Investigation and Development of a Centrifugal Pump for Dishwashers

Master of Science Thesis in the Master Degree Programmes, Product Development and Applied Mechanics

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2012-06-14

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Cover:
Impeller and volute of a centrifugal pump used in dishwashers manufactured by Asko Appliances
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Abstract

Investigation and Development of a Centrifugal Pump for Dishwashers

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For costs reasons, Asko Appliances decided to change their sub-contractor of centrifugal pumps. With the new pumps installed, tests of the dishwashers showed a decrease in wash performance even though the parameter values of the tests were the same (pressure, flow, temperature etc.). At that point interest was put into the actual design of the pump, not only due to its efficiency, but also its wash performance.

The purpose of this project is to find out parameters that affect the wash performance of a dishwasher and not only the efficiency of the pump. The project also aims to develop a pump that increases the wash performance for the dishwasher in comparison to the one Asko Appliances is using today.

The study used a product development approach where concepts were generated and eliminated in a systematical way. Simulations were used to find out the concept's turbulence and efficiency to make preferable assumptions in the elimination process.

Three prototypes were manufactured through rapid prototyping and tested at Asko Appliance's test laboratory, to find out their wash performance. They were chosen to represent a majority of the concepts due to their design and properties. This was a part of the elimination process and the result was analyzed and supposed to be applied on concepts with similar designs and properties. Due to time limits only one of the prototypes was tested and analyzed. The prototype that was tested was the one that generated the lowest turbulence in the pump.

The tests showed that turbulence in the pump has a mayor impact on wash performance. The concept returning a low turbulence in the pump resulted in an increase of wash performance in the dishwasher. Tests also showed a decrease in efficiency of the pump for this prototype.

The use of a product development approach, together with CFD simulations, was a good way of attacking this kind of problem.

keywords centrifugal pump, wash performance, efficiency, dishwasher, product development, simulations, turbulence, elimination process, rapid prototyping

Acknowledgements

This report, *Investigation and Development of a Centrifugal Pump for Dishwashers*, is written as a Master's thesis during the spring of 2012. It is the final project for the MSc program of Product Development and Applied Mechanics at Chalmers University of Technology. This thesis is collaboration between Chalmers University of Technology and Asko Appliances.

The project is intended to help developing centrifugal pumps for the dishwasher industry. Both by recommendations of changes and improvements and areas where more research would be appropriate.

We would like to thank Chalmers University of Technology and the company Asko Appliances for letting this project happened. Both regarding the financial, - and support aspect.

We would like to thank our supervisors:
Patrik Ivarsson (PhD), Asko Appliances (the promoter of the project).
Anders Forslund (PhD Student), Chalmers University of Technology.

Without their help and support, this project could not been done.

We would also like to thank the examiner of this MSc thesis:
Lars Lindkvist (Docent), Chalmers University of Technology.

One last thank we would give to the opponents of this report
Gustav Andtbacka (Student), Chalmers University of Technology.
Niklas Dyverfors (Student), Chalmers University of Technology.

for their work with reading this report and adding valuable information.

Gothenburg June 2012
Rickard Dahl & Robin Höstman

Nomenclature

C_r	Radial absolute velocity
C_t	Circumferential absolute velocity
C_z	Axial absolute velocity
W_r	Radial relative velocity
W_t	Circumferential relative velocity
W_z	Axial relative velocity
U	Rotational velocity
r	Impeller radius
ω	Angular velocity
C_m	Meridional absolute velocity
W_m	Meridional relative velocity
Q	Mass flow
P	Power
g	Earth acceleration
ρ	Density
H_{th}	Theoretical head
β_{F2}	Local flow angle
L	Distance from leading edge
δ	Boundary layer thickness
μ	Dynamic viscosity
ν	Kinematic viscosity
α	Constant in boundary layer thickness calculation
S_{Mx}	Source term in the x-momentum equation
S_{My}	Source term in the y-momentum equation
S_{Mz}	Source term in the z-momentum equation
$\mathbf{u}$	Velocity vector
u	x-component of the velocity vector
v	y-component of the velocity vector
w	z-component of the velocity vector
p	Pressure (normal stress)
i	Sum of internal energy
T	Temperature
k	Conductivity
Φ	Dissipation function
ϕ	General variable
S_ϕ	Source term in general transport equation
Γ	General variable
$\mathbf{n}$	Position vector
P	Node of interest
W	Node to the west
E	Node to the east
T_E	Temperature in the east node
T_W	Temperature in the west node
Δx	Length of a cell, in the x-direction
δx_e	Distance between node P and E
δx_w	Distance between node W and P
k_e	Heat conductivity at the east wall
f_x	Heat conductivity factor at cell wall
a_E	Variable for the east node in discretized equation
a_W	Variable for the west node in discretized equation
a_P	Variable for the current node in discretized equation
S_U	Source term in discretized equation

R	Residual
ϵ	Convergence criterion residual
U	Instantaneous velocity
$\overline{U}$	Mean velocity
u	Fluctuating velocity
τ_{tot}	Total stress
μ_t	Turbulent viscosity
k	Turbulent kinetic energy
ϵ	Viscous dissipation of the turbulence
σ_k	Adjustable constant in k-ϵ model
σ_ϵ	Adjustable constant in k-ϵ model
$C_{1\epsilon}$	Adjustable constant in k-ϵ model
$C_{2\epsilon}$	Adjustable constant in k-ϵ model
μ_l	Empirical constant in k-ϵ model
μ_t	Eddy viscosity
S_{ij}	Mean component of the rate of deformation
ω	Turbulent frequency
σ_k	Model constant in k-ω model
σ_ω	Model constant in k-ω model
β^*	Model constant in k-ω model
γ_1	Model constant in k-ω model
β_1	Model constant in k-ω model
P_k	Rate of production of turbulent kinetic energy
σ_k	Revised constant in SST k-ω model
$\sigma_{\omega,1}$	Revised constant in SST k-ω model
$\sigma_{\omega,2}$	Revised constant in SST k-ω model
γ_2	Revised constant in SST k-ω model
β_2	Revised constant in SST k-ω model
β^*	Revised constant in SST k-ω model
U_i	Normalizing velocity
δ_{ij}	Kronecker delta
I	Turbulence intensity
u'	Root-mean-square value of the turbulent velocity fluctuations
U	Reynolds average mean velocity
d_h	Hydraulic diameter
d	Diameter
ΔP	Operating pressure
Δh	Height difference between pump and strainer

Abbreviations

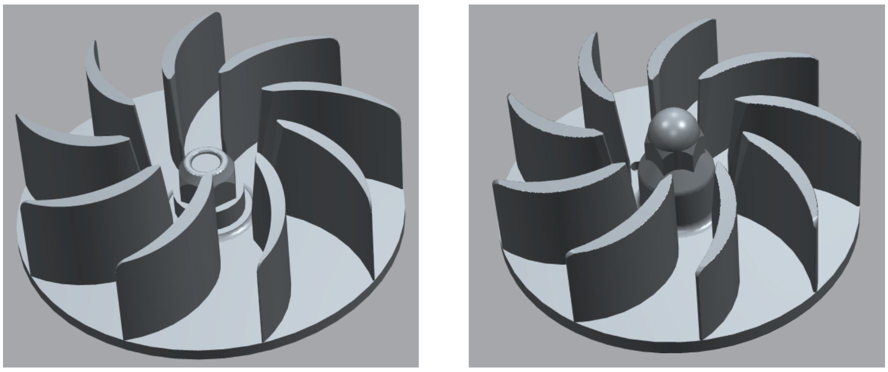
CFD	Computational Fluid Dynamics
FVM	Finite Volume method
Re	Reynolds number
PDE	Partial Differential Equation
CAD	Computer Aided Design
MRF	Multiple Reference Frame
SRF	Single Reference Frame
QUICK	Quadratic Upwind Interpolation for Convective Kinematics
SST	Shear Stress Transport

Contents

1 Introduction

1.1 Background

For cost reasons, Asko Appliances decided to change sub-contractor of centrifugal pumps, when developing their latest dishwasher model. Unfortunately the change of subcontractor resulted in a 10% decrease in wash performance. Further investigation showed a difference in the impeller eye, located at the centre of the impeller; the new subcontractor had a much lower impeller eye installed compared to the old one (see Figure 1). Letting the new sub-contractor manufacture an impeller with similar dimensions as the old one, resulted in equal wash performance as the old pump. No more investigation why the impeller eye is crucial has been done. Therefore it is possible to gain knowledge about the problem and also come to conclusion why the impeller eye is so crucial. By gaining this knowledge even better modifications can be made on the impeller eye in purpose to increase the wash performance of the dishwasher.



(a) (b)

Figure 1: Comparison between the lower impeller eye (a) and the impeller eye that return a better wash performance (b).

Centrifugal pumps uses the centrifugal force on the fluid to built up a pressure difference between the inlet and outlet of the pump to set the liquid in motion. These sorts of pumps are widely used in the dishwashing industry today. The design of the impeller of the pumps affects its outputs (pressure, turbulence etc.). It will further more affect the wash performance of the dishwashers. A poor design can result in small particles occurring in the reused water that is pumping around in the dishwasher. In order to obtain the water pressure and water flow required, and to minimize the number of particles in the water, it is of big importance to design the impeller and its belonging volute in a proper way.

1.2 Purpose

The purpose of this project is to investigate what impact an impeller and its surrounding volute, of a centrifugal pump, has on the wash performance in a dishwasher. Therefore a deeper understanding of which parameters affect the wash performance need to be obtained. The main aim for this project is to develop a centrifugal pump, which performs better regarding wash performance, than the pump used today. The project was accomplished during the spring of 2012.

To enable this, a number of sub-goals were accomplished. The project aims to define a methodology, which will help Asko Appliances to evaluate and analyze the performance of their centrifugal pumps. This will be done by enabling an evaluation structure using a product development approach and by enabling the use of CFD simulations. The project also aims to manufacture prototypes, which will be tested at Asko Appliance's test laboratory, against wash performance under European standards.

By improving the wash performance, Asko Appliances will increase product quality and customer satisfaction. It will benefit their development towards different standards, which they are working towards today, and therefore also result in a more environmentally friendly product.

1.3 Method

The project is a collaboration between the Master's programs, Product Development and Applied Mechanics. Therefore the project will have a product development approach and calculations, especially simulations, will be highlighted and used as a tool during the product development process.

A product development approach can often be visualized as a funnel. In the beginning of the process the funnel is wide and tools are used to generate as many concepts as possible. A pilot study and interviews will be used for this purpose. The pilot study consists of reading and analyzing articles about pumps, and going through test data of different impeller designs. Interviews will be held with experts in different fields at Asko Appliances.

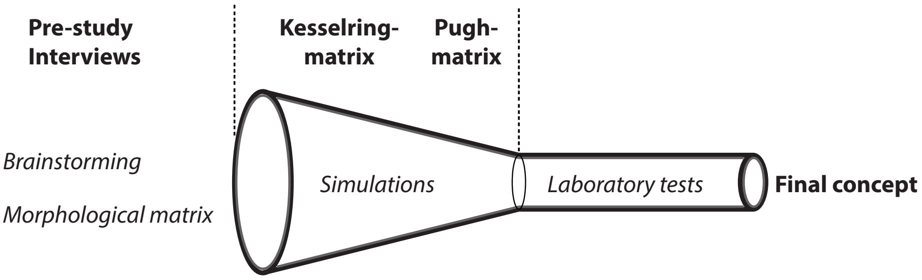


Figure 2: Visualization of a Product Development approach, funnel design.

The eliminations matrices, Pugh and Kesselring, will be used to narrow the funnel down. To be able to make proper decisions in the matrices, simulations and tests in Asko Appliance's test laboratory will be done. Therefore they will be highlighted in this process.

Simulations will be performed to find out the different concept's efficiency and turbulence. The result will then be used in the decisions matrices to make correct assumptions regarding the elimination.

Laboratory tests will be performed on three of the concepts to find out their wash performance in a dishwasher. The concepts will be manufactured by rapid prototyping and the results from the tests will also be used in the decision matrices and applied on concepts with similar designs.

1.4 The scope of the work and limitations

The project is all about finding a centrifugal pump that can produce a better wash performance for the dishwasher, and which parameters that are affecting it. Therefore the pilot study was focused on a literature review instead of mapping the company and its competitors, would be a more typical way of approaching the problem if a traditional product development process was strictly followed [1].

A dishwasher consists of many components which affect its wash performance. In this study the centrifugal pump is going to be defined as the system, not the whole dishwasher. That means that parameters that affects the wash performance are positioned outside the system, e.g. angled pipes and filters, will not be considered.

A lot of modifications can be made on the centrifugal pump to change its properties. Since simulations are time- and data consuming, some limitations were made to narrow the concepts down before the simulations. These limitations can be seen in Chapter 3.4.1. A majority of the modifications were made on the impeller eye.

The simulations was chosen to perform in steady state, which reduces the number of terms in the governing equations and do not demand as much time and computer resources as the transient approach.

The use of MRF (Multiple Reference Frame) when dealing with rotating machinery problems is a restriction due to the fact that it is a so called *frozen rotor* approach. In a frozen rotor approach the computational grid remains fix in time, which limits the accuracy of the result. However it is still a trustworthy method to apply.

The project will use two-equation turbulence models. Even though better models than the two-equation models are provided today, the two-equation turbulence model provides a simple way of setting the turbulence flow in a system.

Due to limitation in cost and time resources only three prototypes were tested at Asko Appliance's laboratory. They were only tested three times in this study and more tests have to be done in order to get an acceptable result. Due to the time limit only one of the prototype tests was analyzed. More tests have to be done and analyzed to get a more accurate result.

1.5 Key results

The project used a product development approach that resulted in a Kesselring matrix with weighted criteria. The Kesselring matrix can be used by Asko Appliances to produce final concepts in the future. More criteria can be added to the matrix and they can be weighted differently due to the company's situation and desire.

The CFD simulations gave important information regarding the concept's efficiency and turbulence. In that way knowledge was gained about the modifications impact on the properties of the pump. This knowledge was used in the decision matrices.

Laboratory tests showed that the wash performance was affected positively by a low turbulence in the pump. To get a good wash performance of the dishwasher, the turbulence has to be kept low. The tests also showed that a low turbulence gave a lower efficiency of the dishwasher, due to power consumption. This is connected to the efficiency of the pump.

2 Theory

2.1 Pre-study

A pre-study contains valuable information about the project and in which way the project is beneficial to proceed. The pre-study will also result in the design requirements for the product [2].

2.1.1 Planning report

In the beginning of projects a planning report is produced and presented to decide how the project should be carried on. Such a report should contain introduction and background, clarification of the issue, the organization of the project and a time plan [3].

2.1.1.1 Clarification of issues To know where the project is suppose to head (the direction) some questions have to be clarified, which the project later on will answer to. This questions are meant to be a driving force through the project and in the final be answered [2]. An example of the questions that were stated in the planning report:

- How will the highest possible wash result be obtained based on the design of the pump?
- Will the result from the project return a dishwasher with better wash performance?
- Would it be a good idea to continue development in this area?

2.1.1.2 Gantt chart A Gantt chart is a tool to present a time plan, which is drawn in a planar coordinate system with the y-axis representing the activity and the x-axis represent the time. The activities are drawn as horizontal lines in the coordinate system and the length of them represent their duration. Also deadlines of hand-ins and meetings can be added to the chart as milestones [2].

2.2 Data collection

In the beginning of a project, a lot of effort is put on gathering information connected to the problem, and then organize it. Two tools for data collection are a literature study and interviews [5].

2.2.1 Literature study

A literature study will provide necessary information about the subject that is to be investigated in the project. It is a small tool to gather information, that later will be used in a larger study, this in order to improve the quality and efficiency of the project. A literature study can reveal information about failures and shortcuts that earlier has been experienced by previous studies and therefore been used with benefits [4]. The tool consists of reading and analyzing literature, e.g. books, articles and theses.

2.2.2 Interviews

Another tool for data collection is interviews. There are two main categories of interviews that can be used to gather data within this tool [5]:

- Question-based method
- Observation-based method

The interviews can be done in many different ways, e.g.

- One-to-one interviews (in-depth interviews)
- Group interviews
- Focus group interviews
- Surveys
- Questionnaires

All these different ways of performing interviews have their pros and cons, but it also depends on the interviewer, interviewee, situation and content. other factors that affects the result from the interview can be the interviewer's social skills, training and experience, motivation and safety, and security. The interviewee's factors that affect the interview are their social skills, ability to answer, willingness to answer, etc. The factors that can affect the situation are time and place, and the factors that affects the content can be factors as sensitivity and complexity [5].

The way of setting up an interview is also important. There are three different way of structure the questions for an interview [5]:

Structured The questions are fully formulated and they are ordered in advance.

Semi-structured The questions are only formulated so that the topic of interest is covered. The order of the questions may vary between interviews.

Unstructured The interviewees are in charge of the interview and the interviewer has a passive role. The questions are not formulated in advance.

To get a good result from the interviews it is also good to imagine the interview as a funnel, where the questions in the beginning covers the complete topic and later on detailed questions are asked so that the detailed topics are covered, which narrows the funnel [5].

2.3 Design requirements

A design requirements list consists of criteria, which the project aims to working towards. It also establishes limits for the project's developing work. It can also be made to formulate criteria and establish different criteria relevance in the elimination process, or just to compile the criteria. Often are the criteria in the design requirement list too many to handle and therefore only some of them will be taken in mind when the project carries on. A signification of the criteria is therefore important to make. It is important to take in mind how the criteria are chosen, grouped, formulated, verified and their meaning [2].

2.4 Concept generation

There are many different ways of generating concepts for a project, e.g. brainstorming, interviewing experts, searches in literature etc. Another tool is the function-means modeling which systematically generates concepts for the project.

2.4.1 Function-means modeling

When applying the function-means model to generate concepts, the function that the concepts will represent first needs to be defined. In that way the main function then can be decomposed into as many sub-functions as possible. The sub-functions will then again be decomposed into sub-sub-functions and this will carry on until no more functions can be found in the hierarchy chart [25].

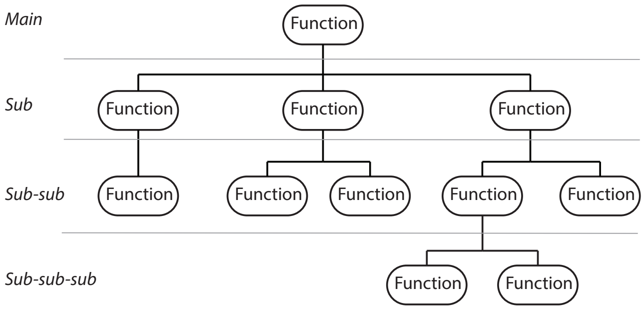


Figure 3: Visualization of a Function-means model

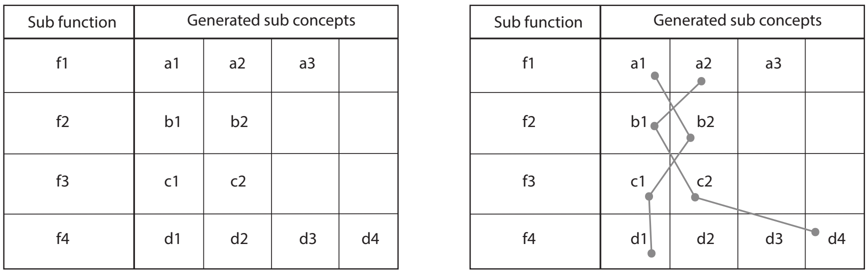
When all the functions are completely decomposed, concepts can be generated to all the functions lowest in the hierarchy chart. With generated concepts to all the functions lowest in the hierarchy, they can now be composed into different main solutions, depending on the assembly. The assembly can be made in many different ways but one common way is by using a Morphological matrix, which ensures that no concepts will be lost, see Chapter 2.4.1.2.

2.4.1.1 Brainstorming A classic method for generating concepts is brainstorming. In a brainstorming session, a group of experts from different fields gather to come up with solution to a given problem. The reason with this exercise is to make the members of the group stimulate each other's creativity by combining and improving each other's ideas. In that way better solutions can be made, compared to people working alone [2].

It is important that the members of the group are well prepared and that the group has a leader when starting the brainstorming. The leader should contribute with new formulations and different angles to address the problems. The session should not be longer than 45-60 minutes. Every member of the brainstorming group must have its time to present and the ideas can not be neglected by anyone [2].

2.4.1.2 Morphological matrix To combine all the generated sub-concepts from the brainstorming, a Morphological matrix can be used. A Morphological matrix systematically goes through all the sub-concepts, and combines them into complete concepts, which returns a maximum number of total concepts that can be obtained from the sub-concepts [2].

An example of a Morphological matrix process can be seen in Figure 4. A Morphological matrix is set up, 4(a), and later a sub-concept is selected from every sub-function and combined to a main concept, 4(b). In the example, two main concepts are created out of 48 possible ($3 \cdot 2 \cdot 2 \cdot 4 = 48$).



(a) (b)

Figure 4: A Morphological matrix process

2.5 Concept elimination

When all the main concepts are generated, tools are needed in order to eliminate concepts. The elimination process should return the concept that is most suitable for fulfilling the main function.

2.5.1 Elimination matrix

The elimination matrix tool is an investigation of whether the concepts

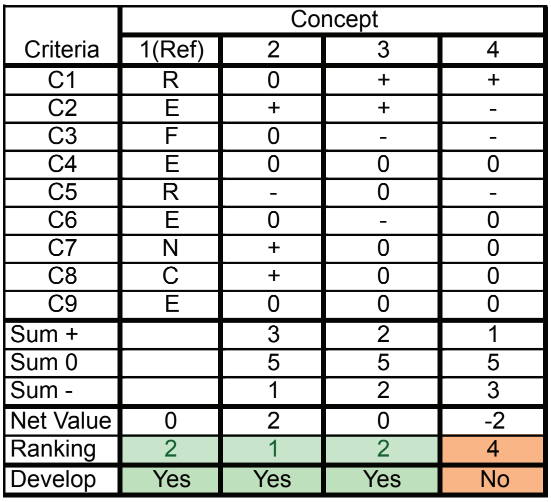
- solves the main function
- fulfills the design requirements
- can be realized in practice
- is within the cost restriction
- is advantageous from an environment-, safety, or ergonomic point of view
- fit in, in the company project program

If the concept does not fulfill all the points, they will be eliminated [2].

2.5.2 Pugh matrix

A Pugh matrix is an elimination-of-concept tool, which compares all the concepts with a reference concept. It does not matter which concept is chosen as the reference but often a well-known concept is chosen, e.g. the solution that is used today, a concept that a lot of analyses and tests have been done on or a competitor's concept.

Furthermore, every concept is compared with the reference concept according to criteria. If the concept is better than the reference it receives a "+", if it is equal to the reference it receives a "0" and if it worse than the reference receives a "−". In the end, all the signs are summed up and the concepts get a rank in comparison to each other. Also, a decision about further development is made at this stage. Sometimes it can be very hard to make a decision with the known data. A second iteration can then be made with another concept as reference [2].



Criteria	Concept			
	1(Ref)	2	3	4
C1	R	0	+	+
C2	E	+	+	-
C3	F	0	-	-
C4	E	0	0	0
C5	R	-	0	-
C6	E	0	-	0
C7	N	+	0	0
C8	C	+	0	0
C9	E	0	0	0
Sum +		3	2	1
Sum 0		5	5	5
Sum -		1	2	3
Net Value	0	2	0	-2
Ranking	2	1	2	4
Develop	Yes	Yes	Yes	No

Figure 5: A Pugh matrix.

2.5.3 Kesselring matrix

Often some criteria affect the solution more than others. Therefore a Kesselring matrix can be good for elimination of concepts. It works similar to the Pugh matrix but the criteria are weighted to generate a more accurate result between the concepts.

Also the concepts can contribute with different values to the criteria (how good/bad they can perform it). Often that will occur when properties can be calculated, measured or assumed and therefore a value list can be defined from the property data. If this is the case, the weighted criteria value will be multiplied by the concept value for that criterion. That will then be added to the concept value. Elimination can then be done from the concept values [2].

Criteria		Concepts							
		Ideal		1(ref)		2		3	
	w	v	t	v	t	v	t	v	t
C1	2	5	10	2	4	4	8	3	6
C2	4	5	20	3	12	3	12	4	16
C3	5	5	25	2	10	4	20	5	25
C4	3	5	15	2	6	1	3	5	15
C5	1	5	5	3	3	5	5	3	3
C6	5	5	25	2	10	5	25	4	20
C7	4	5	20	3	12	3	12	4	16
C8	3	5	15	4	12	4	12	5	15
Sum T		135		69		97		116	
T/Tmax		1		0,51		0,72		0,86	
Rank		-		3		2		1	

Figure 6: A Kesselring matrix with weighted criteria and concept values.

2.6 Simulations

Fluid simulation, based on computational simulation using the Computational Fluid Dynamics (CFD) method, is a tool to analyze and predict the reality of systems containing fluid flow, heat transfer and similar phenomena [9]. Simulations are also performed in other areas, e.g. in structures using the Finite Element Method (FEM), but since only fluid flow is concerned in this project only the CFD method will be described in a deeper manner.

The CFD method is applied in order to solve the governing equations of the case. The governing equations govern the physical parameters of the flow, and by solving them, their behavior can be analyzed. Solving of the governing equations can be done manually without the use of computers, but when applying CFD it results in heavy calculations, why the use of computers are needed [11]. The CFD method is used in a number of different software, e.g. ANSYS Workbench (which provides Fluent and CFX), MATLAB, Abaqus, OpenFOAM. The theory concerning general information of the centrifugal pump, the CFD method and the computational modeling is described in the following chapter. A theoretical base for the centrifugal pump, relying on the general centrifugal pump theory, are definedand described in the following chapter.

2.6.1 Centrifugal pump information

2.6.1.1 Pumps in general Pumps are used in many applications in the society today, e.g. water supply, air conditioning systems and dishwashers. Even though the applications are well separated from each other they are all using the pumps in a similar way; moving fluids that are either returning a physical or mechanical action. The pumps can be divided into three different categories; direct lift, displacement, and gravity pumps [15].

This study has focused on centrifugal pumps that are rotordynamic and converts electrical energy from the motor to an increase of pressure of the fluid through the impellers. The fluid flows from the inlet of the impeller center and out along its blades. The centrifugal force hereby increases the fluid velocity and consequently also the kinetic energy is transformed to pressure [15].

These kinds of pumps are common when moving liquid in pipes. The reason why they are so widely used compared to any other application is because of their advantage in the following factors [16]:

- Its initial cost is low.
- Efficiency is high.
- Discharge is a uniform and continuous flow.
- Installation and maintenance is easy.
- It can run at high speeds without the risk of separation of flow.

The efficiency of a pump is determined by the ratio of the pumps fluid power to the pump shaft horsepower. Therefore the best efficiency point can be found in a head/flow curve. At this point the pump operates most cost-effectively both in terms of energy efficiency and maintenance considerations [15].

The efficiency of a centrifugal pump depends upon the losses in the system such as hydraulic-, disk friction, mechanical- and leakage losses, but also the atmospheric pressure, the gauge pressures in the suction tank, the vapor pressure of the pumped fluid and the static liquid level height [16], [17]. More information about this can be found in the Chapter 2.6.1.5 and 2.6.1.6.

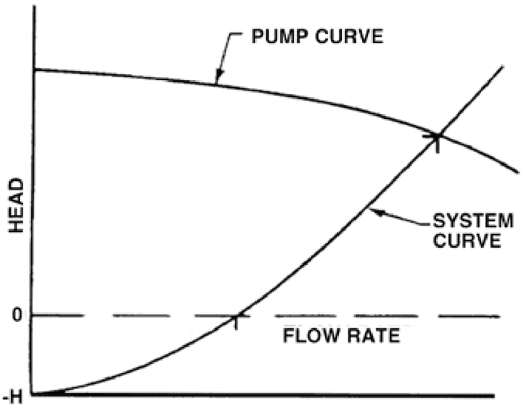


Figure 7: A typical head/flow curve. The efficiency of the pump decreases with an increase of the flow. An intersection of the curves can be found as the optimal working speed [26].

2.6.1.2 Impeller "The rotating impeller imparts energy to the fluid. It is the most important, the only rotating element of the pump" [6]. Tuszon describes carefully, in his book "Centrifugal pump design" [6], what an impeller is. An impeller consists of radial flow passages, formed by rotating blades organized in a circle, in order to impart energy to the fluid [6] [18]. Except the

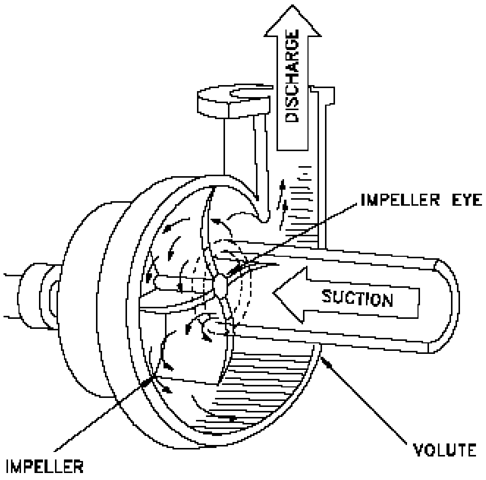
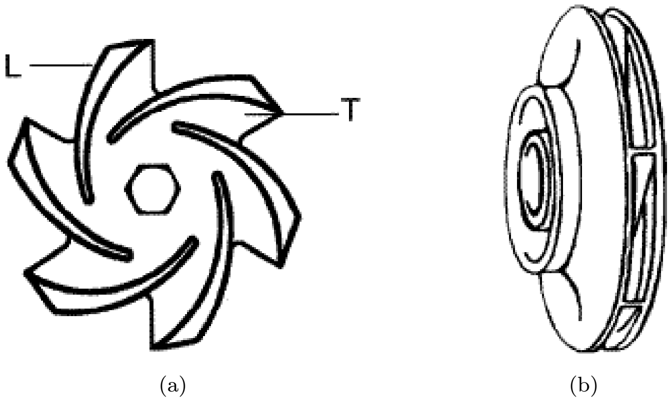


Figure 8: Illustration of a centrifugal pump, impeller and volute with a radial inlet [20].

blades, it consists of one disk (hub), which connects the impeller assembly to the shaft. If it is a closed impeller it consists of another disk too, the shroud, which covers the blades on top, see Figure 9. The flow enters the impeller in the axial direction, near the center of rotation, and turns into the radial direction inside the impeller [6].



(a) (b)

Figure 9: An open impeller (a) and a closed impeller (b) [21].

There are three kind of blade designs; forward, radial (straight) and backward and by varying the design, the number of blades used and the rotating speed, the flow characteristics of the pump can be investigated. By testing five different types of impeller designs in water, the number of impeller blades, the design of the blade profiles and the rotational speed have great impact on the flow characteristics [19].

An increased number of blades are positive in order to reduce vortexes and re-circulations between the blades, and therefore improving the performance of the pump. Of the three kinds of blade designs, the forward and straight blade designs show better performance than the backward blade design [19].

As mentioned above, the blades add energy to the fluid and direct it to the discharge nozzle [21]. A big difference between open and closed impeller is their way of preventing recirculating fluid. The open impeller requires a close gap between the blades and the pump volute, while the design of the close impeller already restricts the amount of fluid recirculating [21].

Trimming, a design method which redesigns the impeller by trimming its diameter, should be limited to about 75% of the pump's maximum impeller diameter, since an excessive trimming can result in a mismatch between the impeller and casing [22]. When decreasing the impeller diameter, the clearance between the impeller and casing increase, which can result in increased re-circulations of the fluid, causing head loss leading to a lower pump efficiency [22].

It is common to describe the flow conditions, velocities and pressures in the impeller in terms of cylindrical coordinates; r, θ and z (radial, circumferential and axial direction) [6].

2.6.1.3 Volute Many things can be done on the volute design to make it more efficient and thereby decrease the losses. The volute throat area is a geometrical parameter that affects the efficiency of the pump. By widening the throat area the flow has to increase through the system to maintain the best efficiency point [23].

Research has also been done on the cross-section area design of the volute. The research contained the four most common shapes; round, horseshoe, trapezoid and rectangular. The round shape is the most appropriate shape when it comes to efficiency [23]. It has also been indicated through CFD simulations that the volute spiral development areas designed according to the constant swirl rule has the highest efficiency. This investigation was made with a round cross-section area [23].

The radial distance between the impeller and the volute tongue can be a critical parameter in pump design. One optimal radial gap can be found due to efficiency. With a small gap the efficiency will be higher but that will decrease the pump vibration characteristic and cause cavitation near the volute tongue, which is explained deeper in the Chapter 2.6.1.5. The opposite will happen when the gap is increasing [23].

2.6.1.4 Impeller eye An impeller eye is the part of the impeller that is located in the centre of it. The inlet flow of the fluid is hitting the eye before it is divided into the impeller blades. The design parameters can be crucial, especially when it comes to efficiency. Research has been made, resulting in that the overall pump efficiency can be increased just by projecting the edges of the blades into the impeller eye [24].

2.6.1.5 Cavitation Losses often occur because of a bad impeller design. One big loss is cavitation, which is a state were the fluid goes from liquid to vapor. It creates cavities which look like bubbles in the fluid. This occurs when the pressure of the fluid locally drops under the vapor pressure so that the fluid starts boiling. These bubbles move from the low-pressure areas, the inlet, to high pressure areas, impeller blade edges were they collapse due to the high pressure. This is a big loss and in the worst case scenario it can also harm the impeller [17].

2.6.1.6 NPSH To avoid cavitation the design of the pump need to consider NPSH, net positive suction head, which is the pressure at the inlet of the pump. To avoid cavitation the available pressure at the inlet (NPSHa) must be larger than the required pressure at the inlet (NPSHr) [17].

There are a several ways to make sure that the NPSHa is greater than NPSHr. NPSHa can be calculated as:

$$NPSH_a = h_{atm} + h_p + h_{el} + h_f + h_{vp} \tag{1}$$

Where h_{atm} is the atmospheric pressure, h_p is the gauge pressure in the suction pump, h_{el} is the static liquid limit height, h_f is the friction/exit/entrance/all losses incurred in the suction line and h_{vp} is the vapor pressure of the pumped fluid determined at the pumping temperature, see Figure 10 [17]. By changing the design of the pump an appropriate NPSH can be created.

These energies are not only the things that can be changed to affect the NPSH. By increasing the ratio of the eye diameter to equal the peripheral diameter the NPSHr typically decreases [18].

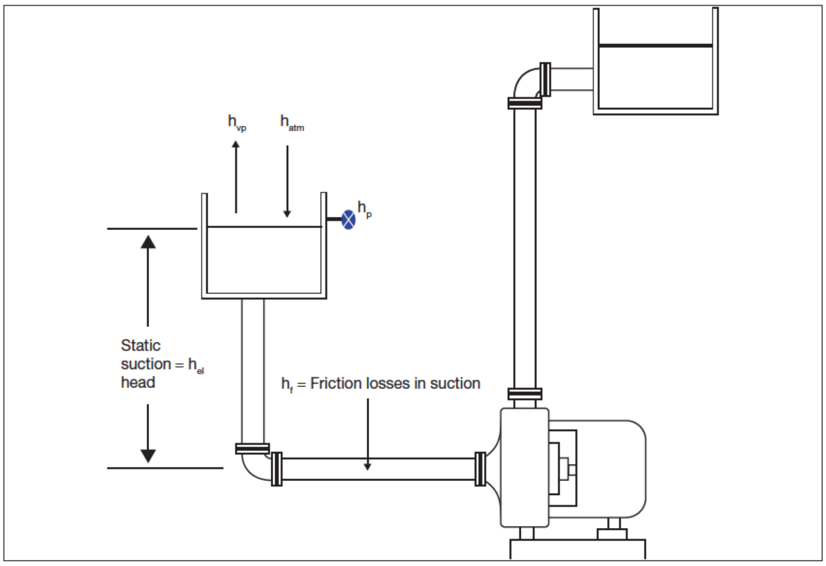


Figure 10: Illustration of a pump, [17].

2.6.2 Physical model of the pump

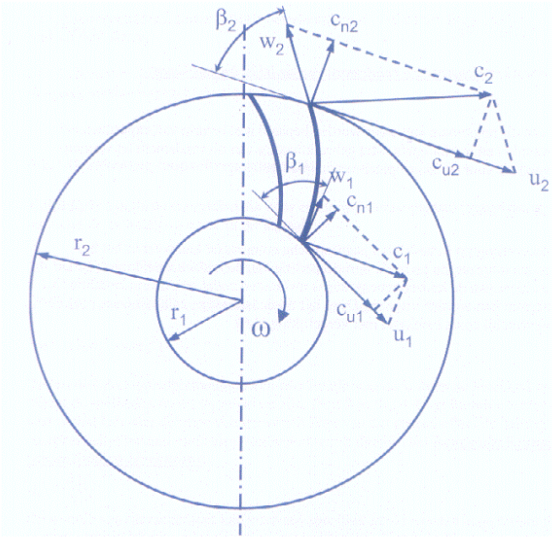


Figure 11: Figure describing the velocity triangles of the flow in the impeller [7].

Quantities of the velocity in a impeller is denoted as [6]

- Absolute velocity components of the fluid C_r, C_t and C_z
- Velocities relative to the impeller W_r,W_t and W_z
- The rotational velocity $U = \omega r$

Velocity along streamlines in the rz-plane is named the meridional velocity C_m, which depends on both the radial variable r and the axial variable z. The meridional velocity component is the same for both absolute and relative velocity ($C_m = W_m$)

It is possible to determine the absolute velocity (C) as the sum of the relative velocity (W) with respect to the impeller (the tangential velocity of the impeller (U)), for fluid flowing through an impeller. These velocity vectors are added through vector addition, forming velocity triangles at the in- and outlet of the impeller. The relative and absolute velocity is the same in the stationary part of the pump.

An important characteristic when dealing with pumps is the head that the pump generates. The head is a magnitude that is measured in length (often in meters [m]) and can be seen as a bar of water that the pump manages to generate. The higher bar the better is the pump. In order to find an expression for the head, other magnitudes need to be defined. The applied torque equals the difference in angular momentum entering and leaving the impeller, due to conservation of angular momentum $\rho C_t r$.

$$T = Q(\rho C_{t2} r_2 - \rho C_{t1} r_1) \tag{2}$$

The power that the pump deliver can therefore be defined as

$$P = T\omega = \rho Q H_{th} g \tag{3}$$

Where H_{th} is the theoretical head, defined as

$$H_{th} = \frac{(C_{t2}r_2 - C_{t1}r_1)\omega}{g} \tag{4}$$

This is known as Euler's equation, which describes the impellers head at tangential and absolute velocities in inlet and outlet.

Using the velocity triangle (see Figure 11), it can be seen that the circumferential component of the absolute velocity (C_{t2}) can be expressed as a function of the radial velocity component C_{r2}, and the local flow angle β_{F2}. The local flow angle is measured from the radial direction in the opposite direction to the flow direction of rotation.

$$C_{t2} = U_2 - W_{t2} = U_2 - W_{r2}\tan(\beta_{F2}) \tag{5}$$

As a consequence of this, the theoretical head can be written as

$$H_{th} = \frac{U_2 C_{t2}}{g} = \frac{U_2^2 - U_2}{g} U_2 - W_{t2} = U_2 - W_{r2}\tan(\beta_{F2}) \tag{6}$$

Note that the negative sign appears since the relative velocity W_{r2} points in the direction opposite to the direction of rotation. It is important to mention that evaluation of the head has not been considered in the simulations, since there is no changes in the motor power (using the same motor as before).

2.6.2.1 Boundary Layer thickness When estimating the boundary layer thickness a dimensional analysis is useful. A dimensional analysis is performed by combining specific values of the variables affecting the boundary layer and divides them into dimensionless groups and define dimensional relationships between them. The boundary layer thickness depends on a number of magnitudes and the following can be said [6],

- Distance from leading edge is defined as L (the beginning of the wall).
- It is reasonable to say that the thickness will increase from the leading edge.
- It depends on viscous and inertia forces acting on the fluid.
- The dynamic viscosity μ (force·time/length^2) and the density ρ (force·time^2/length^4) corresponds to the forces in the fluid.

Using this, the boundary layer thickness δ is found in Equation (7) (where the kinematic viscosity is defined as $\nu = \mu/\rho$).

$$\frac{\delta}{L} \alpha \frac{LU}{\nu} = Re \tag{7}$$

Analytical solution for turbulent flow

$$\frac{\delta}{L} = 0.37(\frac{LU}{\nu})^{-1/5} = 0.37Re^{-1/5} \tag{8}$$

The Reynolds number defines the ratio between the inertia and viscous forces acting on the fluid. It is therefore an important measure of the relative importance them between [6]. By clarifying this it is seen that the inertia forces are dominant when experience high Reynolds number.

$$Re = \frac{inertiaforce}{viscousforce} = \frac{\rho V^2}{\mu V/L} = \frac{\rho VL}{\mu} = \frac{VL}{\nu} \tag{9}$$

Where V is the free stream velocity of the fluid, L is the characteristic distance (in this case the pipe diameter) and ρ and μ are fluid properties, density and dynamic viscosity respectively [6].

2.6.3 Governing equations

Flow characteristics of a fluid are described by five partial differential equations (PDE), together forming a system of PDE's. The equations are mass conservation (continuity), x-, y- and z-momentum equations and energy equation [9] and are written in Equation (10)-(14). The equations are together called the Navier-Stokes equations. The equations are derived using the balance principle, i.e. quantity in minus quantity out equal internal generation of the quantity, on a finite volume called control volume [11].

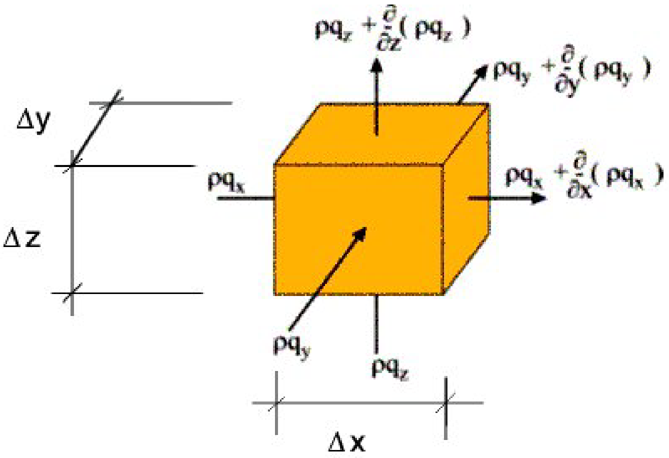


Figure 12: Figure describing a control volume [10].

$$\frac{\partial \rho}{\partial t} + div(\rho \mathbf{u}) = 0 \; (Continuity) \tag{10}$$

$$\frac{\partial \rho u}{\partial t} + div(\rho u \mathbf{u}) = -\frac{\partial p}{\partial x} + div(\mu \; grad \; u) + S_{Mx} \; (x - momentum) \tag{11}$$

$$\frac{\partial \rho v}{\partial t} + div(\rho v \mathbf{u}) = -\frac{\partial p}{\partial y} + div(\mu\ grad\ v) + S_{My}\ (y - momentum) \tag{12}$$

$$\frac{\partial \rho w}{\partial t} + div(\rho w \mathbf{u}) = -\frac{\partial p}{\partial z} + div(\mu\ grad\ w) + S_{Mz}\ (z - momentum) \tag{13}$$

$$\frac{\partial \rho i}{\partial t} + div(\rho i \mathbf{u}) = -p\ div\ \mathbf{u} + div(k\ grad\ T) + \Phi + S_i\ (Energy) \tag{14}$$

As can be seen, there are significant characteristics between the equations, why a general equation called the transport equation (for a general variable ϕ), can be written as [9]:

$$\frac{\partial \rho \phi}{\partial t} + div(\rho \mathbf{u} \phi) = div(\Gamma\ grad\ \phi) + S_\phi \tag{15}$$

The left hand side of the general equation is the rate of increase of ϕ of the fluid element added with the net rate of flow of ϕ out of the fluid element, which equals the right hand side with contribution from the rate of increase of ϕ due to diffusion added with the rate of increase of ϕ due to sources [9].

2.6.4 Computational Fluid Dynamics - Finite Volume Method

Starting with the general transport equation, the Finite Volume Method (FVM) can be applied in order to discretize the equation, i.e. transform it from a continuous differential equation to an algebraic discrete equation [11]. The FVM enables a solution of the equation on a finite volume by integrating it over the finite volume. By applying Gauss's divergence theorem, which converts volume integrals to area integrals, the equation can be simplified as [9]:

$$\frac{\partial}{\partial t}(\int_V \rho \phi dV) + \int_V div(\rho \mathbf{u} \phi) dV = \int_V div(\Gamma\ grad\ \phi) dV + \int_V S_\phi dV \tag{16}$$

$$\frac{\partial}{\partial t}(\int_V \rho \phi dV) + \int_A \rho \mathbf{u} \cdot \mathbf{n} dA = \int_A \Gamma grad\phi \cdot \mathbf{n} dA + \int_V S_\phi dV \tag{17}$$

Solving the system in steady state implies that the general variable (i.e. variable of interest depending on which equation in use) is not changing in time, why the first term of equation (17) equals zero.

$$\int_A \rho \mathbf{u} \cdot \mathbf{n} dA = \int_A \Gamma grad\phi \cdot \mathbf{n} dA + \int_V S_\phi dV \tag{18}$$

The control volume in this case corresponds to one cell in the complete domain of interest, which is formed by the water between the impeller and volute wall inside the pump. To enable solving the flow in the complete domain the domain need to be divided into a huge amount of cells together forming a so called mesh. The finer the mesh is, the better solution it will return, since the system of PDE's is solved with higher accuracy.

Expressions from the integrals can be explored and defined with known values from neighboring cells and also by the use of expressions for quantities on the walls between the cells [9]. To get a deeper understanding of the methodology and how to precede an easy case, 1D diffusion, is described below.

$$\frac{d}{dx}(k\frac{dT}{dx}) + S = 0 \tag{19}$$

This is integrated over a control volume

$$int_w^e[\frac{d}{dx}(k\frac{dT}{dx}) + S]dx = (k\frac{dT}{dx})_e - (k\frac{dT}{dx})_w + S\delta x = 0 \tag{20}$$

The node of interest is denoted P and is placed in the middle of the control volume. The neighboring cells have nodes placed in the middle as well and are in this case denoted W and E (West and East). The walls separating the cells are denoted w and e and the distribution of the volume along the $x-$axis (1D case) is denoted Δx. The distance between the west node W and current node P is denoted δx_w, and thereby the distance between P and E is denoted δx_e.

The needed derivatives of the temperature at the west and east nodes are estimated simply from a straight line between the two adjacent nodes (central differencing)

$$(\frac{dT}{dx})_e \approx \frac{T_E - T_P}{\delta x_e},\ (\frac{dT}{dx})_w \approx \frac{T_P - T_W}{\delta x_w} \tag{21}$$

Approximations for the heat conductivity are also needed at the walls, following Equation (22) below. For an equidistant mesh, i.e. every cell has the same size

$$k_e = f_x k_E + (1 - f_x)k_P,\ f_x = \frac{0.5\Delta x}{\delta x_e} = [Equidistant\ mesh] = 0.5 \tag{22}$$

Inserting (21) into (20) gives the following discretized equation

$$a_P T_P = a_E T_E + a_W T_W + S_U \tag{23}$$

With the following variables

$$a_E = \frac{k_e}{\delta x_e},\ a_W = \frac{k_w}{\delta x_w},\ a_P = a_E + a_W,\ S_U = S\delta x \tag{24}$$

By repeating the steps described for every cell in the domain a system of equations are formed. The system can be solved using matrix inversion but when the number of cells (and thereby the mesh refinement) increases it is impossible to solve the system this way due to limited computational resources [11]. In the real case governed by the Navier-Stokes equation an iterative solution is needed anyway [11].

In the case of three-dimensional convection-diffusion (the centrifugal pump), different differencing schemes than the central differencing schemed (used for the 1D diffusion case) need to be applied. This since the central differencing scheme is relatively simple and not as trustworthy as others schemes [11]. In general there are three criteria for the differencing scheme to fulfill [9].

Conservative The flux between cells should remain the same and not be depent on which cell that is looked at, i.e. flux out of a cell need to equal the flux entering the neighboring cell.

Bounded When computing a quantity at one cell wall it must not be smaller or larger than the cell values contributing to it, which is fulfilled if all coefficients are positive.

Transportive It should reflect the way information is transported, i.e. since it is dependent on both convection and diffusion.

A number of difference schemes to solve the system is provided in the Fluent software. Each of them performs different concerning the three criteria and accuracy. The 2^{nd} order upwind scheme that fulfills criterion one and three is preferred compared to the first order upwind scheme since it is second order accurate [9]. On the other hand the unbounded QUICK scheme (Quadratic Upwind Interpolation for Convective Kinematics) is of third order accuracy [11]. The coupled solver solves all transport equations simultaneously instead of sequentially [9]. This is preferred when the velocity and pressure are strongly coupled, e.g. when both the pressure and velocities are high in the domain. Different types of spatial discretization for the gradients are the least squares cell based, the Green-Gauss Node based and the Green-Gauss Cell based.

Different types of schemes for solving the momentum and the turbulence equations are known. Different schemes for solving the momentum and the turbulence equations are provided, and the easiest way to describe them is to look at the 1D convection-diffusion case, where the domain is divided into cells along the x-axis, with one node in the middle of every cell.

In order to fulfill a solution of the equation stated the difference between the right hand side and the left hand side, is a good measure on how the equation is fulfilled [11]. This is called the residual and for the 1D diffusion case it is defined as

$$R = \sum_{allcells} |a_E T_E + a_W T_W + S_U - a_P T_P| \tag{25}$$

Only evaluating R as in the equation above does not give any information since it equal 1 and is problem dependent [11]. In order to evaluate the residual it has to be normalized against the total flux of the dependent variable denoted F, as

$$\frac{R}{F} <= \epsilon \tag{26}$$

Where ϵ should be a very small number. Depending on equation of interest, F is defined in different ways. For the continuity equation F is the total incoming mass flux [kg/s], while it for Navier-Stokes equation is suitable to define it using Newton's second law [N] at the inlet. For the energy equation it is suitable to define it using the convective flux [W] at the inlet [11].

2.6.5 Turbulence modeling

Nearly all kinds of fluid flows that appear in nature are turbulent. Turbulent flow is hard to define but can be stated using six specific features [12].

Irregularity Turbulent flow is hard to predict since it is chaotic and random and consists of a range of different scales (eddy sizes). The largest eddies are proportional to the size of the geometry while the smallest ones, which by viscous forces, dissipates into internal energy.

Diffusivity The turbulence contributes to an increase of diffusivity.

Large Reynolds number It occurs at high Reynolds number.

Three-Dimensional It is always three-dimensional.

Dissipation As mentioned above, turbulent kinetic energy in the smallest eddies transforms into internal energy, which denotes that turbulence is dissipative.

Continuum The smallest scales in the turbulent flow is really small, but still a lot larger than the molecular scales, why the flow can be treated as a continuum (continuous).

It is possible to solve the Navier-Stokes equations numerically for the whole range of turbulent length scales. This requires huge computer resources, and can only be carried out for low Reynolds numbers [9], why the use of Reynolds decomposition and turbulence models is needed.

$$U = \overline{U} + u \; (Velocity) \tag{27}$$

The left hand side term is the instantaneous velocity, which on the right hand side is divided into a mean and a fluctuating part. By applying this approach, the Reynolds equation (steady state) can be defined as

$$\frac{\partial}{\partial x}(\rho \overline{U}\overline{U}) + \frac{\partial}{\partial y}(\rho \overline{V}\overline{U}) = -\frac{\partial \overline{P}}{\partial x} + \frac{\partial}{\partial y}(\mu \frac{\partial \overline{U}}{\partial y} - \rho \overline{uv}) \tag{28}$$

On the right hand side the $-\rho\overline{uv}$ term is new and unknown. This is an additional stress called the Reyonlds stress, which gives the total stress

$$\tau_{tot} = \mu \frac{\partial \overline{U}}{\partial y} - \rho \overline{uv} \tag{29}$$

It is common to model the turbulence by adding an additional turbulent viscosity (μ_t) to the ordinary viscosity, and rewriting the right hand side of Reynolds equation above gives [11]:

$$\frac{\partial}{\partial y}((\mu + \mu_t)\frac{\partial \overline{U}}{\partial y} \tag{30}$$

By identification, the Reynolds stress is defined as

$$-\rho \overline{uv} = \mu_t \frac{\partial \overline{U}}{\partial y} \tag{31}$$

This is called the Boussinesq assumption and is a fundamental part in all two-equation turbulence models [9].

The k-ϵ model is the most common and well-established two-equation turbulence model [9]. It is also the most validated. It is a simple model where only initial and boundary conditions need to be defined in order to implement it [9]. Another commonly used models are the k-ω and also the SST k-ω. The equations for k and ϵ in the k-ϵ model, where k is the kinetic energy and ϵ is the viscous dissipation of the turbulence is presented below.

$$\frac{\partial(\rho k)}{\partial t} + div(\rho k\mathbf{U}) = div(\frac{\mu_t}{\sigma_k}\ grad\ k) + 2\mu_l S_{ij}\cdot S_{ij} - \rho\epsilon \tag{32}$$

$$\frac{\partial(\rho \epsilon)}{\partial t} + div(\rho \epsilon\mathbf{U}) = div(\frac{\mu_t}{\sigma_\epsilon}\ grad\ \epsilon) + C_{1\epsilon}\frac{\epsilon}{k}2\mu_l S_{ij}\cdot S_{ij} - C_{2\epsilon}\rho\frac{\epsilon^2}{k} \tag{33}$$

Every term in the equations describes different magnitudes of the turbulence. On the left hand side, the first term is the rate of change in k or ϵ (depending on which equation) while the second term describes the transport of k or ϵ due to convection. On the right hand side, the first term describes the transport of k or ϵ due to diffusion, while the two last terms defines the rate of production and destruction of k or ϵ respectively.

The k-ω model is similar to k-ϵ, but instead it uses the turbulent frequency ω ($\omega = \epsilon/k$) as the second variable [9]. The equations for the k-ω model are presented below, and the terms can be described in the same manner as for the k-ϵ, where only the last term differ and is the rate of dissipation of k or ω instead.

$$\frac{\partial(\rho k)}{\partial t} + div(\rho k\mathbf{U}) = div[(\mu + \frac{\mu_t}{\sigma_k})grad(k)] + P_k - \beta^*\rho k\omega \tag{34}$$

where P_k, the rate of production of turbulent kinetic energy, is defined as:

$$P_k = (2\mu_l S_{ij}\cdot S_{ij} - \frac{2}{3}\rho k\frac{\partial U_i}{\partial x_j}\delta_{ij}) \tag{35}$$

$$\frac{\partial(\rho\omega)}{\partial t} + div(\rho\omega\mathbf{U}) = div[(\mu + \frac{\mu_t}{\sigma_\omega})grad(\omega)] + \gamma_1(2\rho S_{ij}\cdot S_{ij} - \frac{2}{3}\rho\omega\frac{\partial U_i}{\partial x_j}\delta_{ij}) - \beta_1\rho\omega^2 \tag{36}$$

Menters SST k-ω model is a hybrid model using a transformation of the k-ϵ model into a k-ω in the near-wall region and the standard k-ϵ model in the fully turbulent region far away from the wall. The model was created due to founding by Menter, which noted that the results of the k-ϵ are much less sensitive to the assumed values in the free stream, while its performance near a wall is unsatisfactory for boundary layers with adverse pressure gradients [9]. For the SST k-ω the equation for the turbulent kinetic energy k is the same as for the k-ω, while the equation for ω is defined as Equation (37) below, by substituting $\epsilon = k\omega$ in the ϵ-equation above.

$$\begin{aligned}\frac{\partial(\rho\omega)}{\partial t} + div(\rho\omega\mathbf{U}) = div[(\mu + \frac{\mu_t}{\sigma_{\omega,1}})grad(\omega)] + \gamma_2(2\rho S_{ij}\cdot S_{ij} - \frac{2}{3}\rho\omega\frac{\partial U_i}{\partial x_j}\delta_{ij}) \\ - \beta_2\rho\omega^2 + 2\frac{\rho}{\sigma_{\omega,2}\omega}\frac{\partial k}{\partial x_k}\frac{\partial \omega}{\partial x_k}\end{aligned} \tag{37}$$

Comparison between the standard ω-equation and the new one explores the extra source term created (the fourth term on the right hand side). The term called the cross-diffusion is a result of the transformation ($\epsilon = k\omega$) of the diffusion term in the ϵ-equation [9].

As mentioned above, the k-ϵ model is a simple turbulence model to use since only initial and boundary conditions need to be defined. It is also preferred since it is well validated and trustworthy. Unfortunately it predicts rotating flows badly since models based on the Boussinesq assumption have problem in swirling flows and flows with highly curved boundary layers and divergent passages that affect the turbulence in a subtle manner [9]. It is also expensive to use since it add two partial differential equations to the solutions to solve. Anyhow the use of a two-equation turbulence model fit the problem well, since limited computer resources demands an easy way of solving the turbulent flow.

2.6.6 Rotating Machinery Setup Theory

The default set up in software like Fluent is to solve the equations of fluid flow in a stationary reference frame [13]. Problems such as centrifugal pumps, with rotating components (impeller), should be modeled in a rotating reference frame. In the case of a rotating reference frame the flow around the rotating parts can be performed as a steady-state problem with respect to the moving frame. For simpler problems it can be modeled by only one reference frame, called the SRF (Single Reference Frame) method, while for more complex cases it is needed to split up the domain into several reference frames, called the MRF (Multiple Reference Frame) method [13]. The MRF method is still considered a simple method compared to the sliding mesh approach.

When applying the MRF model, the domain is divided into multiple cell zones [13]. A cell zone is a zone in the complete domain with specific properties, and by assigning different properties to different cell zones, the problem can be set up as correct as possible. Since only the fluid inside the impeller (between the blades) should rotate in this case, that region is defined as its own cell zone, while the remaining part of the domain, which should remain stationary is defined as another one (See Chapter 3). Between the cell zones, at the interface, a local reference frame transformation is performed in order to use flow variables from one zone to calculate fluxes at the boundary of the adjacent cell zone.

A large restriction with the MRF method is that the mesh remains fixed during the computations, i.e. it does not account for the relative motion of the rotating zone with respect to the adjacent zones [13]. This is similar to the method of freezing the motion of the impeller in a specific position and instantaneously observing the flow field. Due to this, MRF is often referred to as the frozen rotor approach.

As well as the MRF method, the sliding mesh method is based on the use of cell zones. It is a model to compute time-accurate solutions for rotating machinery problems [13]. As well as it is the best method to predict flow solutions it is also the most time- and resource consuming method [13]. Due to the limited computer and time resources it was never discussed to use.

2.7 Rapid prototyping

Rapid prototyping is a fast and simple way of manufacturing models and prototypes. It consists of a printer that creates the model, layer by layer, with a 3-D CAD drawing as basis. Rapid prototyping is an important part of the design process since it provides a great flexibility and cost efficiency when manufacturing only one copy [8].

There are many types of techniques of rapid prototyping. SLA, SLS and FDM are three of the most common ones. The types depend on what properties that are sought after [8].

2.8 Laboratory tests

Asko Appliances performing dishwasher tests in their laboratory on a daily basis. The tests are standardized and there are three different standards; the European, American and Australian. Basically, dirt is applied on the plates, glasses, forks etc. They are then heated up in an oven to make sure it stick well to the materials. The standard program of the dishwasher is then used to make the material clean again. When the program is finished all dirt that still is located on the material is noted and a wash performance index can be calculated.

The tests are completely standardized. Timers are used when preparing the dirt, both when cooking and heating it in the oven. All the dirt is measured and applied in a certain way on the material. The air and the water needs to have defined properties. Also a reference dishwasher is used in parallel so that the test results can be compared.

3 Method

This project had a product development approach, which means that it was using engineering methods and tools to, in the beginning of the project, generate and produce concepts, and in the end of the project, eliminate concepts. For generating concepts, a pilot study and interviews were used to set up a specification of requirement that bound all the upcoming generated concepts. These tools also gave important information for the generating tool of brainstorming, due to the fact that it opened up for different kinds of solutions of how to solve problems regarding pumps.

In the elimination of concepts process, Pugh and Kesselring matrices were used. To make proper estimations in those decisions matrices, CFD simulations had to be performed with main focus of investigating what factors that really affected the wash performance of a dishwasher, but also to rank the concepts according to criteria.

3.1 Data collection

3.1.1 Literature study

In the beginning of the product development process it was very important to understand the underlying problem that affect the wash performance of the dishwasher, especially the affect from the circulation pump. As mentioned in the introduction, a small change in the impeller eye (see Figure 1) made the wash performance drop almost 10%.

The project betan with a literature study. The literature that was used was borrowed books from the library and articles found in databases, a majority of the articles were found in the *ScienceDirect* database.

The main purpose of the literature study was to get a good overview of pumps in general and which parameters that affect its properties. By gaining this sort of information through literature, time and money were saved since no own test had to be done to obtain those changes in properties due to modification of the pump.

Articles and books related to pump theory were red and summarized. The study was especially focused on

- the pump in general
- the impeller
- the volute
- the impeller eye

3.1.2 Interviews

Another tool that was used to understand the underlying problems affecting the wash performance of a dishwasher, was interviews with experts in different fields connected to dishwashers. In this way a better overview about how different concepts affect the separated fields were obtained. E.g. one concept could be beneficial regarding the energy consumption but affect the sound level in a bad way.

The interviews were held as "One-to-One Interviews" with experts in the separated fields stated below:

- Design engineering
- Laboratory testing
- Requirement specification
- Sound
- Overall expert

All of the interviews were question-based except the interview with the laboratory testing members. In that interview an observation-based interview method was used; following a whole wash performance test. Questions were then added to the observation as unstructured.

Since it was a while ago Asko Appliances changed their sub-contractor for the pumps, the interviews started with letting them explain what they could remember about the changes and their reflections on the difference in wash performance. During the explanation, questions were added for better understanding and to force the interview into a correct direction, a typically semi-structured interview. The explanation part and the added questions resulted into a relaxed atmosphere.

When all the one-to-one interviews were finished all the experts merged into a group interview. At that stage the atmosphere was very relaxed and the interview was more about a discussion between the experts about how the wash performance could have changed so dramatically and how changes could be made to make it better. Semi-structured questions were added for better understanding and to keep the discussion active and alive. At this point it was important to ask questions that the discussion stayed inside the boundaries of the project and not passed over to other problems in different fields which the interviewees were working on in their daily basis.

3.2 Design requirements

Based on the literature study and the interviews, a specification of requirements was set up. The specification of requirements was divided into functional and design requirements. It also included a purpose of every requirement, a way of verify the requirement and a priority group. In this way it was easy to get a good overview of the requirements and boundaries were set up so focus could stay on the right topics.

3.3 Concept generation

With the pilot study, the interviews and the specification of requirements done, it was time to widen the funnel that was described in Chapter 1.3. To do that, the function-means model was used. There, a main function was defined and decomposed into sub-functions.

Every function or sub-function had its own responsible component. Dividing the function into appropriate levels, and identifying its responsible component could make different main solutions just by changing one or more component to the sub-functions. In other words, the change in one component would affect the whole solution.

The main function was defined as *"Wash performance is changed when the centrifugal pump is changed"*, and was further divided into sub-functions. The whole decomposition can be seen in Figure 17 in Chapter 4.

3.3.0.1 Brainstorming When the main function was completely decomposed into sub-functions and they were all defined, brainstorming were used to find out solutions for all of them. Since the impeller and its corresponding volute can obtain any given shape the number of solutions could be infinite. Therefore, the brainstorming was based on the material that was produced in the pilot study and the interviews.

First, the team members generated concepts of every sub-function on their own. Then they were merged for visualization and discussion. In that way the concepts were developed with input from different expertise.

3.3.1 Morphological matrix

With the responsible components known, and solutions for all the sub-functions were set up a combination of them all would create main solutions. These solutions were from this point unique concepts that would affect the wash performance in different ways.

To combine all the sub-concepts to main concepts a Morphological matrix was used. In that way no concept would be missed and a maximum number of concepts were generated.

3.4 Concept elimination

These large amounts of concepts were the maximum of concepts in the funnel. From this point, elimination of concepts was started and in the end, only the best suited concepts for good wash performance were left.

3.4.1 Limitations

Unfortunately the amounts of concepts at this stage were too large to put into decision matrices so limitations had to be made. Those limitations had to be imposed because of the time limit and computer data resources for the project was not enough.

The limitations that had to be done to reduce the number of concepts were based on the pilot study and the interviews and were more focused on returning concepts that might solve the wash performance property of the dishwasher.

After the limitations had been defined, a new and reduced Morphological matrix could be created. The new Morphological matrix returned a more manageable number of unique concepts to be handled in the decision matrices.

3.4.2 Pugh matrix

To reduce the concepts even more, decisions matrices were used. First a Pugh matrix was used on the remaining concepts. The reason was to eliminate those concepts that, in comparison with the original pump, were not good enough due to defined criteria. The criteria of the matrix were set up as follows:

Efficiency The pressure difference, $P_{out} - P_{in}$

Performance The wash performance of the whole dishwasher

Cost The cost of the manufactured impeller

Serviceability How easy/hard it is to install and assemble the pump

Turbulence The turbulence measured inside the pump.

Efficiency became one of the criteria since a lot of the pilot study consisted of methods and studies about how to improve it. Also, it would be good for Asko Appliances to improve its efficiency of the pumps both in an environmental aspect and in future development work.

Performance was of course on of the criterion since it was the main function to be solved and what the project was aiming for.

Cost and *serviceability* were added as criteria to add value to the concept. Those criteria were not important to have a good result in, but if concepts were equally weighted, the criteria might play a major role.

The *turbulence* criterion might be connected to the *performance* criterion but that was not proven, either in the pilot study or in any of the interviews. Therefore it was set up as a criterion with the aim of creating as small amount of turbulence as possible.

Since the concepts were made of the same material and the assembly process were identical for all of the concepts there were no difference between the concepts and the reference pump. Therefore the *efficiency*, *wash performance* and the *turbulence* had to be the criteria that made the difference. In order to know if the concepts were better or worse than the reference due to those criteria, investigations had to be made.

These investigations were made by performing computer simulations (*efficiency* and *turbulence*) and laboratory tests (*efficiency* and *wash performance*) of the fluid in the pumps. By analyzing all of the concepts and comparing them with the reference pump, fair decisions could be made.

3.4.3 Kesselring matrix

The use of a Kesselring matrix was also included in the elimination process. This was because of the result of the Pugh matrix that did not eliminate enough concepts when comparisons with the reference pump were made and so the criteria that were used in the Pugh matrix had to be weighted against each other and form a Kesselring matrix. In that way the result from each of the concepts reflects the most important criteria for solving the problem. The criteria were given a value of 1-10 based on the pilot study and the interviews, but also assumptions.

3.5 Simulations

In order to avoid expensive and time-consuming tests of all the concepts, elimination based on estimation from computational simulations have been performed. The simulations have thereby acted as a concept elimination part in this project. The simulations have been accomplished by using commercial computer software, and the governing methodology was set up using the flow chart shown in Figure 13, and which is described in detail below. The simulations were performed to find out the efficiency and the turbulence of the concepts. In that way the information could be used in relation to each other in a Pugh- and a Kesselring matrix.

3.5.1 Preparing simulations

3.5.1.1 Gathering info To prepare the simulations, knowledge about how a centrifugal pump works were gathered and compiled in the pilot study (See Chapter 3.1.1). Also general CFD theory was taken into account (Chapter 2) in order to understand how the software solves the fluid flow problem.

3.5.1.2 Software to use The software to use was chosen to be ANSYS Workbench, which consist of many different applications, and especially includes two different applications for fluid flow simulations (CFD), Fluent and CFX. The choice of ANSYS was based on earlier experience of using it, and in particular because Chalmers could provide the project team with student licenses. Information about Fluent was easy to gather and that, combined with supervisors experience in Fluent, resulted in that Fluent was selected as the software to use. To establish the case also ANSYS Meshing and ANSYS DesignModeler were used, based on the good interaction between them.

3.5.1.3 Learning to use the software To get familiar with the ANSYS software, tutorials including basic items such as how the meshing and fluid set up works were performed. Since it was a rotating machinery problem especially tutorials concerning rotating machinery problems were completed.

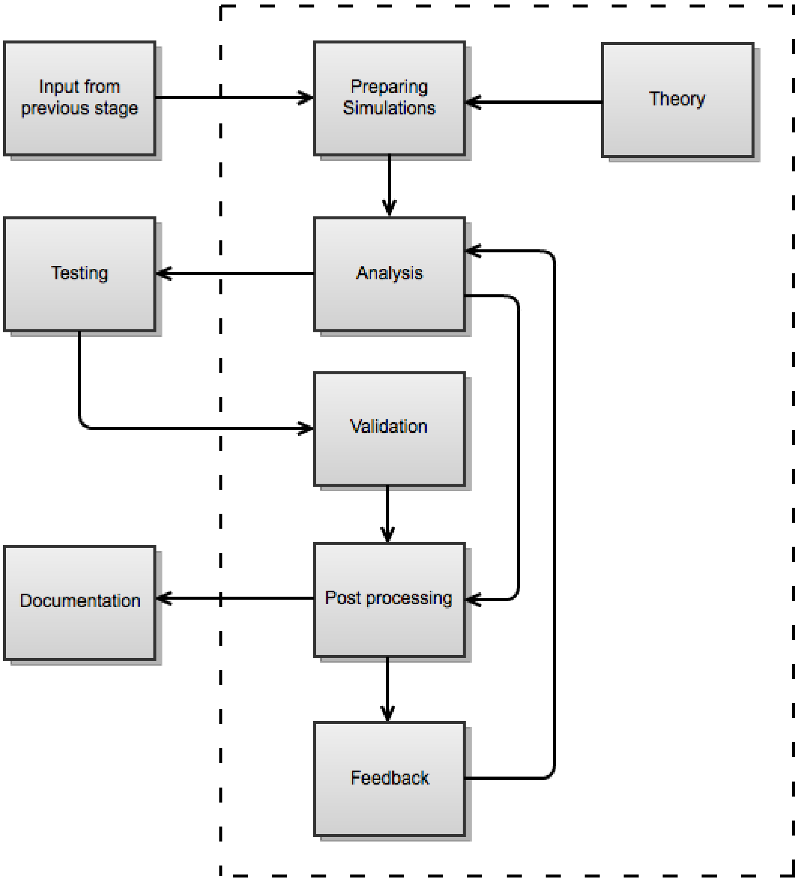
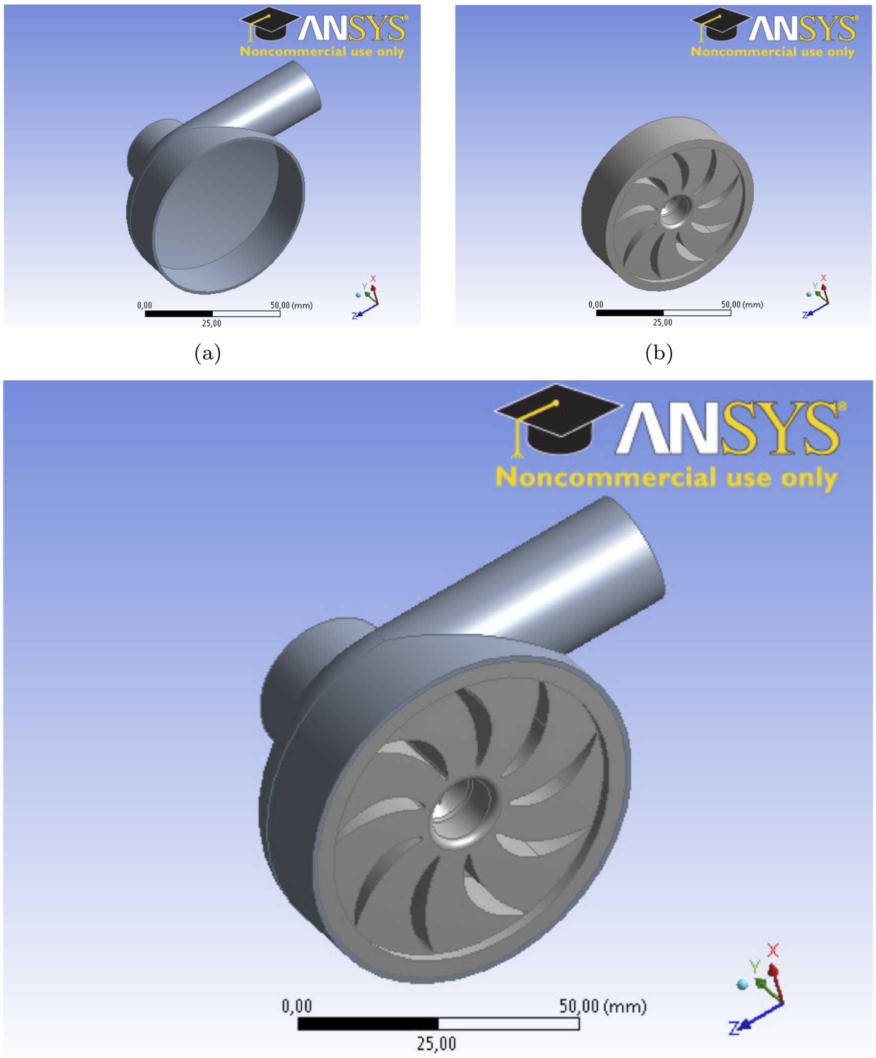


Figure 13: Flow chart

3.5.1.4 Input from previous stages The simulations were only one part in the chain of methods applied in the product development approach and inputs from previous stages were needed. In the previous stage (elimination process), a numbers of concepts were developed. In order to prepare the concepts for computational analysis, a domain for each one were drawn using the CAD software, SIEMENS NX. This software was mainly chosen for its good interaction with the ANSYS Workbench. The domain in this case is the fluid inside the pump (between the impeller and volute wall).

3.5.1.5 Set up of computational domain (Ansys DesignModeler and Meshing) When dealing with rotating machinery problems the domain needs to be divided into zones with different properties, so called cell zones (See Chapter 2). This is due to the fact that only the fluid between the impeller blades should be rotating (one cell zone), while the surrounding fluid inside the volute should remain stationary (another cell zone).

It was therefore drawn as a domain describing the whole pump and then split up into two zones. One described the fluid motion between the rotating blades and one described the motion outside the blades that also covered the inlet and outlet of the pump. Before the domains were meshed, they were brought into the software, ANSYS DesignModeler. The software could convert the model from two parts to one part but still let it remained as two zones. This would later be useful in the mesh analysis, see Figure 14.



(a)

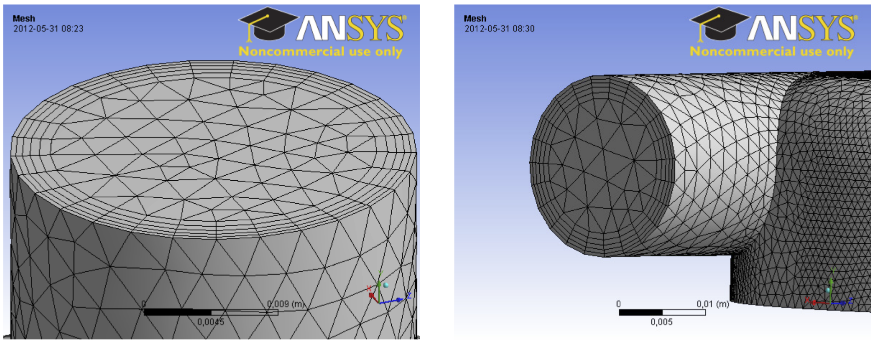
(b)

(c)

Figure 14: The domain between the inlet and the outlet of the pump is represented by (a). The domain within the blades (rotational) is represented by (b). Together they form the total domain of the pump (c)

The needed mesh (see Chapter 2.6.4) was created using ANSYS Meshing. In order to define the needed boundary conditions, the command named selection, which enables defining specific properties to a specific area, was used. In the meshing software, different mesh densities (coarse, medium, fine) can be chosen using the build-in tools relevance center, smoothing and spawn angel center.

Beside the build-in tools a number of different settings can be made to fit the specific problem. As described earlier (see Chapter 2.6.2.1), near wall treatment of the problem is of big interest, and especially the use of boundary layers. To create boundary layers, the inflation tool was used. The boundary layers were merged into the mesh at the inlet, outlet, impeller blades and at the interface between the two cell zones. The layers that were created by the inflation tool can be seen in Figure 15. In order to evaluate how the mesh affects the solution, a mesh independency test was performed.



(a) (b)

Figure 15: Mesh on the inlet (a) and outlet (b) with applied inflation tool.

3.5.1.6 Mesh independency test To see how the mesh accuracy affects the solution, a mesh independency test was performed. A solution that is mesh dependent, i.e. changes when the mesh is changed, is bad, why the independency test is of big interest. Three standard meshes (coarse, medium and fine relevance center), and also a mesh using the build-in inflation tool, were tested, and data for the four cases can be seen in Table 3.

Table 3: The number of nodes and element depending of the coarse, medium, fine and inflation settings.

Mesh accuracy	Number of nodes	Number of elements
Coarse (no inflation)	71 000	383 000
Medium (no inflation)	122 000	665 000
Fine (no inflation)	409 000	2 254 000
Medium (inflation)	622 000	2 561 000

Even though the mesh accuracy increased, both by using the inflation tool and by refining the relevance center, the convergence unfortunately did not improve. Due to time limits and the limited computer resources it was decided to perform the simulation with a coarse mesh without boundary layers.

3.5.2 Analysis

When the computational domain was fully defined and the mesh was generated, a setup of the case in Fluent was done. Fluent solves the system of partial differential equations, which can be performed with a number of different settings. The set up in Fluent follows a straightforward scheme that is well structured and easy to understand (see Figure 16). Below the set up for this case is described in detail.

The simulations were chosen to run in steady state, due to the limited computer resources. As described in the theory chapter, many different ways of dealing with the turbulence modeling are possible, and especially in this case a two-equation model comes well in hand since they are easy to implement. The $k{-}\omega$-model with SST was chosen to be used, since it is an improvement of the standard $k{-}\omega$ equation.

The needed initial and boundary conditions for the turbulence (see Chapter 2.6) were defined by the turbulent intensity (in percent) and the hydraulic diameter, at both the inlet and the outlet. The cause of using the intensity and the hydraulic diameter is the difficulty of estimating reasonable values of the turbulence variables k and ω to begin the simulations with. As described below general recommendations were used to predict the turbulent intensity while the hydraulic diameter was calculated using a simple geometrical formula. The intensity of the turbulence is defined as [29]:

$$I = \frac{u'}{U} \tag{38}$$

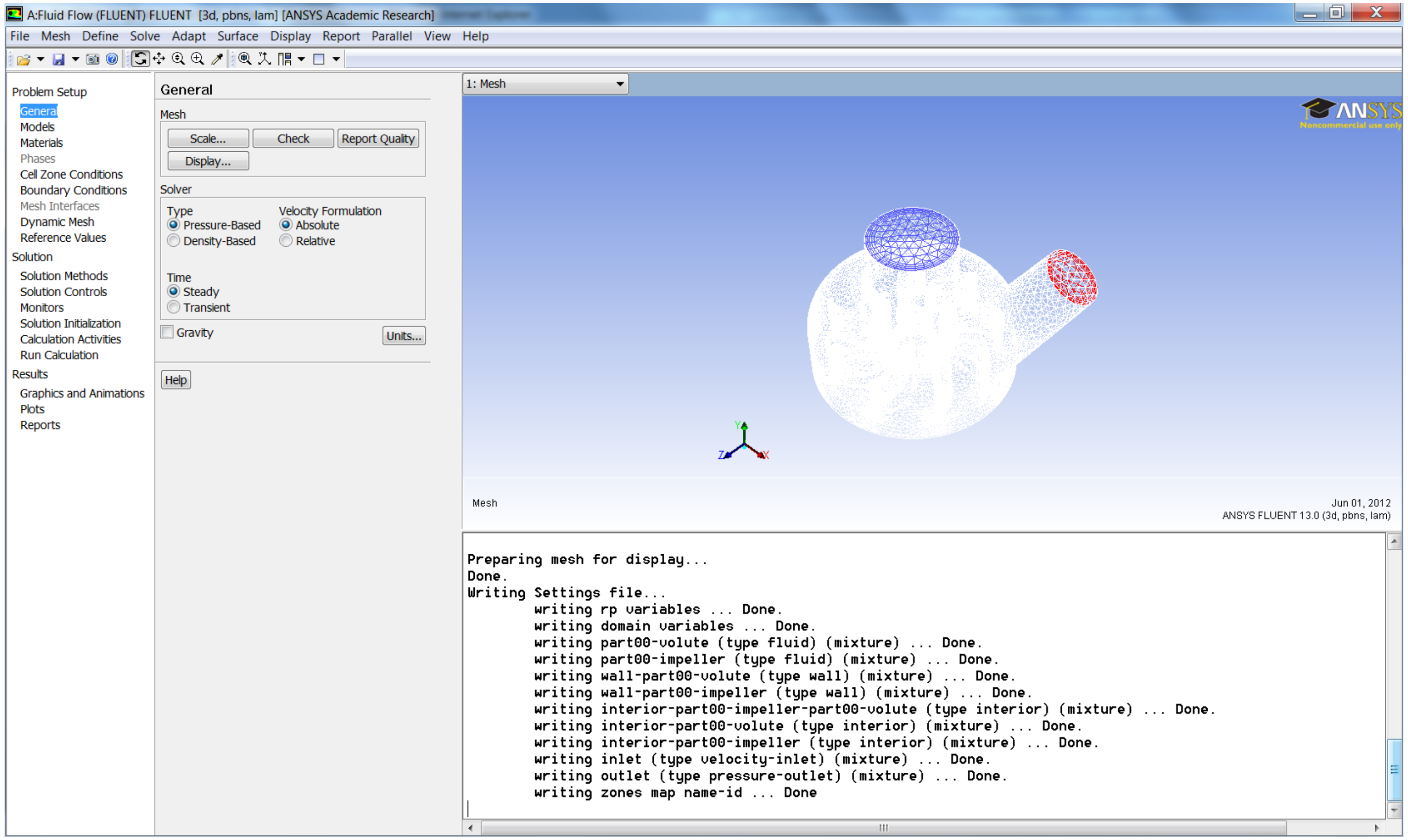
Where u' is the root-mean-square of the turbulent velocity fluctuations and U is the Reynolds average mean velocity, both defined as:

$$u' = \sqrt{\frac{1}{3}(u_x'^2 + u_y'^2 + u_z'^2)} = \sqrt{\frac{2}{3}k} \tag{39}$$

$$U = \sqrt{U_x^2 + U_y^2 + U_z^2} \tag{40}$$

Since initial and boundary conditions were needed, the intensity was predicted using general recommendations. For such a complex geometry as a rotating machinery device, the turbulence intensity can be between 5 and 20 percent. Therefore an intensity of 10 percent was chosen, well above the lower limit of 5 but still not close to the upper limit 20. The hydraulic diameter is a measure of the turbulent length scales, and is a good estimation when determine turbulent boundary conditions for inlet and outlet that experience fully developed flow. For a circular duct, the hydraulic diameter equals the diameter of the duct, as described in equation (4) below [29]. The hydraulic diameters for the boundaries are defined in Table 4.

$$d_h = 4\frac{\frac{\pi d^2}{4}}{\pi d} = d \tag{41}$$



Type
● Pressure-Based
○ Density-Based

Velocity Formulation
● Absolute
○ Relative

Time
● Steady
○ Transient

☐ Gravity

```
Preparing mesh for display...
Done.
Writing Settings file...
        writing rp variables ... Done.
        writing domain variables ... Done.
        writing part00-volute (type fluid) (mixture) ... Done.
        writing part00-impeller (type fluid) (mixture) ... Done.
        writing wall-part00-volute (type wall) (mixture) ... Done.
        writing wall-part00-impeller (type wall) (mixture) ... Done.
        writing interior-part00-impeller-part00-volute (type interior) (mixture) ... Done.
        writing interior-part00-volute (type interior) (mixture) ... Done.
        writing interior-part00-impeller (type interior) (mixture) ... Done.
        writing inlet (type velocity-inlet) (mixture) ... Done.
        writing outlet (type pressure-outlet) (mixture) ... Done.
        writing zones map name-id ... Done
```

Figure 16: Figure of the Fluent software, where the set up followed the scheme in the menu to the left, each headliner with different sub-settings.

Table 4: The hydraulic diameter of inlet and outlet

Boundary	Hydraulic diameter [mm]
Inlet	27.3
Outlet	22

The multiple reference frame were set up by assigning a specific angular velocity and rotational axis for the rotating cell zone and let the stationary cell zone remain stationary. Due to design requirements the rotating cell zone was defined to rotate with an angular velocity of 2700 rpm. Physical parameters for water at 50 degree Celsius were defined and are presented in Table 5 [14].

Table 5: Properties of the fluid(water)

Density	1000 $[kg/m^3]$
Dynamic viscosity	0.0001 $[Ns/m^3]$

The pressure at which the pump works is defined using Pascal's law, where the difference in height is the difference between the layers of the strainer and the pump.

$$\Delta P = \rho g \Delta h \tag{42}$$

$$\Delta P = 1000[kg/m^3] \cdot 9.81[m/s^2] \cdot 0.05[m] = 490.5 \approx 500[Pa] \tag{43}$$

3.5.3 Boundary conditions

Two boundary conditions were needed in order to solve the system. Due to design requirements the mass-flow at the inlet and the pressure at the outlet could be defined (Table 6). The dishwashers perform different programs where the in- and outlet properties vary, but in the simulation a worst-case scenario have been modeled.

Table 6: Boundary condition for the inlet and outlet. Describes both the type and the quantity.

Boundary	Type	Numerical value
Inlet	Mass-flow	0.83 [kg/s]
Outlet	Pressure	31 [kPa]

A number of different solution methods were concerned. A coupled scheme was chosen to use preferred to simple scheme, since the coupling between velocity and pressure is strong. For the gradient solution the Green-Gauss Node Based was chosen, while the 2^{nd} order upwind scheme was used for solving the momentum and the turbulence (Turbulent kinetic energy k and Specific dissipation rate ω) equations, since it provides a higher accuracy than the first order scheme. Values on the residuals used were default values.

3.5.4 Testing and validation

To determine the accuracy of the simulation some kind of validation is preferred. Therefore the chosen concepts were tested at the laboratory at Asko Appliances.

Unfortunately, the physical parameters estimated in the simulations, have not been tested, since the tests only can validate the wash performance of the dishwasher. This anyhow tells how the concepts worked in practice.

3.5.5 Post processing and documentation

Beside ordinary flow characteristics like velocity and pressure profiles, the efficiency of the pump have been documented. As well the generated turbulence for every concept have been documented. Data from the simulations have been saved as figures in Appendix E and in the same manner for every one (see Chapter 4).

3.5.6 The loop (Feedback/Analysis)

ideally an iterative loop should be performed, in order to optimize the result, but due to time limits, documentation and presentation of the result have been done after only one iteration (Analysis/Testing/Validation/Post processing).

3.6 Concepts for further development

The result from the simulations was brought into the decisions matrices again. Now more accurate decisions could be made within the matrices. Information about the wash performance played a major role but was still not known. By performing laboratory tests of the concepts, wash performance of the dishwasher could be obtained, but due to cost resources and time limit only a few concepts could be tested.

Generally, the concepts scoring top results in the Kesselring matrix would be tested in the laboratory at Asko Appliances. In this case the information from the laboratory tests of the prototypes would be applied on those concepts that were not tested. Therefore the concepts that were chosen to be tested should represent the concepts that were not chosen to be tested. In that way the result could approximately be applied on all the concepts.

3.7 Rapid prototyping

The chosen concepts for testing were manufactured by rapid prototyping. In that way the manufacturing process was very quick and accurate prototypes were delivered. Since the real product is also made of plastic, it would not affect the pump in another way due to the material.

3.8 Laboratory tests

Standardized wash performance tests of dishwashers were performed on the prototypes at Asko Appliance's laboratory. They were tested against the European standard and resulted in a wash performance index that could be analyzed. Due to time limit only one of the concepts were analyzed and conclusions and recommendations were drawn from that.

4 Results

4.1 Pre-study

A planning report was written in the beginning of the project, including an introduction, background of the project, clarification of issue, the organization of the project and a time plan. Both Chalmers and Asko Appliances approved the report and so the project could begin.

4.2 Data collection

4.2.1 Literature

The project started with a pilot study. Focus was on the centrifugal pump and how modification of it would affect its properties. By this research a lot of own test could be skipped since a lot of information were given through the study.

No book or article that was read about pumps had any connection to wash performance for dishwashers. The majority of the articles were studies about how to increase the efficiency of the centrifugal pump.

The study was summarized and can be seen in Chapter 2.6.1.

4.2.2 Interviews

One-to-one interviews and one group interview were performed at Asko Appliances. One of the interviews was observation-based and the other ones were question-based. They were having semi-structured questions added to maintain the discussion.

Since it was a while ago Asko Appliances changed their sub-contractor for the pump, the interviews started with letting them explain what they could remember about the changes and their reflections on the difference in wash performance.

Since properties such as pressure and the flow out of the pump, had the same values for both pump designs, it took a long time until they realized that it was the impeller eye that affected the wash performance. The theory of why the design of the impeller eye was so crucial was the appearance of turbulent flow. With a high turbulent flow, the experts thought that it would split the dirt particles into small pieces that would not get caught in the nets that prevent the dirt to recirculate in the system. In that case the wash performance would drop.

From the interviews, the importance of having a low turbulent flow was a very important topic. On the old pump, changes had already been made, such as rough surfaces on the volute and angles on the impeller blades. There were also theories about how to reduce the turbulence flow even further.

By letting the water enter the impeller in a smoother way the turbulent flow might be reduced. Also adjustments on the impeller blades, such as the thickness nearest the centre becomes thinner might reduce the turbulence flow, due to the fact that more water would be able to enter without any difficulties.

Studies at Asko Appliances have earlier showed that the wash performance increase with increasing output pressure from the pump. But with increased pressure the arms that squirt the wash water spins too fast. Therefore, an adjustment on the outlet holes on the squirting arms must be made if the outlet pressure from the pump would be increased in order to maintain the same performance of the coils. Also one risk with increasing the pressure may be that the water, which is squirting out from the arms can form foam of the dishwasher detergent, which would not increase the dishwasher performance.

From the interviews it was clear that no consideration regarding the assembly process had to be made. A company today assembles the pump and the process works well. There is no service performed on the pump. If the pump breaks they simply just switch to a new one. Therefore no consideration regarding service compatibility has to be performed.

The material selection was not important either, the impeller and its volute are today made of plastic and that works well.

From the literature study, it was clear that the phenomena cavitation, played a huge role when it comes to efficiency of the pump. From the interviews it was clear that no sign of cavitation had appeared on their pumps. No destroyed impeller blades or different kind of sound when the pump was running had been detected.

4.3 Design requirements

The set-up requirements, based on the literature study, were divided into the following categories:

- No leakage in the pump system
- Maximum retail price
- Budget for prototype
- Pressure in the coils arm produced by the pump
- The flow through the pump system
- Wash result
- Efficient pump
- Water consumption
- No cavitation in the system
- No vortexes in the system
- The pump requires to cooperate with the existing motor
- Test standards

- Maintenance free when using the dishwasher at normal operation (see 2.7.1v1 Lifetime)
- Impeller and volute are not allowed to corrode
- Same material as the current solution
- Geometrical constraints
- Rapid prototyping
- The pump should not be dangerous to install
- The pump should not affect the user
- Strength
- Lifetime
- Sound level

The whole specification of requirement can be seen in Appendix C.

Table 7: A part from the Performance section in the specification of requirements. Numbers can not be seen due to confidentiality

2.3 Performance	
Priority	High
Requirement:	2.3.1v1 Pressure acting on the centrifugal pump
	Following pressures need to be fulfilled: Inlet: 0.5 kPa Outlet: 31 kPa
Purpose:	The specified pressure is required due to the rotation of the coils arms and the velocity of the fluid coming out from the arms. It all affects the wash performance of the dishwasher.
Verification:	Sensors in the test laboratory at Asko Appliances will return the pressure.
Priority	High
Requirement:	2.3.2v1 The rotation velocity of the centrifugal pump
	The rotation velocity of the centrifugal pump requires to be: RPM: 2700 With a rotation velocity of 2700 RPM the actual velocity of the top of the impeller blade is equal to 1.4209 m/s.
Purpose:	The velocity of the impeller is connected to the resulting pressure of the centrifugal pump.
Verification:	Sensors in the test laboratory at Asko Appliances will return the water flow.
Priority	High
Requirement:	2.3.3v1 Wash result
	The wash result requires being better than with the old pump, Hanning, with a result of 1.09 in wash efficiency index.
Purpose:	To increase the efficiency of the dishwasher.
Verification:	Wash performance tests will be made in the test laboratory at Asko Appliances.
Priority	High
Requirement:	2.3.4v1 Efficient pump
	The energy consumption requires being less than with the old pump, Hanning, with a result of 1.14 kWh.
Purpose:	With a more efficient pump, Asko Appliances can develop more environmental friendly programs.
Verification:	The efficiency can be tested in the test laboratory at Asko Appliances.

4.4 Concept generation

With a complete specification of requirements, the concept generation process begun. There are many ways of attacking this process. In this project the function-means model was used.

4.4.1 Function-means model

The function-means model is a method that decomposing the main function to sub-functions. The main function was defined as

- *"Wash performance is changed when the centrifugal pump is changed"*

and was further divided into sub-functions

- *"Transforms the engine torque to the fluid"*
- *"Casing"*
- *"Converting the electrical energy to kinetic energy"*

It was divided even further until no more sub-functions could be found. The whole dividing process can be seen in Figure 17.

4.4.1.1 Brainstorming The brainstorming process was used to generate concepts for the sub-functions. Every sub-function was handled separately. For the impeller and its belonging volute any shape could be given. Therefore some of the sub-concepts were not properly defined, e.g. the impeller blades angle: *large angle*, *small angle* and *straight*. Between the small and large angle there are an infinite number of angles that not all can be handled. The result from the brainstorming can be found in Figure 18.

4.4.2 Morphological matrix

A Morphological matrix was used to combine the sub-concepts to main concepts so that no concept was lost in the generation process. see Figure 18. The Morphological matrix returned a large amount of unique main concepts. At this point the maximum number of concepts was reached.

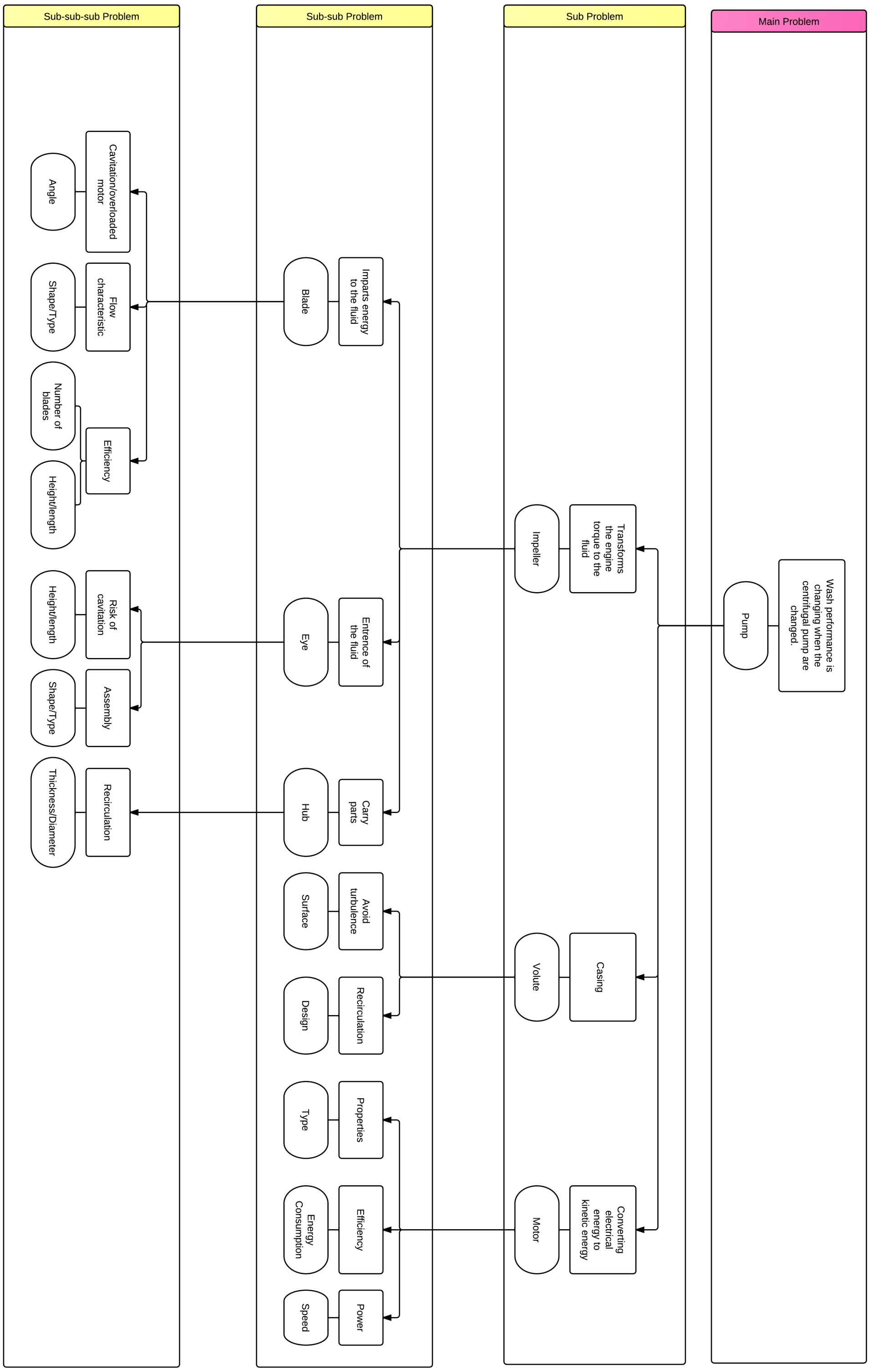
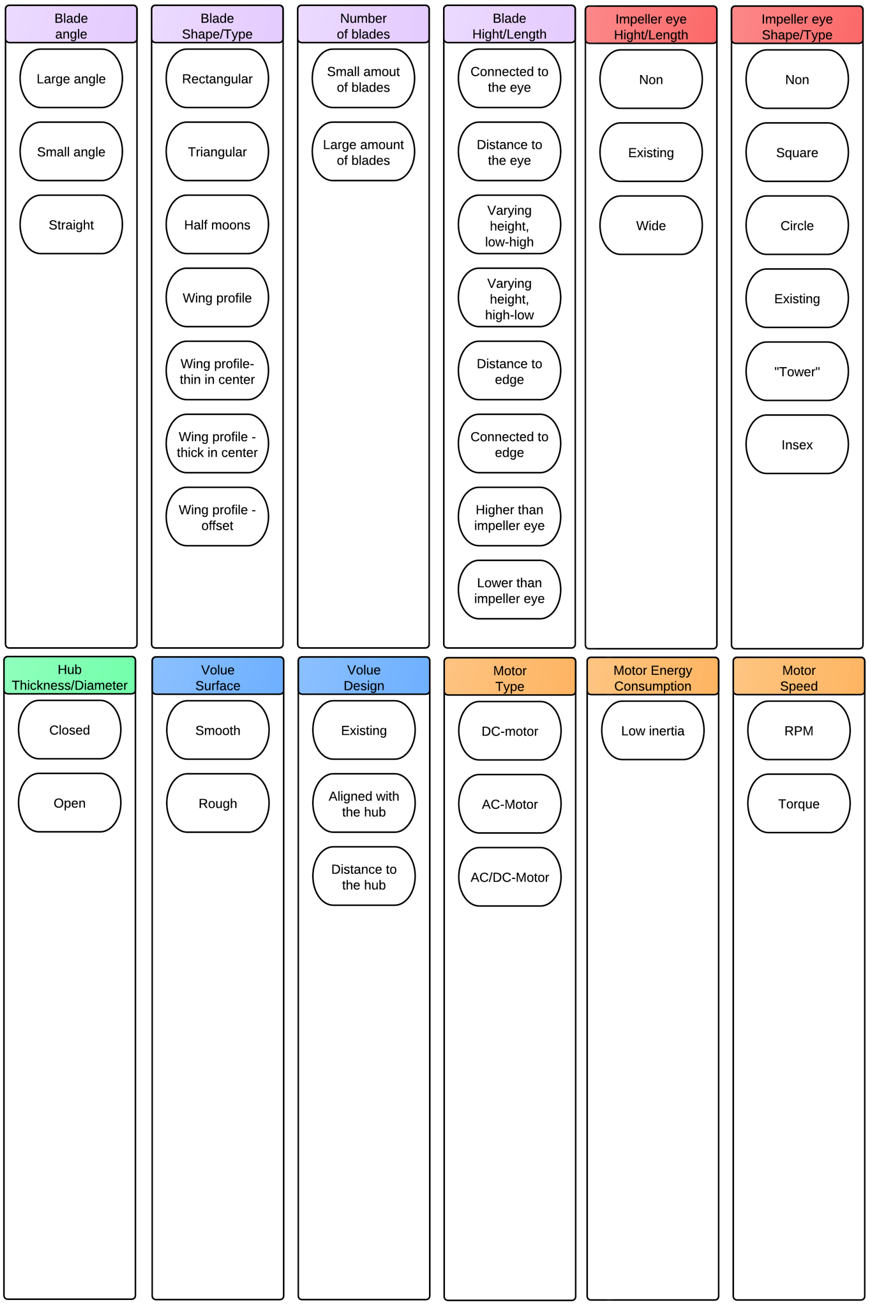


Figure 17: The main function, *Wash performance is changed when the centrifugal pump is changed*, is divided into sub-functions and its responsible components.



Blade angle	Blade Shape/Type	Number of blades	Blade Hight/Length	Impeller eye Hight/Length	Impeller eye Shape/Type
Large angle	Rectangular	Small amout of blades	Connected to the eye	Non	Non
Small angle	Triangular	Large amount of blades	Distance to the eye	Existing	Square
Straight	Half moons		Varying height, low-high	Wide	Circle
	Wing profile		Varying height, high-low		Existing
	Wing profile- thin in center		Distance to edge		"Tower"
	Wing profile - thick in center		Connected to edge		Insex
	Wing profile - offset		Higher than impeller eye		
			Lower than impeller eye		

Hub Thickness/Diameter	Volue Surface	Volue Design	Motor Type	Motor Energy Consumption	Motor Speed
Closed	Smooth	Existing	DC-motor	Low inertia	RPM
Open	Rough	Aligned with the hub	AC-Motor		Torque
		Distance to the hub	AC/DC-Motor		

Figure 18: A cross fertilization of the sub-concepts. One concept from every section together forms a main solution - a unique concept.

4.5 Concept elimination

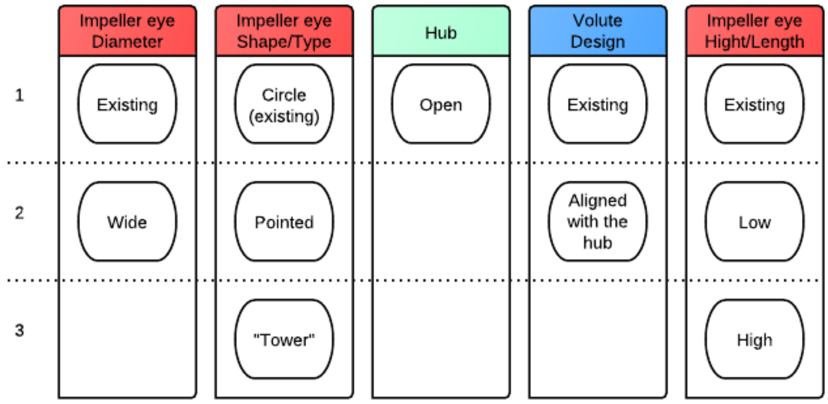
The large amount of unique concepts was to many to handle in decision matrices so some kind of limitations were needed in order to reduce them.

4.5.1 Limitations

Based on the pilot study and the interviews, following limitations were defined:

- Since the drop of wash performance had occurred when the design of the impeller eye was changed, and the design of the impeller blades creates a lot of concepts, one limitation was to let the impeller blades be remained as the original. Therefore no changes in blade angle, shape/type, high/length were done and also the number of blades remained unchanged.
- Restrictions for the volute design were also defined, in order to reduce the amount of concepts. The roughness of the surface was not considered due to the fact that it has already been investigated by Asko Appliances, and they have been running surface tests. Instead, the gap between the end of the impeller blade and the wall of the volute was considered, but only by increasing the impeller diameter and therefore not decreasing the volute diameter.
- The impeller is restricted to an open impeller.
- Change of the motor was not considered because the project would then be large, and the sound from the motor might affect the total sound level of the dishwasher. Tests for sound verification would have been too time consuming.

With stated limitations a new, reduced, Morphological matrix could be set up, see Figure 19.



	Impeller eye Diameter	Impeller eye Shape/Type	Hub	Volute Design	Impeller eye Hight/Length
1	Existing	Circle (existing)	Open	Existing	Existing
2	Wide	Pointed		Aligned with the hub	Low
3		"Tower"			High

Figure 19: The reduced Morphological matrix with five different sections. The numbers on the left side of the table were used to name every different concept.

The new matrix returned 36 main concepts, but combining a *wide impeller eye diameter* and the impeller eye shape *tower*, the difference was so small that they were not considered. In that way the remaining concepts were reduced to 30 concepts, named with five digits. Every digit represents a sub-solution from a section in the reduced Morphological matrix.

Table 8: The names of the concepts are defined by five digits, representing a sub-solution from a section in the reduced Morphological matrix.

Name of the concepts				
11111	12111	13111	21111	22111
11112	12112	13112	21112	22112
11113	12113	13113	21113	22113
11121	12121	13121	21121	22121
11122	12122	13122	21122	22122
11123	12123	13123	21123	22123

4.5.2 Pugh matrix

With the 30 remaining concepts, a Pugh matrix was used to eliminate the concepts further. The impeller Asko Appliances using today (11111) was set as the reference concept and the other concepts were then compared with it.

The criteria of the matrix were set as follow:

Efficiency The pressure difference, $P_{out} - P_{in}$

Performance The wash performance of the whole dishwasher

Cost The cost of the manufactured impeller

Serviceability How easy/hard it is to install and assemble the pump

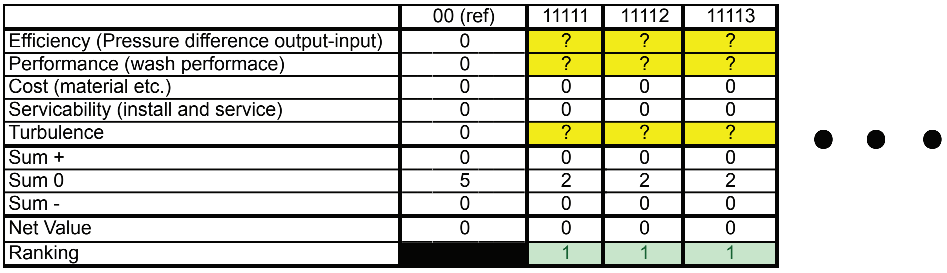
Turbulence The turbulence in the pump.

The efficiency, performance and turbulence could not be known for the concepts at this time and therefore an investigation of these had to be done. This kind of investigation was decided to be a simulation of the flow of the pump to detect the true values of the efficiency and the turbulence, and laboratory tests to find out the performance.

30 concepts could be handled in the simulation part, but not in the laboratory testing part. Therefore, the information from the simulations had to be a basis for elimination before the laboratory testing.

4.5.3 Kesselring matrix

In the same way, the Kesselring matrix could not result in anything until the simulation part was finished. In the Kesselring matrix, the criteria were weighted against each other. Every criterion was given a value of 1-10 compared to each other. In that way more correct assumptions could be done.



	00 (ref)	11111	11112	11113
Efficiency (Pressure difference output-input)	0	?	?	?
Performance (wash performace)	0	?	?	?
Cost (material etc.)	0	0	0	0
Servicability (install and service)	0	0	0	0
Turbulence	0	?	?	?
Sum +	0	0	0	0
Sum 0	5	2	2	2
Sum -	0	0	0	0
Net Value	0	0	0	0
Ranking		1	1	1

● ● ●

Figure 20: A part of the Pugh matrix without information regarding the *efficiency*, *performance* and *turbulence*. The whole matrix can be seen in Appendix D.

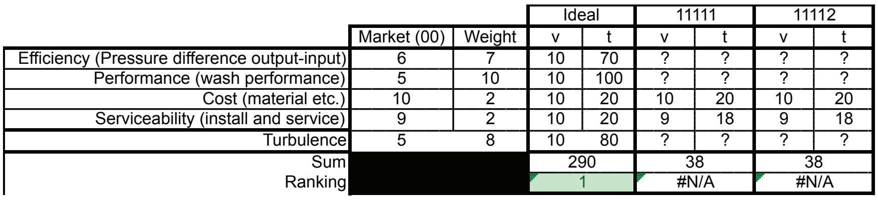
Through interviews it was found out that the higher the output pressure from the pump is, the better. Therefore efficiency was given a high value of 7. Also from the interviews it was known that it is important to generate a low turbulence in the pump. One theory from the interviews was that the turbulence might have broken the dirt into smaller pieces, which later on had passed through the net and filters and stayed on the washing-up. Therefore the turbulence criterion was given a high value of 8 (a smaller value of the turbulence resulted in a higher credit in the Kesselring matrix).

As mentioned earlier, the cost and serviceability were very much the same for all the concepts. Due to that, they could be eliminated from the matrices since they did not make any significant difference. To enable usage of these matrix later on, for Asko Appliances, they were kept and were given a small value of 2.

Performance was given the high value of 10, mostly because of the fact that the criterion corresponds with the main problem of this project.

Table 9: Summarization of the criteria and its corresponding values, which were used in the Kesselring matrix.

Criteria values	
Criteria	**Value**
Efficiency (Pressure difference output-input)	7
Performance (wash performance)	10
Cost (material etc.)	2
Serviceability (install and service)	2
Turbulence	8



			Ideal		11111		11112	
	Market (00)	Weight	v	t	v	t	v	t
Efficiency (Pressure difference output-input)	6	7	10	70	?	?	?	?
Performance (wash performance)	5	10	10	100	?	?	?	?
Cost (material etc.)	10	2	10	20	10	20	10	20
Serviceability (install and service)	9	2	10	20	9	18	9	18
Turbulence	5	8	10	80	?	?	?	?
Sum			290		38		38	
Ranking			1		#N/A		#N/A	

Figure 21: A part of the Kesselring matrix with no information regarding the *efficiency*, *performance* and *turbulence*.

4.6 Simulations

The results from the simulation acted as a base for decision making when the number of concepts were narrowed down (See Chapter 3). In order to solve and evaluate the concepts, a set up of the fluid flow case was accomplished using computer software. Post processing, using a number of different visualization and documentation tools were then accomplished.

4.6.1 Simulation set-up

In the setup of the fluid flow case, numerical values for a set of variables were needed to enable the system to be solved in Fluent. Initial conditions for the turbulence model were established on both the inlet and the outlet (See Chapter 2). The initial conditions were defined by applying the theory of turbulent intensity and hydraulic diameter, since they are easier to predict than values on the turbulent kinetic energy k and the turbulent frequency ω. Using general recommendations telling that the turbulent intensity for such a complex geometry as a rotating machinery device should be between 5-20%. The hydraulic diameter for inlet and outlet was calculated and is shown in Table 10 below.

Table 10: The hydraulic diameter of inlet and outlet

Boundary	Hydraulic diameter [mm]
Inlet	27.3
Outlet	22

The operating pressure of the pump was defined using Pascal's law, where the difference in height is the difference between the layers of the net and the pump (See Chapter 3). The value of the pressure became

$$\Delta P = 1000[kg/m^3] \cdot 9.81[m/s^2] \cdot 0.05[m] = 490.5 \approx 500[Pa] \qquad (44)$$

The boundary conditions needed to solve the system were established from the design requirement list

4.6.1.1 Mesh independent test Three different relevance centre meshes were compared with one mesh with inflations. Statistics for the four different meshes are presented in Table 12 below.

Table 11: Boundary condition for the inlet and outlet. Describes both the type and the quantity.

Boundary	Type	Numerical value
Inlet	Mass-flow	0.83 [kg/s]
Outlet	Pressure	31 [kPa]

Table 12: The number of nodes, element depending of the coarse, medium, fine and inflation settings.

Mesh accuracy	Number of nodes	Number of elements
Coarse (no inflation)	71 000	383 000
Medium (no inflation)	122 000	665 000
Fine (no inflation)	409 000	2 254 000
Medium (inflation)	622 000	2 561 000

As can bee seen in Figure 22 and 23, which shows the convergence of the solution with the coarsest and the finest mesh, the improvement of the solution is small even though the accuracy of the mesh increased a lot. As well as it is good to have a mesh independent solution, it is poor that the solution for the coarsest mesh results in nearly the same solution as the finest one.

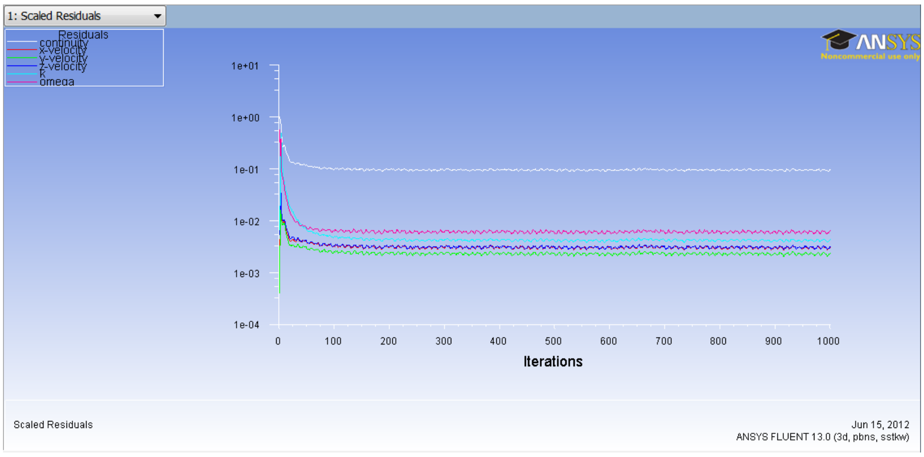


Figure 22: Residuals with the coarse mesh

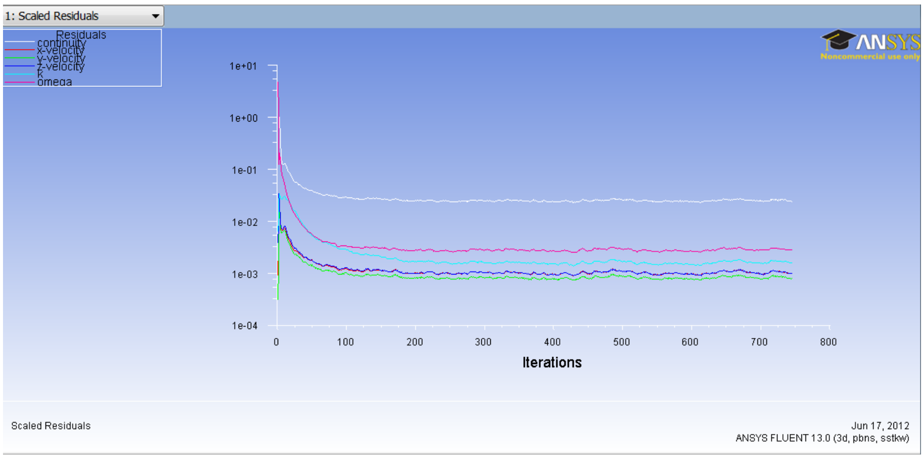


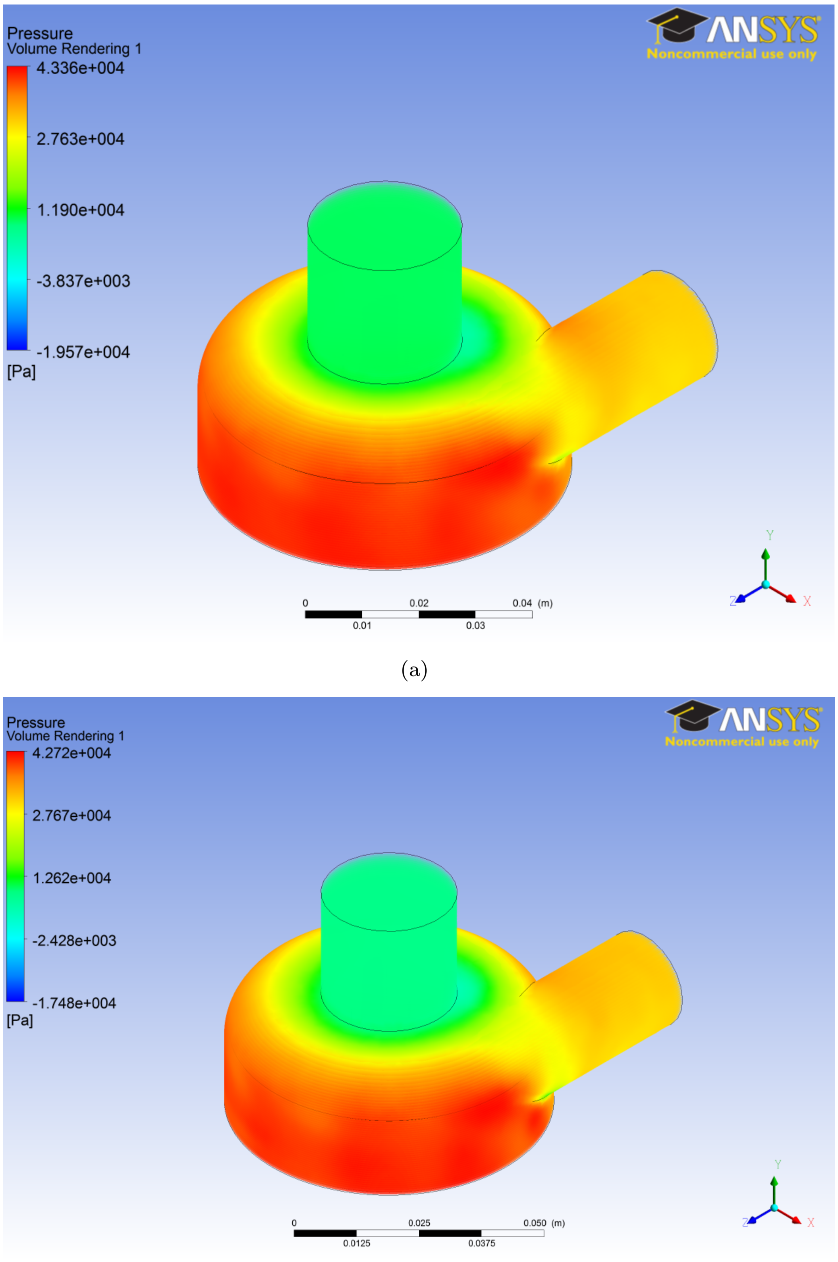
Figure 23: Residuals with the mesh with merged inflations

4.6.2 Post processing

Flow characteristics, i.e. velocity and pressure profiles of the flow in the domain, were post processed and documented, see Appendix E. But only slight differences between the concepts could be seen. To in some way evaluate the concepts the generated turbulent energy [k], where some difference between the concepts could be seen, were documented for every concept. Also some differences in the efficiency of the concepts were noticed, why it was post processed and documented.

Therefore the 30 different concepts were evaluated due to efficiency, the amount of turbulence generated by the designs and also by looking at the pressure and velocity profiles generated. In the beginning, only evaluation of the old designs were accomplished, to in some way establish the difference them between.

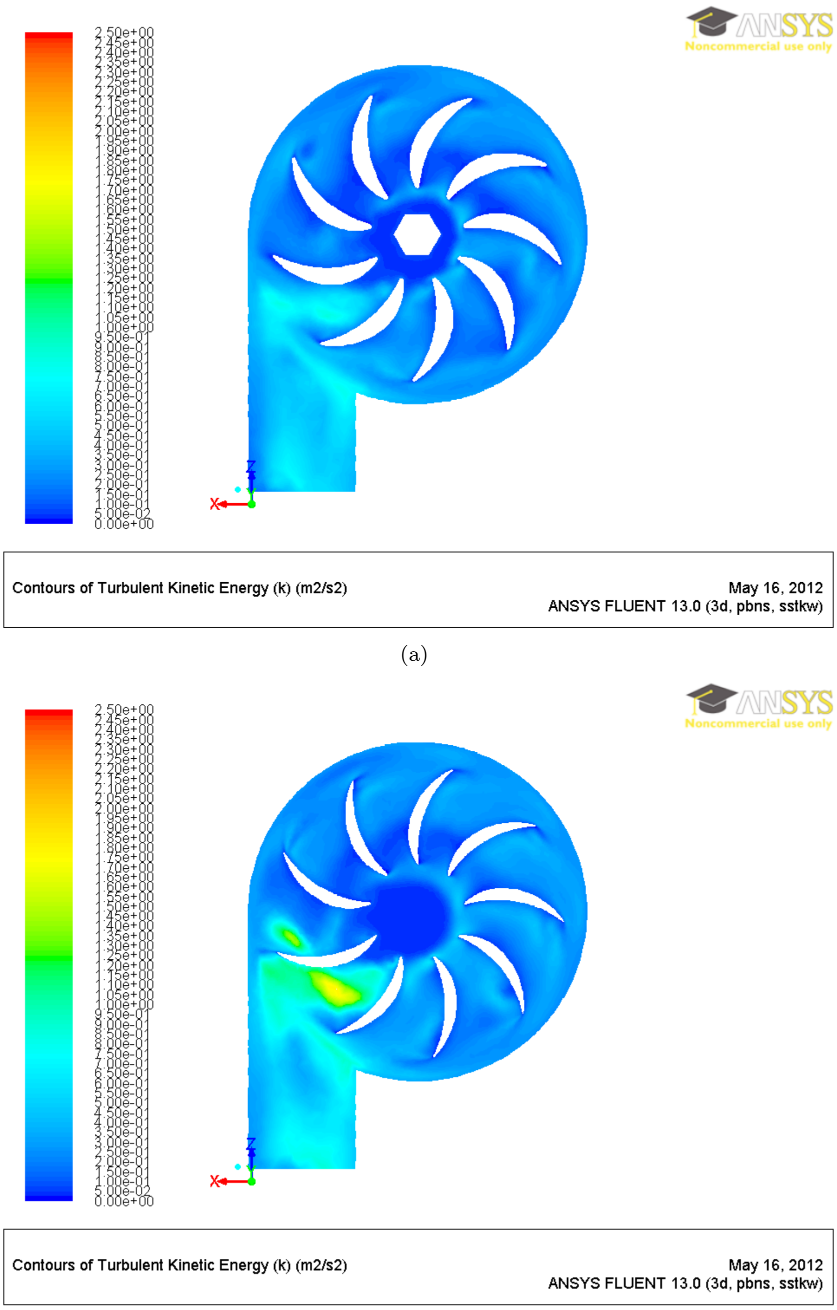
4.6.2.1 Post processing of the two old pump designs At the start the two old pumps designs (design 00 and design C) were compared, to in some way manage to establish conclusion on why they differ with respect to wash performance, using the results from the simulation. Only insignificant differences in the physical quantities (pressure and generated turbulence) could be seen in Figure 24-25, which is strange due to the fact that the difference them between in wash performance is relatively large (see Chapter 1). Figures 24-25 visualize volume rendering of the pressure [Pa] in the domain and contour plots of the turbulent kinetic energy [k] at a specific xz-plane 0.016 [m] from the bottom of the domain.



(a)

(b)

Figure 24: Volume pressure rendering of design 00 (a) and of design *C* (b).



(a)

(b)

Figure 25: Contours of the turbulence in the xz-plane, for design 00 (a), and for design C (b).

4.6.2.2 Concept results As can be seen in Figure 28, the results differs them between. For instance, the concepts 13121 and 13122 generate large turbulent kinetic energy (5.98 m^2/s^2) compared with concepts 11111 and 13113 (1.24 m^2/s^2). On the other hand the concepts with high generated turbulent kinetic energy were the most efficient working pumps.

When looking at velocity and pressure profiles of the 30 concepts, the difference is extremely small. Figures 26-27 visualize the velocity profiles for the four concepts mentioned above. The figures visualize contours on a xy-plane through the centre of the domain.

The efficiency and turbulent kinetic energy data was then used as a decision making part in the elimination matrixes (see Chapter 3)

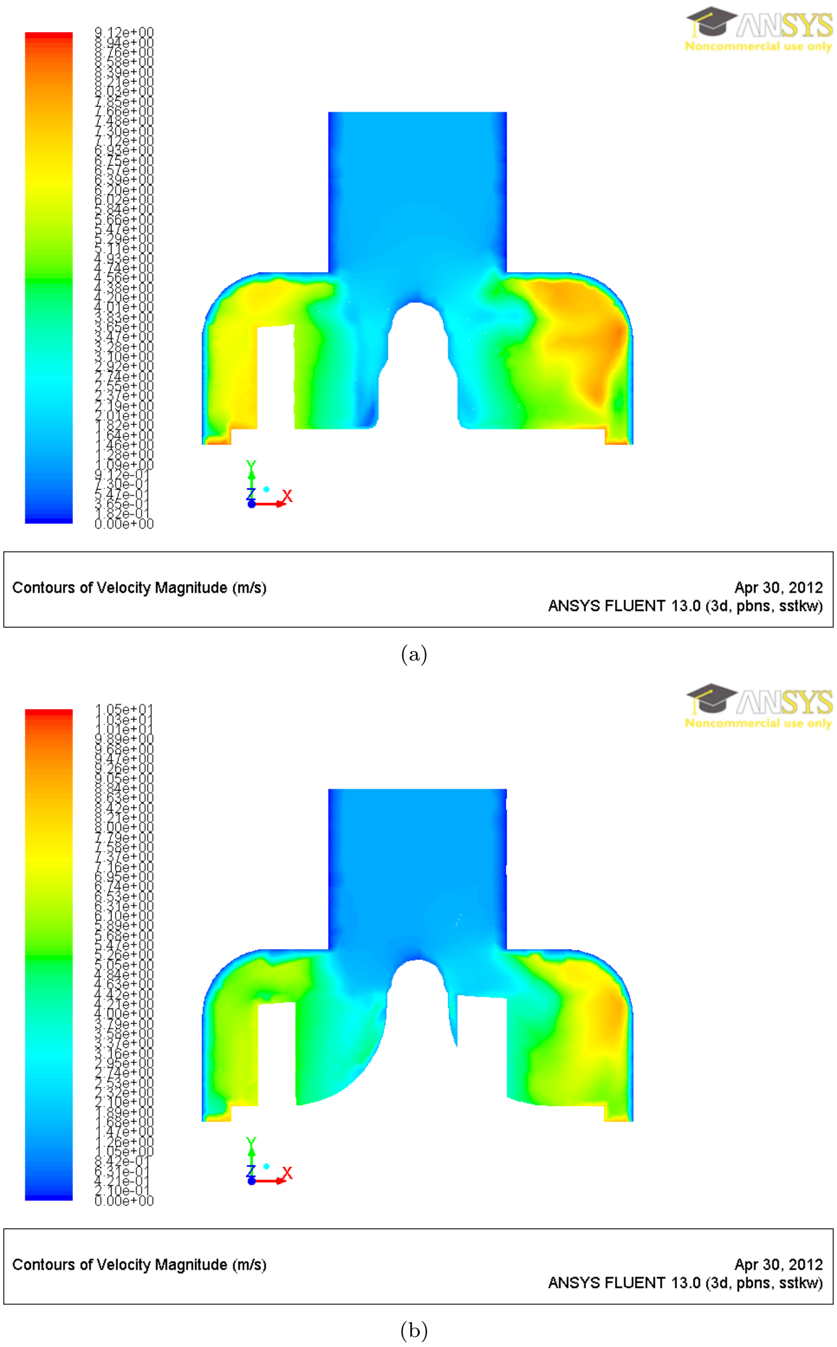
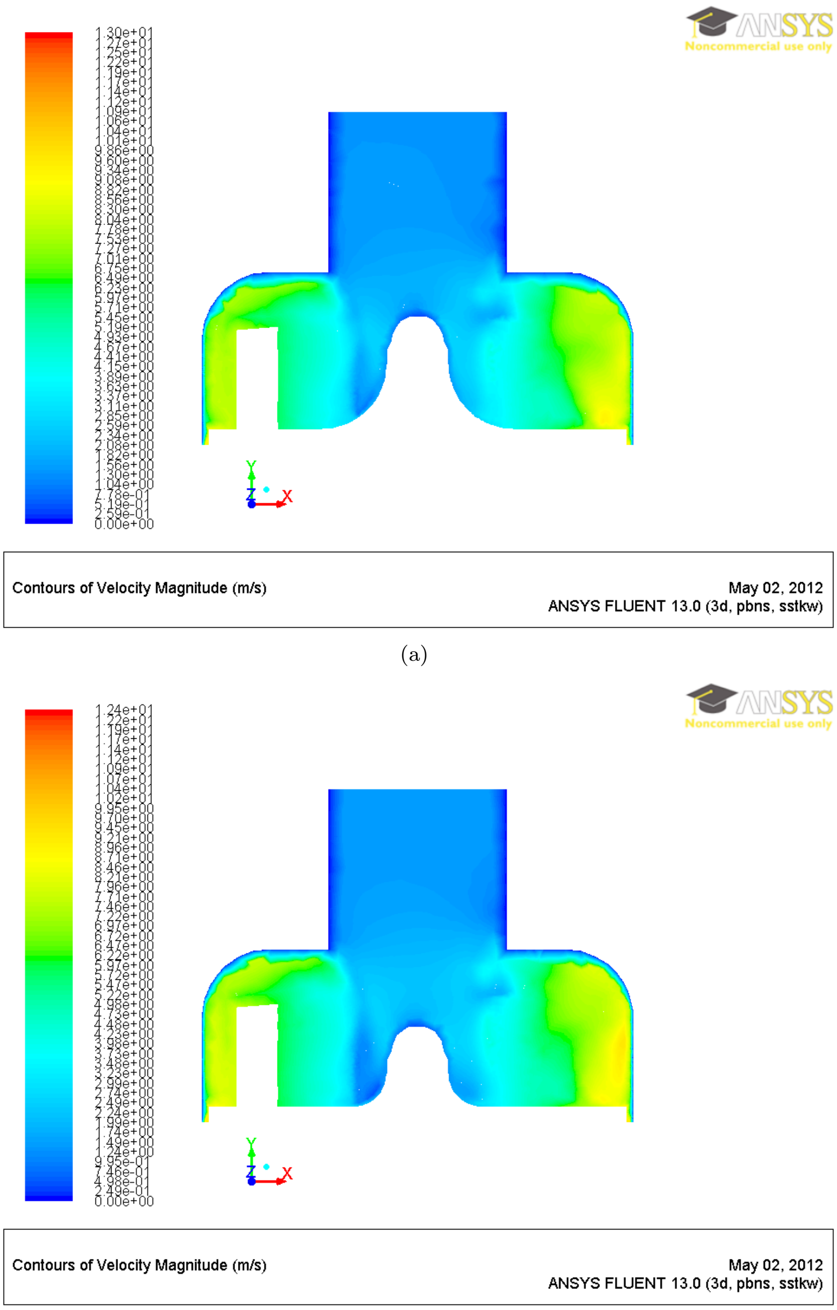


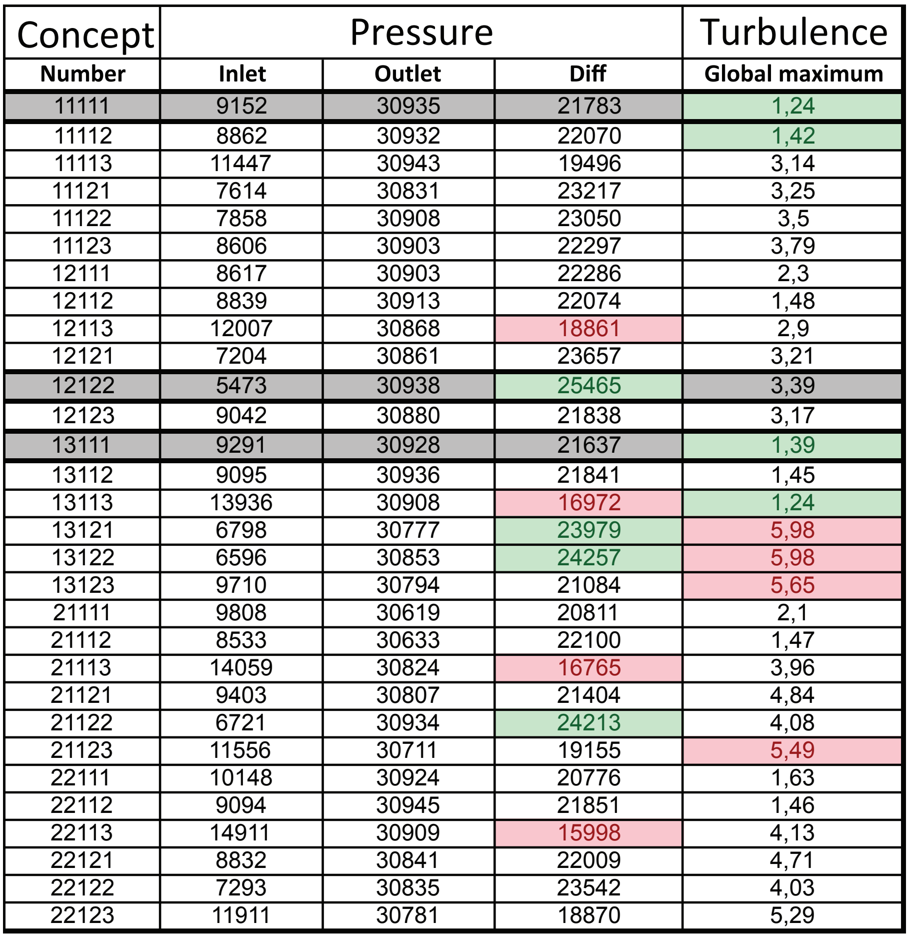
Figure 26: Velocity contour in the xy-plane for design 11111 (a) and design 13113 (b).



(a)

(b)

Figure 27: Velocity contour in the xy-plane for design 13121 (a) and design 13122 (b).



Concept	Pressure			Turbulence
Number	Inlet	Outlet	Diff	Global maximum
11111	9152	30935	21783	1,24
11112	8862	30932	22070	1,42
11113	11447	30943	19496	3,14
11121	7614	30831	23217	3,25
11122	7858	30908	23050	3,5
11123	8606	30903	22297	3,79
12111	8617	30903	22286	2,3
12112	8839	30913	22074	1,48
12113	12007	30868	18861	2,9
12121	7204	30861	23657	3,21
12122	5473	30938	25465	3,39
12123	9042	30880	21838	3,17
13111	9291	30928	21637	1,39
13112	9095	30936	21841	1,45
13113	13936	30908	16972	1,24
13121	6798	30777	23979	5,98
13122	6596	30853	24257	5,98
13123	9710	30794	21084	5,65
21111	9808	30619	20811	2,1
21112	8533	30633	22100	1,47
21113	14059	30824	16765	3,96
21121	9403	30807	21404	4,84
21122	6721	30934	24213	4,08
21123	11556	30711	19155	5,49
22111	10148	30924	20776	1,63
22112	9094	30945	21851	1,46
22113	14911	30909	15998	4,13
22121	8832	30841	22009	4,71
22122	7293	30835	23542	4,03
22123	11911	30781	18870	5,29

Figure 28: A summary of all the pressure and turbulence data of the concepts, from the simulation study.

4.7 Decisions matrices

With the result from the fluid simulations a new iteration of the Pugh and Kesselring matrix could be performed. (This time with information about the efficiency and the turbulence). Since the information from the simulation was given for all the concepts and the criteria were already weighted the Kesselring matrix was used again.

Since the interval of the criteria were between 1 and 10 it would be appropriate for the concepts to have the same interval on their properties. The intervals were divided into the following, see Table 13

Table 13: The intervals for the weighted criteria; *efficiency* (a) with the unit [Pa] and *turbulence* (b) with the unit $[m^2/s^2]$.

(a)

Efficiency	
10	>24604
9	23744
8	22883
7	22022
6	21162
5	20301
4	19441
3	18580
2	17719
1	<16859

(b)

Turbulence	
10	<1.671
9	2.102
8	2.533
7	2.964
6	3.395
5	3.825
4	4.256
3	4.687
2	5.118
1	>5.549

With the weighted criteria and the result from the simulations, a new Kesselring matrix was accomplished, see Figure 29. The new matrix returned 7 concepts, which were better than the rest.

	Market (00)	Weight	Ideal		11111		11112		11121		11122		11123		12111		12112	
			v	t	v	t	v	t	v	t	v	t	v	t	v	t	v	t
Efficiency (Pressure difference output-input)	6	7	10	70	6	42	7	49	8	56	8	56	7	49	7	49	7	49
Performance (wash performance)	5	10	10	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cost (material etc.)	10	2	10	20	10	20	10	20	10	20	10	20	10	20	10	20	10	20
Serviceability (install and service)	9	2	10	20	9	18	9	18	8	16	8	16	8	16	9	18	9	18
Turbulence	5	8	10	80	10	80	10	80	6	48	5	40	5	40	8	64	10	80
Sum			290		160		167		140		132		125		151		167	
Ranking			1		4		2		14		15		18		10		2	

12121		12122		12123		13111		13112		13121		13122		13123		21111		21112	
v	t	v	t	v	t	v	t	v	t	v	t	v	t	v	t	v	t	v	t
8	56	10	70	6	42	6	42	6	42	9	63	9	63	5	35	5	35	6	42
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	20	10	20	10	20	10	20	10	20	10	20	10	20	10	20	10	20	10	20
9	18	8	16	8	16	9	18	9	18	8	16	8	16	8	16	9	18	9	18
6	48	5	40	6	48	10	80	10	80	1	8	1	8	1	8	9	72	10	80
142		146		126		160		160		107		107		79		145		160	
13		11		17		4		4		20		20		24		12		4	

21113		21121		21122		21123		22111		22112		22113		22121		22122		22123	
v	t	v	t	v	t	v	t	v	t	v	t	v	t	v	t	v	t	v	t
1	7	6	42	9	63	3	21	5	35	6	42	1	7	5	35	8	56	3	21
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	20	10	20	10	20	10	20	10	20	10	20	10	20	10	20	10	20	10	20
9	18	8	16	8	16	8	16	9	18	9	18	9	18	8	16	8	16	8	16
4	32	2	16	4	32	1	8	10	80	10	80	4	32	2	16	3	24	1	8
77		94		131		65		153		160		77		87		116		65	
25		22		16		27		9		4		25		23		19		27	

Figure 29: The new Kesselring matrix with weighted criteria and result from the simulations.

When looking closer on the data generated from the simulations, the turbulence was noted to increase when the impeller diameter increased. Since the simulations only had been calculated with two different radiuses, it was decided that the simulations would carry on with concept 11111, since that concept had the lowest turbulence, and change its radius such as the minimum would be found.

4.8 Simulations with different radius

The simulation was defined in the same way as the earlier ones but this time with domains corresponding to different radius of the impeller. The radius can be seen in Table 14.

Simulations were made out of the radius and their turbulences were returned and can be seen in Figure 14. The returned turbulences an existing minimum in the interval of the radiuses. The lowest value returned was 0.84 m^2/s^2 at 27.25 mm of radius, which is a lot smaller than the original impeller. A graph that describes the result can be seen in Figure 30.

Table 14: Radius of the tested impellers and its corresponding turbulences.

Radius [mm]	Turbulence [m^2/s^2]
26.5	1.45
27.25	0.84
28	0.926
28.5	1.24
29.5	2.98
30.5	2.9
32	3.25

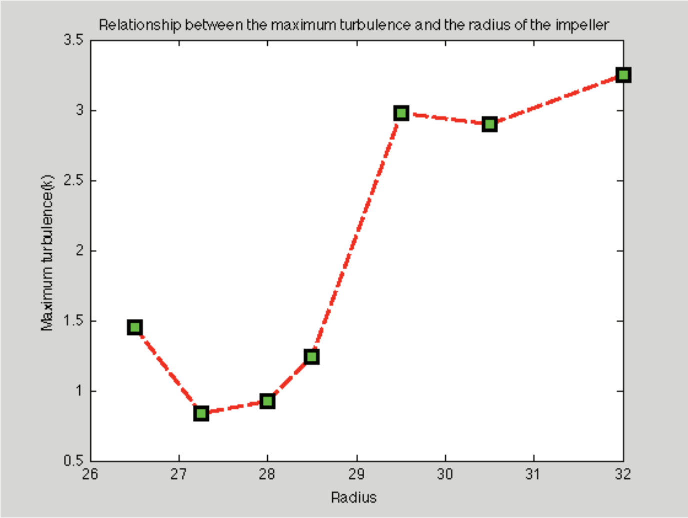


Figure 30: A graph of the values from the Table 14, turbulence-radius

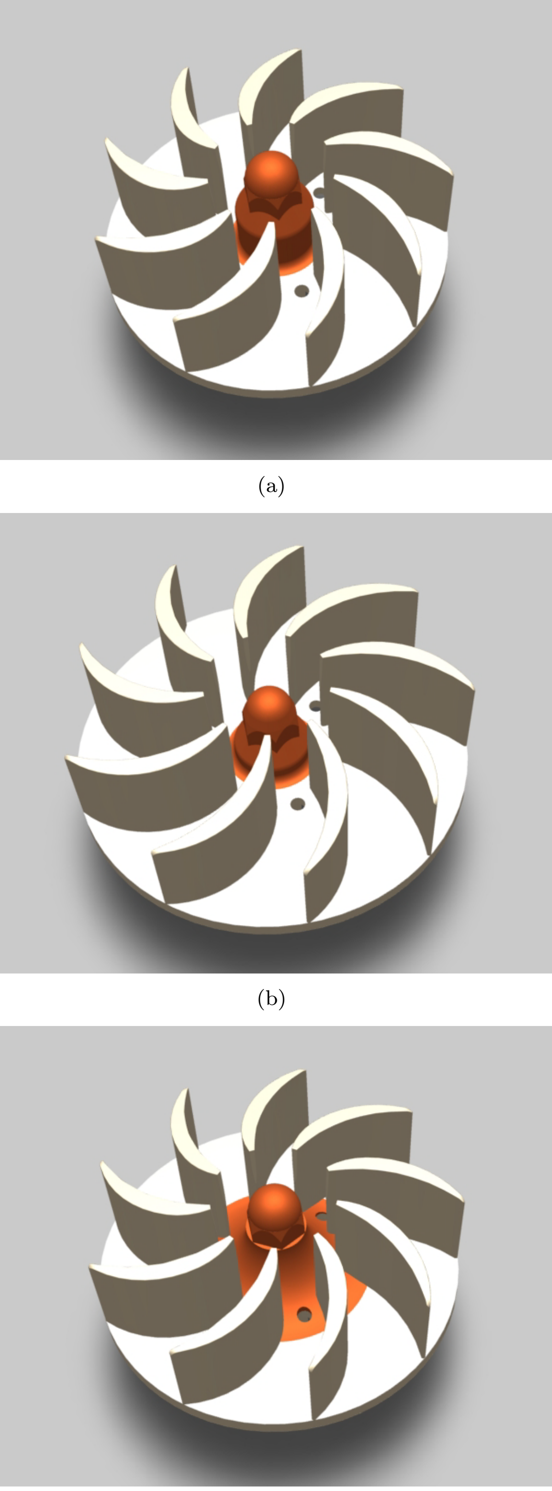
4.9 Concepts for rapid prototyping

To be able to decide which concept that would be the final product, laboratory tests had to be made to decide the wash performance. Three concepts were chosen to be manufactured based on the CFD simulations, through rapid prototyping, and later on be tested in the test laboratory at Asko Appliances. It was important that the chosen concepts could represent a big range of the 30 concepts. In that way the results from the three tested concepts could be applied on the concepts that were not tested.

11111 with 27.25 mm of impeller radius The concept was placed in the top of the Kesselring matrix because of its low turbulence. After some modifications on its impeller radius the turbulence had dropped even more. Therefore it was chose to be tested in the laboratory and represent those concepts with a low turbulence.

12122 This concept was not placed in the top of the Kesselring matrix but was chosen to be tested because of its representation of high efficiency. In that way the effect from the efficiency on wash performance would be obtained. If the wash performance would be better a reconsideration of the weighted criteria would be beneficial.

13111 This concept was placed in top of the Kesselring matrix and is also chosen because of its design at the water entrance. The entrance to the impeller blades for the water is smooth, which was appreciated from the interviews in the beginning of the project.



(a)

(b)

(c)

Figure 31: The concepts that proceeded to laboratory tests, $11111_{27.25mm}$ (a), 12122 (b), 13111 (c).

4.10 Laboratory tests

Laboratory tests were performed at Asko Appliances to establish the wash performance for the different prototypes (11111_{2725mm}, 12122, 13111). Due to time limit only one prototype was tested. The prototype that was chosen to be tested was the design of 11111_{2725mm}. In that way the effect from the turbulence on the wash performance would be obtained.

The prototype was tested three times under European circumstances. The tests were compared with a reference dishwasher using the ordinary centrifugal pump. The turbulence could not be measured in this kind of tests and therefore the flow simulations could not be validated.

Result from the three tests showed an increase of wash performance for the dishwasher of $4-5\%$ when the prototype, representing 11111_{2725mm}, was tested, compared to the original centrifugal pump. In the same tests the efficiency of the dishwasher dropped $4-5\%$. Note that the efficiency of the dishwasher not has to be the same as the efficiency of the centrifugal pump. The efficiency of the dishwasher is represented by its energy consumptions while the efficiency of the pump is defined by the different in pressure between the outlet and inlet.

4.11 Final design

Since not all the prototypes were tested a final design could not be decided. More tests were needed to make assumptions about the efficiency and the design on the inlet. At that point the only knowledge was that a prototype generating a lower turbulence in the centrifugal pump had an improvement of $4-5\%$ in wash performance. The prototype could therefore be assumed to be the final design since it solves the main aim. But another design could result in a better wash performance due to other criteria. Therefore the prototype cannot be defined as the final design.

5 Discussion

The aim of this project was to develop a centrifugal pump with improved wash performance compared to the pump used in Asko Appliances dishwashers today. The last step in the evaluation process was to test the wash performance of the concepts, since the wash performance was defined as the most important property of the pump. Due to time limits the concepts were not tested to desired extent.

Only one of the three chosen concepts, concept 11111_{2725mm} that generated the lowest turbulence in the CFD-simulations, was tested. It was tested three times following the European standard. The results proved an improvement of $4-5\%$ of the wash performance compared with the old design. It was also denoted that the efficiency of the dishwasher dropped with $4-5\%$ compared to the old one.

To some extent it can therefore be said that the aim is fulfilled, the tested prototype performed better, due to wash performance, than the pump used today. Anyhow, it is not clarified that the tested prototype is better than the two other prototypes that represented other designs and properties.

One sub-goal was to gather deeper knowledge of which parameters that affects the wash performance in a dishwasher. During the project it came clear that it is difficult to determine the wash performance, and that physical testing is needed to do so. Even though it could be seen in the tests that a concept generating low turbulence increased the wash performance, it cannot be stated how the turbulence affect the wash performance.

The simulations of the concepts also played a major role. Not only was it a tool for elimination of concepts, it was a way to understand how different parameters affect the wash performance and also to save money and time (since not all concepts needed to be tested in the laboratory). Due to the complexity of the wash performance, the best results would be obtained by testing all the concepts at Asko Appliance's test laboratory. On the other hand, no information regarding efficiency and turbulence would have been given.

Cavitation was something that was investigated a lot in the beginning of the project (pilot study and interviews), but it was not investigated properly in the simulation process, since it was too time consuming. If it would have been included in the simulations a new criterion could have been added to the decision matrices and further returned a better elimination, depending on how much the cavitation affected the wash performance.

The result is not fully trustworthy for two reasons. They converge poorly and the mesh independency showed no improvement of the convergence when increasing the mesh accuracy. The simulations also need to be validated through testing of physical parameters, to see how they correspond to the actual case. Since only wash performance was tested in this project the validation could not be accomplished. However, the simulations to some extent, tells how the different concepts performs in terms of efficiency and turbulence, and Asko Appliances can use the simulation methodology that has been accomplished in the future.

Only small differences in physical parameters were seen between the two old pump designs when comparing the simulation outcome them between. This is strange due to the difference in wash performance them between. The simulation process proceeded with analyzes of the 30 concepts. The difference them between were also small, but some differences in the critical parameters efficiency and turbulence could be seen. Due to the bad convergences this result should be used carefully, and preferable not be used until proper simulations with more accurate convergence have been performed.

CFD simulations are heavy and demand a lot of computational force, therefore restrictions concerning the simulations were established in order to make the problem solvable. It is healthy to treat these restrictions as computational errors in the simulations, since they decrease the accuracy of the result, in order to evaluate the performance of the simulations in a proper way.

The use of a two-equation turbulence model must be seen as an acceptable method for modeling of the turbulence. Nevertheless it is a simplification and need to be dealt as an potential error. The decision of choosing the SST k-ω model in front of more advance models nevertheless can be considered as a valid choice due to the limited time and computer resources available in this project.

The MRF method is a frozen rotor approach, and is therefore not as accurate as the sliding mesh method. This project is in an early stage of analyzing flow in centrifugal pumps using CFD simulations at Asko Appliances, why the team felt it was also important to reach an solution with the purpose of increasing knowledge about the pump's flow characteristics and therefore not aiming towards an exact solution. Therefore the choice of the MRF method in front of the Sliding mesh method is accurate. Also, this choice was decided due to the restricted resources.

A lot of different settings in the ANSYS Meshing software were considered, but focus was on the relevance center. Refinement of the mesh was done both by changing the relevance center from coarse via medium to fine, but also by using specific tools for refinement, such as the inflation tool. The mesh independency test failed, or, the result did not improve when the accuracy of the mesh increased. This can be seen as the worst error source, since a proper mesh is required when solving CFD problems. The team did not manage to solve the problem, why it was decided to proceed with a poor mesh. The team thinks that the poor mesh probably is the reason why the simulations converge badly.

The boundary conditions were defined in a proper way since they were based on values defined in the design requirement list. The velocity at the inlet was calculated knowing the required mass flow through the pump while the pressure at the outlet was determined knowing the pressure in the coils arms. The boundary conditions can therefore be seen as accurate.

The decision of using the turbulent intensity and hydraulic diameter instead of the actual parameters k and ω when defining the initial conditions for the turbulence model was valid due to the fact that it was much easier to predict accurate values on those. The defined operating pressure was based on the fact that there is a difference in height between the strainer and the pump. This is an large uncertainty since it not considering the atmospheric pressure. More time investigating the operating pressure should have been done.

No further investigation of how solver related settings affected the outcome was performed. The defined settings were kept during the whole process since they already in the beginning were defined on an accurate level.

Not enough time was spent on connecting the simulation outcome to the fundamental theory of a centrifugal pump. In order to understand the outcome to a greater extend this would have been preferable.

The best result would have been obtained by testing all concepts, due to the complexity of the wash performance. It was not possible to evaluate the wash performance in the CFD simulations. Although the number of uncertainties in the simulation process, it anyway, provides a good alternative to physical testing since it much less money and time consuming.

Another sub-goal was to define a structured methodology that Asko Appliances can use in the future to evaluating their pumps, both by applying a product development approach and CFD simulations. The project applied a product development approach, which means that methods and tools to achieve the most suitable concept were used. In that point of view the process was very efficient.

Since the decisions matrices, Pugh and Kesselring, were used as elimination tools, uncertainties always occurs. Since assumptions are made and applied on the concepts, wrong assumptions can affect the result a lot and the elimination can be false. The knowledge of the wash performance for the concepts was not known before the laboratory tests. Therefore some concepts might have been eliminated too early. They might have given a very good result in the testing, which not could be proved since they performed badly in the simulations and were not chosen for the testing.

In the matrices, one of the criteria was wash performance. That criterion can be widely discussed whether it belongs there or not. Since the criterion also is the aim of the project, to improve the wash performance, it should not be in the matrices. But on the other hand, it is a criterion that can be measured and the matrices are meant be used in further development too. In that future development work, the criterion has not to be the aim and therefore it is good to keep it in the matrices.

Interviews were performed with experts in different fields, connected to dishwashers, at Asko Appliances. Since the interviewees had discussed the problem regarding the change of sub-contractor earlier, it was hard to get them think outside the previous discussion. Interviews should therefore also have been performed on experts that had not worked with this problem earlier, e.g. other companies or newly recruited employers at Asko Appliances.

In the pilot study, no information of centrifugal pumps connected to wash performance was obtained. Therefore it is very hard to relate the study to other studies.

The use of a product development approach, together with CFD simulations, was a good way of attacking this kind of problem. However, the scope was too extensive for this kind of project, which made it hard to find the best solution due to the restrictions that had to be done.

6 Conclusion

The tested concept, 11111_{2725mm}, performs better than the centrifugal pump used today, in terms of wash performance. However, it is not clarified that this concept is the best one. A more comprehensive testing is needed in order to determine which of the three concepts that is the best.

Due to its complexity, wash performance need to be obtained using physical testing. No relationships between physical parameters and wash performance have been obtained. Nevertheless it was seen that a concept generating low turbulence resulted in an increased wash performance, compared to the old centrifugal pump.

The CFD simulations are not trustworthy because of two reasons. The convergence is poor, which means that the result is not reliable. The simulations also need to be validated through testing of physical parameters, to see how they correspond to the actual case in reality.

The use of a product development approach, together with CFD simulations, was a good way of attacking this kind of problem. However, the scope was too extensive for this kind of project, which made it hard to find the best solution due to the restrictions that had to be done.

The best result would have been obtained by testing all concepts. However, that would have been to costly and time-consuming, as simulations is a good alternative to the tests.

7 Recommendations

An improvement of wash performance occurred when the prototype, generating low turbulence, was tested. It was only tested three times, which is a small sample, and should therefore be continued tested by Asko Appliances. Also test should be done on a prototype that generates a high turbulence in the pump. In that way better assumptions can be made on the effect from the turbulence parameter.

The project also suggested tests of two other prototypes, representing high efficiency of the pump and a smooth entrance for the water into the pump. Due to time limit they could not be tested within the project and therefore it is highly recommended to do that after the project.

A recommendation is also to develop the laboratory test procedure such as physical parameters can be monitored more closely. In that way CFD simulations can be validated and the parameters can compare more closely towards the wash performance.

Due to the CFD simulations more accurate simulations should be performed in the future to obtain the flow through the pump. In this project, no proper validations have been done on the simulations and the iterations in the simulations have not been enough to reach the recommendations regarding residuals. However, the project still recommends Asko Appliances to start using fluid simulations to obtain crucial parameters when designing their centrifugal pumps.

A Kesselring matrix was produced by the project for future work at Asko Appliances. It can be used to evaluate concepts and the project highly recommends extending its criteria and changing the values of the criteria depending on the centrifugal pump that is to be designed. The project did not include a research regarding the dishwasher market and Asko Appliance's competitors. Such a research would be beneficial and is recommended for future development.

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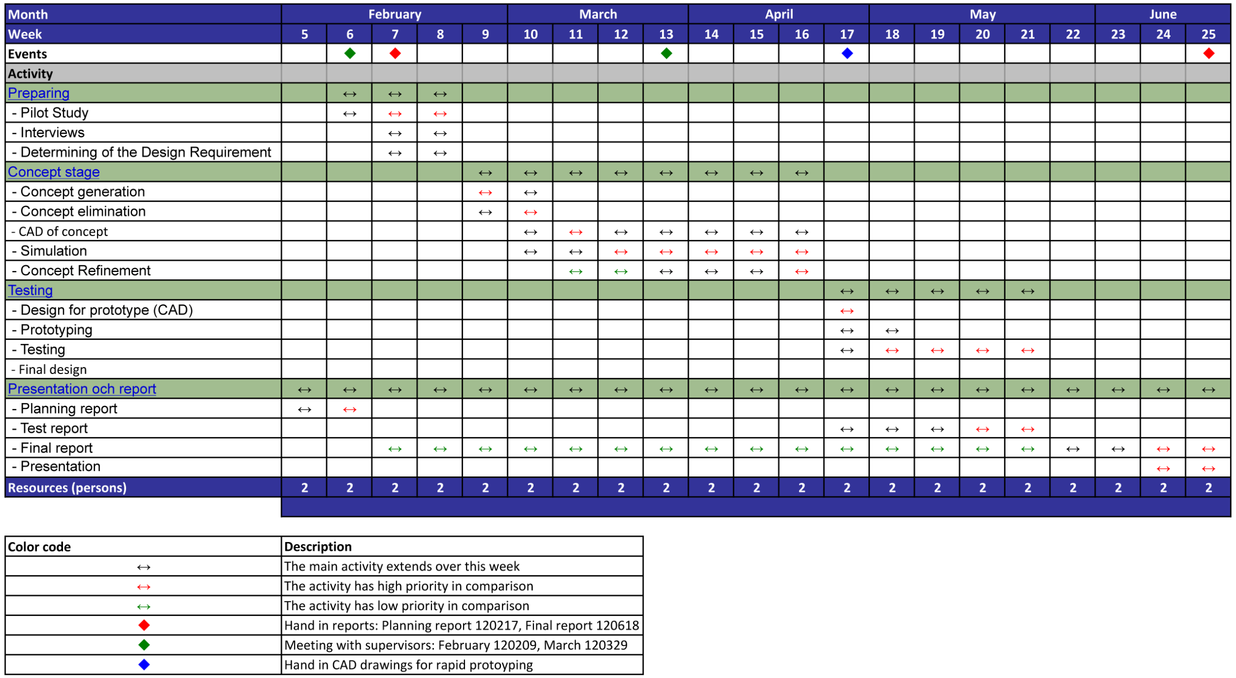
Appendix

A Gantt Chart

Time plan - Optimering av cirkulationspump



Month	February					March				April				May					June		
Week	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Events		◆	◆						◆				◆								◆
Activity																					
Preparing		↔	↔	↔																	
- Pilot Study		↔	↔	↔																	
- Interviews			↔	↔																	
- Determining of the Design Requirement			↔	↔																	
Concept stage					↔	↔	↔	↔	↔	↔	↔	↔									
- Concept generation					↔	↔															
- Concept elimination					↔	↔															
- CAD of concept						↔	↔	↔	↔	↔	↔	↔									
- Simulation						↔	↔	↔	↔	↔	↔	↔									
- Concept Refinement							↔	↔	↔	↔	↔	↔									
Testing													↔	↔	↔	↔	↔				
- Design for prototype (CAD)													↔								
- Prototyping													↔	↔							
- Testing													↔	↔	↔	↔	↔				
- Final design																					
Presentation och report	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔
- Planning report	↔	↔																			
- Test report													↔	↔	↔	↔	↔				
- Final report			↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔	↔
- Presentation																				↔	↔
Resources (persons)	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2

Color code	**Description**
↔	The main activity extends over this week
↔	The activity has high priority in comparison
↔	The activity has low priority in comparison
◆	Hand in reports: Planning report 120217, Final report 120618
◆	Meeting with supervisors: February 120209, March 120329
◆	Hand in CAD drawings for rapid protoyping

B Interviews

Notes from interviews at Asko Appliances 2012-03-01

- Today the assembly process consist of a threaded shaft to connect the the impeller with the motor. This is a good process that should be preserved.
- Hard to make the impeller eye smaller than the C model. Then it is going to be hard to assemble. It is okay to make it bigger. Prefer that the interface is preserved.
- The assembly process is preformed before the delivery to Asko Appliances. The assembly process is good and therefore no focus should be on changing that.
- The geometry of the volute should be kept unchanged.
- Completely smooth surface on the volute does not work out good. Less turbulence are created with rough surface.
- The RPM of the motor is 2700.
- An increase of pressure is not always a benefit for the wash performance. Sometimes the result is better with a lower pressure. The spray arms might spin to fast which might result in a bad wash performance.
- There are no requirements on the sound level from the centrifugal pump, but there are requirements on the whole dishwasher. The sound is very important!
- There are no maintenance on the centrifugal pump. If the pump is not working correctly it will be replaced.
- Impeller and volute is usual made in plastic, no sub-contractor offers anything else.
- The transparent volutes might be tested with stroboscope.
- When the reduction of performance was noted, Asko looked back on their five latest impellers and noted that they all had a higher impeller eye.
- The pressure out of the pump and the spin rotation of the washing arm had the same data on the new pump. Therefore it took month to discover the difference in impeller eye due to the wash performance.
- The impeller blades should be thinner at the centre of the impeller, so that water can enter the pump easier.
- A smaller impeller eye might result in a higher turbulence flow.
- In theory, the cavitation is reduced with a larger diameter of the impeller eye. Maybe the result would be similar if the blades entered the small diameter impeller eye.
- If the pressure is to high on the outlet it will result in fast spinning arms. That might result in creation of foam in the dishwasher. Not good!

- No corrode damage has been noted in the pump due to either cavitation or dish soap.
- Smoother surface on the volute result in a more turbulence flow. A rough surface results in a less turbulence flow. How rough the surface is supposed to be for optimal flow is not investigated.
- When tests were made with increased amount of impeller blades the motor had problem to spin as specified.
- The output angle of the impeller blades is important.

C Specification

Specification – Investigation and Development of a centrifugal pump

Distribution

Project group	**External people**
Robin Höstman	Lars Lindkvist, examiner
Rickard Dahl	Patrik Ivarsson, supervisor Asko Appliances
	Anders Forslund, supervisor Chalmers

Revision History

Revision	**Author**	**Date**	**Description**
1	Robin Höstman	2012-02-24	First draft

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0 Requirement log

0.1 Requirements List

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2.3.2v1 The rotation velocity of the centrifugal pump
2.3.3v1 Wash result
2.3.4v1 Efficient pump
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0.2.1 New requirements

0.2.2 Updated requirements

0.2.3 Removed requirements

1 Introduction

1.1 Product Description

This design requirement list refers to a centrifugal pump in a dishwasher, developed and manufactured by Asko Appliances. The purpose of the pump is to pump the reused water to the coils arms.

1.2 Purpose

The aim of this project is to investigate which impact an impeller and its surrounding house in a circulation pump have on the wash performance in a dishwasher. Also the surface roughness will be considered. By knowing the impact the aim is to find an optimal design of the impeller and its house, for which the highest possible wash performance is obtained.

This document will help the project by setting up all the requirements needed to make the product.

1.3 Characteristics

The Document is divided into four sections:

1. List of requirements
2. Functional requirements, non-functional, Design Requirements
3. User Documentation
4. Restricted requirements

1.4 Users

This document is written by Robin Höstman and Rickard Dahl for the master thesis; Investigation and Development of a circulation pump. It is ment to be used by the authors, the supervisors and examiner.

1.5 Related equipment and local

A rapid prototyping company will manufacture the prototype and the test of it will be fulfilled in test laboratory at Asko Appliances.

1.6 Assumptions and dependencies

There will be no investigation concerning the type of pump and related motor. Other geometrical aspects that do not depend on the pump, such as angled pipes before and after the pump, will neither be considered?

1.7 Notes

Requirements with verification status ”-”, means that no tests will be made to verify the requirements.

2 Functional requirements

2.1 Safety

Priority: High

Requirements: **2.1.1v1 No leakage in the pump system**

Purpose: There cannot be any leakage in the pump system due to performance and hot water coming out from the dishwasher. There is also of big importance that no electricity comes in contact with water.

Verification: Make sure that there aren't any pressure drop, by measurement equipment, and no leaked water under the dishwasher when testing.

2.2 Economy / Mannufactory ost

Priority: Low

Requirements: **2.2.1v1 Maximum retail price**

The impeller and it surrounding volute can't be manufactured in another material than plastic.

Purpose: To keep the costs down.

Verification: -

Priority: Low

Requirements: **2.2.2v1 Budget for prototype**

Prototypes are going to be manufactured. Rapid prototyping is going to be used. Asko haven't set up any constraints due to cost. The time limit will be the crucial factor.

Purpose: To stick to the time plan of the project.

Verification: Check and make updates in the time plan every week.

2.3 Performance

Priority: High

Requirement: **2.3.1v1 Pressure acting on the centrifugal pump**

Following pressures need to be fulfilled:

Inlet: 0.5 kPa
Outlet: 31 kPa

Purpose: The specified pressure is required due to the rotation of the coils arms and the velocity of the fluid coming out from the arms. It all affects the wash performance of the dishwasher.

Verification: Sensors in the test laboratory at Asko Appliances will return the pressure.

Priority: High

Requirement: **2.3.2v1 The rotation velocity of the centrifugal pump**

The rotation velocity of the centrifugal pump requires to be:

RPM: 2700

	With a rotation velocity of 2700 RPM the actual velocity of the top of the impeller blade is equal to 1.4209 m/s.
Purpose:	The velocity of the impeller is connected to the resulting pressure of the centrifugal pump.
Verification	Sensors in the test laboratory at Asko Appliances will return the water flow.
Priority:	High
Requirement:	**2.3.3v1 Wash result**
	The wash result requires being better than with the old pump, Hanning, with a result of 1.09 in wash efficiency index.
Purpose:	To increase the efficiency of the dishwasher.
Verification:	Wash performance tests will be made in the test laboratory at Asko Appliances.
Priority:	High
Requirement:	**2.3.4v1 Efficient pump**
	The energy consumption requires being less than with the old pump, Hanning, with a result of 1.14 kWh.
Purpose:	With a more efficient pump, Asko Appliances can develop more environmental friendly programs.
Verification:	The efficiency can be tested in the test laboratory at Asko Appliances.
Priority:	High
Requirement:	**2.3.6v1 No cavitation in the system**
	The pump needs to be design so that no cavitation appears in the system.
Purpose:	Durability
Verification:	CFD simulations.
Priority:	High
Requirement:	**2.3.7v1 No vortexes in the system**
	The pump need to be designed so that no vortexes appears in the system
Purpose:	Minimize the losses in the system.
Verification:	CFD simulations.

2.4 Useage

Priority:	Medium
Requirement:	**2.4.1v1 The pump requires to cooperate with the existing motor**
Purpose:	To avoid changing the size and the design of the motor. If the pump becomes more efficient a change in motor size might be done.
Verification:	The efficiency can be tested in the laboratory at Asko Appliances. The design of the impeller and the volute will correspond to the motor design.

2.5 Standards and legal requirements

Priority: Low

Requirement: **2.5.1v1 Test standard**

Standards due to testing of the wash performance of the dishwashers

Purpose: To make comparisons of the new wash performance with other dishwashers.

Verification: Will use the standard test procedure in the test laboratory at Asko Appliances.

2.6 Maintenance

Priority: Low

Requirement: **2.6.1v1 Maintenance free when using the dishwasher at normal operation**

The centrifugal pump should not need any maintenance when the dishwasher operates normally.

Purpose: To provide a user friendly and qualitative product.

Verification: This cannot be verification to this topic due to the time frame.

2.7 Lifetime

Priority: Low

Requirement: **2.7.1v1 Lifetime**

The lifetime of the centrifugal pump shall be at least the lifetime of the whole dishwasher, 20 years.

Purpose: To provide a qualitative product.

Verification: This cannot be verification to this topic due to the time frame.

2.8 Materials

Priority: High

Requirement: **2.8.1v1 Impeller and volute are not allowed to corrode**

The impeller and volute need to be made out of a material that doesn’t corrode with contact to water.

Purpose: Lifetime and Quality

Verification: The material properties

Priority: High

3 Design Requirements

3.1 Geometry

Priority: High

Requirement: **3.1.1v1 Geometrical constraints**

The new pump can’t exceed the dimensions of the current pump.

Purpose: In order to fit into the current dishwasher.

Verification: Compare with the old pump

3.2 Prototype

Priority: Low

Requirement: **3.2.1v1 Rapid prototyping**

The prototype will be manufactured through a rapid prototyping company.

Purpose: Timesaving and economy.

Verification: Receipt from the rapid prototyping company.

3.3 Safety

Priority: Low

Requirement: **3.3.1v1 The pump should not be dangerous to install**

Purpose: Safety

Verification: Same installation procedure as the old pump.

3.4 Usage

Priority: Low

Requirement: **3.4.1v1 The pump should not affect the user**

The user should not be required to do maintenance on the pump

Purpose: The pump should be user friendly

Verification: This cannot be verification to this topic due to the time frame.

3.5 Quality

Priority: High

Requirement: **3.5.1v1 Strength**

The centrifugal pump should not fail due to strength conditions.

Purpose: To provide a sustainable and qualitative product

Verification: FEM analysis in ANSYS.

Priority: Medium

Requirement: **3.5.2v1 Lifetime**

The lifetime of the centrifugal pump shall be at least the lifetime of the whole dishwasher, 20 years.

Purpose: To provide a qualitative product

Verification: This cannot be verification to this topic due to the time frame.

4 User Documentation

Simulations will be made in the CFD software Ansys. These simulations will be used for verification of losses and durability. Also FEM analysis will be made in Ansys for verification of the sustainability of the pump.

Tests of the wash performance will be made at Asko Appliances test laboratory for verification of wash result, efficiency, water consumption etc.

5 Design and implementation constraints

5.1 Design

Priority:	Medium
Requirement:	**5.1.1v1 Sound level**
	The vibrations from the motor should not be connected to the cover of the dishwasher.
Purpose:	Time constraints
Affect the requirement:	**3.1.1v1 Geometrical constraints**

5.2 Implementation

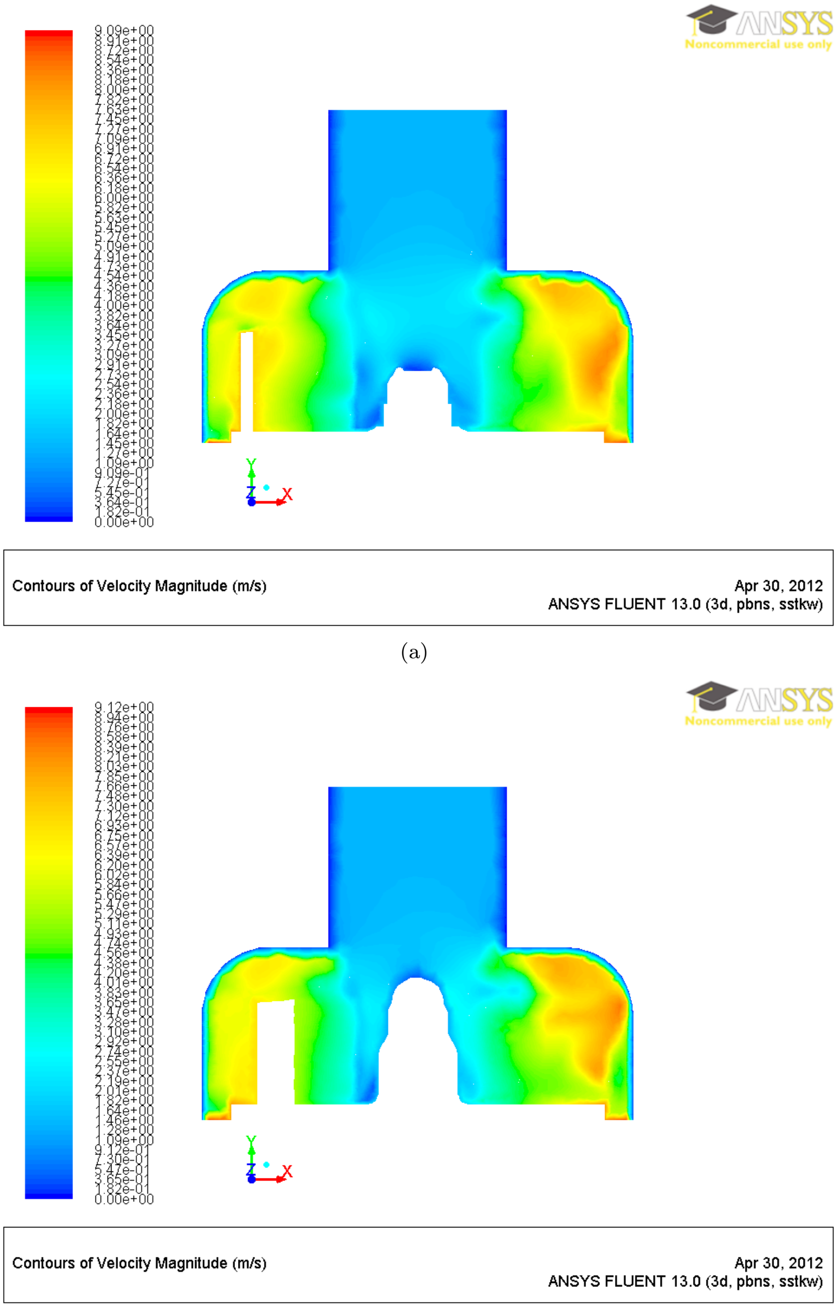
Priority:	Medium
Requirement:	**5.2.1v1 Sound level**
	The sound level from the pump affects the final result and can be crucial for implementation.
Purpose:	Time constraints.
Affect the requirement:	**3.3.1v1 The pump should not affect the user**

D Pugh matrix

	00 (ref)	11111	11112	11113	11121	11122	11123	12111	12112	12113	12121	12122	12123	13111	13112	13113
Efficiency (Pressure difference output-input)	0	0	0	-	0	0	0	0	0	-	+	+	0	0	0	-
Performance (wash performace)	0	0	?	?	?	?	?	?	?	?	?	?	?	?	?	?
Cost (material etc.)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Servicability (install and service)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Turbulence	0	0	0	-	-	-	-	-	0	-	-	-	-	0	0	-
Sum +	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0
Sum 0	5	5	4	2	3	3	3	3	4	2	2	2	3	4	4	2
Sum -	0	0	0	2	1	1	1	1	0	2	1	1	1	0	0	2
Net Value	0	0	0	-2	-1	-1	-1	-1	0	-2	0	0	-1	0	0	-2
Ranking		1	1	24	16	16	16	16	1	24	1	1	16	1	1	24

	13121	13122	13123	21111	21112	21113	21121	21122	21123	22111	22112	22113	22121	22122	22123
Efficiency (Pressure difference output-input)	+	+	0	0	0	-	0	+	-	0	0	-	0	+	-
Performance (wash performace)	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?
Cost (material etc.)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Servicability (install and service)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Turbulence	-	-	-	0	0	-	-	-	-	0	0	-	-	-	-
Sum +	1	1	0	0	0	0	0	1	0	0	0	0	0	1	0
Sum 0	2	2	3	4	4	2	3	2	2	4	4	2	3	2	2
Sum -	1	1	1	0	0	2	1	1	2	0	0	2	1	1	2
Net Value	0	0	-1	0	0	-2	-1	0	-2	0	0	-2	-1	0	-2
Ranking	1	1	16	1	1	24	16	1	24	1	1	24	16	1	24

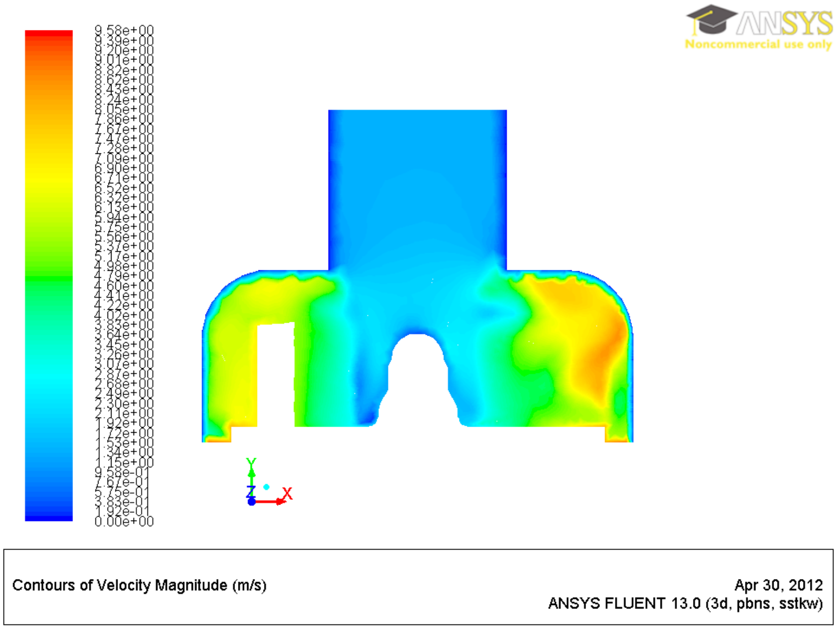
E Figures



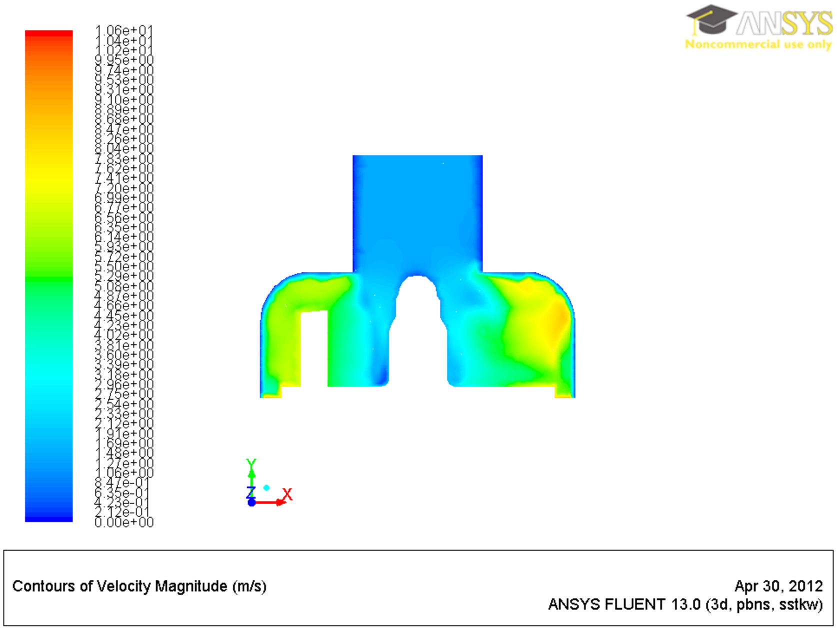
(a)

(b)

Figure 1: Velocity profile in the xy-plane of the design 11111 (a) and C (b).

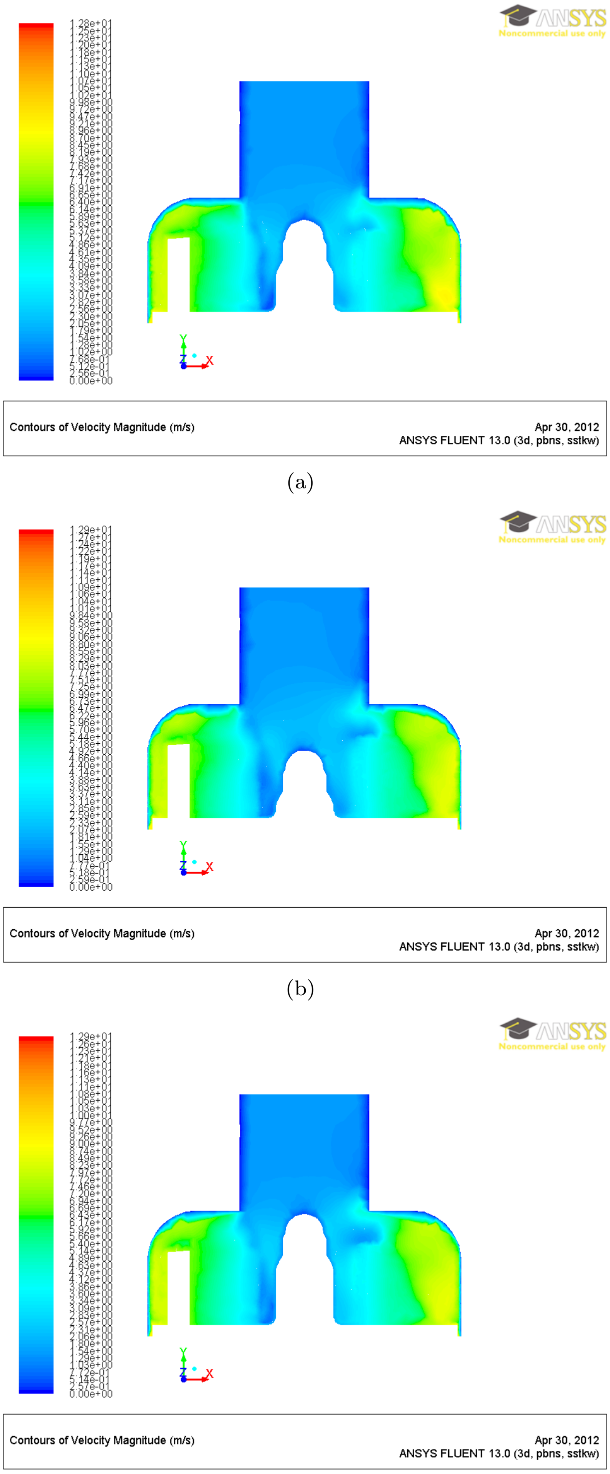


(a)



(b)

Figure 2: Velocity profile in the xy-plane of the design 11112 (a) and 11113 (b).

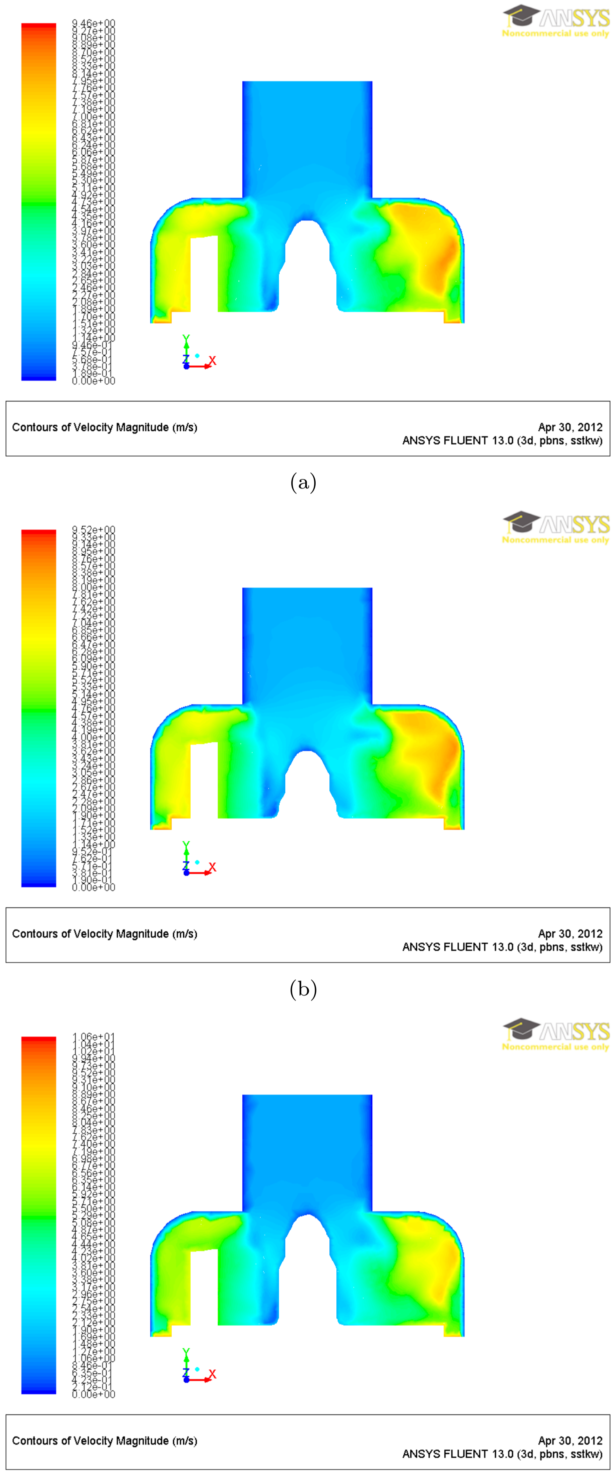


(a)

(b)

(c)

Figure 3: Velocity profile in the xy-plane of the design 11121 (a), 11122 (b) and design 11123 (c).

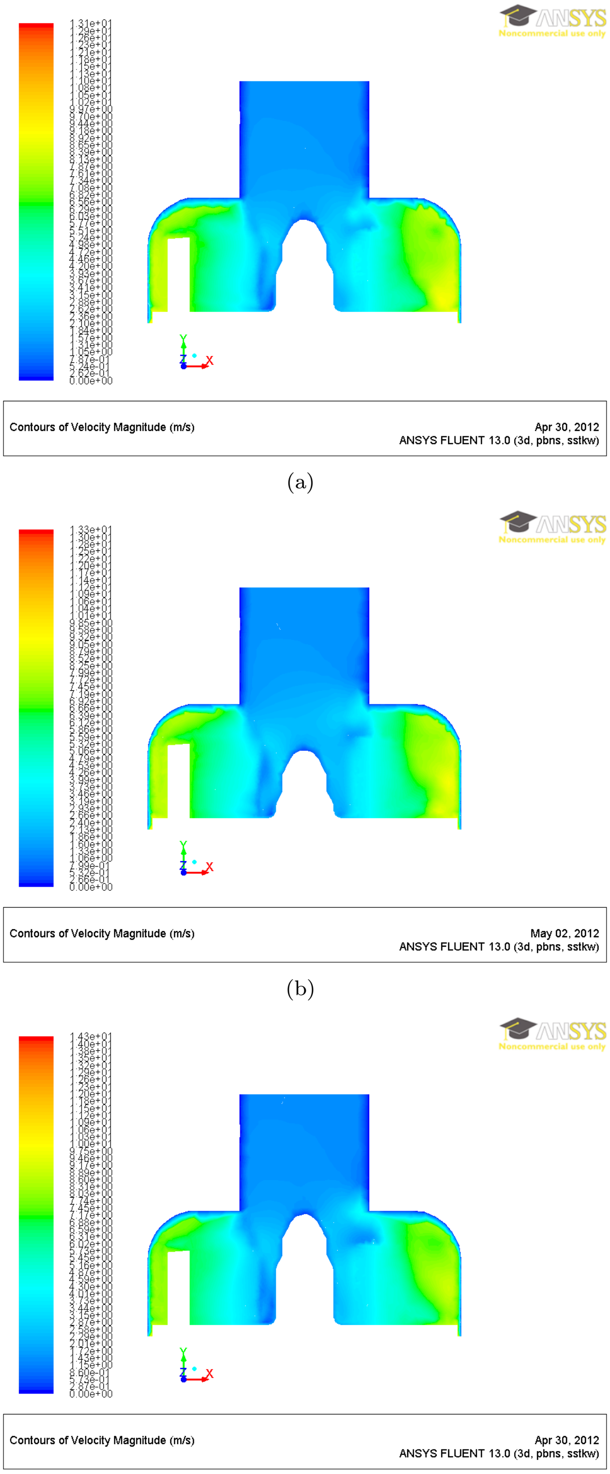


(a)

(b)

(c)

Figure 4: Velocity profile in the xy-plane of the design 12111 (a), 12112 (b) and design 12113 (c).

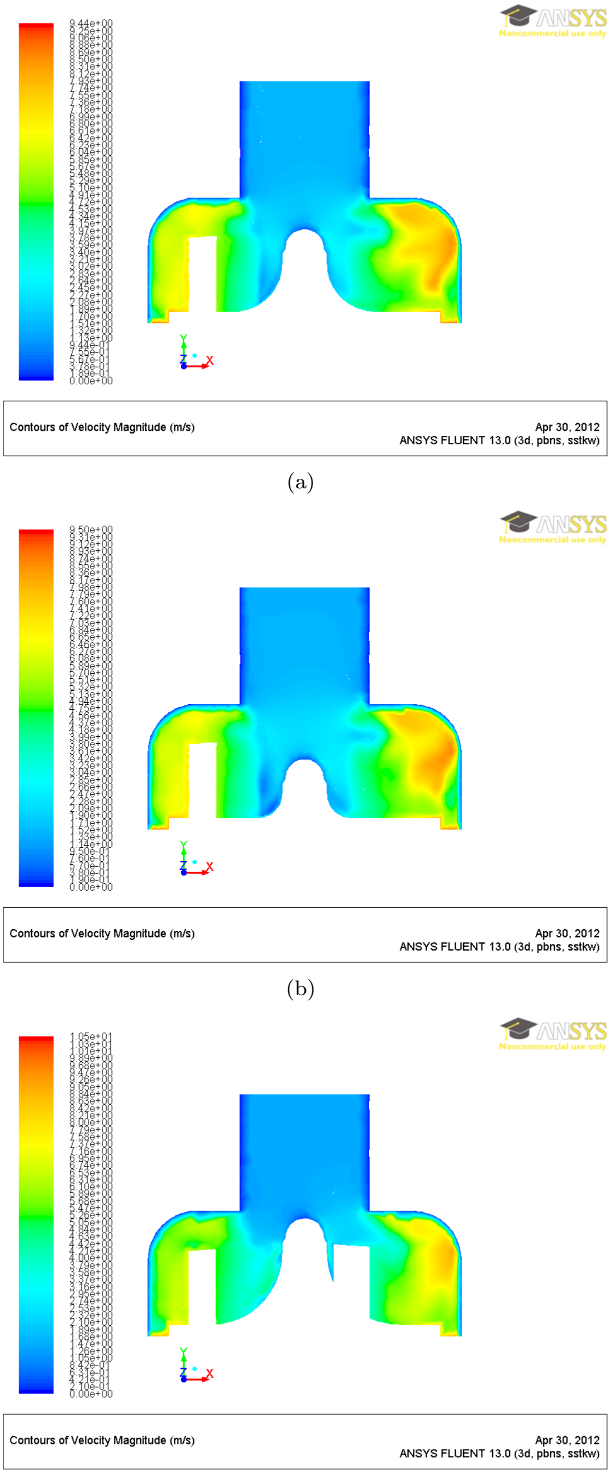


(a)

(b)

(c)

Figure 5: Velocity profile in the xy-plane of the design 12121 (a), 12122 (b) and design 12123 (c).

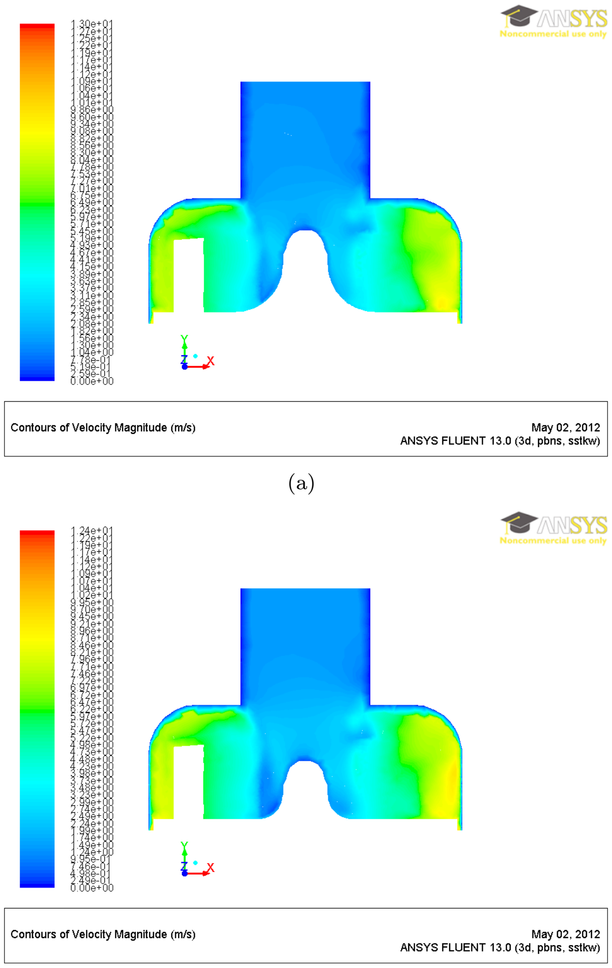


(a)

(b)

(c)

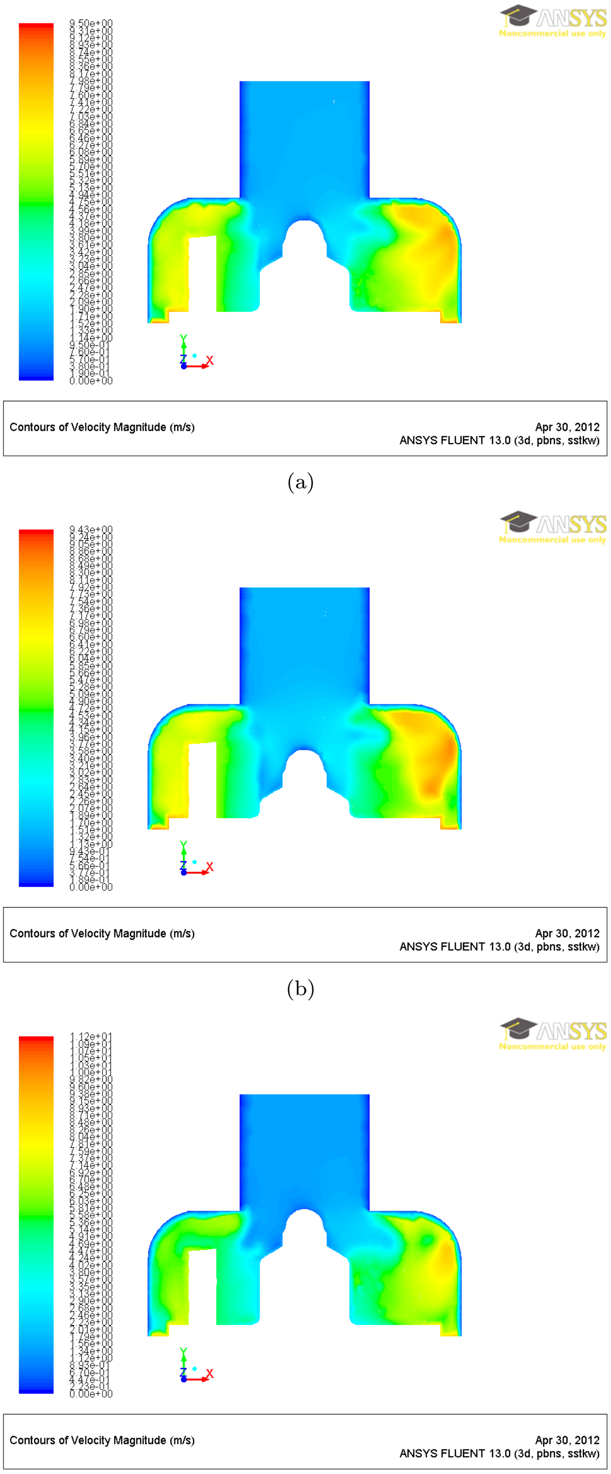
Figure 6: Velocity profile in the xy-plane of the design 13111 (a), 13112 (b) and design 13113 (c).



(a)

(b)

Figure 7: Velocity profile in the xy-plane of the design 13121 (a) and design 13122 (b).

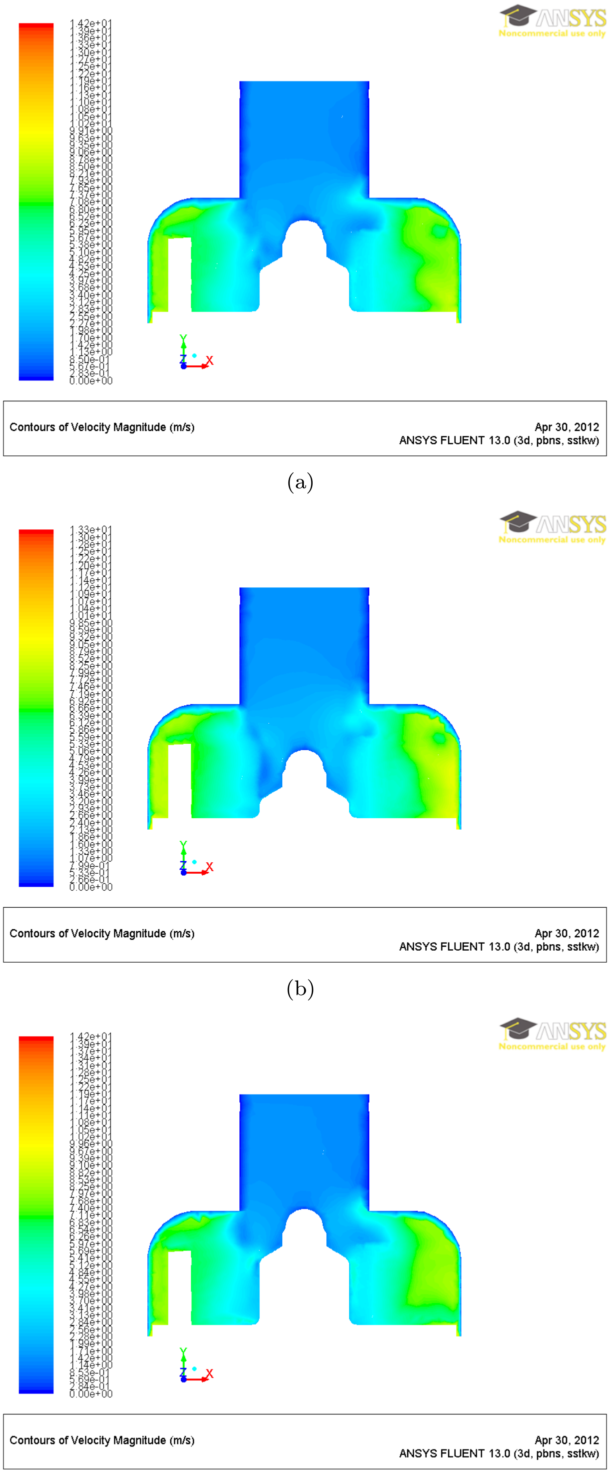


(a)

(b)

(c)

Figure 8: Velocity profile in the xy-plane of the design 21111 (a), 21112 (b) and design 21113 (c).

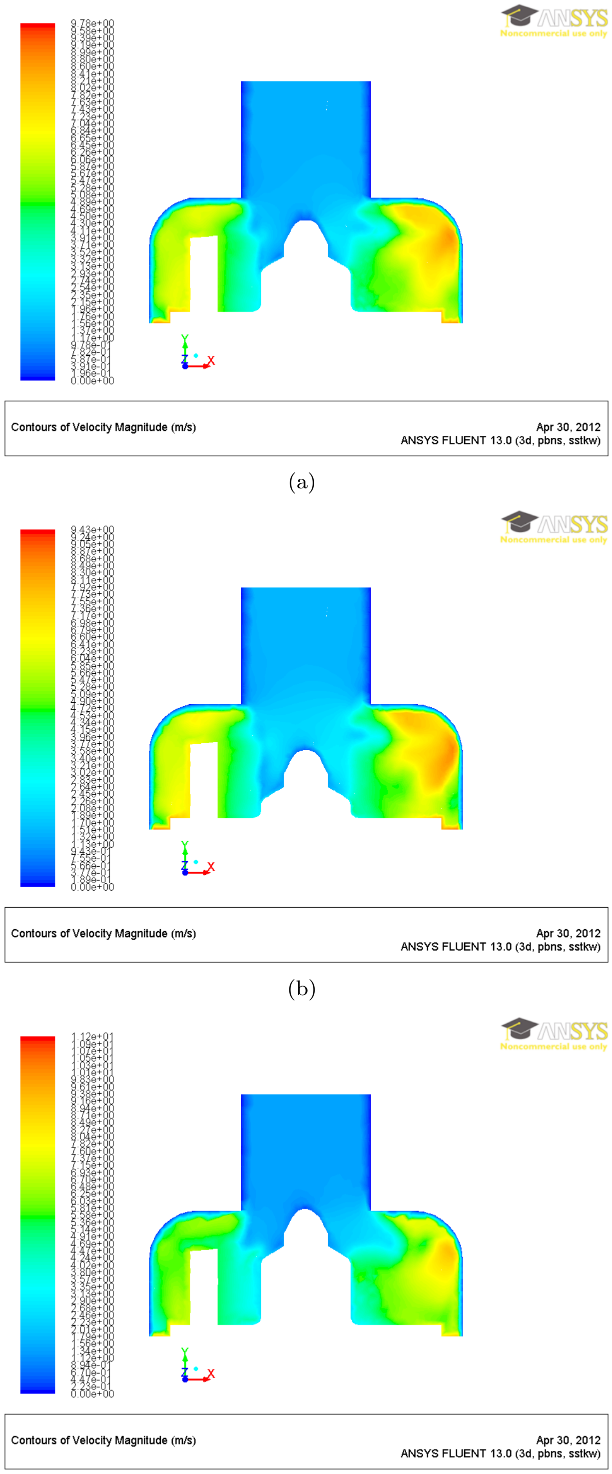


(a)

(b)

(c)

Figure 9: Velocity profile in the xy-plane of the design 21121 (a), 21122 (b) and design 21123 (c).

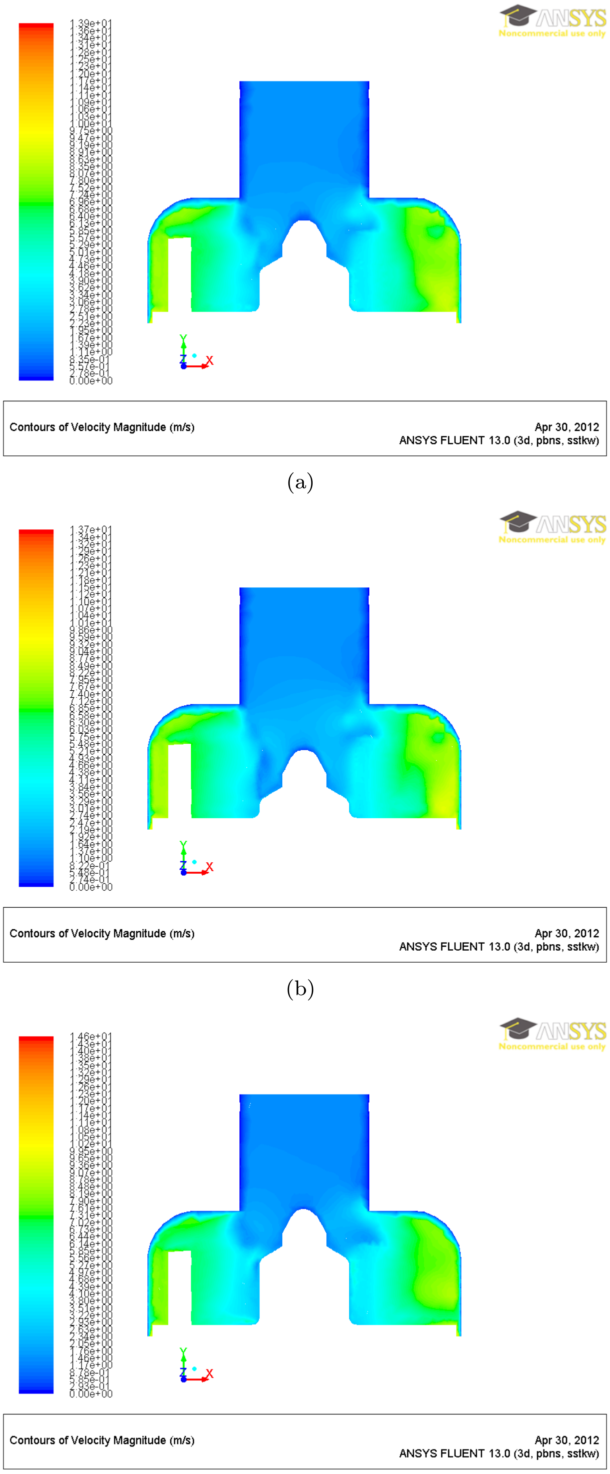


(a)

(b)

(c)

Figure 10: Velocity profile in the xy-plane of the design 22111 (a), 22112 (b) and design 22113 (c).



(a)

(b)

(c)

Figure 11: Velocity profile in the xy-plane of the design 22121 (a), 22122 (b) and design 22123 (c).