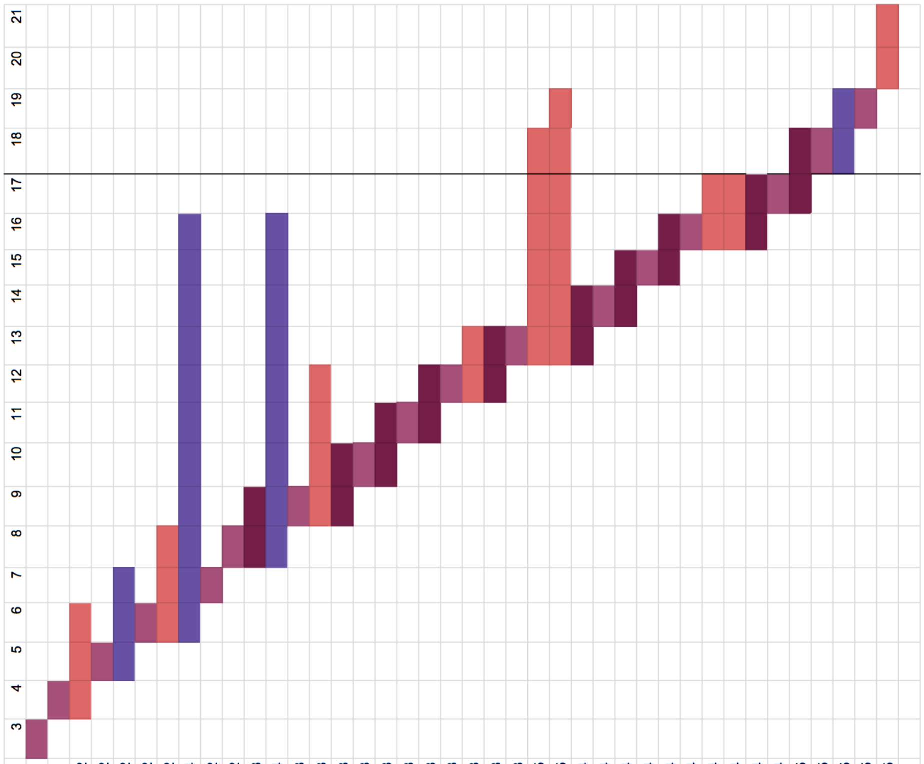
Appendix

Appendix A – Gantt Chart

A Gantt Chart was made to get structure of the project and to ensure that the deadlines would be reached, see Table 1.

Table 1: The Project's Gantt Chart.

TASK LIST	PERCENT COMPLETED	RESPONSIBILITY	DUE DATE
Progress Report 1	100%	Jordan	2017/20/1
Progress Report 2	100%	Ashleigh	2017/27/1
Planning Report	100%	Mikaela	2017/12/2
Progress Report 3	100%	Ben	2017/3/2
CAD/CFD First draft	100%	Jordan, Vilma	2017/17/2
Progress Report 4	100%	Erica	2017/10/2
Proposal Presentation	100%	Ashleigh	2017/23/2
Final Concept Finished	100%	Erica	2017/19/4
Progress Report 5	100%	Mikaela	2017/17/2
Progress Report 6	100%	Vilma	2017/24/2
Simulations 1 Finished	100%	Erica	2017/6/3
CAD/CFD Finished	100%	Jordan, Vilma	2017/19/4
Progress Report 7	100%	Jordan	2017/3/3
Midterm Report	100%	Mikaela	2017/22/3
Simulations 2 Finished	100%	Vilma	2017/10/3
Progress Report 8	100%	Ashleigh	2017/10/3
Simulations 3 Finished	100%	Mikaela	2017/17/3
Progress Report 9	100%	Ben	2017/17/3
Simulations 4 Finished	100%	Erica	2017/24/3
Progress Report 10	100%	Erica	2017/24/3
Midterm Presentation	100%	Ben	2017/30/3
Simulations 5 Finished	100%	Vilma	2017/31/3
Progress Report 11	100%	Mikaela	2017/31/3
PSU Final Report Due	100%	Ashleigh	2017/1/5
Chalmers Final Report	100 %	Mikaela	2017/12/5
Simulations 6 Finished	100%	Ashleigh	2017/7/4
Progress Report 12	100%	Vilma	2017/7/4
Simulations 7 Finished	100%	Erica	2017/14/4
Progress Report 13	100%	Jordan	2017/14/4
Simulations 8 Finished	100%	Jordan	2017/21/4
Progress Report 14	100%	Ashleigh	2017/21/4
PSU Final Presentation	100%	Ben	2017/25/4
PSU Showcase	100%	Ben	2017/27/4
Simulations 9 & 10 Finished	100%	Mikaela	2017/28/4
Progress Report 15	100%	Erica	2017/28/4
Simulations 11 Finished	100%	Vilma	2017/4/5
Progress Report 16	100%	Mikaela	2017/5/5
Scale Prototype Finished		Erica	2017/19/5
Progress Report 17		Vilma	2017/12/5
Chalmers Final Presentation		Vilma	2017/23/5



Appendix B - The risks’ impacts and probability

The risks’ impact was split in three categories:

- High: the impact on the project is great.
- Medium: the impact on the project is intermediate.
- Low: the impact is on the project is relatively small.

The same system was used for rating the probability of the risks:

- High: great probability of occurrence.
- Medium: less probability of occurrence.
- Low: very low probability of occurrence.

The risks that are included in the red and yellow area of Table 2 were applied to the risk plan and therefore were evaluated and minimized. The green areas’ risks were not evaluated since their effect on the project were not as great.

Table 2: The risks’ impact and probability

Probability	**High**			
	Medium			
	Low			
		Low	**Medium**	**High**
			Impact	

Appendix C - Risk Plan

The risk plan, Table 3, includes the risks that are considered critical. It also contains the level of critically as well as the actions to prevent the risks.

Table 3: The risk plan including the critical risks.

Risk	Level	Actions
Exceeds budget	Low	- Planning all outlays - Consider cheaper alternatives
Uneven work distribution	Moderate	- Plan the work - Have an open discussion - Use a time log - Talk to supervisor
Loss of data	Moderate	- Constant backups - Cloud functions
Unexpected results	Moderate	- Acknowledge reasons in report - Evaluate results
Not achieve the sponsor's expectations	Moderate	- Regular contact and communication with the sponsor - Weekly reports
Conflicts within the group	High	- Discussion at team meetings - Democratic decisions
Unable to hand in at deadline	High	- Plan ahead so the work starts in time to be completed before the deadline - Use Gantt chart
Misunderstanding the task	High	- Clarify all doubts by speaking to the supervisor or sponsor
Unusable simulation and calculation results	High	- Always check with supervisor before proceeding
Unable to finish project on time	High	- Careful planning of time
Prototype gets lost in the mail	High	- Careful tracking of the package and as short travel time as possible

Appendix D - AHP

The Analytic Hierarchy Process is used evaluate the importance of each customer need compared to each other, see Table 4.

Table 5: The Analytic Hierarchy Process for the project.

Critera	Fan power usage	Efficiency	Static pressure rise	Size	Volumetric flow rate	Rotation speed	Safety	Weight	Durability	Cost	Sound pressure	Total	Weight	Rank
Fan power usage	1	0,9	1	1,4	1,2	1,2	1,3	1,5	1,4	1,5	1,4	13,8	0,12432432	2
Efficiency	1,1	1	1,1	1,5	1,3	1,3	1,4	1,6	1,5	1,6	1,5	14,9	0,13423423	1
Static pressure rise	1	0,9	1	1,4	1,2	1,2	1,3	1,5	1,4	1,5	1,4	13,8	0,12432432	2
Size	0,6	0,5	0,6	1	0,8	0,8	0,7	1,1	1	1,1	1	9,2	0,08288288	6
Volumetric flow rate	0,8	0,7	0,8	1,2	1	1	1,1	1,3	1,2	1,3	1,2	11,6	0,1045045	3
Rotation speed	0,8	0,7	0,8	1,2	1	1	1,1	1,3	1,2	1,3	1,2	11,6	0,1045045	3
Safety	0,7	0,6	0,7	1,1	0,9	0,9	1	1,2	1,3	1,2	1,3	10,9	0,0981982	4
Weight	0,5	0,4	0,5	0,8	0,7	0,7	0,8	1	0,8	1	0,8	7,2	0,06486486	9
Durability	0,6	0,5	0,6	1,1	0,8	0,8	0,9	1,1	1,1	1,1	1,1	9,7	0,08738739	5
Cost	0,5	0,4	0,5	0,9	0,7	0,7	0,8	1	0,9	1	0,9	8,3	0,07477477	8
Sound pressure	0,6	0,5	0,6	0,9	0,8	0,8	0,9	1,1	0,9	1,1	0,9	9,1	0,08198198	7
SUM												111		

Appendix E - Engineering Specification

Engineering Specification established the aims that the final product needed to fulfil. It contains the different function criteria including if they are a demand or desire, the authentication method, target value and their reference, see Table 5.

Table 6: Engineering Specification containing the different function criteria.

Engineering specification				
Project:	An Investigation and Comparison of Split Fan Blades' Performance			
Modified:	4/4 2017			
Function criterias	**Demand/Desire**	**Authentication method**	**Target value**	**Reference**
1. Configuration of the fan				
1.1 Diameter of the fan	Demand	Measurement	750 mm	Volvo Group
1.2 Weight	Demand	Weighing	3-4 kg	Volvo Group
1.3 Weight	Desire	Weighing	1-2 kg	Volvo Group
1.4 Fit to existing system	Demand	Design		Volvo Group
1.5 Ease of installation	Desire	Tests		Project Group
1.6 Attack angle	Demand	Calculations	23,78°	Project Group
1.7 Split fan blade	Demand	Design		Volvo Group
2. Usage				
2.1 Safety	Demand	Simulations		Volvo Group
2.2 Maintenance-free	Desire	Simulations		Project Group
2.3 Efficieny	Demand	Simulations	> 42 %	Volvo Group
2.4 Power usage	Demand	Simulations	< 35 kW	Volvo Group
2.5 Rotation speed	Demand	Simulations	2400 rpm	Volvo Group
2.6 Volumetric flow rate	Demand	Simulations	8 m^3/s	Volvo Group
2.7 Volumetric flow rate	Desire	Simulations	4 m^3/s	Volvo Group
2.8 Static pressure rise	Demand	Simulations	> 2000 Pa	Volvo Group
2.9 Extreme temperature interval	Demand	Material selection	87 - 112 ℃	Volvo Group
2.10 Usage temperature	Demand	Material selection	< 87 ℃	Project Group
2.11 Max deformation at operational speed	Demand	FEA analysis	5 mm	Volvo Group
2.12 Max deformation at operational speed	Desire	FEA analysis	2,5 mm	Project Group
3. Environment				
3.1 Environmental production	Desire	Production analysis		Project Group
3.2 Environmental usage	Desire	LCA		Project Group
3.3 Small range of materials	Desire	Construction		Project Group
3.4 Recyclable	Desire	Material analysis	35 %	Project Group
4. Life				
4.1 Life	Demand	Simulations & Calculations	20 years	Volvo Group
5. Costs				
5.1 Manufacturing cost	Desire	Calculations		Project Group

Appendix F - Attack angle

Calculation of the optimal attack angle used for the concept development.

Given data:

$$Q = 8\ m^3/s$$
$$D_p = 2000\ Pa$$
$$P = Q \cdot D_p = 16\ kW$$

$$\rho = 1{,}18\ kg/m^3$$
$$\dot{m} = Q \cdot \rho \approx 9{,}44\ kg/s$$

$$D_cF = \frac{P}{w \cdot \dot{m} \cdot R_m} \approx 28{,}05\ (Euler)$$

$$R_{hub} = 0{,}1\ m$$
$$R_{shroud} = 0{,}325\ m$$
$$R_m = \sqrt{\frac{{R_{hub}}^2 \cdot {R_{shroud}}^2}{2}} \approx 0{,}24\ m$$

$$w = 2400\ rpm = 2400 \cdot \frac{2\pi}{60}\frac{rad}{s} \approx 251{,}33\ rad/s$$

$$A = ({R_{hub}}^2 - {R_{shroud}}^2) \cdot \pi \approx 0{,}30\ m^2$$
$$V = C = \frac{Q}{A} = 26{,}6\ m/s$$
$$u = R_m \cdot w \approx 60{,}43\ m/s$$

Attack Angle

$Angle\ in: \beta_1$	$Angle\ out: \beta_2$
$C_1 = (26{,}6\ \ 0\ \ 0)$	$C_2^V = 26{,}6\ m/s$
$u = (0\ \ 0\ \ 60{,}43)$	$C_2^H = -60{,}43 + D_cF = -21{,}38\ m/s$
$w_1 = (26{,}6\ \ 0\ \ -60{,}43)$	$C_2 = (26{,}6\ \ 0\ \ -32{,}38)$
$\beta_1 = \tan^{-1}(\frac{26{,}6}{60{,}43}) \cdot \frac{180}{\pi} \approx 23{,}78°$	$u = (0\ \ 0\ \ 60{,}43)$
	$w_2 = (26{,}6\ \ 0\ \ -32{,}38)$
	$\beta_2 = \tan^{-1}(\frac{26{,}6}{\lvert -32{,}38 \rvert}) \cdot \frac{180}{\pi} \approx 39{,}4°$

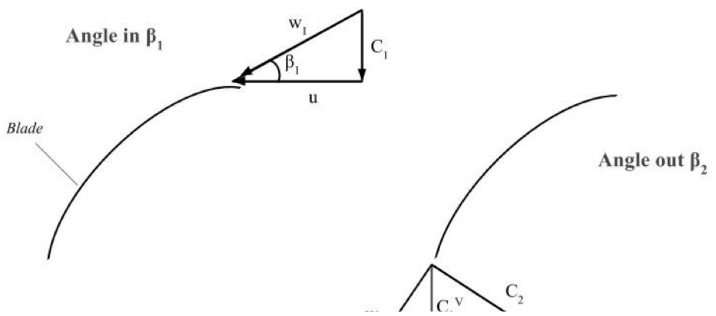


Figure 2: Calculation of the optimal attack angle.

Figure 3: Calculation of the optimal attack angle.

Appendix G – Finite Element Analysis Calculations

The calculated forces on the blades.

$$\omega = 2400\ rpm * (2\pi\ rad/1\ rev) * (1\ min/60\ sec) = 251.33\ rad/s$$

$$v = \omega * r = 88\ m/s$$

$$F_c = m * v^2/r = m * \omega^2 * r$$

$$F_{air} = 0.5 * \varrho_{air} * A_s * \omega^2 * r^2$$

Figure 4: Calculations used for the FE-analyses.

Appendix H - Values from the Simulations

The documented values of the results from the simulations, see Table 6-17.

Table 7: Results from the simulations of the Reference fan.

Reference fan			**Rotation speed: 251 rad/s**		
m^3/s	**Pressure rise (Pa)**	**Moment (Nm)**	**P_{in} (W)**	**P_{ut} (W)**	**Efficiency (%)**
4	2770,402	154,273	38722,611	11081,608	28,618
5	2584,8	149,820	37604,743	12924	34,368
6	2354,458	145,954	36634,529	14126,748	38,561
7	2229,981	147,684	37068,584	15609,867	42,111
8	2169,612	155,130	38937,555	17356,896	44,576

Table 8: Results from the simulations of Concept 1.

Concept 1			**Rotation speed: 251 rad/s**		
m^3/s	**Pressure rise (Pa)**	**Moment (Nm)**	**P_{in} (W)**	**P_{ut} (W)**	**Efficiency (%)**
4	785,060	50,551	12688,301	3140,240	24,749
5	694,993	47,098	11821,498	3474,967	29,395
6	523,540	40,578	10184,953	3141,242	30,842
7	425,376	42,219	10596,944	2977,631	28,099
8	195,549	39,851	10002,551	1564,390	15,640

Table 9: Results from the simulations of Concept 2.

Concept 2		Rotation speed: 251 rad/s			
m^3/s	Pressure rise (Pa)	Moment (Nm)	P_{in} (W)	P_{ut} (W)	Efficiency (%)
4	1056,415	68,732	17251,657	4225,66	24,494
5	888,380	62,517	15691,692	4441,902	28,307
6	805,828	57,679	14477,354	4834,970	33,397
7	576,997	49,806	12501,281	4038,981	32,309
8	376,543	51,229	12858,379	3012,344	23,427

Table 10: Results from the simulations of Concept 3.

Concept 3		Rotation speed: 251 rad/s			
m^3/s	Pressure rise (Pa)	Moment (Nm)	P_{in} (W)	P_{ut} (W)	Efficiency (%)
4	709,917	46,938	11781,413	2839,668	24,103
5	564,854	40,362	10130,787	2824,270	27,878
6	479,609	39,178	9833,653	2877,655	29,263
7	247,794	38,706	9715,256	1734,557	17,854
8	0	35,722	8966,297	0	0

Table 11: Results from the simulations of Concept 4.

Concept 4		**Rotation speed: 251 rad/s**			
m^3/s	**Pressure rise (Pa)**	**Moment (Nm)**	**P_{in} (W)**	**P_{ut} (W)**	**Efficiency (%)**
4	698,218	44,961	11285,186	2792,873	24,748
5	623,937	42,466	10658,841	3119,687	29,269
6	471,141	38,244	9599,119	2826,848	29,449
7	345,369	38,253	9601,528	2417,585	25,179
8	262,970	34,974	8778,424	2103,756	23,965

Table 12: Results from the simulations of Concept 5.

Concept 5		**Rotation speed: 251 rad/s**			
m^3/s	**Pressure rise (Pa)**	**Moment (Nm)**	**P_{in} (W)**	**P_{ut} (W)**	**Efficiency (%)**
4	903,32	68,827	17275,602	3613,28	20,915
5	830,552	65,828	16522,903	4152,760	25,133
6	723,513	61,847	15523,472	4341,079	27,965
7	656,544	63,613	15966,938	4595,805	28,783
8	429,681	61,107	15337,857	3437,450	22,412

Table 13: Results from the simulations of Concept 6.

Concept 6		Rotation speed: 251 rad/s			
m^3/s	Pressure rise (Pa)	Moment (Nm)	P_{in} (W)	P_{ut} (W)	Efficiency (%)
4	1029,474	87,006	21838,506	4117,896	18,856
5	893,525	86,15	21648,45	4467,623	11886,5
6	855,777	78,962	19819,387	5134,662	25,907
7	804,164	79,295	19903,120	5629,149	28,283
8	586,146	75,694	18999,244	4689,165	24,681

Table 14: Results from the simulations of Concept 7.

Concept 7		Rotation speed: 251 rad/s			
m^3/s	Pressure rise (Pa)	Moment (Nm)	P_{in} (W)	P_{ut} (W)	Efficiency (%)
4	1234,311	107,482	26977,907	4937,244	18,301
5	1165,721	104,529	26236,704	5828,605	22,215
6	1089,968	100,995	25349,720	6539,808	25,798
7	1046,523	102,716	25781,766	7325,661	28,414
8	978,811	105,504	26481,579	7830,486	29,570

Table 15: Results from the simulations of Concept 8.

Concept 8		Rotation speed: 251 rad/s			
m^3/s	Pressure rise (Pa)	Moment (Nm)	P_{in} (W)	P_{ut} (W)	Efficiency (%)
4	1025,923	78,464	19694,364	4103,692	20,837
5	912,131	73,737	18508,012	4560,654	24,642
6	778,808	66,749	16753,974	4672,849	27,891
7	776,356	72,519	18202,269	5434,495	29,856
8	646,459	67,354	16905,904	5171,672	30,591

Table 16: Results from the simulations of the Final Concept.

Final Concept		Rotation speed: 251 rad/s			
m^3/s	Pressure rise (Pa)	Moment (Nm)	P_{in} (W)	P_{ut} (W)	Efficiency (%)
4	1090,676	61,278	15380,703	4362,704	28,365
5	864,258	55,758	13995,158	4321,29	30,877
6	701,094	53,320	13383,420	4206,562	31,431
7	367,494	49,423	12405,098	2572,457	20,737
8	0	40,935	10274,785	0	0

Table 17: Results from the simulations of the Final Surface.

Final Surface		**Rotation speed: 251 rad/s**			
m^3/s	**Pressure rise (Pa)**	**Moment (Nm)**	**P_{in} (W)**	**P_{ut} (W)**	**Efficiency (%)**
4	1143,45	74,4	18674,4	4573,8	24,492
5	903,639	56,639	14216,364	4518,194	31,782
6	750,836	55,956	14044,956	4505,018	32,0756
7	455,055	52,018	13056,518	3185,385	24,397
8	0	43,172	10836,147	0	0

Table 18: Results from the simulations of the Comparing Concept.

Comparing Concept		**Rotation speed: 251 rad/s**			
m^3/s	**Pressure rise (Pa)**	**Moment (Nm)**	**P_{in} (W)**	**P_{ut} (W)**	**Efficiency (%)**
4	774,3735	37,1565	9326,2815	3097,494	33,21252956
5	317,9218	30,4808	7650,6808	1589,609	20,77735357
6	0	19,2511	4832,0261	0	0
7	0	4,2632	1070,0632	0	0
8	0	0	0	0	0

Appendix I - Residuals

The appendix contains the residuals of each concept at the air flow 6 m^3/s, shown in Figures 3-13.

Figure 5: Residuals for Concept 1.

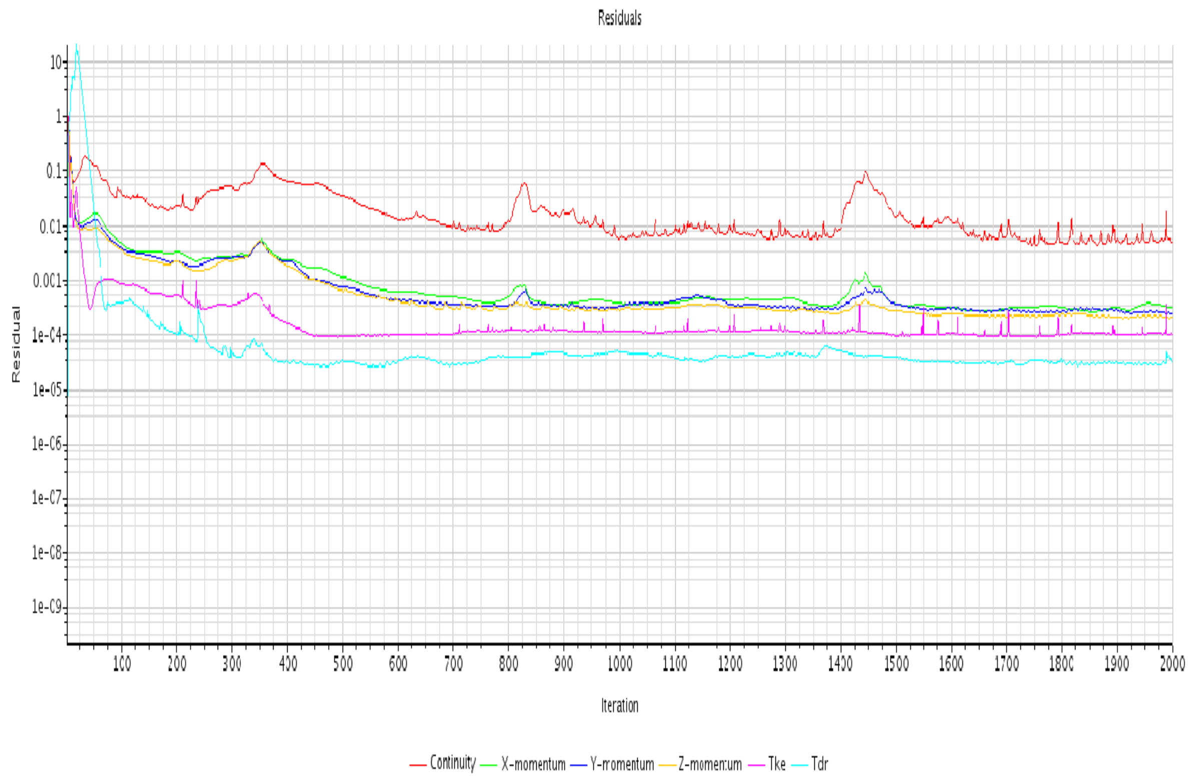


Figure 6: Residuals for Concept 2.

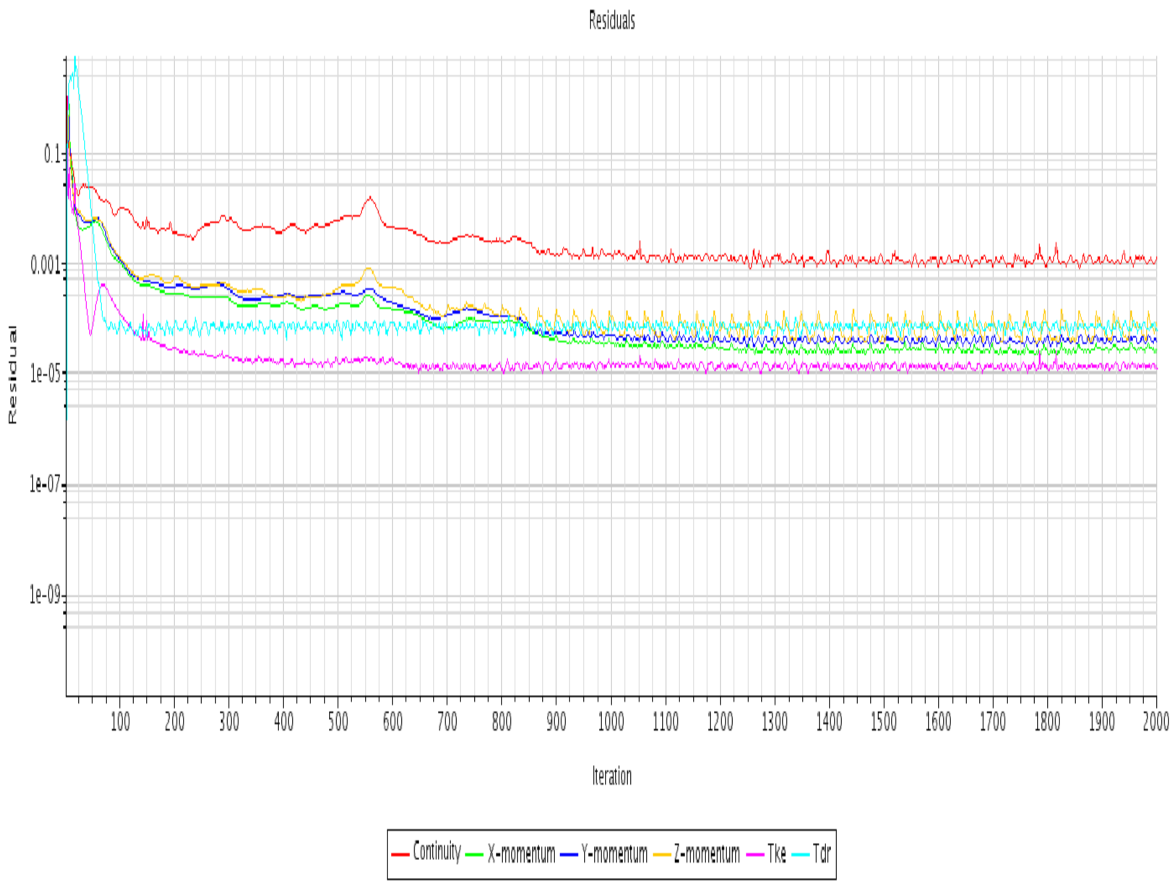


Figure 7: Residuals for Concept 3.

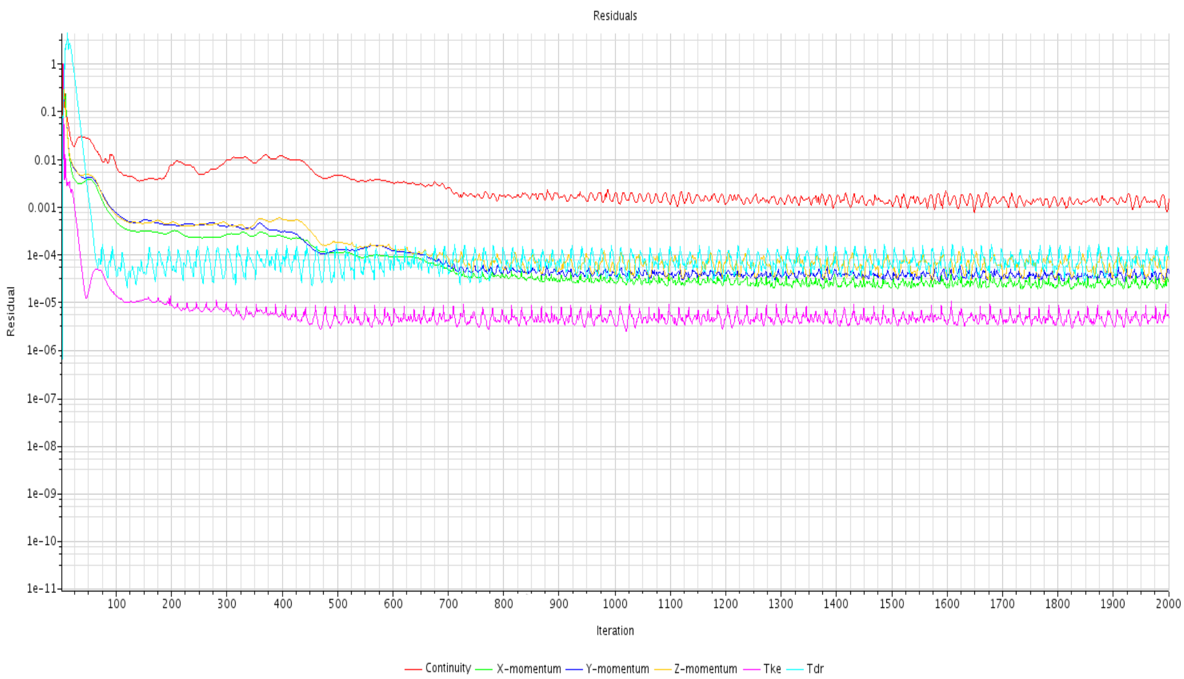


Figure 8: Residuals for Concept 4.

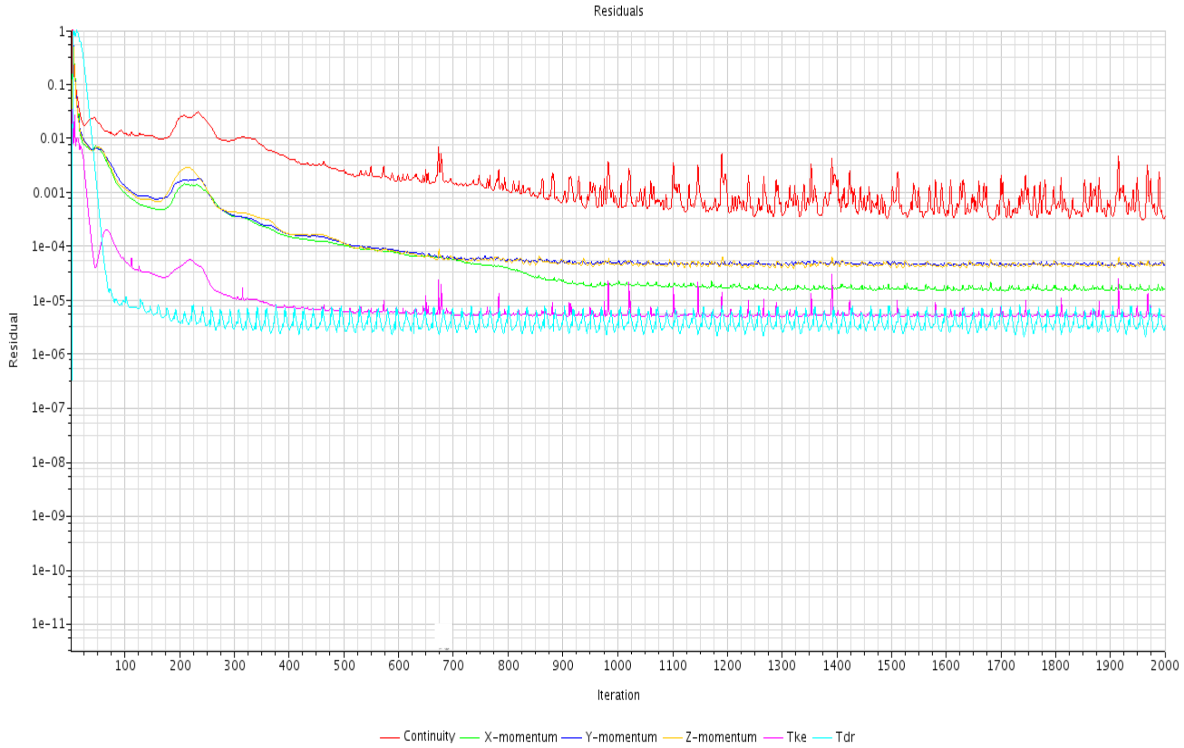


Figure 9: Residuals for Concept 5

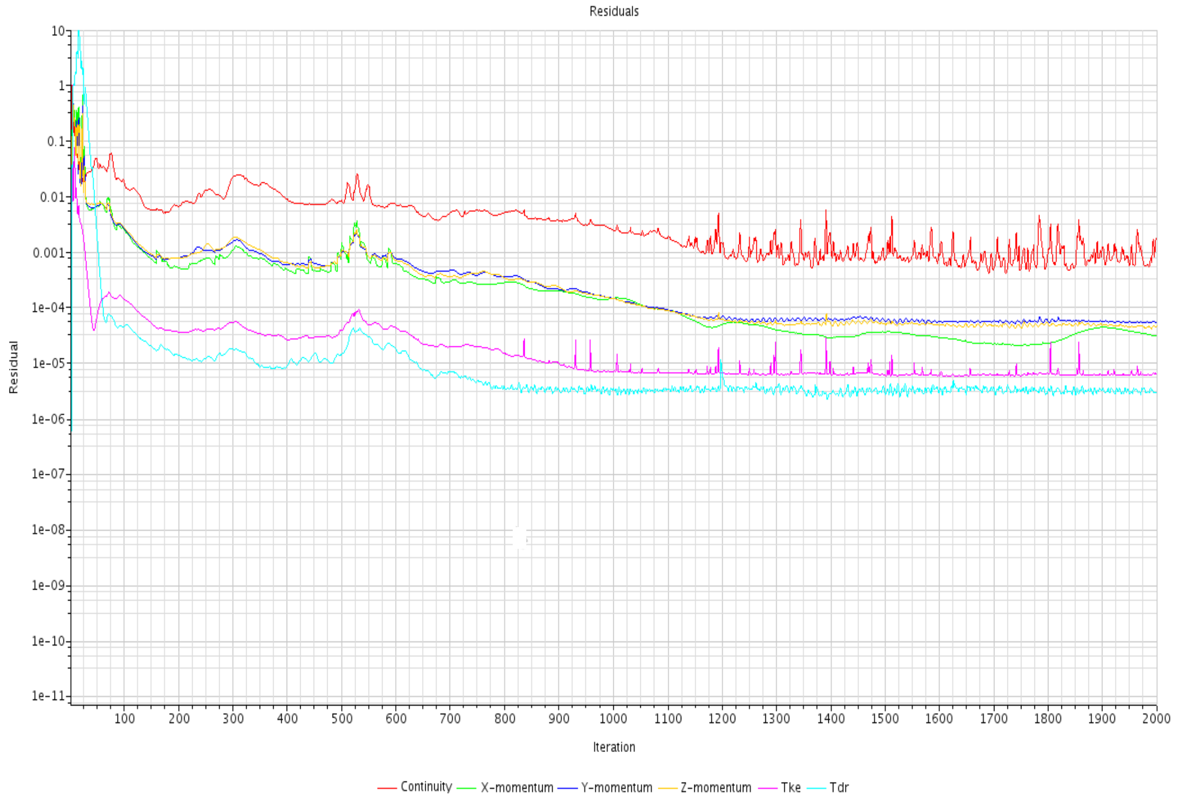


Figure 10: Residuals for Concept 6.

Figure 11: Residuals for Concept 7

Figure 12: Residuals for Concept 8

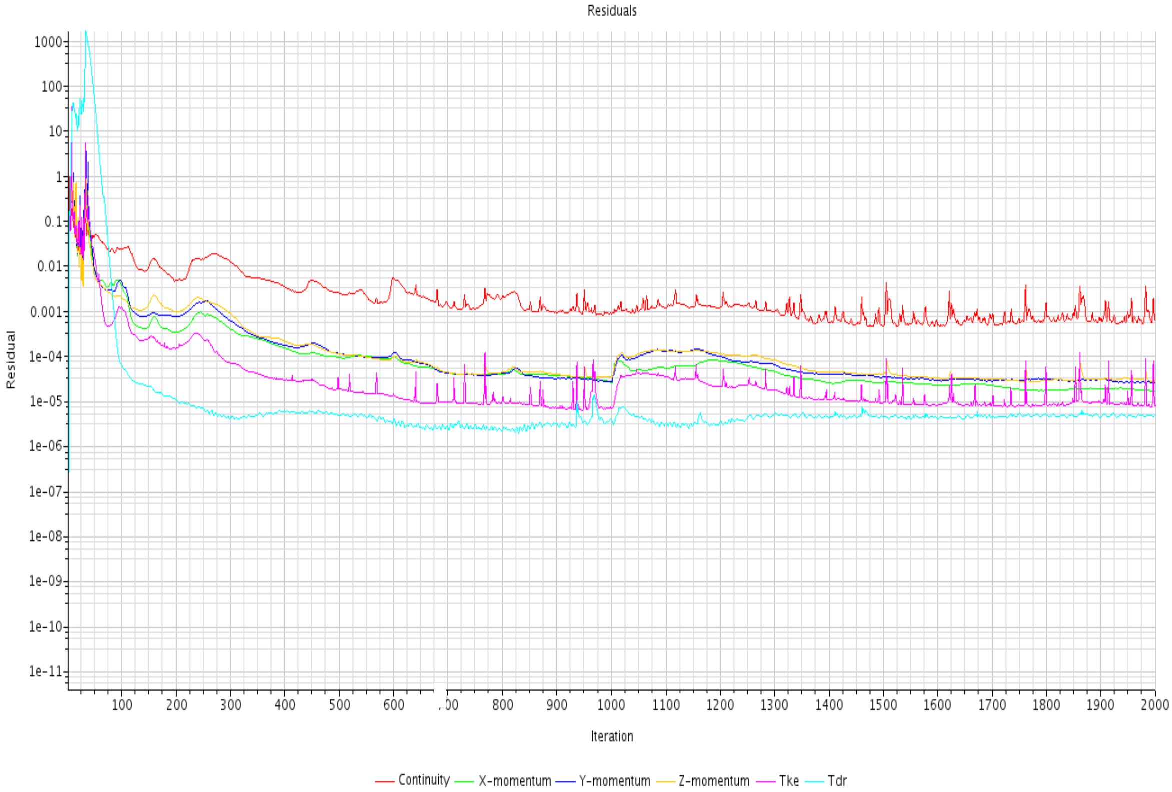


Figure 13: Residuals for the Reference fan.

Figure 14: Residuals for the Final Concept, iterated 2000 times and started from a solution already iterated 2000 times. Therefore, it looks like the concepts was iterated 4000 times instead of the real 2000 iterations.

Figure 15: Residuals for the Comparison Concept.

Appendix J- Volume Mesh

Pictures of the volume mesh around the fan, establishing the justice in the simulations, see Figures 14-21. The volume mesh contained about 5 million cells.

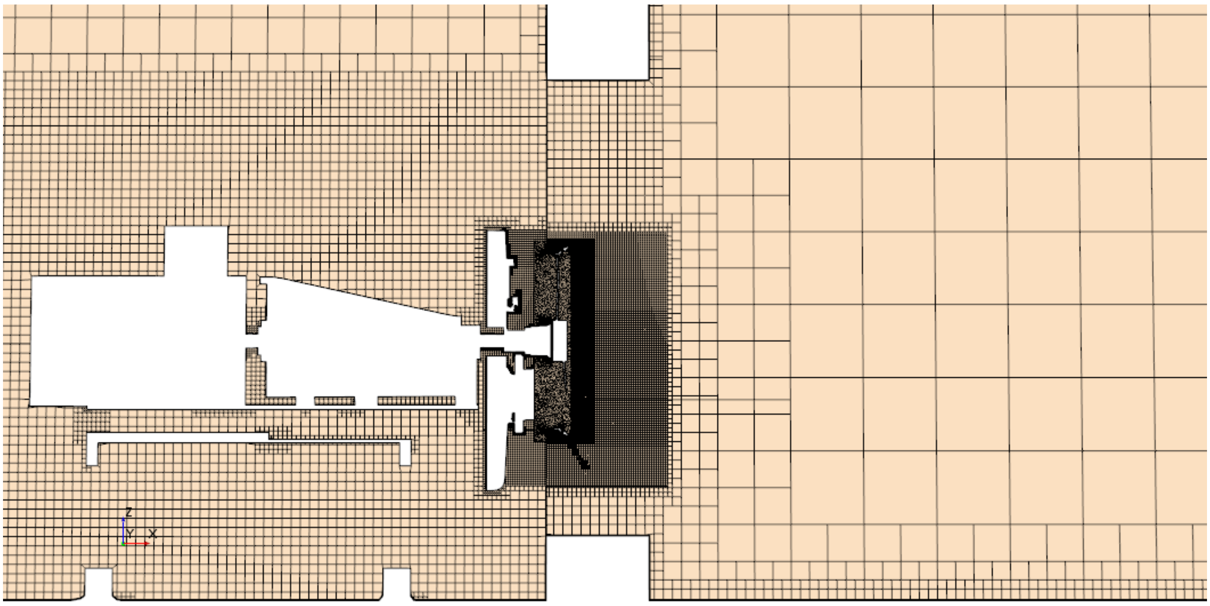


Figure 16: Volume mesh of Concept 1

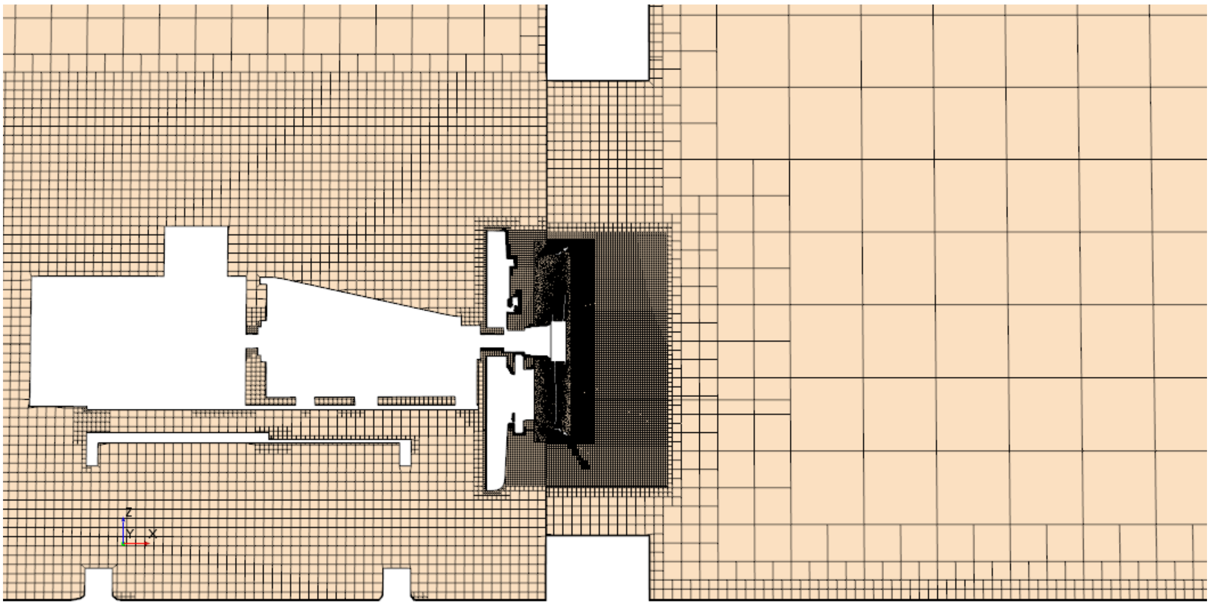


Figure 17: Volume mesh of Concept 2.

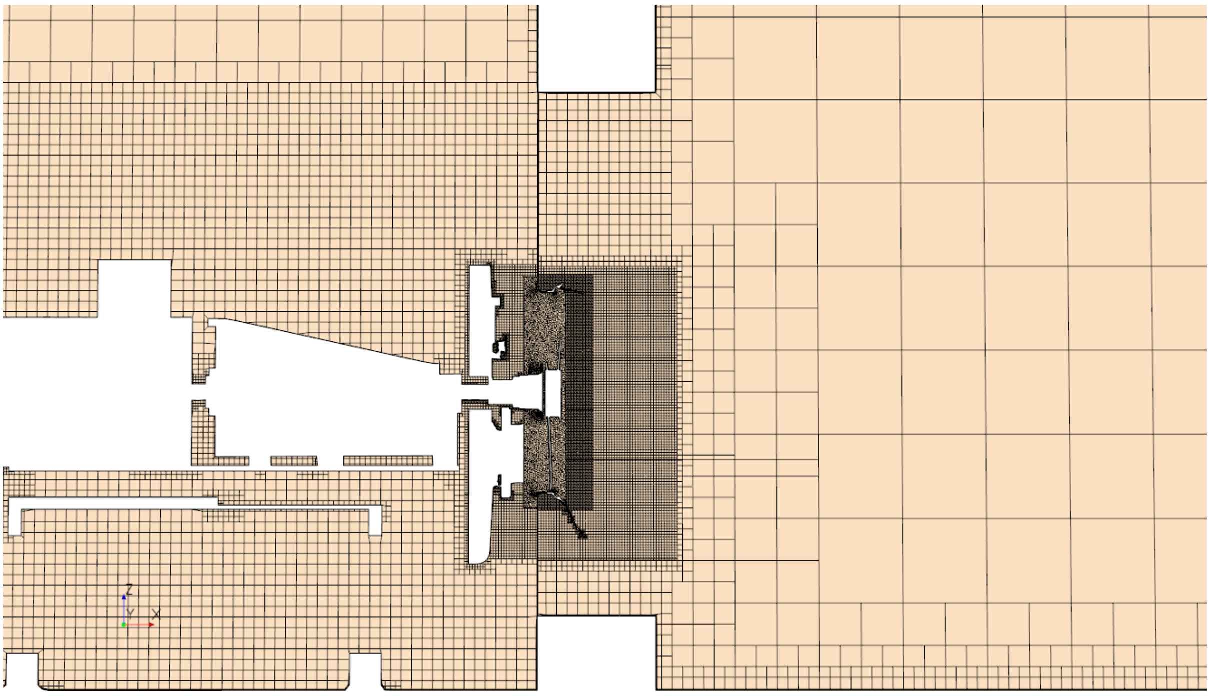


Figure 18: Volume mesh of Concept 3.

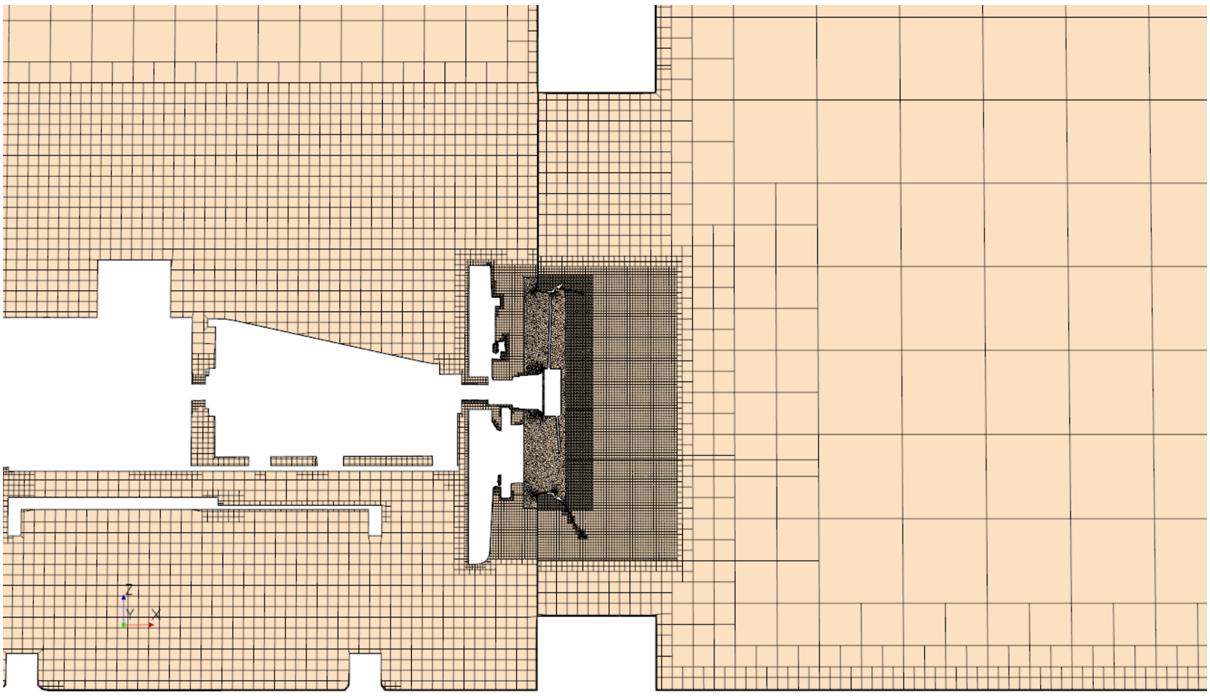


Figure 19: Volume mesh of Concept 4.

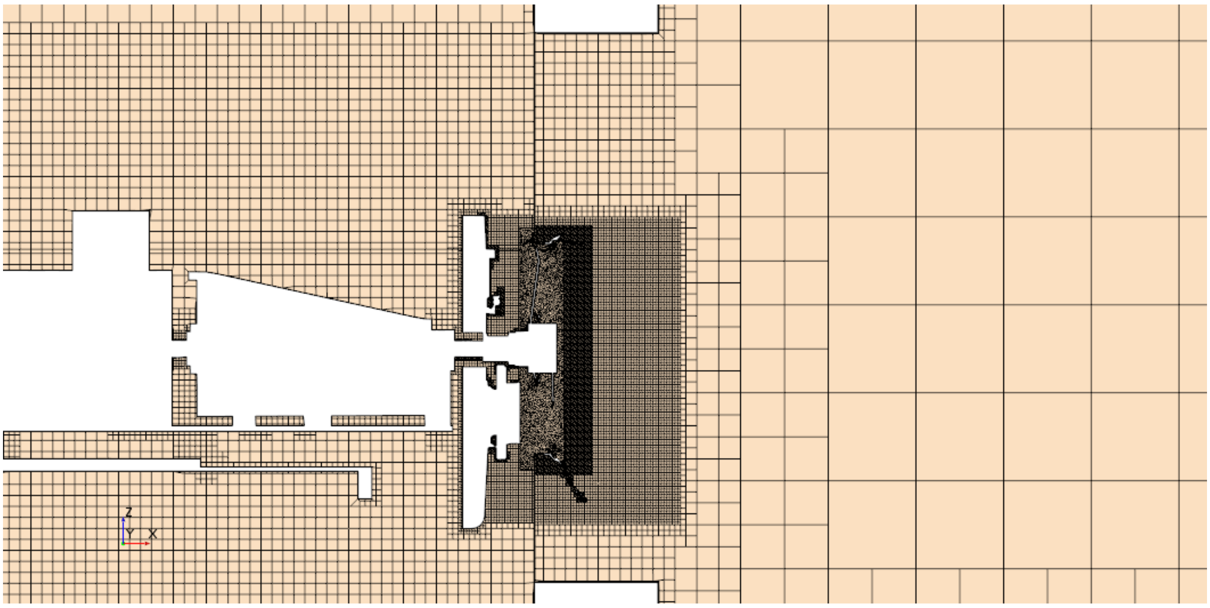


Figure 20: Volume mesh of Concept 5.

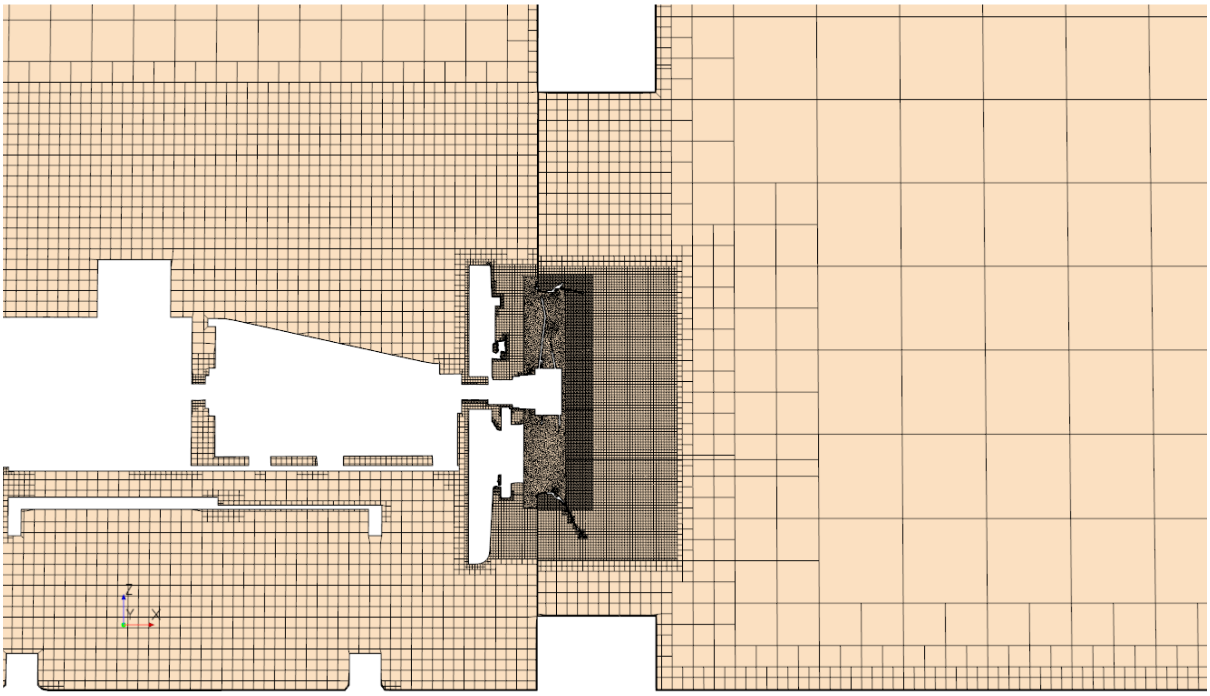


Figure 21: Volume mesh of Concept 6.

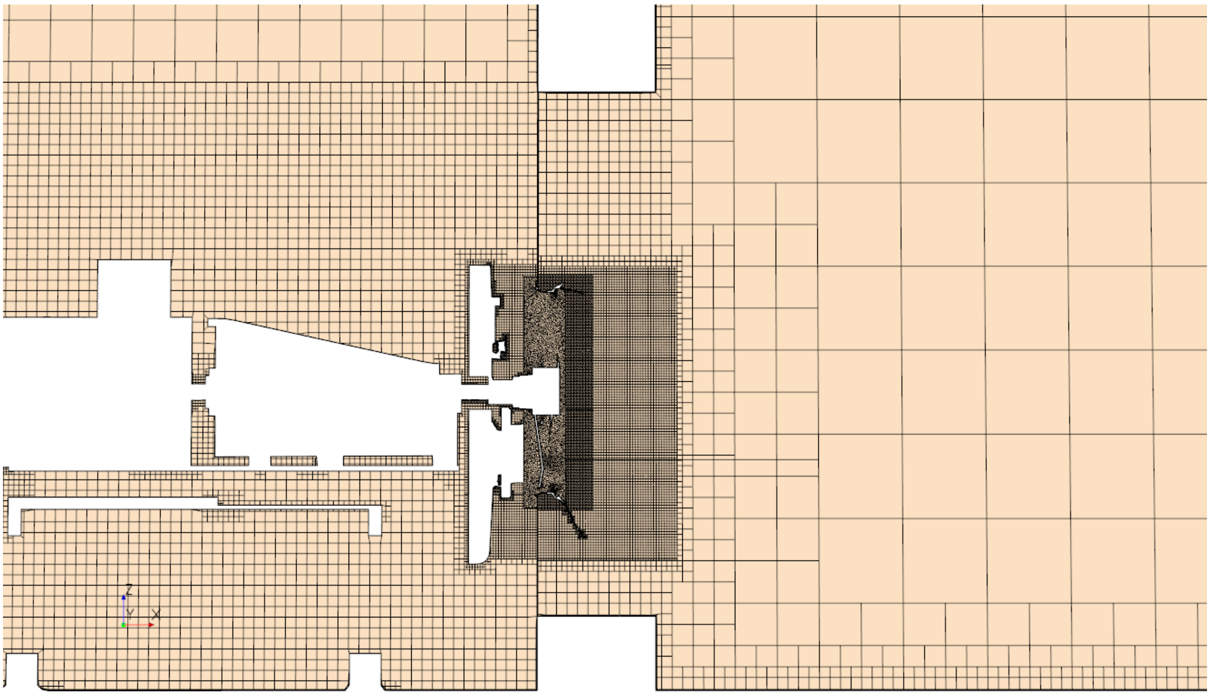


Figure 22: Volume mesh of Concept 7.

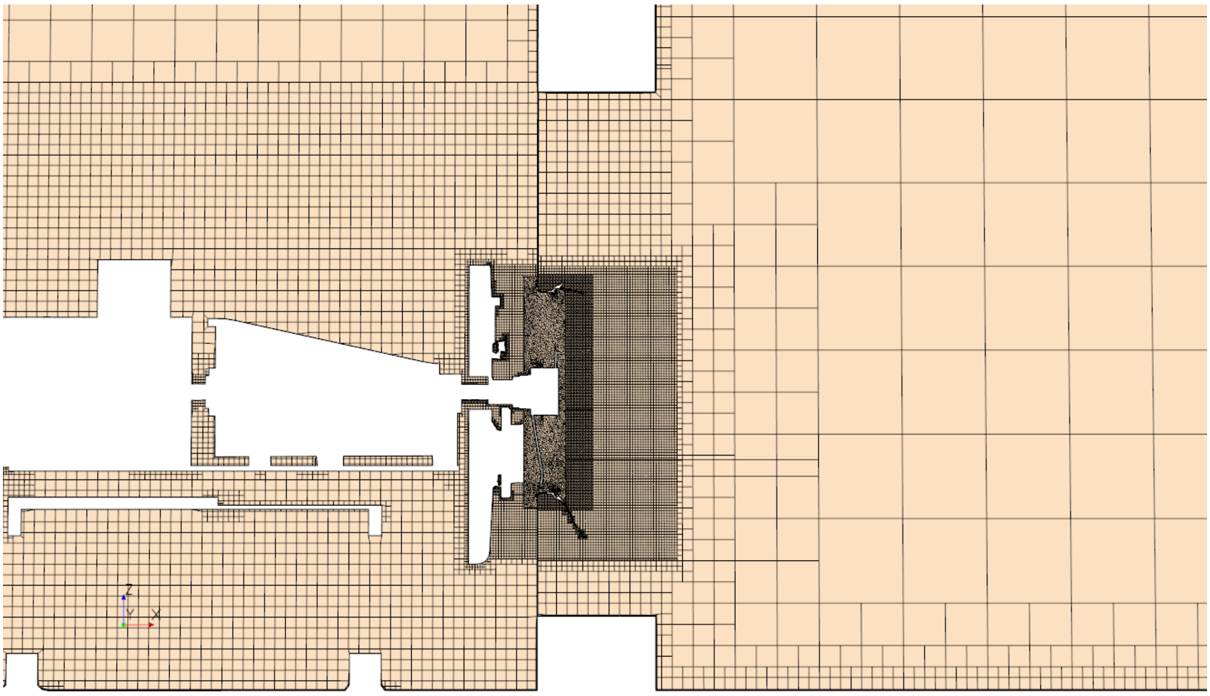
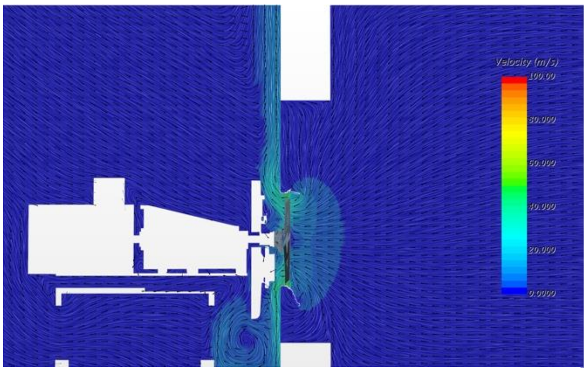


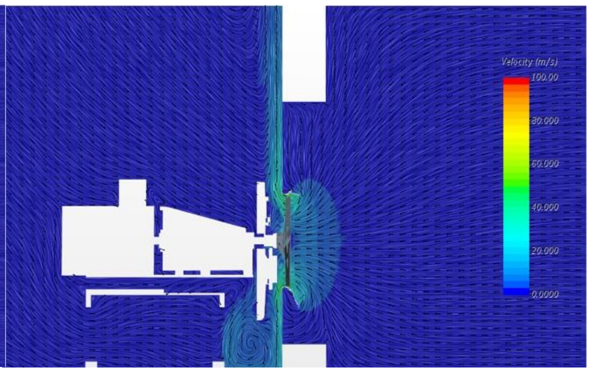
Figure 23: Volume mesh of Concept 8.

Appendix K - Streamlines

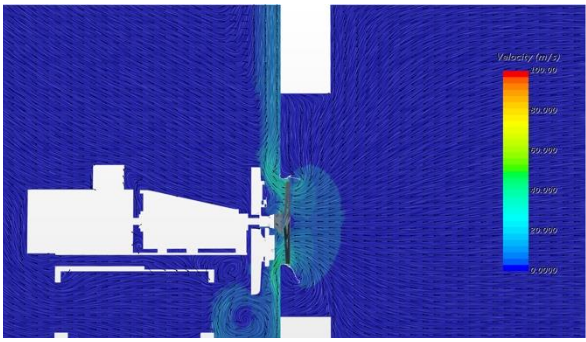
The streamlines and the velocity of the air around the fan at 6 m^3/s, Figure 22 (a) - (h).



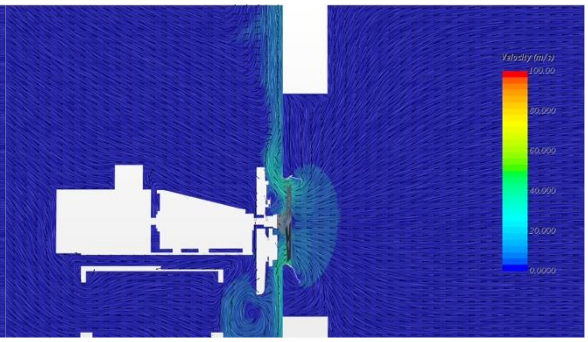
(a)



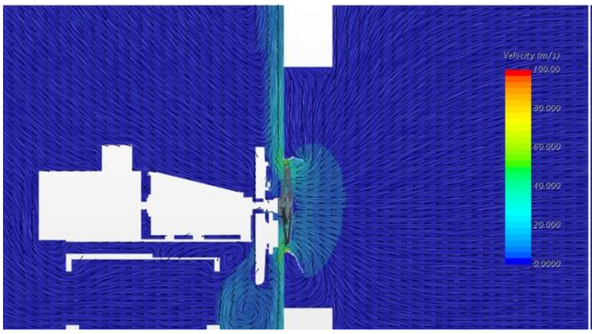
(b)



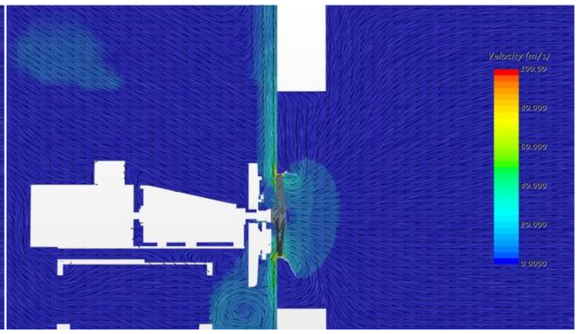
(c)



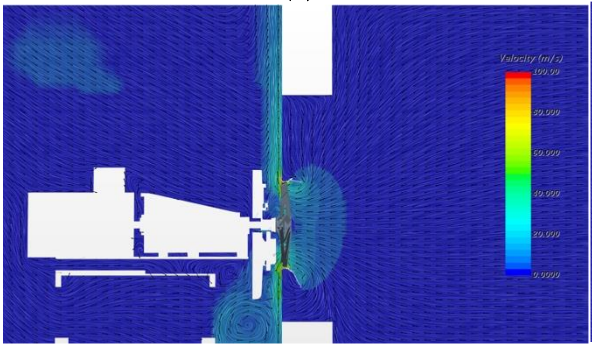
(d)



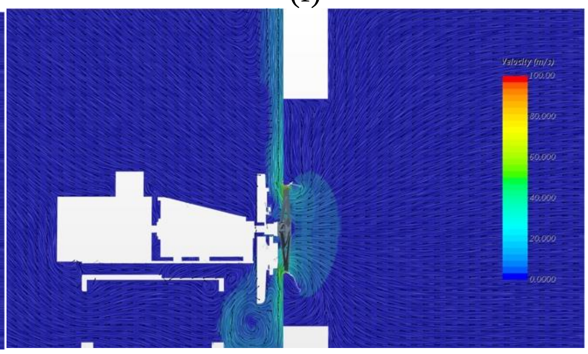
(e)



(f)



(g)



(h)

Figure 24: The streamlines and velocity of: (a) Concept 1, (b) Concept 2, (c) Concept 3, (d) Concept 4, (e) Concept 5, (f) Concept 6, (g) Concept 7 and (h) Concept 8.

Appendix L - Pressure Rise

The pressure rise between the inlet and the outlet for all eight concepts at 6 m^3/s, shown in Figure 23 (a) - (h).

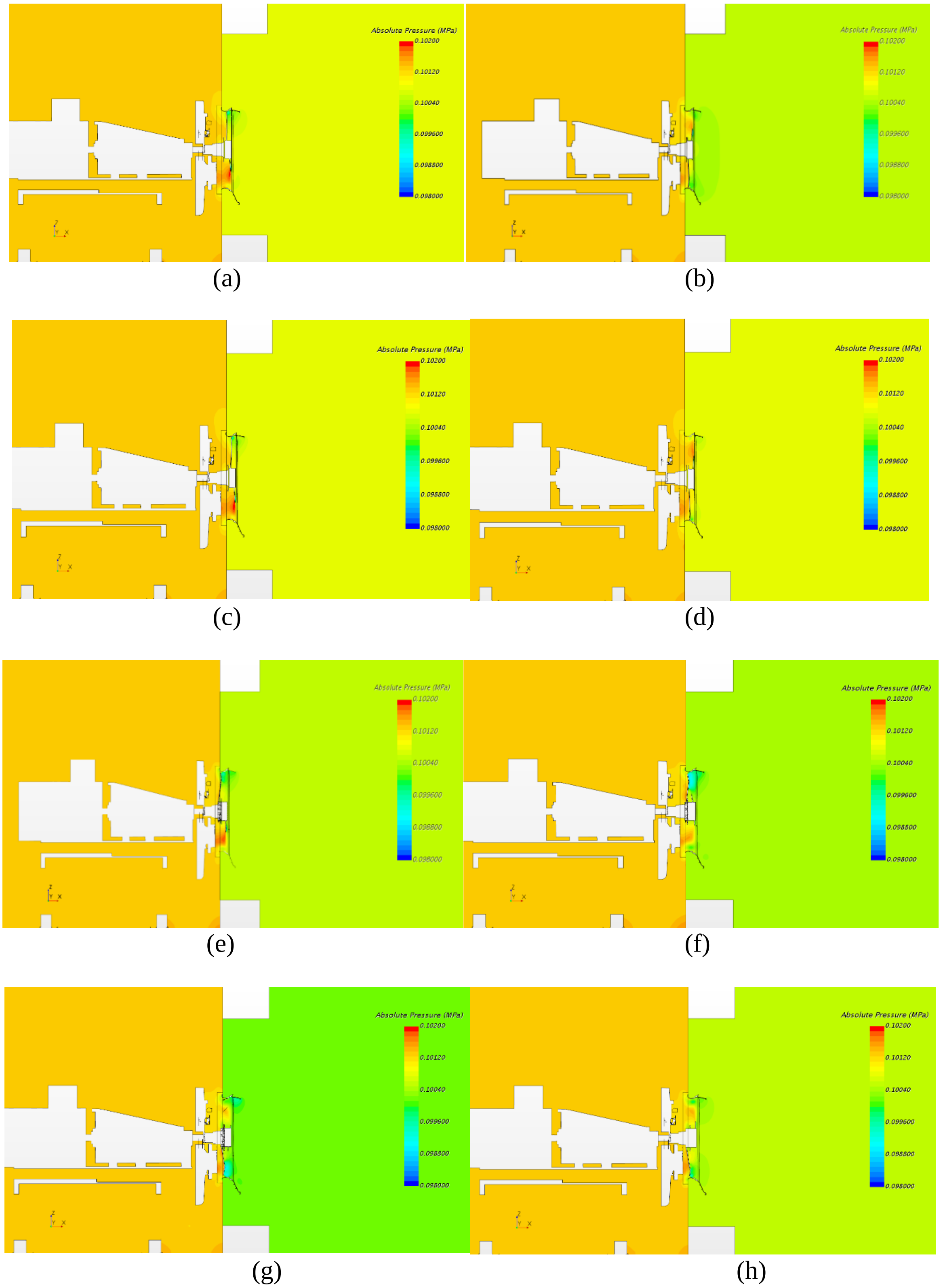
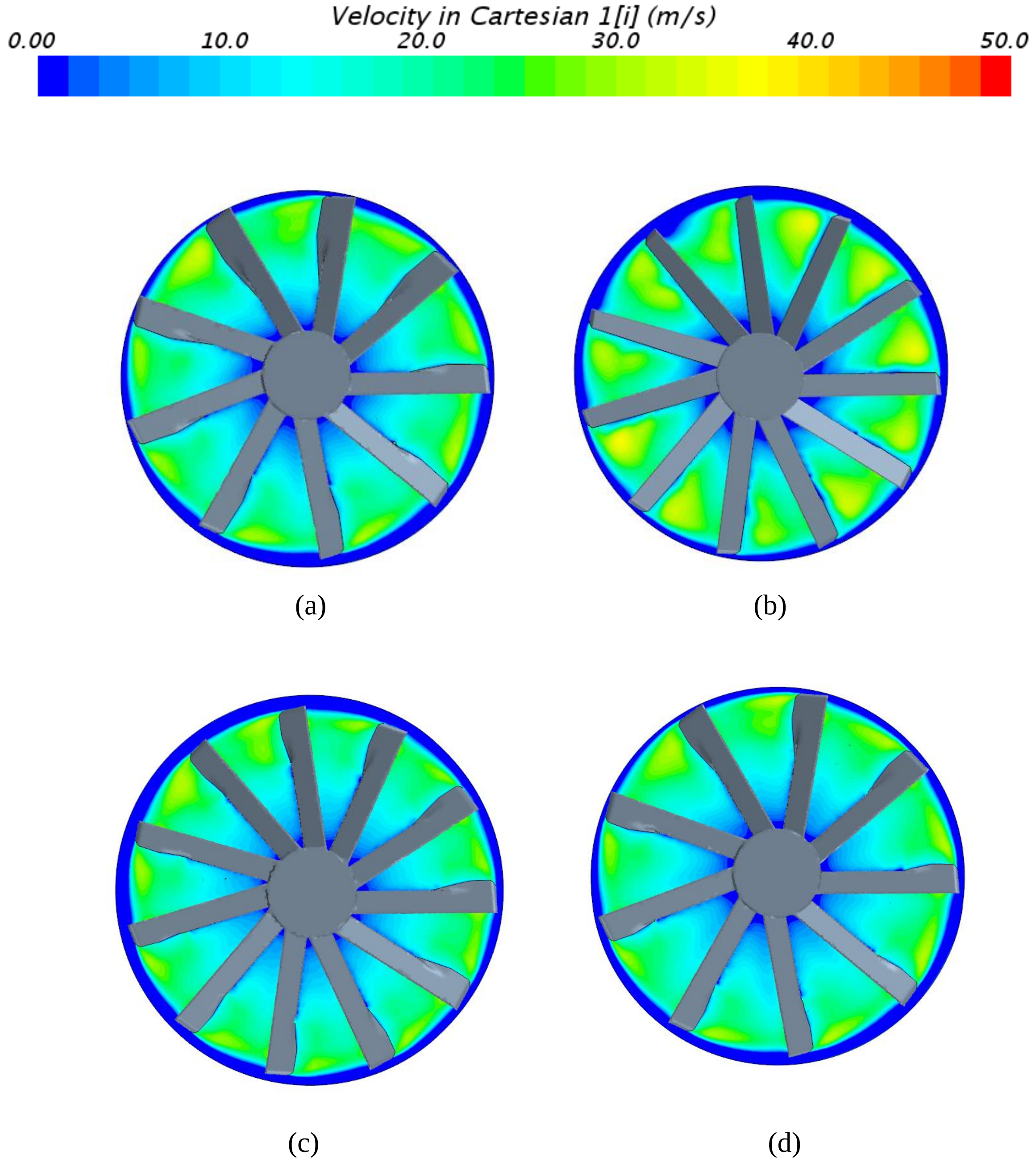


Figure 25: The pressure rise of: (a) Concept 1, (b) Concept 2, (c) Concept 3, (d) Concept 4, (e) Concept 5, (f) Concept 6, (g) Concept 7 and (h) Concept 8.

Appendix M - Backflow

The magnitude of the velocity going through the fan. The figures are visualizing the backflow of air, the blue area, for each of the concepts at 6 m^3/s, see Figure 24 (a) - (h).



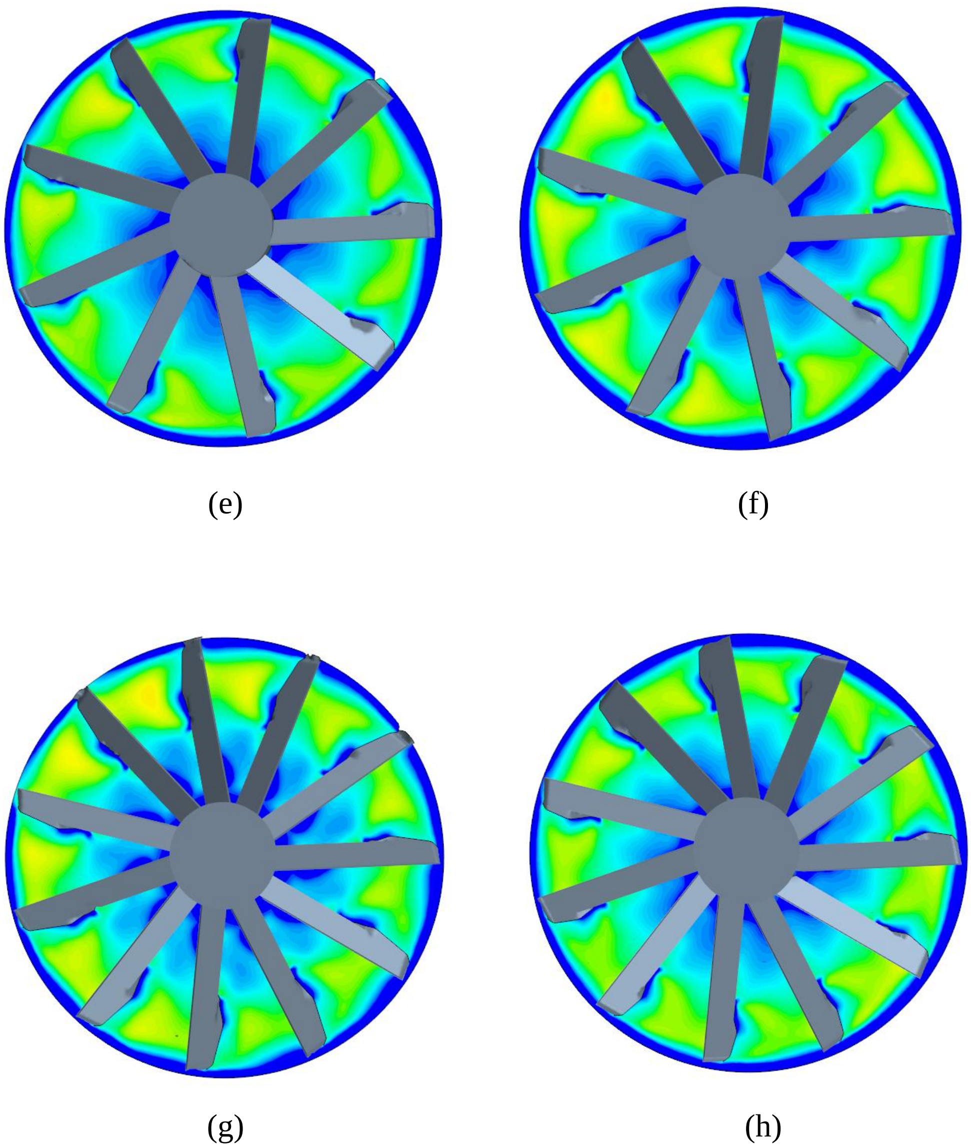


Figure 26: The backflow of air for: (a) Concept 1, (b) Concept 2, (c) Concept 3, (d) Concept 4, (e) Concept 5, (f) Concept 6, (g) Concept 7 and (h) Concept 8.

Appendix N - Results of the Reference Fan

Results of the Reference fan from the simulations at 6 m^3/s, Figure 25-28.

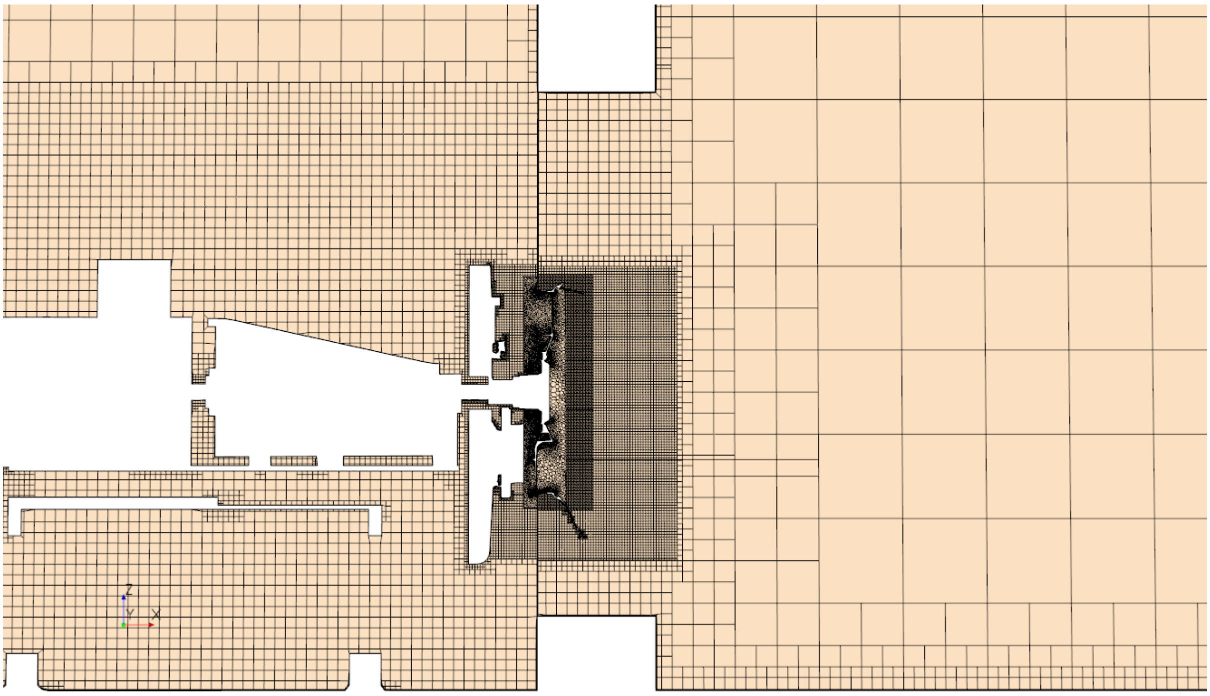


Figure 27: Picture of the volume mesh around the fan for the Reference fan.

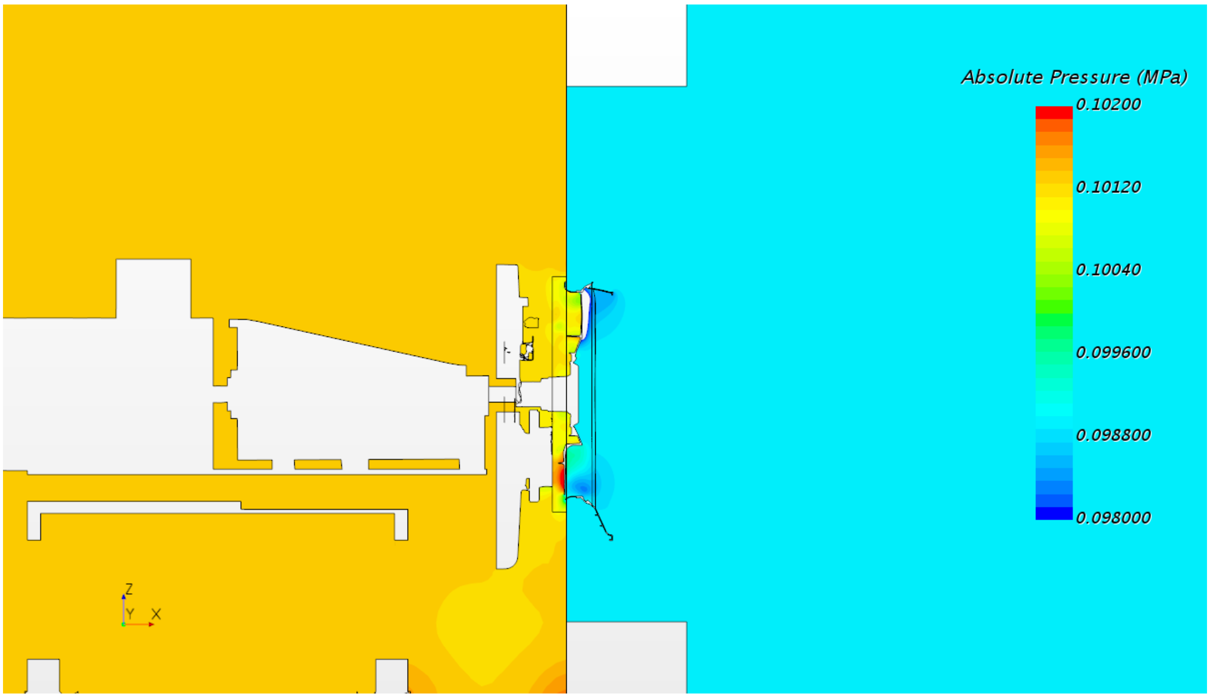


Figure 28: Illustration of the pressure rise over the Reference fan.

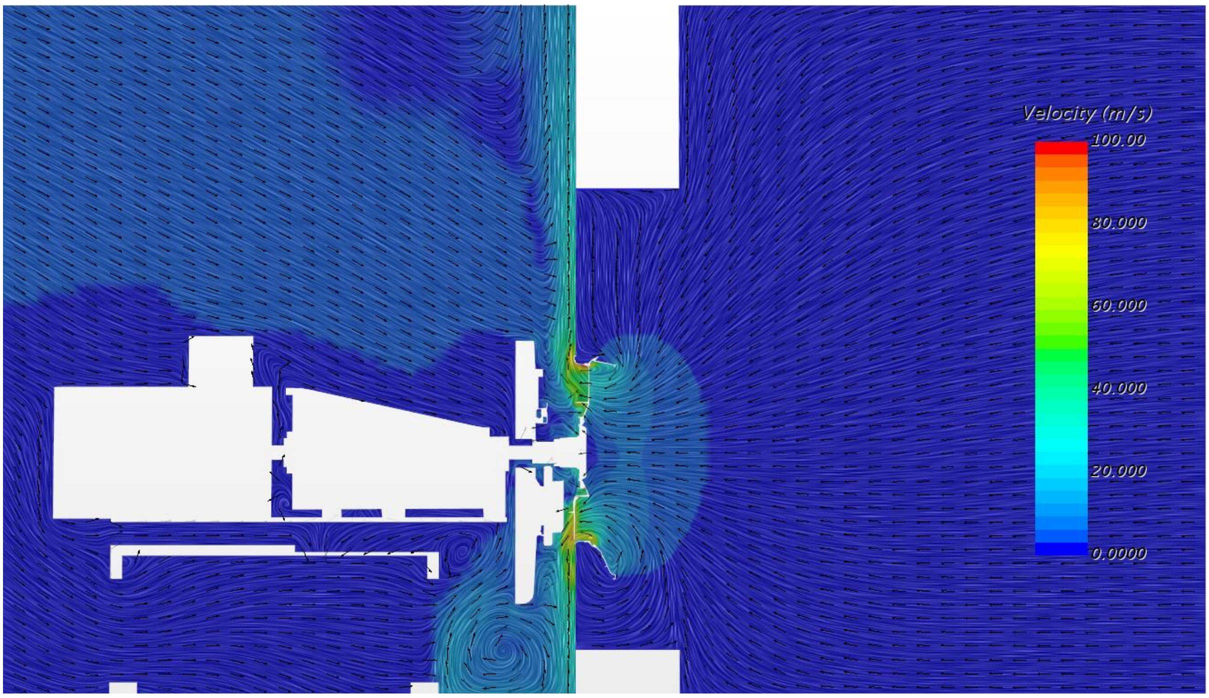


Figure 29: Picture of the velocity of the air around the Reference fan.

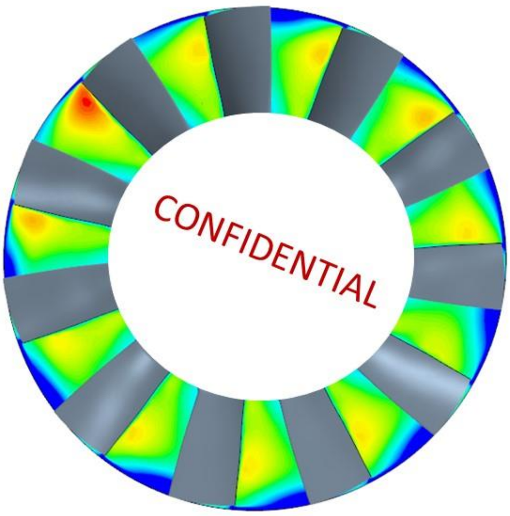


Figure 30: Illustration of the back flow of the Reference Fan. The blue area illustrates the backflow.

Appendix O - Results of the Final Concept

Results of the Final Concept from the simulations at 6 m^3/s, shown in Figures 29-32.

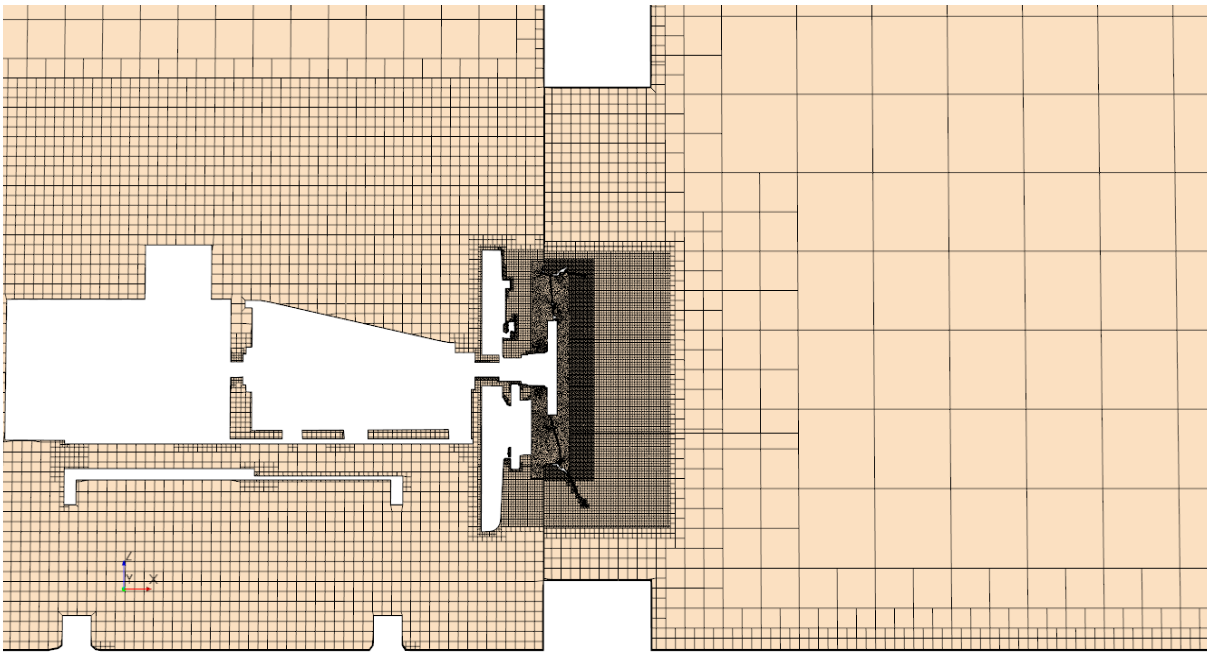


Figure 31: Picture of the volume mesh around the fan for the Final Concept.

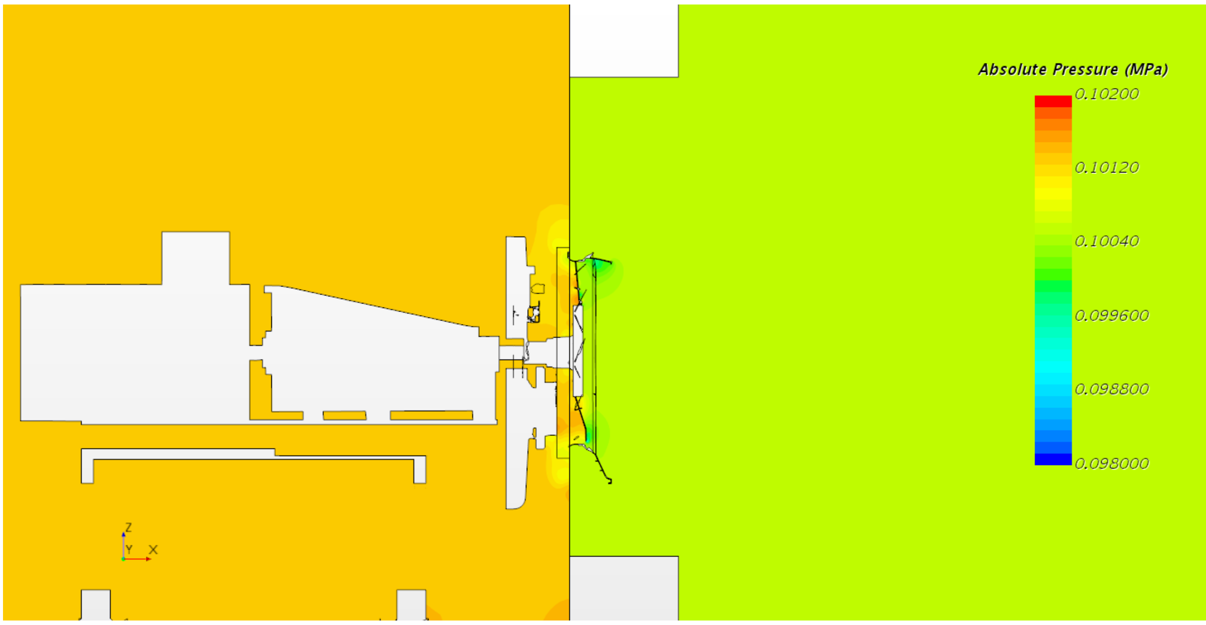


Figure 32: Figure 30: Illustration of the pressure rise over the Final Concept.

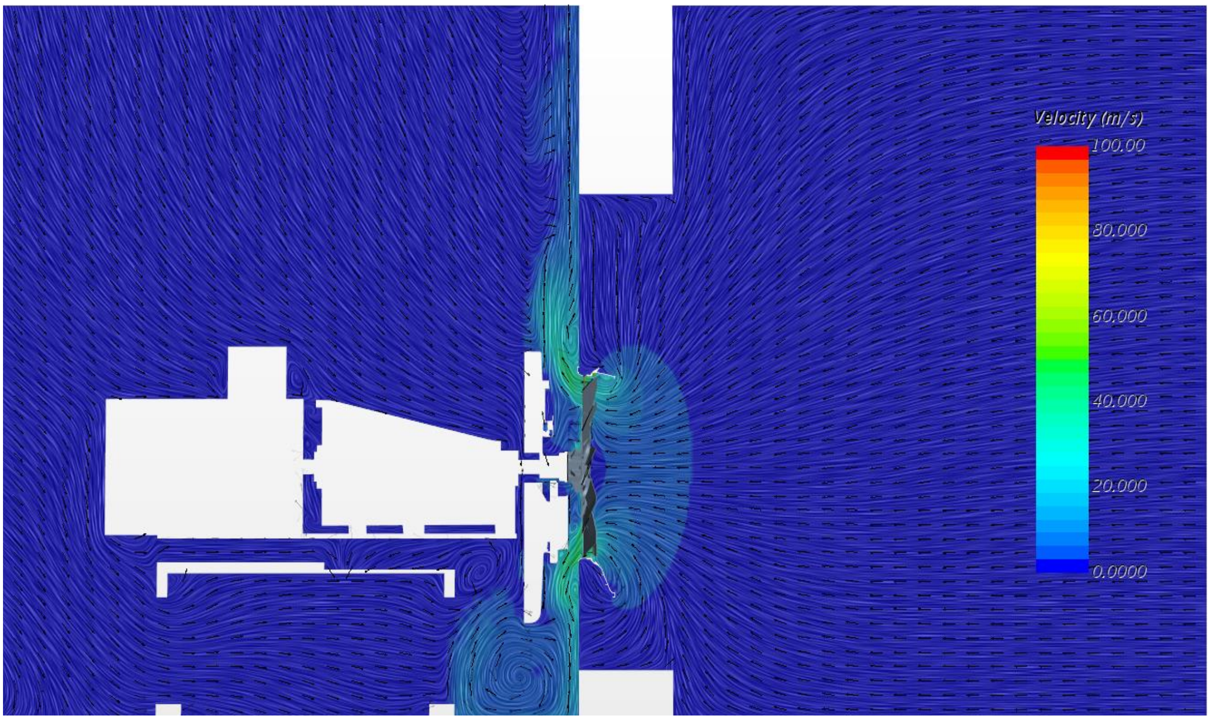


Figure 33: Picture of the velocity of the air around the Final Concept.

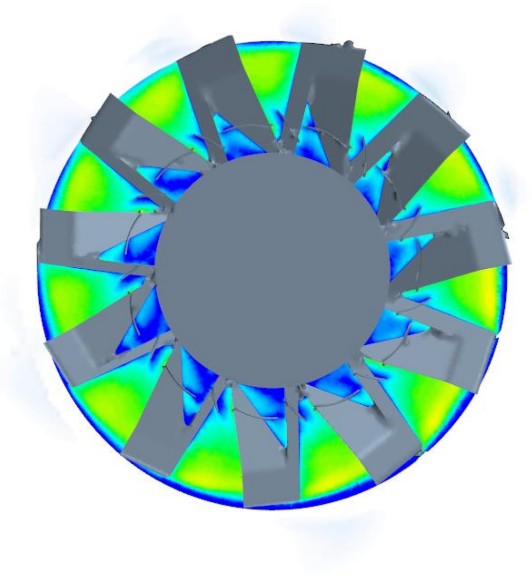


Figure 34: Picture of the back flow of the Final Concept. The blue area illustrates air flowing the wrong way.

Appendix P - Results of the Comparison Concept

Results of the Comparison concept from the simulations at 6 m^3/s, see Figures 33-36.

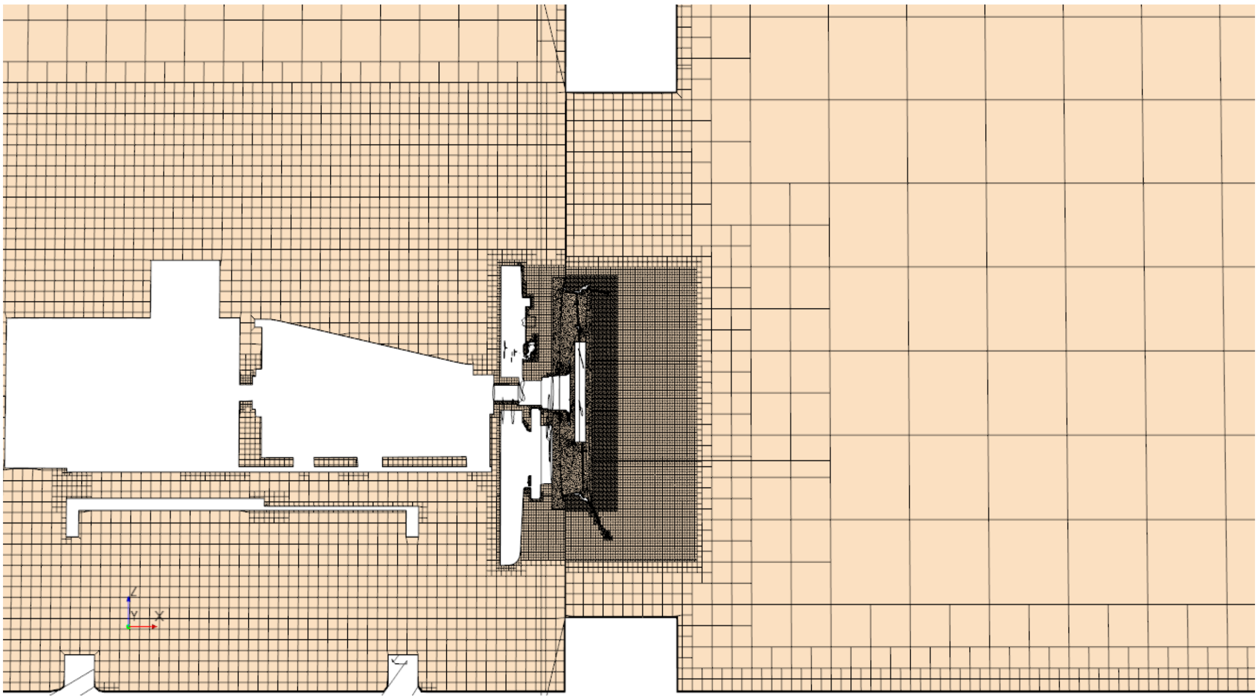


Figure 35: Picture of the volume mesh around the fan for the Comparison Concept.

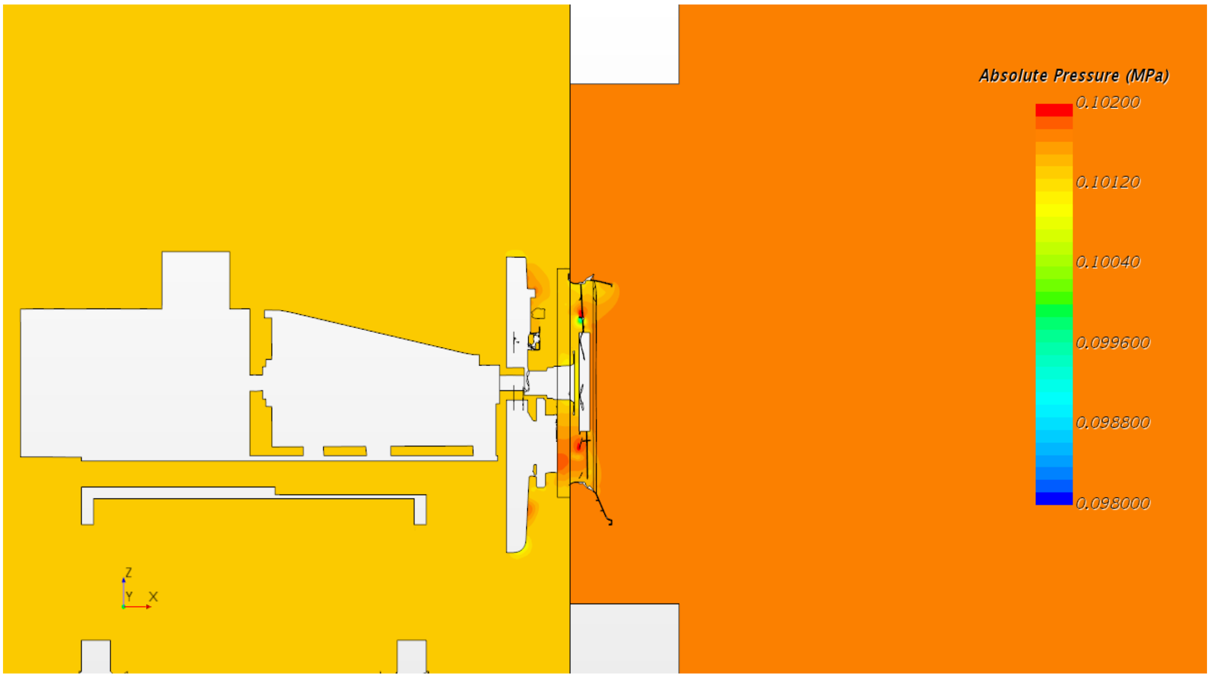


Figure 36: Illustration of the pressure rise over the Comparison Concept. In this case the pressure rise is negative.

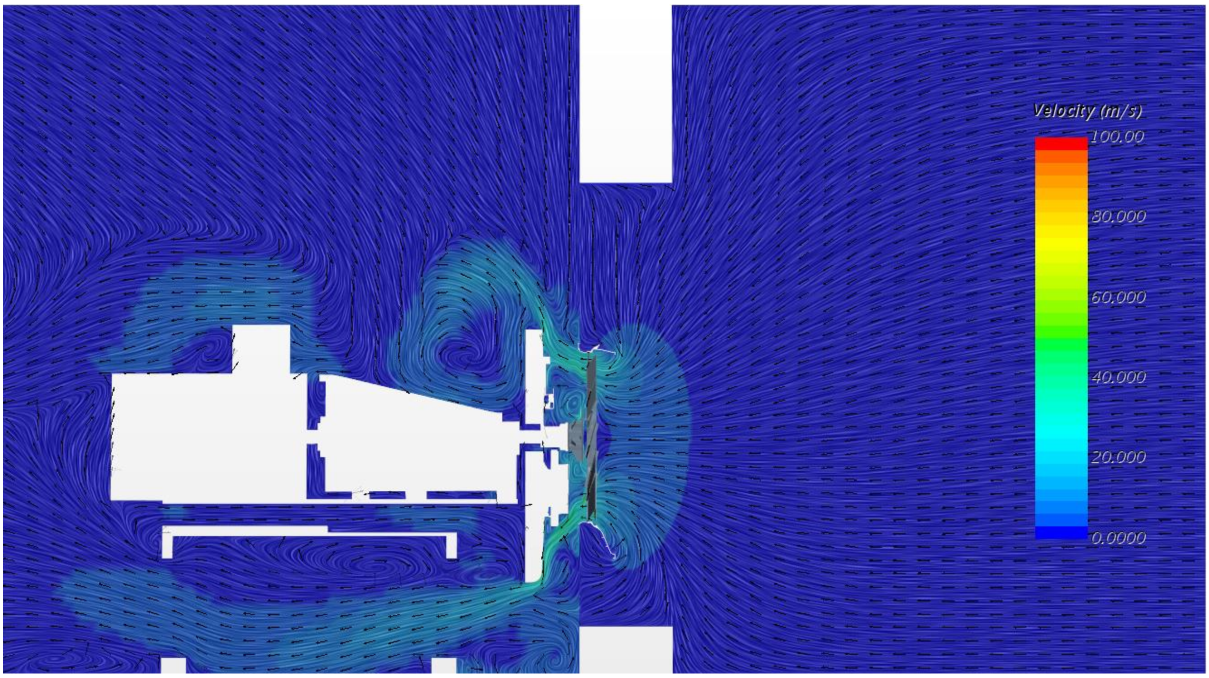


Figure 37: Illustration of the velocity of the air around the Comparing Concept.

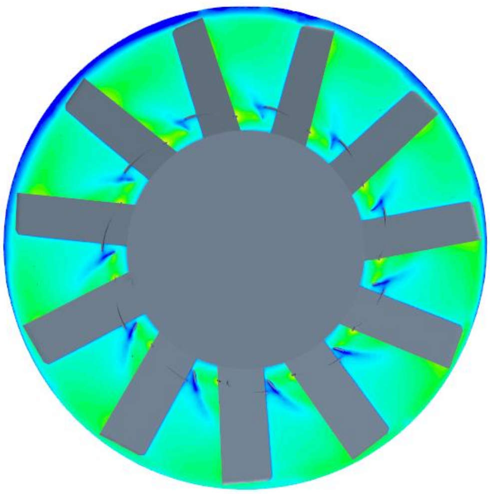


Figure 38: Picture of the back flow of the Comparison concept, the blue area illustrates air flowing the wrong way.

Contribution Report

The contribution report illustrates the work distribution within the project. The report is a combination of both the implementation and the writing.

- Abstract, Acknowledgement and Nomenclature made by Mikaela.
- Introduction was made in the beginning of the project as a joint effort.
- Team and project management was made as joint effort in the section Project Management and Risk Plan and Safety. Ethics Statement was made by Ben and the Environmental Statement was made by the Chalmers Students. The Gantt Chart was made by Mikaela.
- Patent research about the Divided Fan Blade and the Split Blade Radial Fan were both made by Vilma.
- Research about the existing products axial fan, radial fan and diagonal fan were all executed by Vilma.
- Customer need assessment was made by Erica.
- The AHP was made by Erica and Mikaela.
- Engineering specification was executed by Mikaela.
- Concept Development and evaluation
  - Engine Theory was made by Jordan.
  - Black box was made by Mikaela.
  - Sub-function diagram was made by Erica.
  - Important parameters were produced by the Chalmers students.
  - Design of Experiment was made by Erica and configured by Mikaela and Vilma.
  - Optimal attack angle calculated by Vilma and configured by Erica.
  - Concepts were developed by the students at Chalmers.
  - Final- and Comparison concept was developed by the Chalmers students.
- Concept refinement and simulations
  - CAD-drawings were all made by Jordan.
  - Mesh in ANSA was executed by Vilma.
  - FE-analyses in SolidWorks was made by Ashleigh.
  - Blades Cut Out in ANSA made by Vilma.
  - FE-analyses of the Final Concept in ANSYS was made by Mikaela.
  - Simulations in Star CCM+ were executed by Vilma and Erica.
  - Scenes and pictures in Star CCM+ was made by Erica.
  - Plots and comparison of the concepts was made by Erica.
  - Compilation of the results was compiled by Erica and Vilma.
  - Power Input, Power Usage and Efficiency calculated by Vilma and Erica
  - Sending jobs to HEBBE was done by Vilma and Erica.
  - Evaluation of Concept 1-8, the reference fan, the Final Concept and the Comparison Concept was done by Erica and Vilma
- Detailed design of the concept, such as cost analysis and material selection in CES was made by Mikaela.

- Manufacturing plan and CAD drawing of the Final Concept was done by Erica
- Final discussion
    - Methodology was written by Vilma.
    - Sources of errors was made by Erica, Vilma and Ashleigh.
    - Project achievement was executed by Vilma.
    - Fulfilment of objectives was made by Vilma.
    - Fulfilment of purpose was made by Vilma.
    - International collaboration was made by Erica.
- Future Work was made by Vilma.
- Conclusion was made by Erica.
- Self-assessment: The Customer Needs Assessment was made by Vilma and the Global and Societal Needs Assessment was made by Mikaela.
- Recommendations was made by Erica.
- Report appearance, structure and layout was fixed by Mikaela.
- The introductions to each chapter and section was made by Mikaela.
- Remaining figures and tables done by Mikaela.