Study of efficiency of welding fume extraction nozzles

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Nederman



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Abstract

The aim of the Master's thesis was to evaluate the performance of two existing extraction nozzles at Nederman, and to use the findings to create a concept for a new nozzle. The purpose of the new nozzle was to be attached to a welding cobot, resulting in a change in requirements and design possibilities.

The project followed the product design process as described by Ulrich and Eppinger, consisting of identifying customer needs, establishing target specifications, creating and selecting concepts, among others. The data gathering process primarily consisted of analyzing existing findings in the area and conducting interviews with experts. Following the data gathering, standardized test setups were created, reflecting real-world conditions. Digital models were created of the respective nozzles, and their believability was verified through physical testing. CFD simulations were performed, in order to analyze the performance of the respective nozzles at varying positions, working distances, and air volume flows.

Following the results from the simulations, additional discussions were conducted with experts, combined with a customer visit and further research regarding cobot welding. Using the findings, concepts of a cobot nozzle were created. The concepts were evaluated using screening and scoring matrices in an iterative process, where new concepts were created following the new findings. From the concept development process, it was clear that either freedom of movement or operating cost would be the limiting factor of the design.

Since no current solution exists in the field of study, it is yet to be seen which factor will be most important. Because of this, two final concepts were created, each mainly focusing on solving one of the two challenges. Even though it is early in the development process, the two proposed concepts provide clear indications of where to continue development, depending on where the priorities of the industry will lie in the future.

Keywords: Extraction nozzle, Product development, Computational Fluid Dynamics, Design

Sammanfattning

Målet med examensarbetet var att utvärdera prestandan av två existerande munstycken för rökutsug i Nedermans sortiment, samt att använda resultaten för att skapa ett koncept för ett nytt munstycke. Syftet med det nya munstycket är att fästas på en svets-cobot, vilket resulterade i en förändring av krav och designmöjligheter.

Projektet baserades på designprocessen som beskrivs av Ulrich och Eppinger, som består av identifiering av kundbehov, skapande av målspecifikationer, skapande och val av koncept med mera. Datainsamlingsprocessen bestod främst av analyser av existerande resultat och intervjuer med experter. Efter datainsamlingen skapades standardiserade testfall som motsvarade verkliga förhållanden. Digitala modeller av de respektive munstyckena skapades, vars tillförlitlighet verifierades genom fysiska tester. CFD-simuleringar genomfördes för att analysera prestandan av respektive munstycke vid olika positioner, arbetsavstånd samt volymflöden.

Efter framtagningen av resultaten hölls ytterligare diskussioner med experter, i kombination med ett kundbesök samt ytterligare faktainsamling kring cobotsvetsning. Med dessa resultat som grund skapades initiala koncept för ett munstycke för en svetscobot. Koncepten utvärderades genom "screening-" och "scoring-" matriser i en iterativ process, där nya koncept skapades utifrån de nya resultaten. Från konceptutvecklingsprocessen stod det klart att antingen rörelsefrihet eller driftkostnad skulle vara den beränsande faktorn i designen.

Då det i nuläget inte existerar någon funktionell produkt inom ämnesområdet, återstår det att se vilken faktor som kommer att vara viktigast. På grund av detta skapades två slutgiltiga koncept, med respektive främsta syfte att lösa en av de två utmaningarna. Trots att det är tidigt i utvecklingsprocessen ger de två föreslagna koncepten tydliga indikationer kring vart utvecklingsprocessen kan styras, beroende på var industrins prioriteringar ligger i framtiden.

Nyckelord: Utsugsmunstycke, Produktutveckling, Computational Fluid Dynamics, Design

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Lund, June 2026

Eskil Wilgodt, Elliot Sandström

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1 Introduction

In this section, background information relevant to the study is presented. The scope of the project is covered, in addition to the ethical considerations, delimitations, and time plan.

1.1 Welding and its hazards

Welding is the process in which two workpieces, usually metal, are bonded together by exposing them to high heat (see Figure 1). The parts are melted together in the contact area, and when cooled, the weld forms a strong joint [17]. There are several different welding types, the most common being; MIG, MAG, TIG, and Stick.

MIG and MAG welding use a weld gun that feeds a consumable wire electrode as well as a shielding gas. MIG welding uses inert gas, whereas active gas is used in MAG welding. An electric arc is generated between the workpiece and the wire electrode. This generates heat and melts the materials.

In TIG welding, a non-consumable tungsten electrode is used to produce the weld. The weld area and electrode are protected by an inert shielding gas, such as argon or helium. A constant-current welding power supply provides electrical energy, which is conducted across the arc through a column of highly ionized gas and metal vapors known as a plasma. This plasma is used to melt the workpiece.

Stick welding uses an electric current to form an electric arc between the electrode and the metals to be joined. The workpiece is heated until it melts, creating a pool of molten metal. After this, the flux covered electrode is dipped in the pool. When the workpiece cools, a weld has been formed [9].

An important aspect of most weld methods is the shielding gas. It protects molten metal from oxide formation and keeps the weld uncontaminated. This is important to preserve its strength [8].



Figure 1: Welder in action. Image created by ChatGPT.

Cobot welding, or collaborative robot welding, is a method increasingly used in the industry. A cobot is a robot designed to work side by side with humans without putting them at risk (Figure 2). In cobot welding, a weld gun is attached to the cobot, which is then guided along its welding path through physical correction and programming. In the industry today, cobots generally perform less complex automated weld patterns alongside manual welders [3].

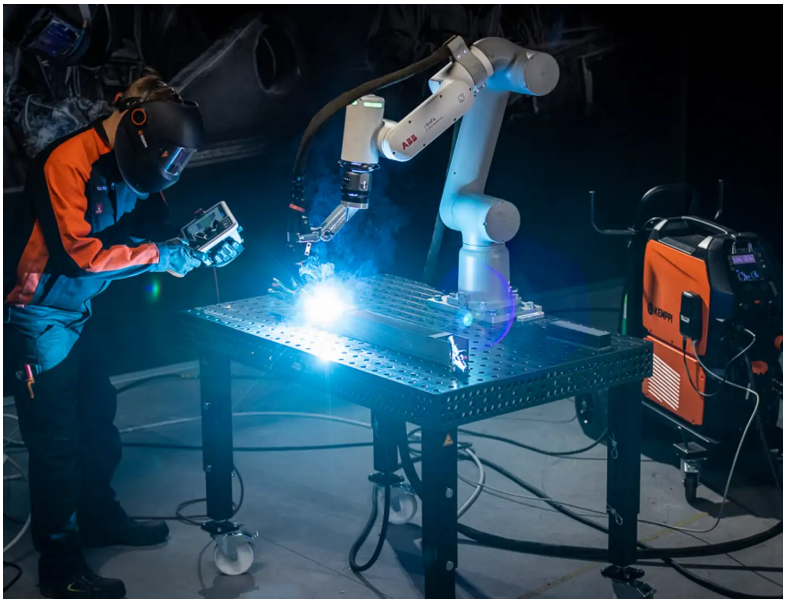


Figure 2: Welding cobot in action. Image taken from *www.kemppi.com*

When welding, using any of the mentioned methods, fumes are emitted as a byproduct [10]. In 2017, the International Agency for Research on Cancer (IARC), reevaluated these welding fumes as carcinogenic to humans (Group 1). IARC also estimates that 11 million workers have the job title of welder, with around 110 million additional workers incurring welding-related exposures yearly [16].

1.2 About Nederman

Nederman is a global leader in industrial air purification solutions. Their goal is to protect humans, the environment, and production by reducing emissions, dust, fumes, and other pollution in the industry.

Nederman offers solutions in Extraction and Filtration Technology, Duct and Filter Technology, Monitoring and Control Technology, and Process Technology. The company is active in more than 65 countries, and their largest markets are in Europe and the United States.

The study was conducted in the field of Extraction and Filtration Technology. This is an area where Nederman has extensive experience and has been an expert since 1944 [15].

1.3 Existing solutions

There currently exist several methods to protect users from toxic fumes, depending on the working conditions. Among these are central ventilation systems, extraction nozzles, and extraction torches (Fig. 3). The extraction nozzles are divided into high-vacuum and low-vacuum models, depending on the air volume flows present in the systems, as well as the outlet geometry.

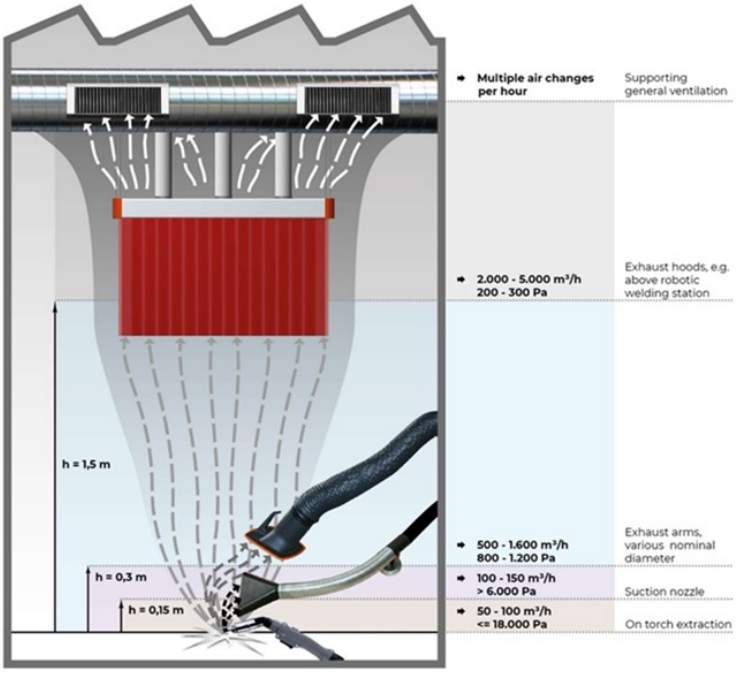


Figure 3: Most common fume extraction methods. Image taken from *www.safe-welding.com*

Although all solutions provide protection against welding fumes, it is important that some level of extraction occur at, or close to, the source. Relying solely on central ventilation far away from the source tends to fail in protecting workers sufficiently. This is particularly an issue for indirect users in the near vicinity of the welder, who often do not wear adequate protection.

In addition to the health hazards, central ventilation systems require a very high volume flow to offer the required protection, leading to substantial amounts of hot air being transferred from the working space [11]. This is inefficient, both from an environmental and economic perspective. Due to these factors, many industries today utilize a combination of the different extraction methods, with the main focus being near-source extraction.

In this study, the nozzles of extraction arms will be evaluated. The two chosen nozzles are the funnel nozzles TM-80 (Fig. 4) and TM-200 (Fig. 5), made by Nederman.



Figure 4: Funnel nozzle TM-80 from Nederman. Image taken from *www.nederman.com.*



Figure 5: Funnel nozzle TM-200 from Nederman. Image taken from *www.nederman.com.*

1.4 Project Description

The study was divided into two main parts: evaluating the performance of the nozzles presented in Section 1.3, and using the findings to develop a concept for a new product. These are referred to as Part 1 and Part 2, respectively.

For Part 1, the nozzles were evaluated against the requirements found in *SS_EN_ISO_21904* [14]. The aim was to obtain clear data on how different distances, angles, and volume flows impact the air velocity of the two nozzles. This information would be used to provide the sales team at Nederman with data regarding the performance of the nozzles.

Part 2 consisted of developing a concept for a new nozzle based on the results from Part 1. During this process, a high level of freedom was given regarding which area to develop and how the design process would be structured. Through data gathering, it was decided to create concepts for the integration of an extraction nozzle on a cobot. The final delivery would provide possible directions for future development to build upon, in addition to mid-fidelity prototypes.

1.5 The ISO Standard

The International Organization for Standardization (ISO) is a global, independent organization that works on developing standards to ensure quality, safety, and efficiency in a variety of areas.

ISO standards can be implemented as a national standard, or by organizations such as the EU. The ISO standard most relevant to the chosen field is the *"SS-EN ISO 21904"*. This standard covers the health and safety measures in welding, and is used as a standard both in Sweden and in the European Union as a whole [14].

1.6 Ethical Considerations

During this experiment, several measures were taken to ensure a comfortable experience for the participants involved in the data gathering process. Before questioning was performed, the interviewees were clearly informed of the purpose of the data gathering, how the information was to be utilized, and assurances of anonymity. In addition to this, they were informed that every part of the process was completely voluntary and that they were free to drop out whenever they wanted. The results from interviews, user testing, and observations have been properly anonymized to comply with GDPR.

In addition to the human aspects, strong consideration was given to the environmental impact of the design choices. This is strongly reflected in the core values

at Nederman [1] [2], and it was therefore important to adhere to the established standards. This is further discussed in Section 9.5.

1.7 Delimitations

Due to the scope of the study, several delimitations had to be considered. Firstly, only two of the nozzles available at Nederman were to be analyzed, even though there are several other variants of extraction nozzles. Secondly, due to the given time constraints, it was decided that the development phase would result in a mid-fidelity prototype rather than a high-fidelity one.

1.8 Use of AI

In this project, the LLM AI "ChatGPT" has been used as an aid to evaluate whether text written in the report follows academic standards. The AI aided by pointing to formulations or words that were ill fitting in academic writing. No text has been generated by AI, however word and phrasing suggestions have been used at specific places.

Chat GPTwas used to create figure 1. Furthermore, ChatGPT was also used to create the backgrounds to the renderings presented in Figures 57 & 62.

1.9 Time plan and work distribution

To get a clear view of the time requirements for each part of the study, a Gantt chart was created (see Appendix A.1). Throughout the project, a revised Gantt chart was created (App. A.2) to ensure that important deadlines were met and to maintain a clear view of the remaining parts of the project.

In addition to this, a "to-do" list was created to get a more precise picture of what to do each individual day, and how to structure the required tasks in an optimal way. This is found in Appendix A.3. To ensure all parties were in agreement during the project, weekly meetings were scheduled with the Nederman supervisors in addition to meetings with the supervisors at LTH when deemed suitable.

Due to the structure of the project, most tasks required both members to participate, sharing the workload between smaller sub-tasks. Through thorough communication and keeping a clear structure of the tasks, the total distribution of the workload ended up being roughly 50/50.

1.10 Structure of thesis

The thesis begins by introducing the chosen area of work to provide a clearer understanding of the purpose of the study. Following this, the theory relevant to the study is presented, relating to both the calculations and product development. After this, the methodology of Part 1 is described, followed by an illustration of the findings from the evaluation. These findings are reflected upon and serve as a basis for the methodology of Part 2. The steps of the product development process are described, resulting in two final concepts. Lastly, the results of Part 2 are reflected upon concerning the reliability of the results and future development.

At the end of the report, appendices containing additional images and tables are found for further reading.

2 Theory

In this chapter, the theory relevant to the project is presented. This covers information about the impact of extraction velocities, results from previous experiments conducted at Nederman, and the chosen design process.

2.1 Impact of extraction velocities

2.1.1 SS-EN ISO 21904

As mentioned in Section 1.4, the *SS-EN ISO 21904* is a central factor in the safety in welding, and is thus used as a baseline for all experiments in the field. The standard presents the minimum air velocity required to sufficiently remove toxic fumes. The velocity required to achieve this is approximately 0.3 m/s. Furthermore, the standard defines a measurement plane at a set distance measured orthogonally from the nozzle outlet. This distance is 1.5 times the diameter of the tube. Within this plane, an area with a peripheral velocity of 0.3 m/s can be found. The ISO states that within this zone, toxic fumes will be extracted. In this report this area will be referred to as the "Safe zone". If the nozzle is placed directly above the working area, the distance that corresponds to a certain safe zone can be doubled, because of the welding fumes rising behavior. Labels illustrating these zones are placed on the corresponding extraction nozzles, serving as a guide for safe usage (see Fig. 6) [14].

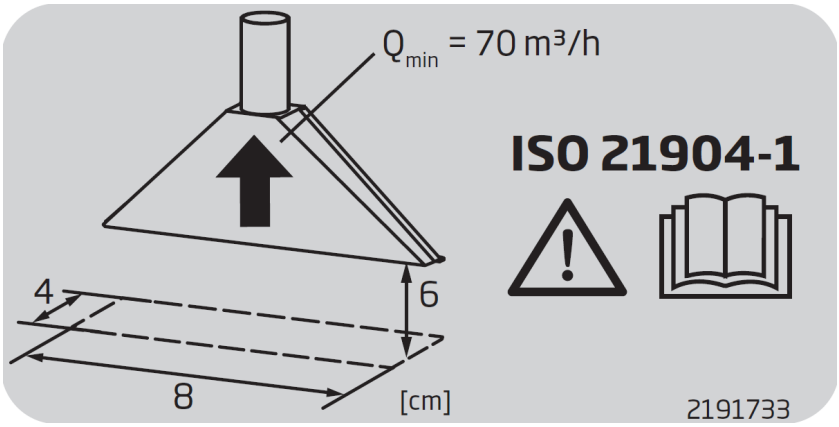


Figure 6: Label on TM-200, illustrating the safe zone as described by *SS-EN ISO 21904*. Image provided by Nederman.

The safe zone is measured using the following procedure:

- The nozzle is positioned in such a way that it is free standing and sited away from any obstructions. The impact of disturbing air drafts in the near vicinity shall average less than 0.1 m/s after five minutes of testing. The anemometer shall be placed in such a way that it is movable in the measurement plane.
- A controlled air volume flow is introduced to the system. The flow rate is monitored to ensure that it remains consistent throughout the entire experiment.
- The anemometer is placed on the horizontal axis of the measurement plane, and is thereafter manually adjusted until sufficient air velocity is measured, as specified earlier. If this is not feasible, the air volume flow rate is adjusted accordingly.
- When the requirements are met, the anemometer is moved to the opposite side of the horizontal axis and the results are recorded. The distance between the two points is calculated.
- When the requirements are fulfilled for the opposite side, the same procedure is repeated for the vertical axis. The measured velocities for the respective points are calculated as the average for a five minute testing period, with a maximum logging interval of five seconds.

2.1.2 Extraction of shielding gas

While it is important to keep extraction at a level high enough to keep users safe, excessively high velocities also have a negative impact on the welding process. As mentioned in Section 1.1, shielding gas is used to prevent weld defects from occurring. At a certain air velocity, the shielding gas starts to get extracted, potentially resulting in an insufficient weld [6]. Although it is currently unclear at exactly what velocity this starts to happen when using an extraction nozzle, the ISO has established that 0.4 m/s is the critical velocity for extraction torches [14]. Through consultation with an expert at Nederman, it was deemed sufficient to apply this limit on extraction nozzles as well, even though extraction torches is a different kind of device. Furthermore, there are higher limits suggested by other sources, however, as the ISO was the most conservative, it was selected as a reference point in the study. This is further covered in Section 5.1.

2.2 Results of previous experiments at Nederman

In 2013, Nederman performed a number of digital experiments on selected nozzles to verify how different air volume flows impacted the safe working surface as described by *SS-EN ISO 21904*. The tests were performed on larger low-vacuum

nozzles, so the input parameters differed from those of the given task. With that in mind, the data from the experiments was used as a baseline for the creation, visualization and evaluation of the digital model.

Although the results clearly illustrated the impact of varying air volume flows, all previous experiments were conducted at the distances described by *SS-EN ISO 21904*. These do not necessarily reflect the real-world conditions of the welding industry.

2.3 Fluid dynamics

When studying the behavior of fluids, there are a number of factors that need to be considered.

2.3.1 Steady vs unsteady flow

One consideration regarding fluid behaviors is if the flow is steady or unsteady, meaning whether the flow properties change over time or not (Equation 1).

$$\frac{\delta}{\delta t} = 0, \tag{1}$$

For a fixed pipe geometry with no pulsed flow or moving boundaries, the flow can be assumed as steady-state [5]).

2.3.2 Incompressible vs Compressible flow

Another factor in determining the behavior of a fluid is whether it can be considered incompressible or not. A fluid being considered incompressible means that its density does not change significantly during the flow. For gases like air, this is usually determined using the Mac number (Equation 2):

$$Ma = (\frac{v}{c}), \tag{2}$$

where v is the velocity of the air and c is the speed of sound. For air at room temperature (20° C), c=343 m/s. The air velocity is calculated using the following formula:

$$v = (\frac{Q}{A}), \tag{3}$$

where Q is the working air volume flow, and A is the cross-sectional area of the tube.

If Ma<0.3, the compressibility of the air can be considered negligible [4].

2.3.3 Laminar vs Turbulent flow

A third aspect to consider is whether the flow of the fluid is laminar or turbulent. The behavior depends on the Reynolds number, where a value less than 2300 corresponds to a laminar flow, and a value more than 4000 corresponds to a turbulent flow for fluids in a pipe [7]. If the Reynolds number falls between the two values, it indicates that the flow is in a transient state and that further analysis is required to identify the behavior.

The Reynolds number is calculated using the following formula:

$$Re = \frac{\rho v D}{\mu}, \tag{4}$$

where ρ is the density of the fluid, v is the average air velocity, D is the diameter of the tube, and μ is the dynamic viscosity of the fluid. Air at room temperature possesses the following properties:

ρ=1.205 kg/m^3, μ=1.8 $\cdot$ 10^{-5} kg/m^3.

2.4 Ulrich and Eppinger, "Product Design and Development"

Karl T. Ulrich and Steven D. Eppinger (referred to as **"U&E"** in the study) state that the development process consists of three main parts: Product planning, Product development and Production. The product development part consists of six phases: Planning, Concept Development, System-Level Design, Detail Design, Testing and Refinement, and Production Ramp-Up [13]. This process is illustrated in Figure 7. Due to the size and scope of the study, the main focus was on the Concept Development part.

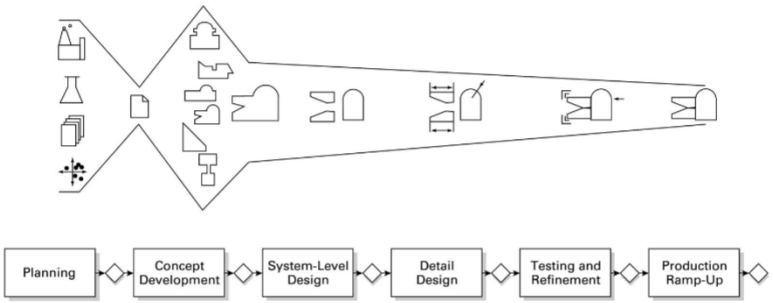


Figure 7: The six phases of product development according to Ulrich and Eppinger. Image provided by *www.researchgate.net*.

2.5 Concept development according to Ulrich & Eppinger

2.5.1 Mission statement

A mission statement is formalized information from the company, consisting of market opportunities, broad constraints and objectives. The purpose of a mission statement is to give the developers a direction to work towards [13].

2.5.2 Identify customer needs

The purpose of identifying customer needs is to understand what is most important to the customer, and to provide the development team with this information in an efficient and structured way. The output of this step is described as *"a set of carefully constructed customer need statements, organized in a hierarchical list, with importance weightings for many or all of the needs"* [13].

U&E presents a five step method for identifying customer needs:

1. Gather raw data from customers

There are three commonly used methods to gather raw data: Interviews, focus groups and observing the product in use. While collecting data, it is essential to be receptive to information provided by the customer, while avoiding confrontations or defensiveness. The goal is to elicit an honest expression of needs from the customer [13].

2. Interpret the raw data in terms of customer needs

After the data has been gathered, the next step is to interpret it into customer needs. A statement or observation from the gathered data can be translated into any number of customer needs. Because different analysts could translate the same statement into different needs, it is beneficial to have more than one translator in the working team.

There are five guidelines for writing the need statements. The first two are fundamental, while the last three aid in ensuring consistency in the statements.

1. Express the need in terms of what the product has to do, not in terms of how it might do it.

2. Express the need as specifically as the raw data.

3. Use positive, not negative, phrasing.

4. Express the need as an attribute of the product.

5. Avoid the words ***must*** *and* ***should*** [13].

3. Organize the needs into a hierarchy of primary, secondary, and tertiary needs.

The goal of this step is to create a hierarchical list of needs, where primary needs are described more in detail by secondary and, if relevant, tertiary needs. The chosen method is based on dividing the needs into groups, which are then labeled. The chosen label becomes the primary need, with the needs grouped underneath becoming secondary needs. The importance of the respective secondary needs is subsequently rated from 1, *not that important*, to 3, *critical* [13].

4. Establish the relative importance of the needs.

The fourth step in identifying customer needs is to establish the relative importance between them. According to the literature, there are two possible approaches to achieve this. One method is to rely on the judgment and experience of the team, whereas another is to conduct further customer surveys. The goal is to gain an understanding of which features are critical, important, desirable, and undesirable, respectively [13].

5. Reflect on the results and the process.

It is highly important to challenge the results and the intuition that the team has built through interaction with customers [13].

2.5.3 Establish target specifications

U&E describe establishing target specification as *"providing a precise description of what a product has to do."* Target specifications are the translation of customer needs into technical and quantifiable terms. They are set early in the design process and represent the aims of the development team. Later in the process, these specifications become refined to be consistent with the constraints imposed by the chosen product concept. The quantifiable terms are summarized in a list of target specifications, where each specification consists of a metric, and marginal and ideal values of that metric [13].

2.5.4 Concept generation

The purpose of concept generation is to *"thoroughly explore the space of product concepts that may address the customer needs"*. This may consist of a mix of external search, problem solving within the development team, and systematic exploration of the concepts and features generated by the members of the development team. The phase usually results in a set of 10 to 20 concepts, typically represented by sketches with short descriptions.

U&E outlines a five-step method for concept generation. The method is presented below:

1. Clarify the problem
The objective is to get a better and more comprehensive understanding of the problem at hand. By dividing a complex problem into simpler sub-problems, the developer can address smaller problems one at a time. Meanwhile, it also becomes clearer to the developer what requirements the solution needs to fulfill. Furthermore, it is recommended to focus on solving the most critical sub-problems first. This is because the solution to a sub-problem could impact other solutions.

2. Search externally
External search is defined as the search for solutions, to the main problem and its sub-problems, outside of the development team. The rationale is that it is more cost effective and efficient to use existing solutions to sub-problems where feasible. Rather than developing a new solution where suitable solutions already exist, the development team can focus their efforts on solving unsolved problems. U&E proposes five methods to gather this external information: lead user interviews, expert consultation, patent searches, literature search and competitive benchmarking.

3. Search internally
The internal search utilizes the knowledge and creativity within the development

team to create solutions. The most commonly applied method is brainstorming. U&E presents four guidelines for brainstorming:

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

4. Explore systematically
After completing steps 2 and 3, the team will have collected several fragments of solution for the subproblems. U&E defines the aim of step 4 as *"navigating the space of possibilities by organizing and synthesizing these solution fragments."* [13]. Furthermore, a tool called a "concept combination table" is introduced. This enables developers to systematically consider combinations of different solutions.

5. Reflect on the solution and the process
U&E highlights the importance of reflection and, although placed at the end of the process, it is emphasized that reflection and questioning should be performed throughout the process.

The authors encourage developers to question whether the entire solution space has been explored and to seek alternative solution approaches. Lastly, it is important to ensure that all members of the team have had their ideas considered.

2.5.5 Concept selection

U&E define "Concept selection" as *"the activity in which various product concepts are analyzed and sequentially eliminated to identify the most promising concept(s)"*. Usually, several iterations are required to achieve this, during which new concepts are created and refined.
U&E presents two tools, the"concept screening" and "concept scoring" matrix, which simplify the selection process.

A concept screening matrix evaluates concepts against different criteria by grading them as "better than", "equal to" or "worse than" a reference concept. The output is one or more concepts deemed worthy of further development.

A concept scoring matrix evaluates concepts against weighted criteria, by assigning them a score from 1 to 5. The scores are summed, and the output is one or more final concepts. These concepts are either finalized concepts or concepts that are deemed worthy of further development.

2.5.6 Concept testing

Following the concept selection, tests are performed on the chosen concepts. This is done in order to verify that the needs of the customers are met, to assess the market potential of the product, and to identify existing flaws or issues that need to be resolved before finalizing the development phase. If the results from the testing are poor, it may indicate that further iterations of previous steps are needed.

2.6 Human-centered design

Throughout the study, a human-centered design process was followed. This means that key decisions were made based on satisfying the needs of the users, by identifying customer needs and pain points.

Harvard Business School breaks human-centered design down into four stages [12]:

1. Clarify: Data collection and customers observations are performed. The purpose of this is to identify what users really want, rather than basing decisions on previous assumptions.

2. Ideate: Based on the insights and inspirations from the first step, design thinking tools such as brainstorming are used in order to generate ideas.

3. Develop: The brainstormed ideas are combined and critiqued, in order to find a range of possible solutions. The most suitable concepts are selected for prototyping, based on desirability, feasibility, and viability.

4. Implement: The final models are created and finalized. It is important to clearly communicate the value of the created concept to internal and external stakeholders. Consideration should be taken regarding the optimal way of marketing the products to the customers.

3 Method of Part 1

In this chapter, the method of Part 1 is covered. This consists of the creation of standardized test setups, digital models and physical experiments.

3.1 Creation of standardized test setups

As stated previously, it was important that the evaluations were performed using real-world conditions of the welding industry. In order to achieve this, changes had to be made to the setup as described in *SS-EN ISO 21904*. After consultations with sales experts, it was determined that the three most important factors were the working air volume flow, distance to the measurement plane and angle of the nozzle.

For the air volume flow, a range of 100-250 m^3/h was considered reflective of real-life. With respect to the angles, having the nozzle perpendicular to the working area (0°) or with a 45° angle was both present, with the 45° setup most common. Aside from this, having the nozzle directly to the side of the working area, with a 90° angle, was also common. When using this setup, the nozzle was either freely suspended in the air, or placed directly on a table.

When working on the 90° set up, the distance to the measurement effectively became either 0 (for the freely suspended nozzle) or the radius of the TM-80/ the shorter side of the TM-200 (for the nozzle placed on the table). For the 0° and 45° angle however, working distances commonly used in the industry was determined as 10 - 15 cm.

Based on these findings, eight standardized test setups were created. Below, illustrations showing the positioning and resulting safe zone geometry(green) of these set ups, are presented. Dimensions are not included since these are part of the results.

3.1.1 TM-80 nozzle, 0° angle

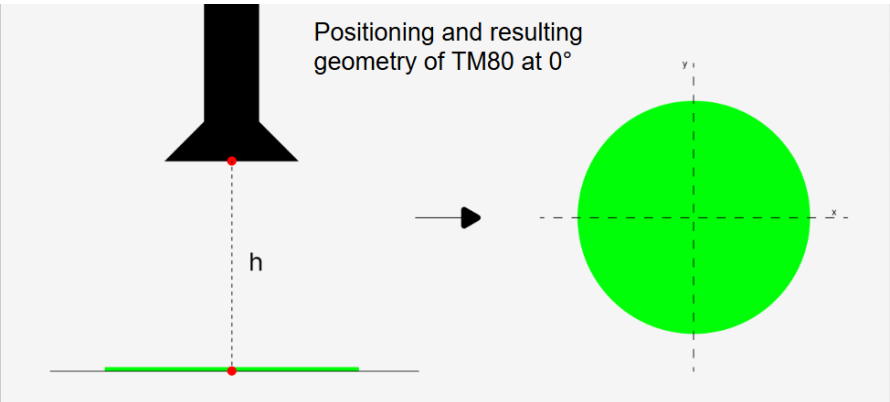


Figure 8: Illustration of test setup 1 as well as resulting safe zone geometry.

3.1.2 TM-80 nozzle, 45° angle

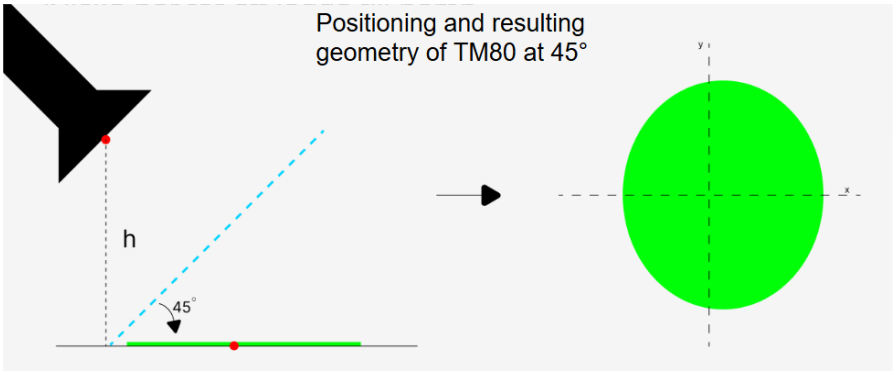


Figure 9: Illustration of test setup 2 as well as resulting safe zone geometry.

3.1.3 TM-80 nozzle, 90° angle, no table

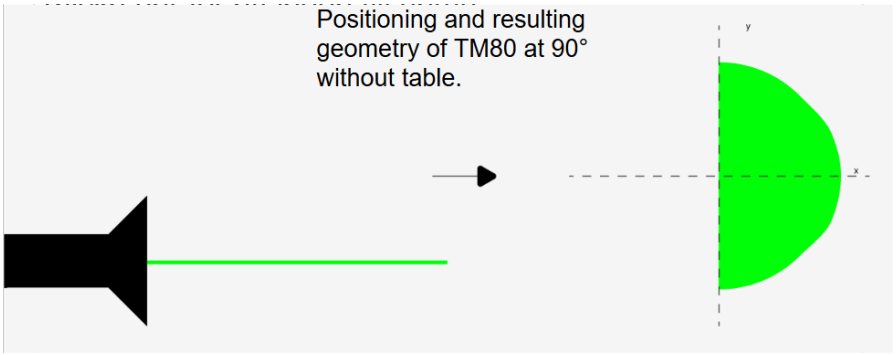


Figure 10: Illustration of test setup 3 as well as resulting safe zone geometry.

3.1.4 TM-80 nozzle, 90° angle, with table

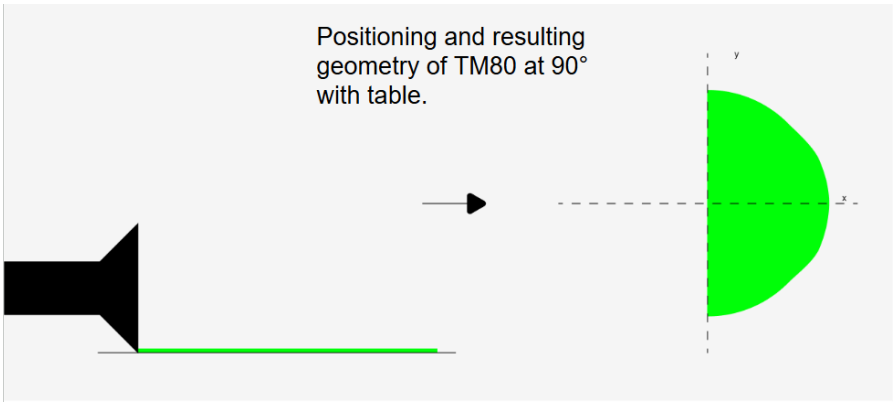


Figure 11: Illustration of test setup 4 as well as resulting safe zone geometry.

3.1.5 TM-200 nozzle, 0° angle

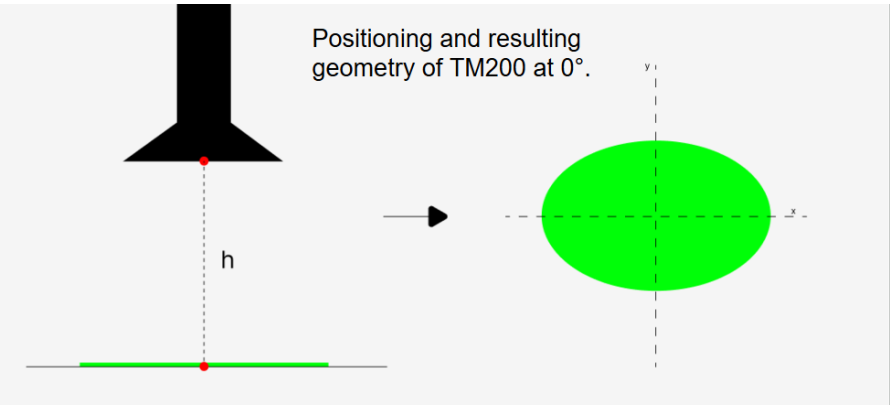


Figure 12: Illustration of test setup 5 as well as resulting safe zone geometry.

3.1.6 TM-200 nozzle, 45° angle

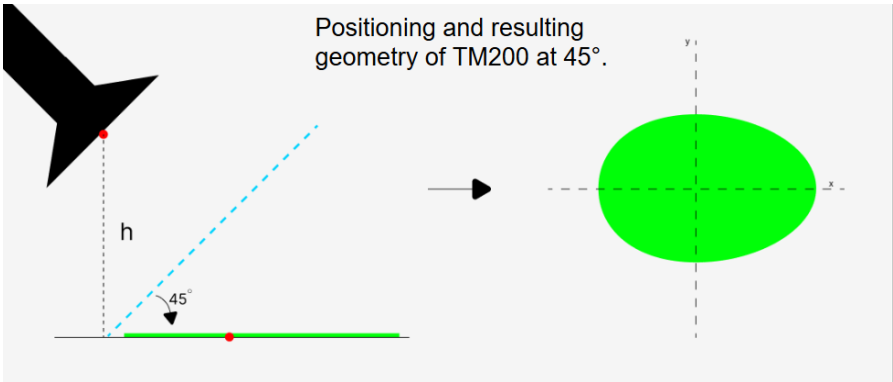


Figure 13: Illustration of test setup 6 as well as resulting safe zone geometry.

3.1.7 TM-200 nozzle, 90° angle, no table

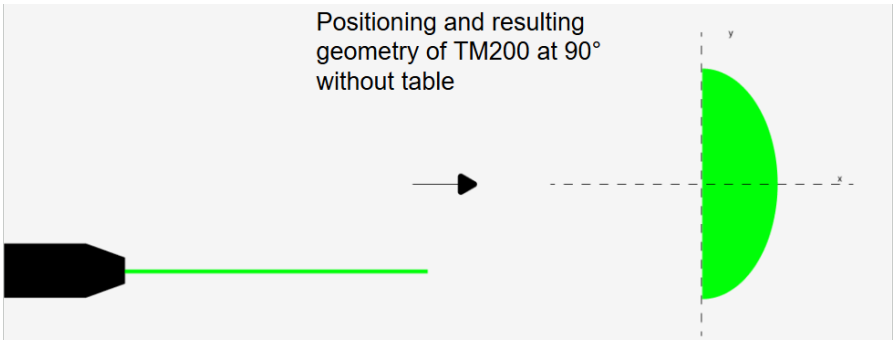


Figure 14: Illustration of test setup 7 as well as resulting safe zone geometry.

3.1.8 TM-200 nozzle, 90° angle, with table

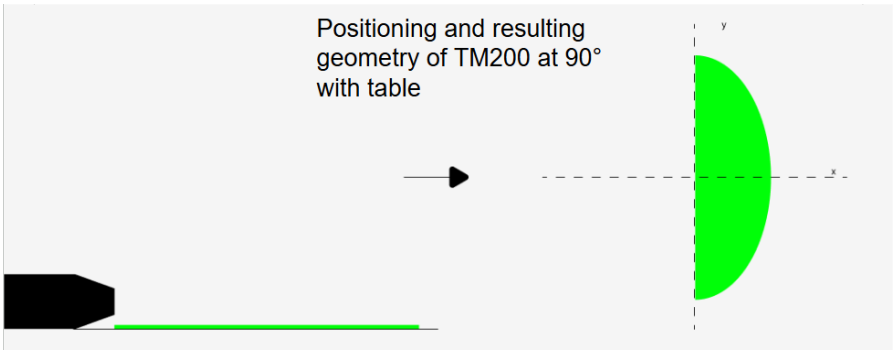


Figure 15: Illustration of test setup 8 as well as resulting safe zone geometry.

All test setups were evaluated using 100, 150, 200, and 250 m^3/h. The test setups illustrated in Figures 8, 9, 12 and 13 were also evaluated at distances of 10, 12.5 and 15 cm from the measurement plane.

3.2 Creation of digital model

To get initial results from the given conditions, a CFD analysis was performed on each of the nozzles. The modeling and analysis parts of the digital model was the same for the TM-80 and TM-200 nozzles, with some minor differences due to the differing geometries.

3.2.1 CAD models

The process started by creating a CAD model of the nozzle and surrounding air. The model consisted of the air volume inside the nozzle as one part, with the surrounding air as a separate part. The outer surfaces of the nozzle were later assigned as walls, with the exception of the inlet and outlet areas. The modeling was performed using the CAD tool Ansys DesignModeler. Eight models were created, corresponding to the test setups established in Section 3.1. These are illustrated in Figures 16 to 23.

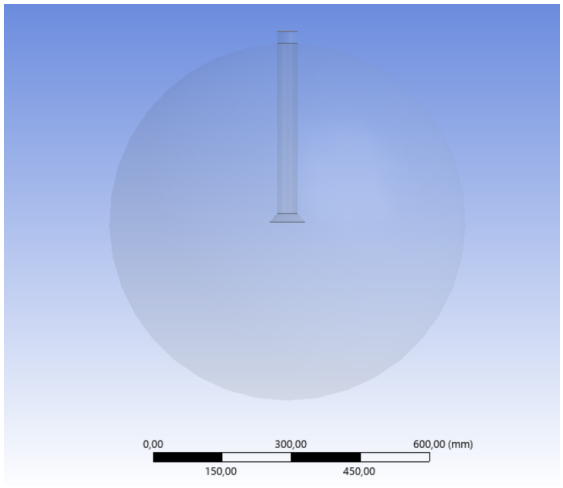


Figure 16: CAD model of test setup 1.

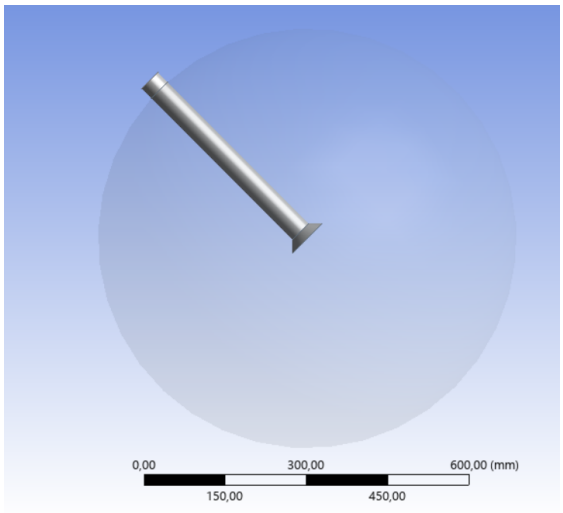


Figure 17: CAD model of test setup 2.

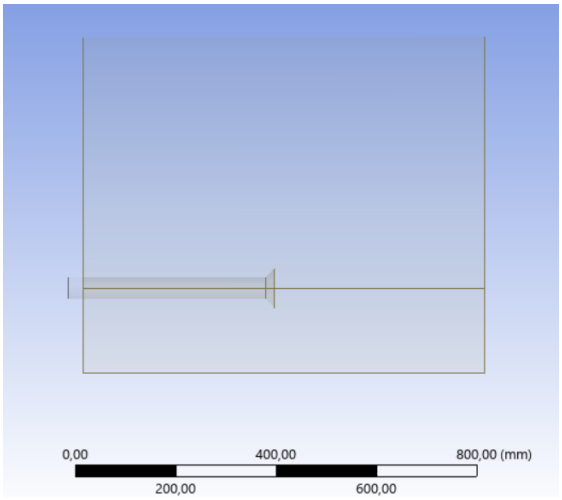


Figure 18: CAD model of test setup 3.

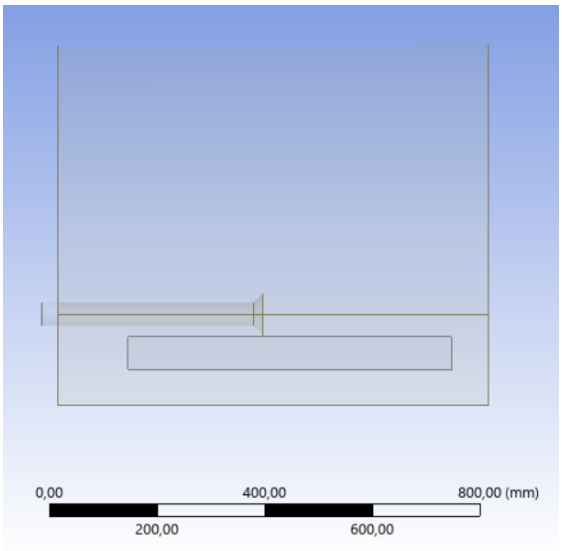


Figure 19: CAD model of test setup 4.

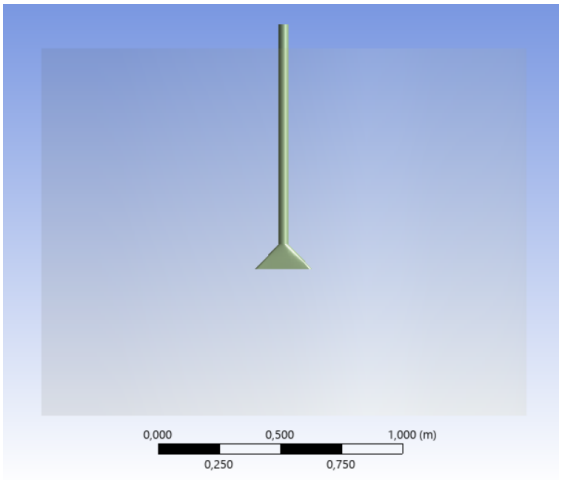


Figure 20: CAD model of test setup 5.

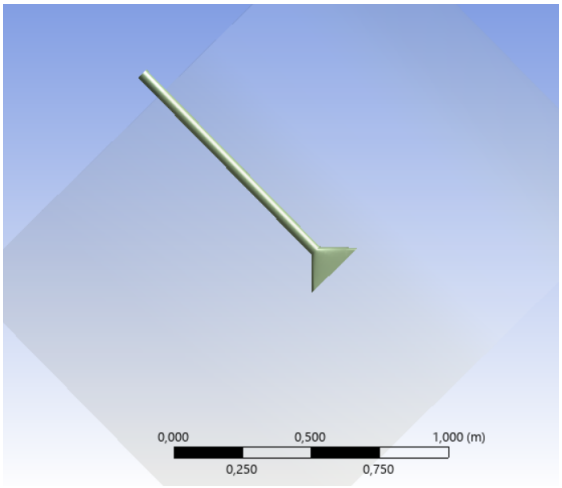


Figure 21: CAD model of test setup 6.

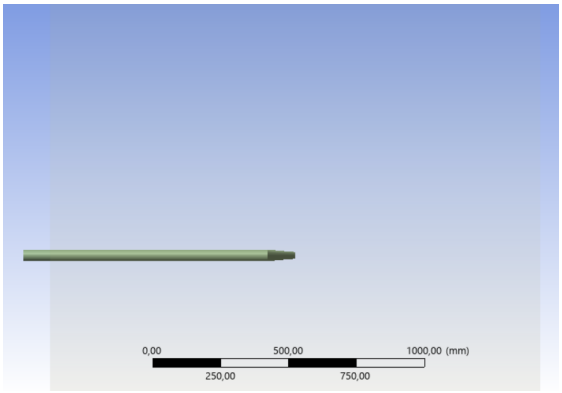


Figure 22: CAD model of test setup 7.

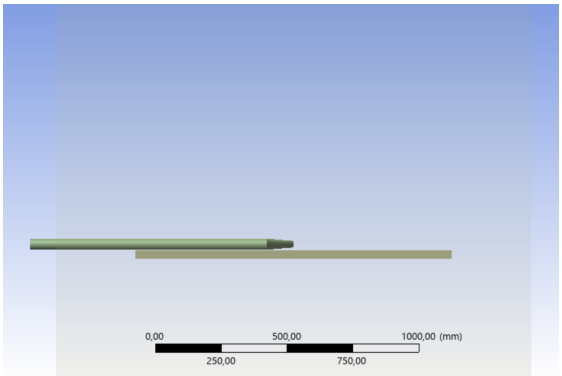


Figure 23: CAD model of test setup 8.

3.2.2 Meshing

The models were imported into Ansys Fluent Mesher, where a suitable mesh was created. The model was created as a watertight geometry, consisting of only fluid regions with no voids. The "Share Topology" function was applied to the two parts of the model. Initially, the standard mesh settings of the program were used in the solving of the model. This did not lead to convergence, even after loosening the convergence criterion by increasing the residual continuity. Due to this, the cell count had to be increased by lowering the maximum size allowed for the elements of the mesh. After several iterations of mesh analysis, it was noted that the area closest to the measurement plane was most critical in regard to the accuracy of the results. This was because increasing the complexity of the entire model did not result in significant changes, whilst changing the geometry of the nozzle outlet and the nearby area had a large impact. Due to this, a Body of Influence (BoI) was placed at the inlet of the nozzle. Following this, iterations with higher cell

counts were performed in order to find at what point convergence would occur. For each measurement step, the maximum size of the elements in the BoI was lowered until the cell count was increased by approximately 50 000. Once the model had converged, additional testing was performed to analyze what impact a further refined mesh would have on the results. The final iterations are illustrated in Table 1.

Table 1: Mesh independence study for the TM-80 model.

Cell count	**Diameter of safe zone (cm)**	**Difference (%)**
44 495	**Did not converge**	–
90 974	**Did not converge**	–
132 843	**Did not converge**	–
195 119	27.8	–
241 145	27.8	0.0

As illustrated in the table, following the point of convergence, no change of results occurred. Because of this, an element count of 200 000 was subsequently used. The final mesh of one of the setups is illustrated in Figures 24, with Figure 25 illustrating the refined area. The selected mesh data was subsequently used for all TM-80 models and the respective simulations. The same procedure was performed for the TM-200 models.

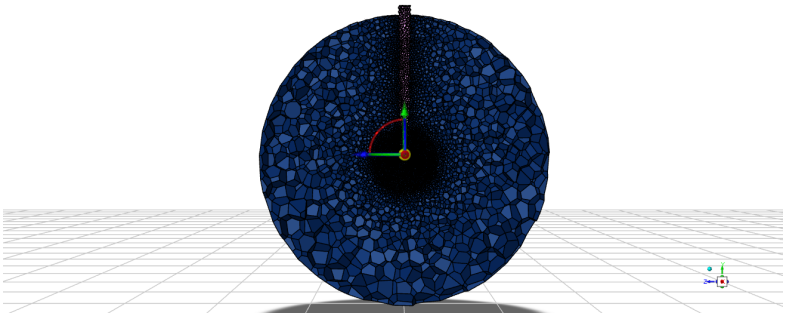


Figure 24: Overall view of final mesh of TM-80.

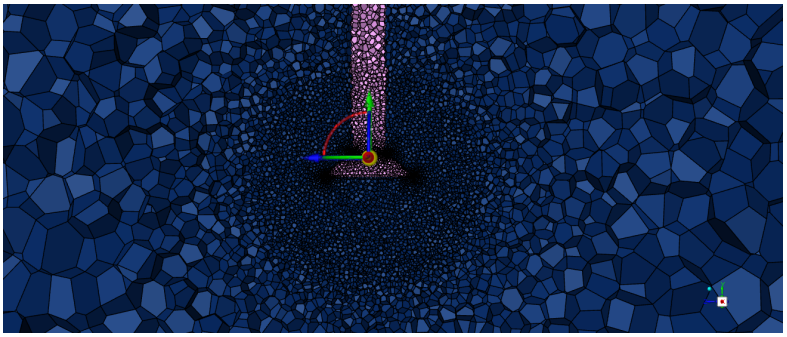


Figure 25: Refined area of final mesh of TM-80.

3.2.3 Solving

Using the data from the industry experts, the behavior of the air flow was determined in order to assign the correct solver settings. Based on the given air volume flows (100-250 m^3/h) combined with the diameter of the tube (50 mm), the air velocities were calculated to be between 14.1 and 35.4 m/s (Eq. 3). Using Equation 2, the resulting Mach numbers were between 0.04 and 0.1. Since the Mach numbers for all volume flows fall well below 0.3, it was deemed reasonable to consider the air incompressible.

Following this, the Reynolds number was calculated using Equation 4. For the calculated range of air velocities, the Reynolds numbers were in the range of $7.5 \cdot 10^4 - 1.9 \cdot 10^5$. This meant that the flow was fully in a turbulent state.

After the meshes were created, the models were exported into Fluent Solution, where the conditions for the solver were set. The correct material properties were assigned to the respective parts, as well as to the walls and the interactions between the two air masses. All intersecting areas of the two air volumes were assigned as walls, with the exception of the outlet area, which remained an internal boundary. The boundary conditions were set, with the outer perimeter of the surrounding air volume being the inlet and the end of the nozzle being the outlet (Fig. 26). The intersecting surfaces of the air volume and nozzle were set as walls. To ensure a clear separation between the two parts, a boundary layer was added between the nozzle and the surrounding air volume. This further ensured that air would not flow in through the walls of the nozzles, only through the outlets.

During the solve, different solver settings were tried in order to ensure that the digital model behaved realistically. Since the flow was calculated to behave turbulently, the turbulent k-epsilon solver was initially used. Following further testing with the turbulent k-omega solver and the laminar solver, it was concluded that the changes in results were negligible. Because the laminar solver made the mod-

els converge significantly faster than the turbulent solvers, it was deemed most suitable for the study. The selection between solvers is further covered in Section 5.1.

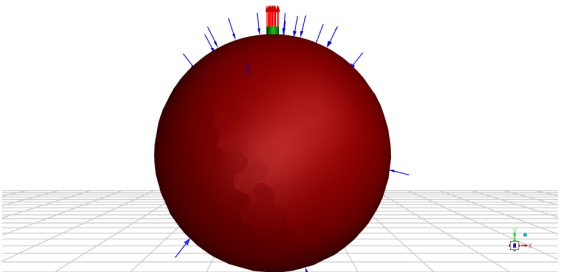


Figure 26: Placement of inlet and outlet in the solver.

3.2.4 Measuring

After the simulation had converged, the measurement plane was created in order to gather the relevant results. This was done by creating individual planes for the respective measurement distances, in addition to the side views. Using the Contour (Figures 27 and 28) and Pathline (Fig. 29) tools, the behavior of the system could be identified, and using the XY plot, the respective coordinates were noted. Following this, the lengths of the working surfaces as specified in Subsection 2.1.1 were summarized in the tables presented in Chapter 4.

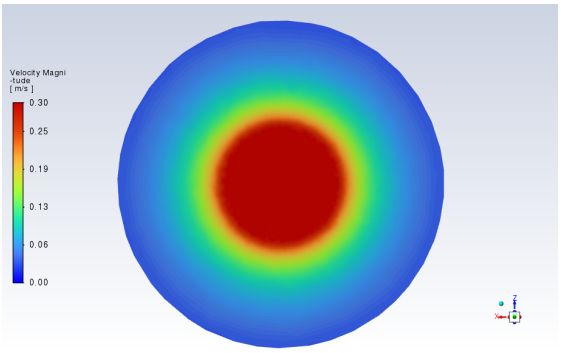


Figure 27: Contour view of air velocity for TM-80 nozzle (Q = 250 m^3/h).

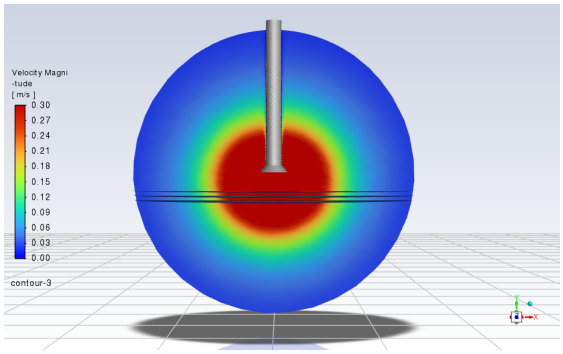


Figure 28: Side Contour view of air velocity for TM-80 nozzle (Q = 250 m^3/h).

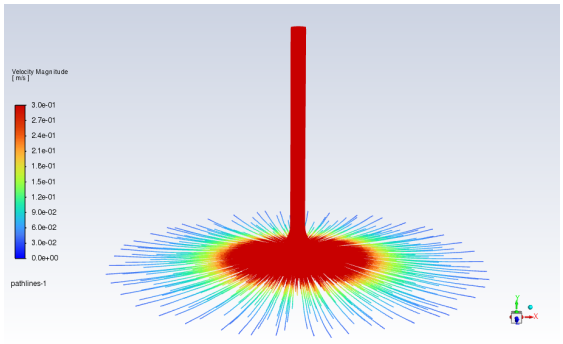


Figure 29: Pathline view of air velocity for TM-80 nozzle (Q = 250 m^3/h).

3.2.5 Creation of working zones

After calculating the safe zones as described by *SS-EN ISO 21904*, additional measurements were performed. As mentioned in Subsection 2.1.2, air velocities above 0.4 m/s could cause defects in the weld. Due to this, new measurements were performed following the procedure described in Subsection 3.2.4, measuring the points with a velocity of 0.4 m/s instead of 0.3 m/s. This resulted in an area inside of the safe zone, where the air velocity would be too high for welding. This area was referred to as the **"zone unfit for work"**. By subtracting this zone from the previously calculated safe zone, an outer zone with velocities between 0.3 and 0.4 m/s was created, which was deemed to be optimal for welding. This resulting area was referred to as the **"working zone"**. An example of this is illustrated in Figure 30.



Figure 30: Illustration of working zone (green) and zone unfit for work (orange).

3.3 Real-world experiments

In order to verify the validity of the digital model, real-world experiments were performed. The purpose was to confirm that the digital model was sufficient to predict the behavior of the flow of the fluid in respective nozzle, as well as the resulting velocities.

A verification test case was performed using the digital models at a 6 cm distance, with a volume flow of 90 m^3/h for each respective nozzle. The same parameters were used for the real-world experiments.

3.3.1 Setup

When performing the real-world experiments, it was crucial that the air volume flow could be provided at a consistent and accurate rate. In order to achieve this, Nederman´s Fume Eliminator GoMax was provided (Fig. 31). Although the GoMax allowed for easy adjustment of the air volume flow, additional calibrating tests had to be performed before the larger-scale experiments. This is because the apparatus measures the air volume flow using a pressure difference, meaning that the actual flow depends on the length of the tube, among other factors.



Figure 31: Nederman's Fume Eliminator GoMax. Image taken from *www.nederman.com.*

This initial measurement was performed by connecting a measuring pipe to two metal pipes (Fig. 32). These pipes were then connected to the GoMax and nozzle, respectively, as illustrated in Figure 33. Following this, an anemometer was connected to the measuring pipe, and a certain pressure was created using the GoMax. Using the anemometer, the pressure difference was noted, and using a formula provided by technical experts at Nederman, the corresponding volume flow was calculated. The same procedure was followed for all the relevant measurement points, and the results were tabulated. The resulting table is found in Appendix C.1.

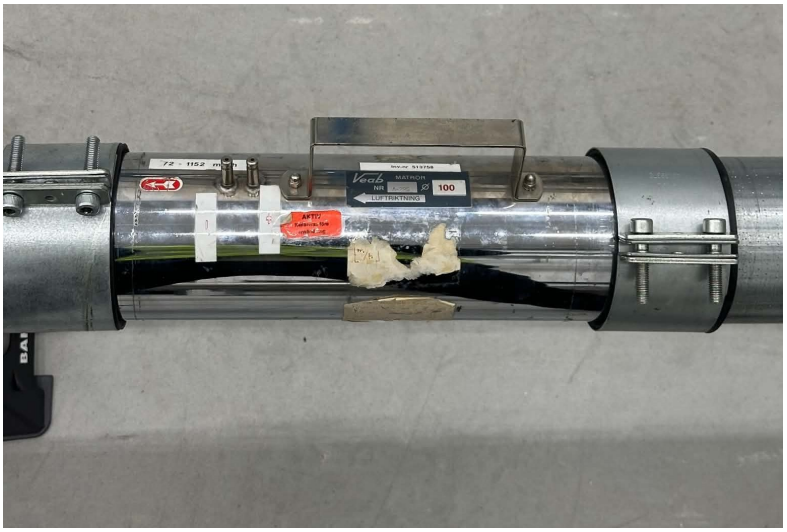


Figure 32: Measuring pipe used in calibrating tests.



Figure 33: Setup for measuring air volume flows from GoMax.

3.3.2 Procedure

Following the measurements of the air volume flow, the experiments were performed. The experiment was based on the procedure presented in Subsection 2.1.1, where a zone with the peripheral velocity of 0.3 m/s is sought in the horizontal plane.

Since the goal of the experiments was to validate the digital model, it was deemed sufficient to perform the experiments using a set air volume flow and distance for each respective nozzle. Once verification was achieved, the remaining iterations were performed through the digital model.

The real-world testing consisted of two experiments: TM-80 at a 0° angle and TM-200 at a 0° angle .

To perform the real-world experiment in accordance with the ISO standard, four main conditions had to be met:

1. The nozzle had to be placed at an adjustable height, perpendicular to the measurement plane. This was achieved by attaching it to a mechanical lift, as illustrated in Figure 34.

2. The anemometer was to be placed at a set distance from the measurement plane, with the ability to move freely along it. To achieve this, a stand was 3D printed (Fig. 35).

3. The coordinates of the four points had to be reliably measured; therefore, a plane with a coordinate grid system was created.

4. The air volume flow had to be easily and accurately adjustable. This was achieved using Nederman's Fume Eliminator GoMax.

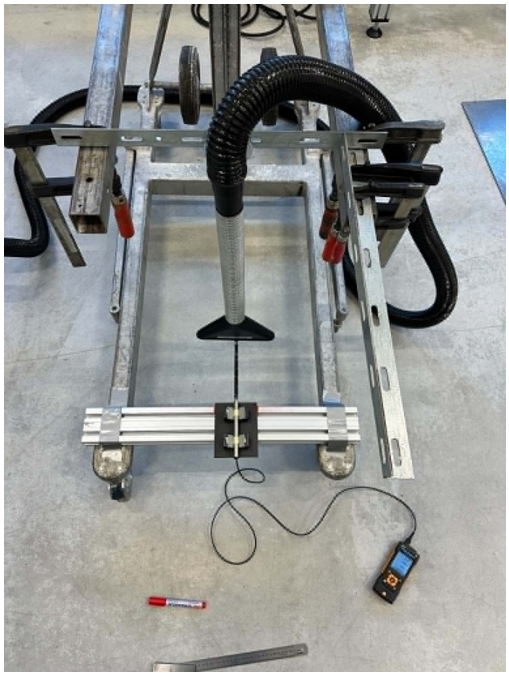


Figure 34: TM-200 nozzle attached to adjustable lift.

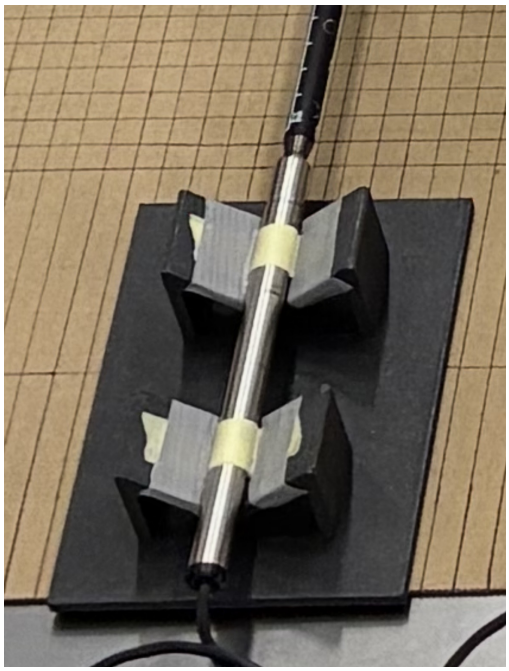


Figure 35: Anemometer mounted on the 3D printed stand.

4 Results of Part 1

In this chapter, the results from Part 1 of the study are presented.

The results found in Section 4.1 show the comparison between real-world experiments and digital models of TM-80 and TM-200.

The dimensions of the resulting safe zones, measured in the digital model, for the two nozzles are tabulated in Sections 4.2 and 4.4 respectively. In the cases where no point of the measurement plane met the required velocity, the cell is instead marked with an "X".

As described in Subsection 3.2.5, work zones were created, illustrating the parts of the safe zone where the shielding gas would not be extracted. These zones for the two nozzles are illustrated in Sections 4.3 and 4.5 respectively.

4.1 Verification of digital models

Table 2: Comparison between real-world experiment and digital model of TM-80.

$\mathbf{TM-80,90\ m^3/h,6\ cm}$					
	$\mathbf{v_{center}\ (m/s)}$	**-x (cm)**	**+x (cm)**	**-z (cm)**	**+z (cm)**
Experiment	0.69	6.7	7.4	7.3	6.2
Model	0.70	7.2	7.1	7.2	7.1

Table 3: Comparison between real-world experiment and digital model of TM-200.

$\mathbf{TM-200,90\ m^3/h,6\ cm}$					
	$\mathbf{v_{center}\ (m/s)}$	**-x (cm)**	**+x (cm)**	**-z (cm)**	**+z (cm)**
Experiment	0.39	9.4	9.5	3.4	3.6
Model	0.36	9.2	9.5	3.6	3.5

4.2 ISO safe zones of TM-80

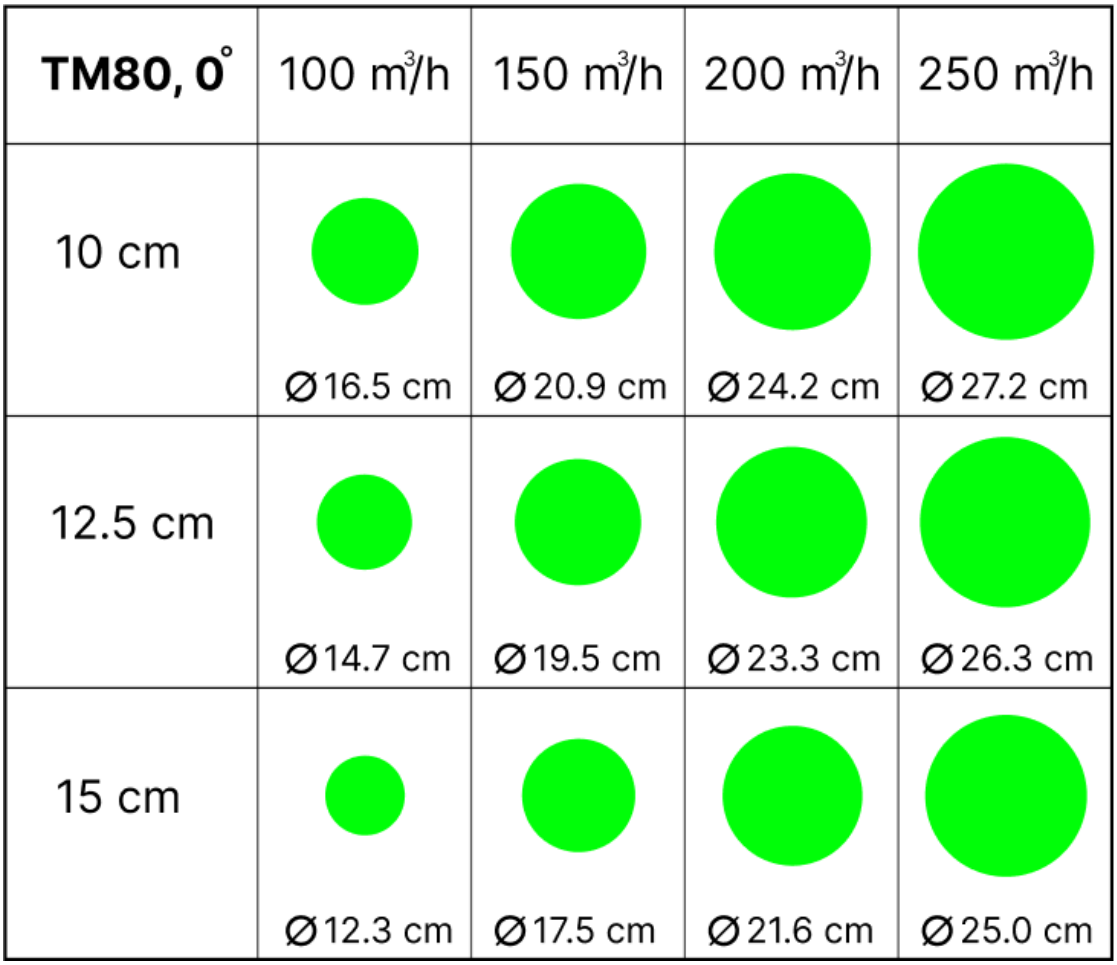


Figure 36: Resulting safe zones of TM-80 at 0° at selected volume flows and distances.



Figure 37: Resulting safe zones of TM-80 at 45° at selected volume flows and distances.

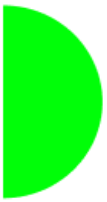
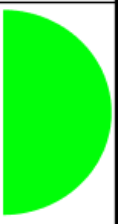
TM80, 90°	100 m³/h	150 m³/h	200 m³/h	250 m³/h
0 cm (No table)	 10.0 × 19.1 cm	 12.1 × 22.6 cm	 15.3 × 26.6 cm	 15.3 × 29.7 cm
0 cm (Table)	 10.3 × 20.0 cm	 13.1 × 24.7 cm	 15.5 × 28.8 cm	 16.7 × 31.6 cm

Figure 38: Resulting safe zones of TM-80 at 90° at selected volume flows and distances.

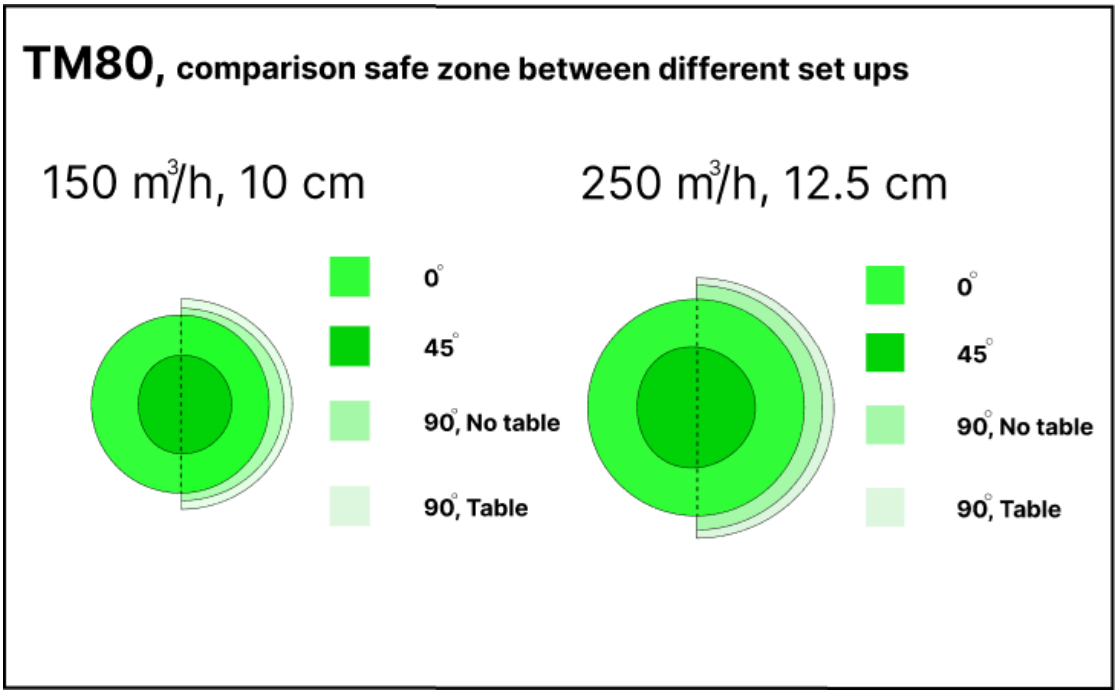


Figure 39: Comparison of resulting safe zones from different setups of TM-80.

4.3 Work zone-Safe Zone comparison, TM-80

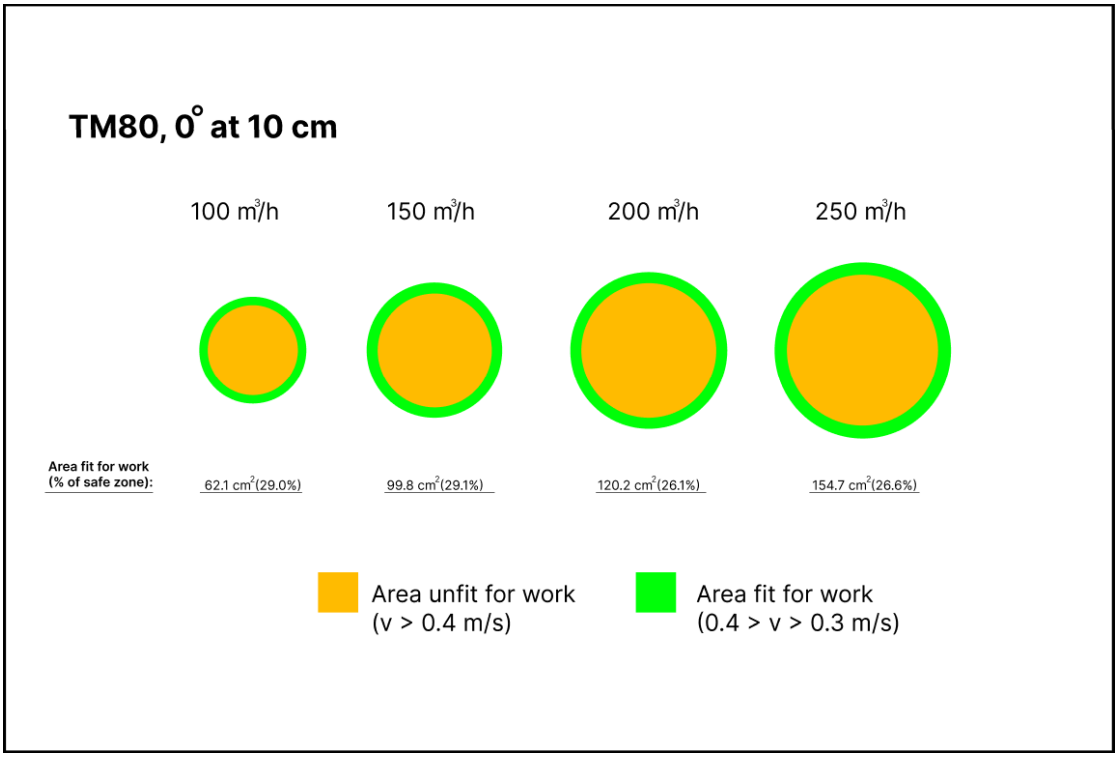


Figure 40: Safe zone-Work zone comparison of TM-80 at varying air volume flows.



Figure 41: Safe zone-Work zone comparison of TM-80 at varying heights.

4.4 ISO safe zones of TM-200

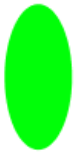
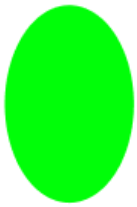
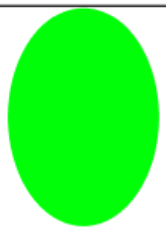
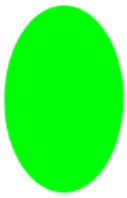
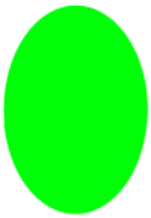
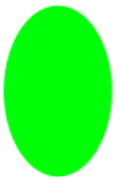
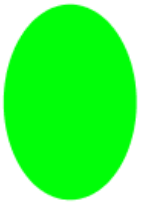
TM200, 0°	100 m³/h	150 m³/h	200 m³/h	250 m³/h
10 cm	 10.4 × 22.4 cm	 15.7 × 27.4 cm	 19.9 × 30.4 cm	 23.3 × 33.6 cm
12.5 cm	 6.9 × 16.7 cm	 14.1 × 25.0 cm	 18.4 × 28.8 cm	 22.2 × 32.1 cm
15 cm		 11.2 × 20.5 cm	 16.7 × 26.3 cm	 20.5 × 30.1 cm

Figure 42: Resulting safe zones of TM-200 at 0° at selected volume flows and distances.

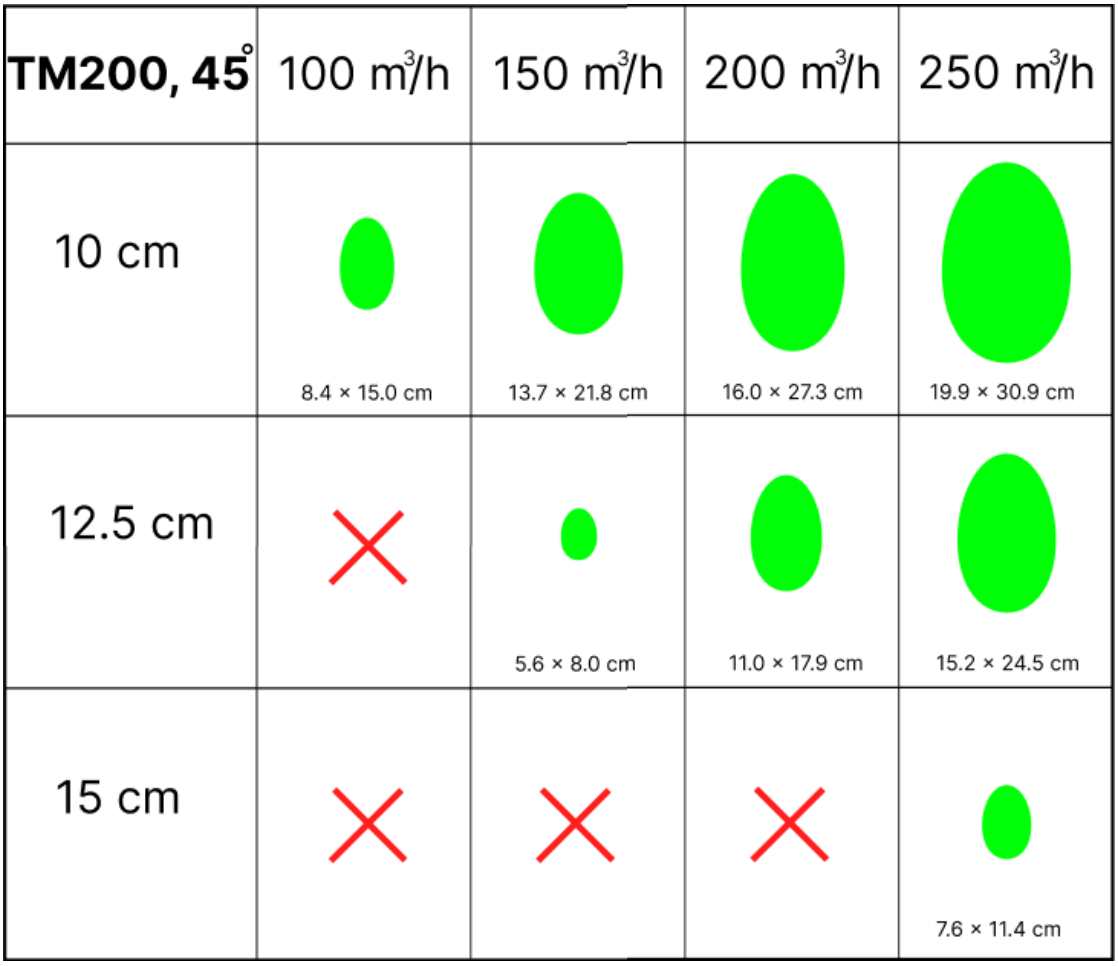


Figure 43: Resulting safe zones of TM-200 at 45° at selected volume flows and distances.

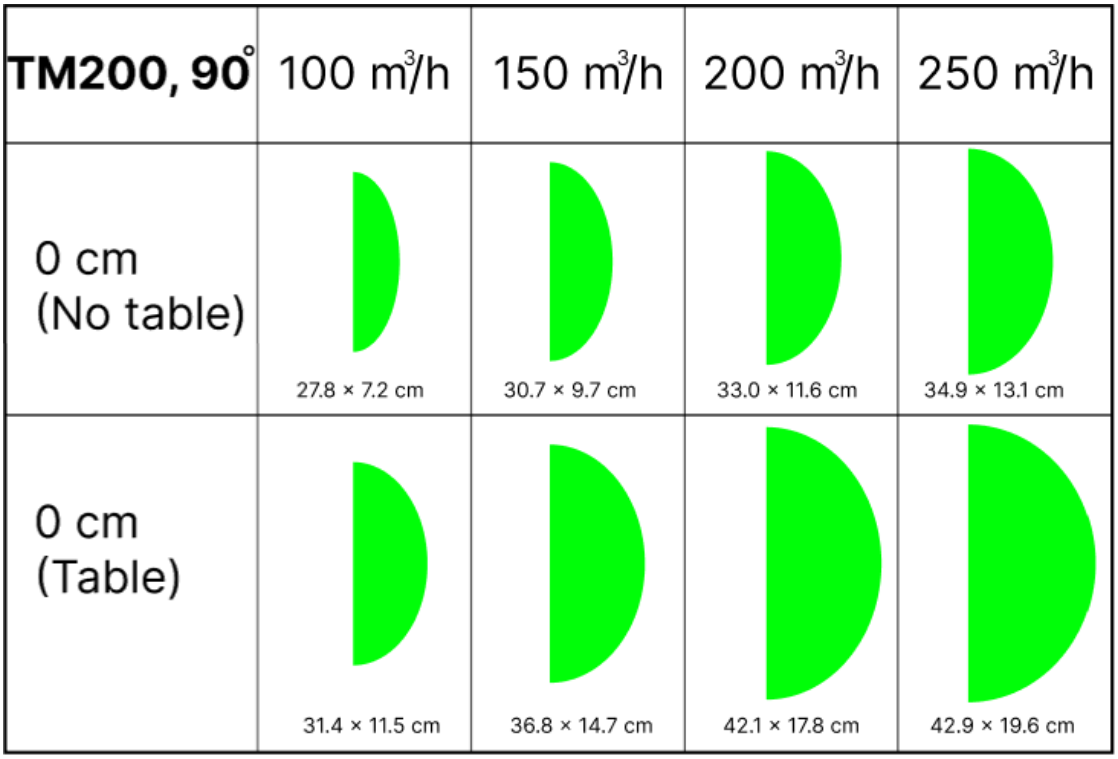


Figure 44: Resulting safe zones of TM-200 at 90° at selected volume flows and distances.

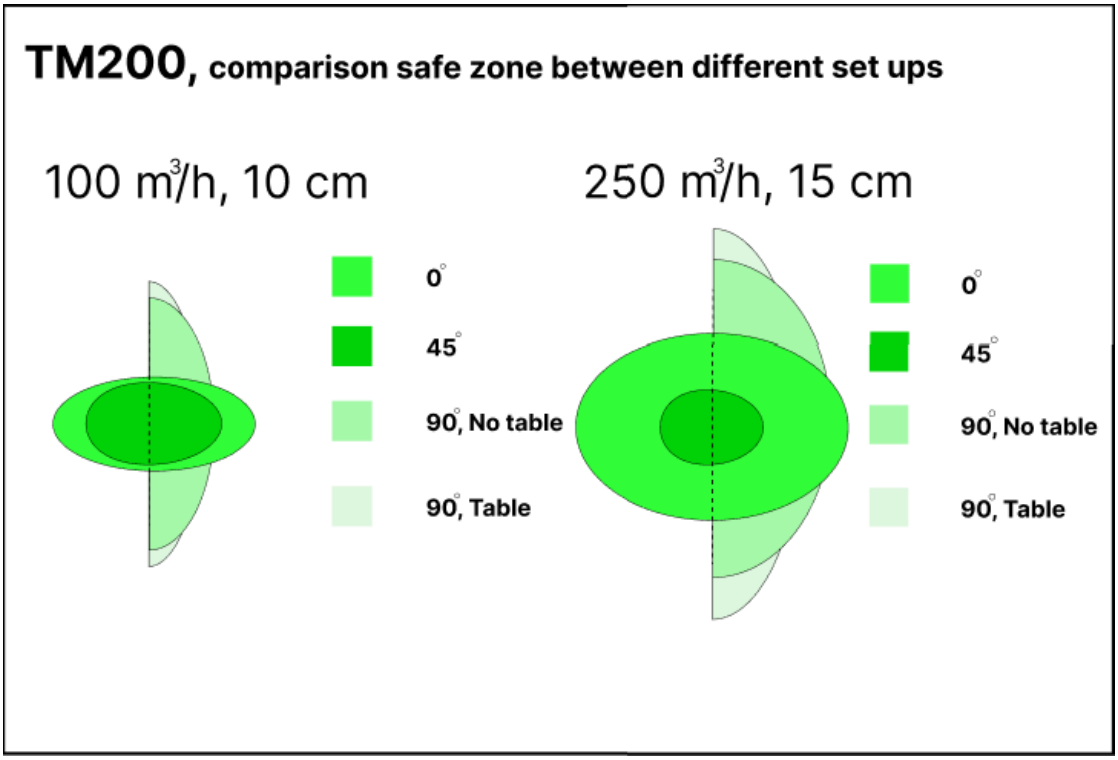


Figure 45: Comparison of resulting safe zones from different setups of TM-200.

4.5 Work zone-Safe Zone comparison, TM-200

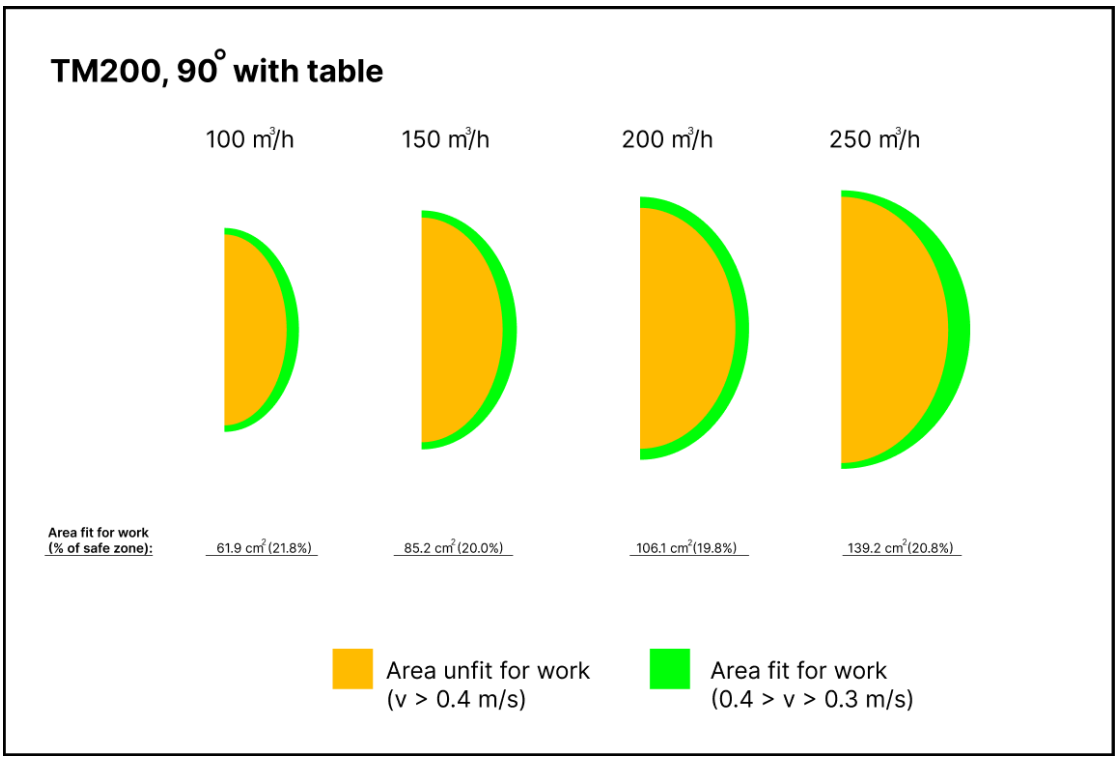


Figure 46: Safe zone-Work zone comparison of TM-200.

5 Discussion of Part 1

In this chapter, the results of Part 1 of the study will be reflected upon with regard to credibility and the impact on Part 2.

5.1 Credibility of results

Although a number of simplifications and assumptions were made in the creation of the digital model, the results can still be considered credible. This is mainly due to there being little or no change in the results after adding a higher level of complexity to the input data. This was true both in choosing between the laminar solver and the two turbulent solvers, and in increasing the amount of mesh elements above 200 000. Because of this, in addition to the fairly simple geometry of the models, convergence occurred after a couple of hundred iterations.

Based on previous experiences of convergence studies, it is possible that the mesh study could be questioned. It is uncommon for a model to instantly yield identical results immediately after the first convergence, which may indicate that the convergence criteria was too strict. The residual continuity was increased to analyze this, but there exist other methods which may have needed to be used instead. However, this would only result in an overly refined mesh, which would not affect the results in any negative way.

Even though the real-world air flow was calculated as being turbulent in Subsection 3.2.3, a laminar solver was used in the evaluation of the two extraction nozzles. This was due to the different solvers providing very similar results, with the laminar solver converging substantially faster. The similarity in results can be explained by the fact that the measurements were made at a macro scale with simple geometries. If the analysis was made at a micro level or with more complex geometries, the turbulent behavior of the air would become apparent. In this case, a turbulent solver, such as the k-epsilon or k-gamma, would potentially have been necessary.

The shapes of the surrounding air volumes differed between the different setups of the digital models. This was because of complexities in the CAD software. Due to the difference in size of the inner and outer volumes however, the impact of this was deemed insignificant. This was confirmed following discussions with experts at both LTH and Nederman.

The real-world experiments were performed in order to verify the validity of the digital models. During this, obtaining the measurements required the testers to adjust the anemometer manually, as described in *SS-EN ISO 21904* [14]. Due to the distribution of the air velocity at the nozzle, small errors in positioning

could lead to faulty measurements. The measuring of the distances and the height adjustments were also performed by hand, which also needs to be considered as potential sources of error. However, it was concluded that these errors would only be in the millimeter range, and since the ISO safe zone is measured in whole centimeters, the models were considered sufficient.

As mentioned in Subsection 2.1.2, it is currently unclear at exactly what air velocity the shielding gas gets extracted while using an extraction nozzle. Following discussions with experts, it was proposed that velocities in the range of 0.6 - 0.8 m/s may be feasible, depending on the working air volume flow and distances. This would in theory create larger working zones, which could have altered the conclusions. Some initial tests were performed to analyze this impact, which concluded that the impact was negligible. The velocity increased exponentially when moving closer to the opening of the nozzle, meaning that increasing the upper limit for air velocity would merely increase the working zone by a matter of millimeters. It was therefore concluded that the evaluations could safely be performed with the original maximum velocity.

5.2 Conclusion of results

After reviewing the results, it became clear that the TM-80 and TM-200 nozzles meet the requirements set by the ISO standard. Therefore, it was concluded that both nozzles provide sufficient protection against the harmful welding fumes. It is important to point out, however, that the ISO standard only considers the safe zone, not the workable zone, as described in Subsection 3.2.5. This means that the zone where welding can safely be performed is significantly more limited than what is indicated by the ISO standard. This issue is illustrated in Figure 47.

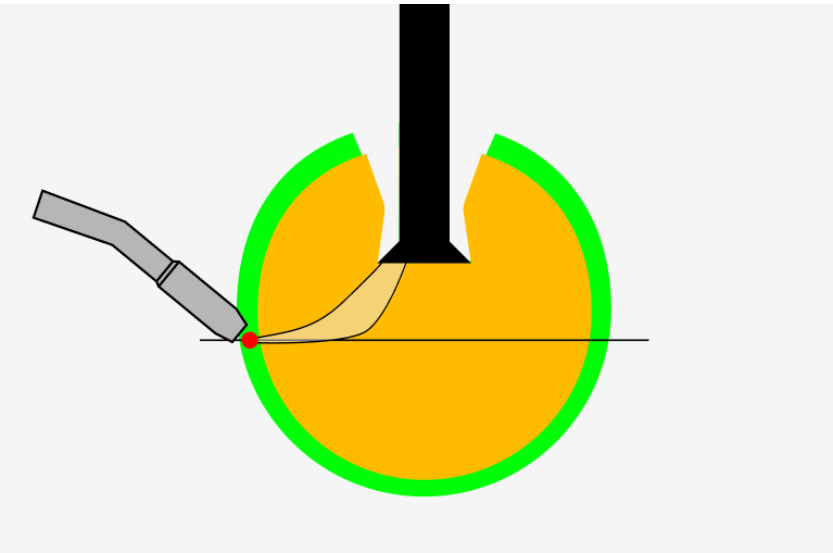


Figure 47: Safe welding when following positioning from ISO standard.

Throughout the study, it has become clear that welders are primarily concerned with the quality of the weld. Welders would therefore position the nozzle in a way that does not impact the quality of their weld. Though they are informed on the importance of protection against fumes, they are in most cases not aware of the precision required to weld inside the safe zone. Due to this, some extraction devices may currently be used in a way that gives the welder a false sense of security, rather than actually offering sufficient protection.

Because of this issue, the study suggests a new positioning of the TM-80 and TM-200 nozzles. The proposed setup is illustrated in Figure 48. The setup utilizes the natural rising behavior of weld fumes, and places the welding point beneath rather than within the safe zone. As long as the welder welds within the sphere "shadow" seen in Figure 48, the fumes will rise into the sphere were the proper extraction conditions exists, and be extracted. This allows the welder to utilize the entire sphere "shadow" instead of the small workable zone.

The setup is based on the ISO standard presented in Subsection 2.1.1, where it is stated that when extracting at an orthogonal distance to the welding point, the safe zone is allowed to be located at further distances than while working at other angles. However, this is only applicable as long as the disturbing air flows in the room do not exceed the limits set by *SS-EN ISO 21904* [14]. Further testing is required to determine at what heights the fumes start to disperse. It is essential however, that the sphere is located below the mouth of the user, in order to avoid inhalation.

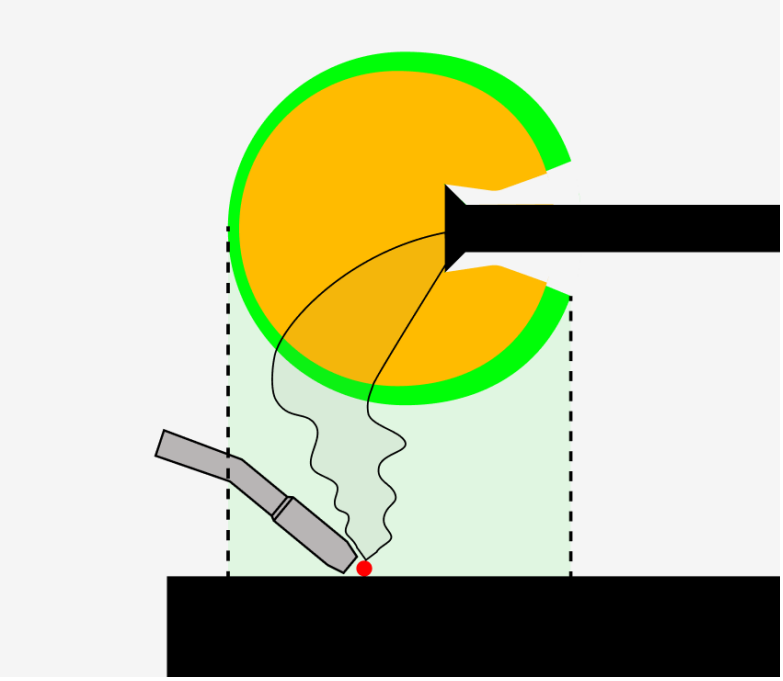


Figure 48: New positioning, as proposed by the study. Welding should occur beneath the sphere with the velocity of 0.3 m/s.

6 Method Part 2

In this chapter, the chosen design process is presented, describing how it differed from the methodology described in Section 2.5.

6.1 Data gathering

The data gathering of Part 2 aimed to provide an area, based on the findings of Part 1, that could be relevant for further development. Due to the scope of the project, it was decided that the final result should be directions for further development rather than a finished product. Individual and group interviews conducted at Nederman resulted in the uncovering of a possible market demand for fume extraction solutions in cobot welding.

The existing solutions for extraction on cobot arms are so called extraction torches, where the extraction is integrated into the top of the welding gun (see Fig. 49).



Figure 49: Extraction torch. Image taken from *www.innoteccn.com*.

According to *SS-EN ISO 21904*, the integration of extraction torches on cobot arms requires the customer to perform testing of air volume flows for every welding session [14]. This requirement is not imposed on extraction nozzles, and following further discussion with the Nederman team, it was therefore decided to explore the possibilities of integration of extraction nozzles in cobot welding. Based on this, a mission statement for the design process was created. In this, the most

essential aspects of the product was described, in combination with stakeholders and market possibilities.

Mission Statement: Extraction nozzle attached to a cobot

Product Description

- A high-vac extraction nozzle attached to a cobot with the purpose of removing toxic fumes at the source.

Benefit Proposition

- Protects industry personnel from toxic fumes. Utilizes energy more efficiently than low-vac nozzles. Easier implementation than existing extraction torch solutions.

Primary Market

- Welding industries where cobots are used

Secondary Markets

- Other industries where cobots are used

Assumptions

- Attached to cobot

Stakeholders

- Industry personnel
- Nederman
- Sales force
- Cobot manufacturers
- Nozzle producers
- Legal department
- Developers

6.2 Identify customer needs

The study used interviews, competitor analysis and the findings from Part 1 to gather the data that formed the basis for the customer needs. From the data gathered, 22 customer needs were elicited. These were then organized into a hierarchy

of primary and secondary needs. Following this, the needs were ranked in order to establish a relative importance, see below:

Customer Needs

The product is easy to work with

- *The product is quick to install.
- *The product is intuitive to install.
- It is easy to perform service on the product.

The welding process is unaltered by the implementation of the product

- ***The extraction is constant.
- ***The product preserves the freedom of movement of the cobot.
- **The product is attached away from the welding gun.
- **The product keeps the working surface intact.

The product keeps the welding process efficient

- **The product utilizes the air volume flow in an efficient way.
- **The product uses industry standard volume flows.
- *The product is lightweight.

The product is manufactured in a competitive way

- ***The product follows Nederman's four core values.
- *The product fits well into the Nederman product portfolio.
- *The production cost is low relative to the cobot arm.
- *The production time is low relative to the cobot arm.
- *The product is manufactured using cheap tools.
- *The product is efficient to transport.

The product has multiple fields of use

- ***The product is compatible with existing cobot arms (universal fit).
- *!The product has secondary applications.

The product keeps the personnel safe

- ***The product ensures that the welding takes place inside of the safe-zone.
- **The noise level of the product is kept at a comfortable level.

The product is resilient

- ***The product is resistant to heat.
- **The product is resistant to wear and tear.

6.3 Establish target specifications

Using the needs gathered from the previous steps, the necessary specifications were established. These are illustrated in Table 4. The specifications that were deemed objective were assigned a suitable unit, with a marginal and ideal numerical value. The other specifications were deemed to be subjective, and marked with a N/A in the corresponding cells. The values were based on information acquired from the data gathering, and verified by experts at Nederman.

Table 4: Established target specifications, with relative importance and corresponding values.

Metric no.	Need no.s	Metric	Imp.	Units	Marginal value	Ideal value
1	1,2	Average time to install	3	min	> 15	> 5
2	3	Average time to service	2	min	> 10	> 3
3	4	Product is attached away from the welding gun	5	Binary	N/A	N/A
4	5	Fluctuation of air volume flow	5	%	(+/-) 5	(+/-) 3
5	6	No contacts with working surface	4	Binary	N/A	N/A
6	7	Diameter of nozzle	4	mm	50	10
7	7,19	Distance between welding point and nozzle	5	cm	15	5
8	7	Angle of rotation of robot head	4	deg	360	360
9	8	Air volume leakage	4	%	10	0
10	9	Air volume flow in tube	4	m^3/h	250	100
11	10	Weight of product	3	kg	3.5	2.5
12	11	Nederman's four core values	5	Subj.	N/A	N/A
13	12	Nederman's product portfolio	4	Subj.	N/A	N/A
14	13,15	Production cost	3	kr	2000	1000
15	14	Production time	3	min	40	15
16	16	Nr of products per pallet	3	Products/pallet	100	250
17	17	Amount of compatible cobot models	5	%	70	100
18	18	Fields of use	3	Fields of use	2	5
19	19	Welding point inside work zone	5	Binary	N/A	N/A
20	20	Noise level	4	dB	75	65
21	21	Max operating temperature	5	deg. C	200	400
22	22	Cycles of welding without breaking	4	Cycles	500 000	1 000 000

6.4 Generate, Test and Select product concepts

6.4.1 Restructure of design process

The study based its concept generation process on the "five step concept generation method" as described in Subsection 2.5.4. In order to fit the project however, some alterations were made. The refined process started by clarifying the problem. Then, it was decided to create a cycle consisting of the remaining parts. This resulted in a cycle consisting of three main steps: Creation of concepts, Testing of concepts, and Selection of concepts. The cycle was then repeated three times and the result of this were two final concepts. The overall process is illustrated in Figure 50.

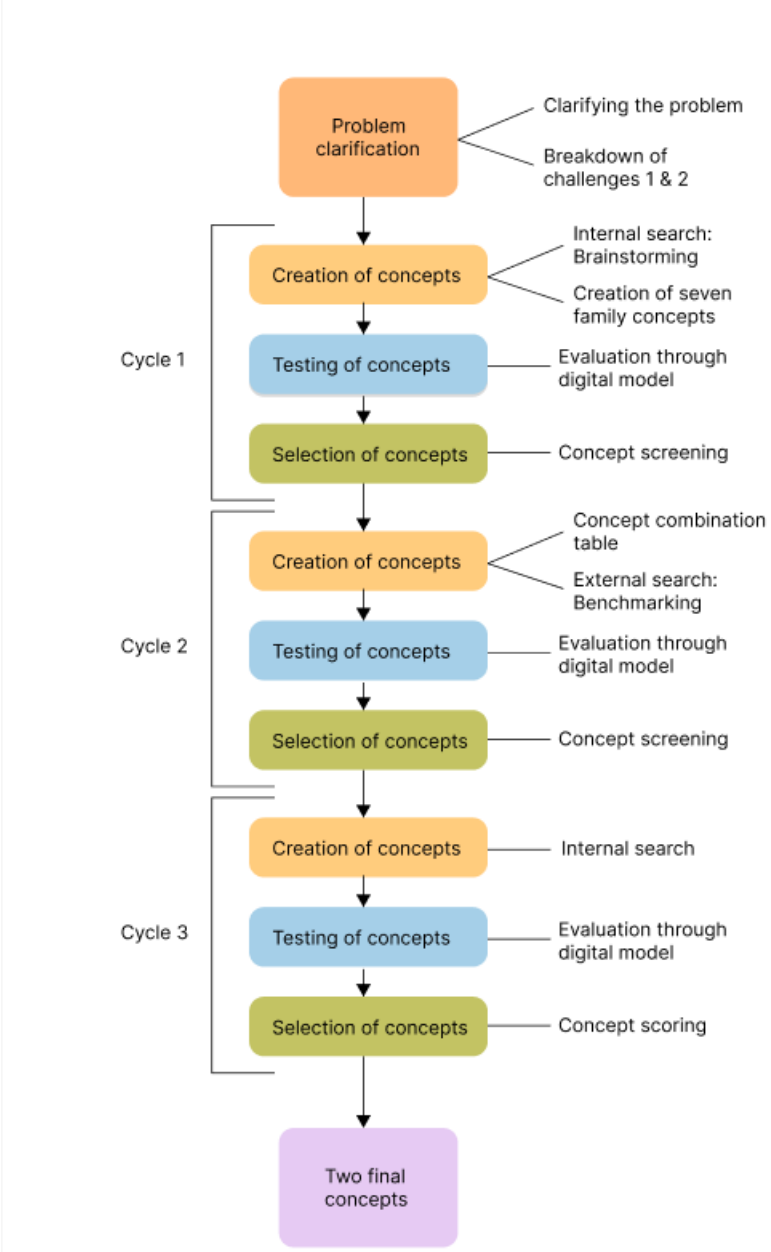


Figure 50: Overview of restructured design process.

The internal search was mainly performed in the "Creation of concepts" part of a cycle. It took the form of brainstorming and was based primarily on the experience gained in Part 1, as well as the data collected when obtaining needs.

The internal search was supplemented by an external search in which data was gathered through expert interviews and a customer visit. This took place throughout all three cycles, however, primarily in Cycles 2 and 3.

Furthermore, "Systematically explore" was used in the "Creation of concepts" step in Cycle 2.

In order to provide a coherent description of the product development process, it was decided to present it chronologically in this report. This was started by clarifying the problem.

6.4.2 Clarifying the problem

The aim of the development part of the project was defined as to "place the welding point of a cobot inside the work zone". Furthermore, it was decided that this was to be achieved primarily through the positioning of an extraction nozzle.

The aim was decomposed into five main challenges:

1. Use reasonable air volume flow.
2. Preserve freedom of movement.
3. Attachment to the cobot.
4. Integration of tube.
5. Serviceability and cleaning.

Due to the scope of Part 2, it was decided to mainly focus on resolving challenges 1 and 2. However, to sufficiently aid future developers, it was deemed necessary that the proposed solutions would not cause issues for future solutions to the remaining challenges.

The two main challenges were then broken down even further with the purpose of understanding all aspects and their effects as well as importance in a proposed solution. From this, demands and guidelines were derived. The following table presents the aspects and the demands or guidelines that followed:

Breakdown of challenges 1 and 2

Challenge 1: Use reasonable air volume flows

- Increasing the working air volume flow will lead to increased energy consumption in operating the machines, directly causing increased operating costs.

- If the product is designed for too high operating air volume flows, it may need a pressure difference above what the existing equipment can achieve. This would require additional, more expensive, machines being purchased, increasing costs.

  Because of this, it was deemed important that the working air volume flows for the concept would follow industry standards for cobot welding. From the data gathering process, this was determined to be between ***100-300 m^3/h****.*

Challenge 2: Preserve freedom of movement

- During the welding process, the cobot may need to access tight spaces or small crevices.

  Because of this, it was deemed important to position the nozzle as far back on the welding gun as possible. From the data gathering, a distance of ***120 mm*** *was deemed suitable.*

  If this would not be possible, it was deemed important to position the nozzle close to the welding gun.

- Another aspect to consider is that the cobot should be able to follow welding patterns of a certain complexity without interruption.

  One way of solving this is to position the nozzle far away from the welding point.

  If this could not be achieved, the nozzle should be positioned in such a way that it only ***occupies one side of the welding gun*** *at a time.*

6.4.3 Cycle 1

Once the clarification and breakdown of the problem had been completed, Cycle 1 began. First, it was decided that a concept should be defined as the shape and positioning of a nozzle. Following this definition, an internal search, using brainstorming, resulted in the creation of 38 individually generated concepts. Examples of these are illustrated in Figure 51, and all 38 are found in Appendix D.1. From these, certain characteristics were identified. Based on these characteristics, seven concept families where created (see Figure 52).

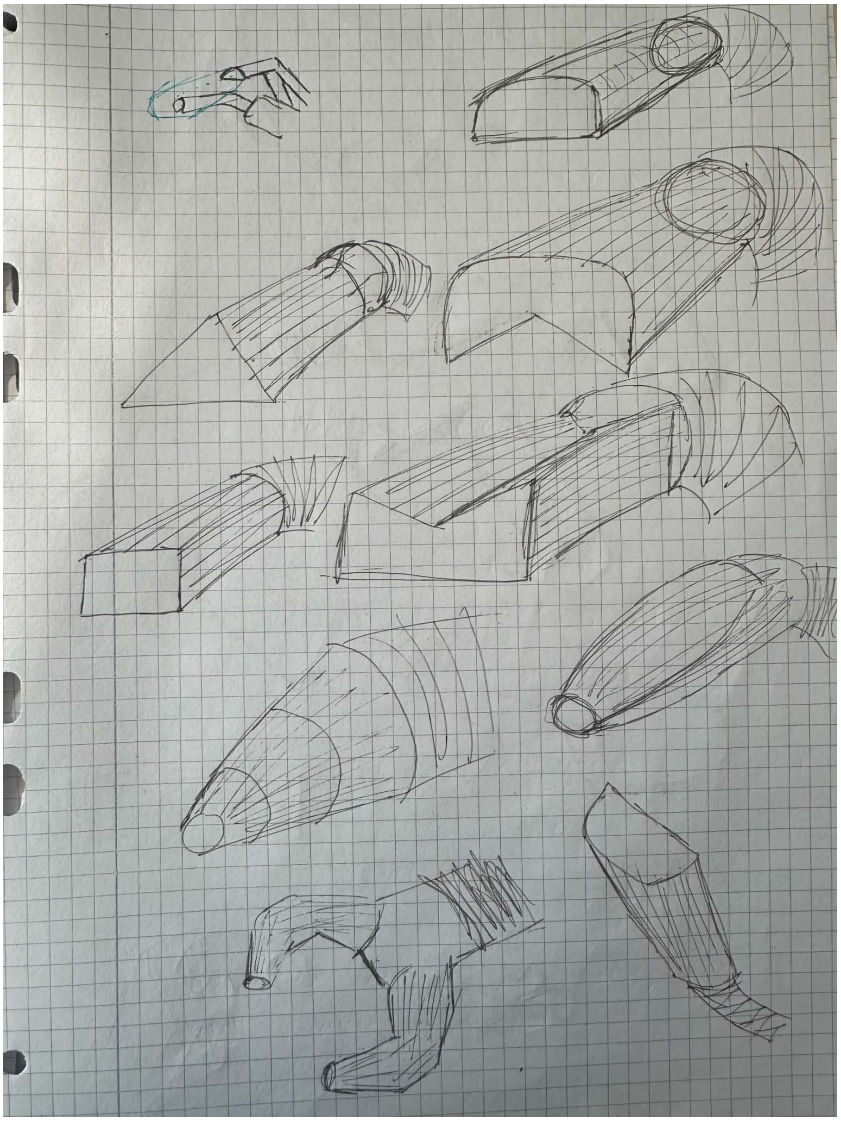


Figure 51: Example of the 38 initial concepts.

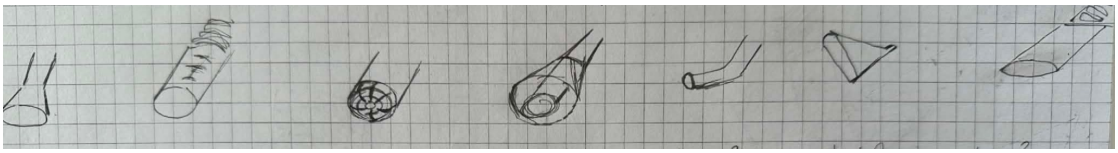


Figure 52: The seven family concepts (positioning excluded).

The seven family concepts were then created in CAD and had their performance evaluated through the digital model created in Part 1 of the project. Results of

this evaluation are found in Appendix D. Lastly, the cycle ended by selecting which families to continue develop through a concept screening matrix (Tab. 5).

Table 5: Concept screening matrix for Cycle 1.

	Concepts						
Selection Criteria	**A**	**B (Reference)**	**C**	**D**	**E**	**F**	**G**
	Mini TM80	Tube	Cone	Dog Cone	Banana	TM50x5	TM-Tilt
Ease of positioning	-	0	0	-	+	-	-
Extraction reach	0	0	+	0	0	0	0
Allows for access of tight spaces	-	0	0	-	+	-	0
Aesthetically pleasing	+	0	+	-	+	-	+
Ease of manufacture	0	+	-	-	0	-	+
Sum +'s	1	1	2	0	3	0	2
Sum 0's	2	4	2	1	2	1	2
Sum -'s	2	0	1	4	0	4	1
Net Score	-1	1	1	-4	3	-4	1
Rank	3	2	2	4	1	4	2
Continue?	No	Yes	Yes	No	Yes	No	Yes

The family concepts chosen to be further developed were "Tube", "Cone", "Banana" and "TM-tilt", see Figure (53). These families were then used as the starting point of Cycle 2.

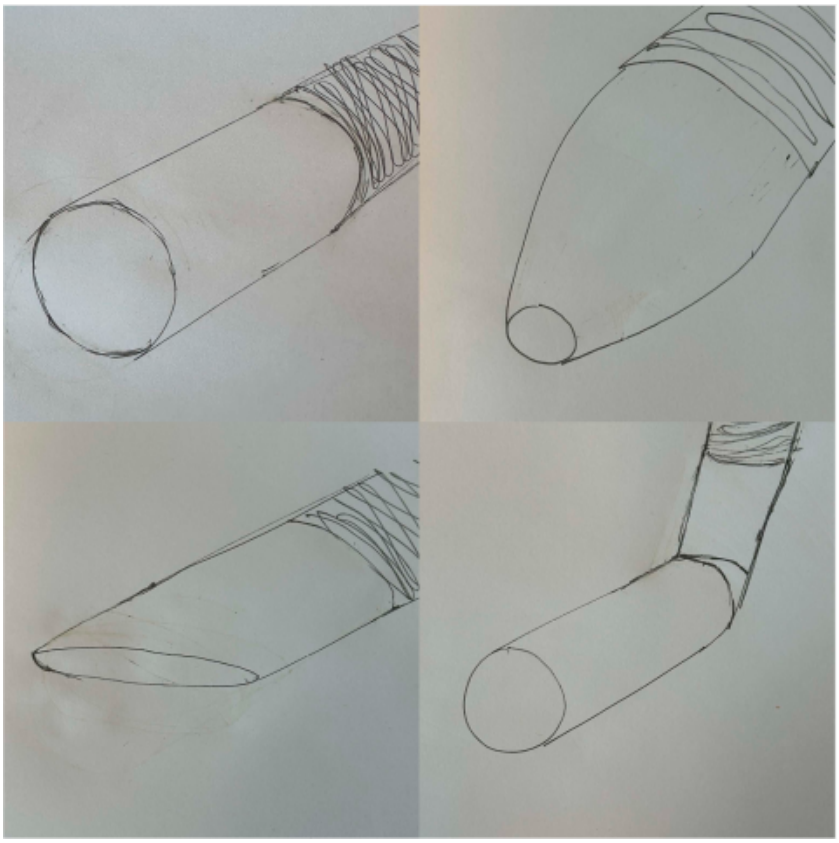


Figure 53: From top left corner: sketches of "Tube", "Cone", "TM-tilt", and "Banana" concepts.

6.4.4 Cycle 2

Cycle 2 began by systematically exploring solutions by combining features from the champions selected in Cycle 1. Using a "Concept combination table", six new concepts were created. Instead of using sub problems as the combination table columns, broader features were used. The chosen features were "Profile", "Distance to gun", "Size of outlet", and "Shape of outlet". These were then divided into opposite words. Lastly, different features were combined to create prompts for new, combined concepts, see Figure 54.

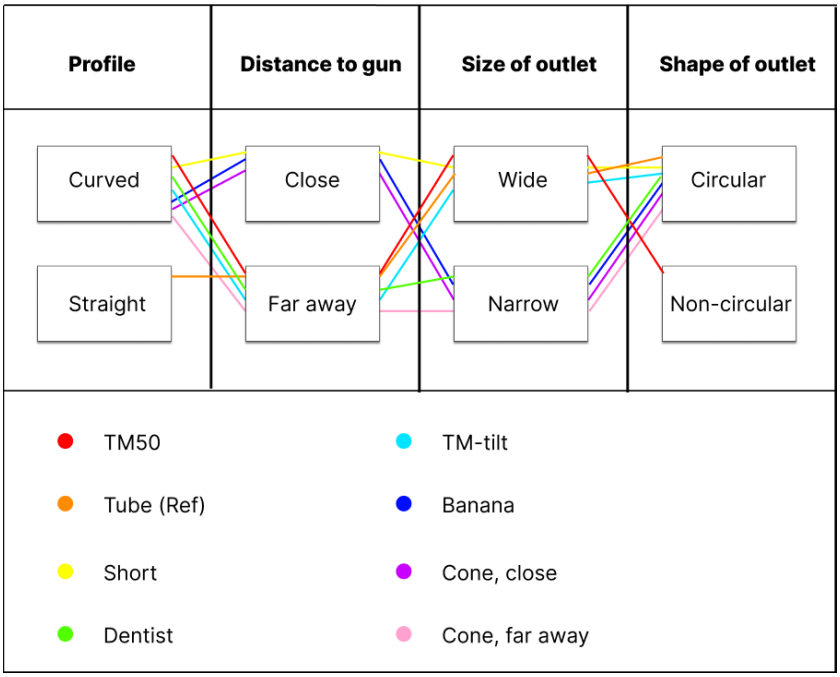


Figure 54: Concept combination table

In addition to the Concept combination table, an external search was conducted. During this, other areas where nozzles are used were explored, including aviation, the medical industry and the energy sector. This resulted in three new concepts, based on the design of Laval-, Venturi-, and Slot nozzles.

In total, 14 concepts were created. Through an external search where an expert was interviewed, 10 of them were deemed relevant for further evaluation. The questions asked during this are found in Appendix E. Results of this evaluation can be found in Appendix D.2. Once the simulations had been performed, the 10 concepts were screened using the concept screening matrix used in Cycle 1, see Table 6.

Table 6: Concept-screening matrix with 10 concepts

	Concepts									
Selection Criteria	**A**	**B**	**C(Reference)**	**D**	**E**	**F**	**G**	**H**	**I**	**J**
	Banana	Slot	Tube	TM-tilt	Cone c.	Cone f.	Short	TM50	Dentist	Laval
Ease of positioning	+	0	0	0	+	0	+	-	0	0
Extraction reach	+	+	0	0	+	-	+	-	-	-
Allows for access of tight spaces	-	0	0	0	-	0	-	-	0	0
Aesthetically pleasing	+	0	0	-	-	-	-	+	-	+
Ease of manufacture	-	0	+	0	0	0	0	-	-	0
Sum +'s	3	1	1	0	2	0	2	1	0	1
Sum 0's	0	4	4	4	0	3	1	0	2	3
Sum -'s	2	0	0	1	2	2	2	4	3	1
Net Score	1	1	1	-1	0	-2	0	-4	-3	0
Rank	1	1	1	7	4	8	4	10	9	4
Continue?	Yes	Yes	Yes	No	No	No	No	No	No	No

From the concept screening, three concepts, "Banana", "Slot", and "Tube", were chosen to be further developed in Cycle 3.

6.4.5 Cycle 3

The three champion concepts chosen in Cycle 2 were combined to create four refined concepts. These were named "Banana, "Cobra", "Tube" and "Slice" (see Figure 55. Following this, the four refined concepts were evaluated through the digital model. The results can be found in Appendix D.3.

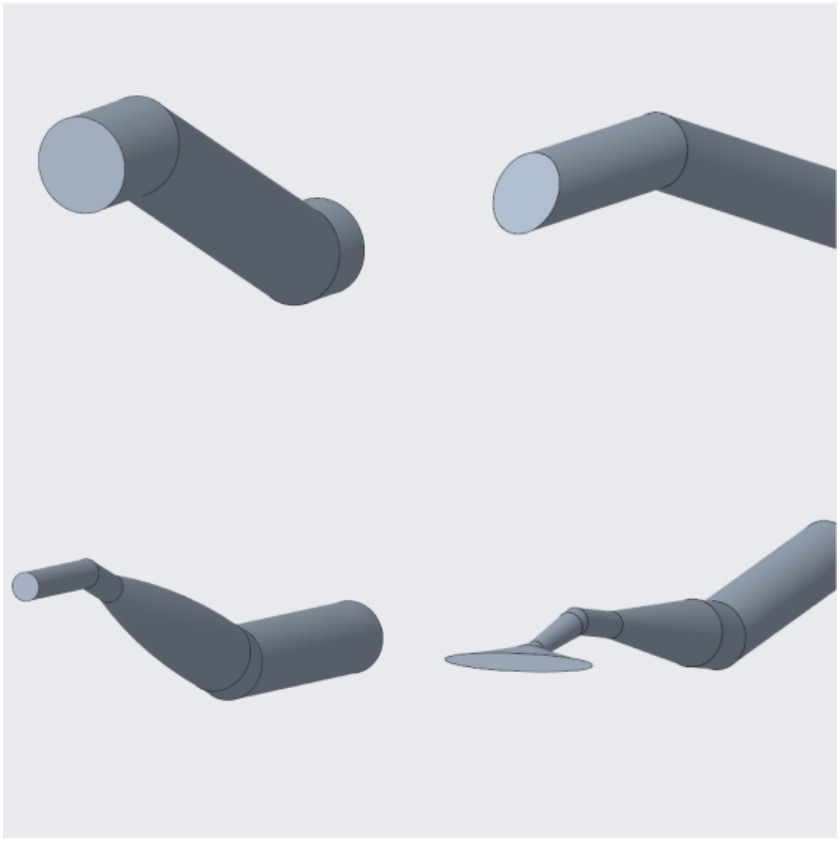


Figure 55: The four refined concepts, from top left: Tube, Slice, Banana, Cobra

Before making the final selection, an external search in the form of a customer visit was conducted. This gave valuable insights on cobot-robot welding as well as the users. After the visit, a final selection was made using a "Concept scoring matrix", see Table 7. The weighting, rating and set up of the scoring matrix is described in Section 9.2.

Table 7: Third round concept scoring matrix

		Concepts							
		Banana		Cobra		Tube		Slice	
Selection Criteria	Weight	Rating	Score	Rating	Score	Rating	Score	Rating	Score
Aesthetic	7%	2	0.14	2	0.14	1	0.07	3	0.21
Non-intrusive	40%	2	0.80	1	0.40	4	1.60	3	1.20
Flexibility of positioning	17%	4	0.68	4	0.68	1	0.17	1	0.17
Cost of operation	10%	4	0.40	4	0.40	2	0.20	2	0.20
Potential of development	22%	4	0.88	4	0.88	1	0.22	3	0.66
Secondary applications	4%	2	0.08	1	0.04	5	0.20	4	0.16
Total Score		2.98		2.54		2.46		2.60	
Rank		1		3		4		2	
Continue?		**Yes**		**No**		**No**		**Yes**	

The Concept scoring matrix resulted in two final concepts: "Banana" and "Slice". Some additional refinements were made to these, resulting in the final concepts described in Chapter 7.

7 Final concepts

In this chapter, the final concepts from the concept generation process in Part 2 are presented.

7.1 Concept 1: VMC-25

7.1.1 Images of product

From the concept selection process, two final concepts were chosen. One concept was named **VMC-25**, illustrated in Figures 56 and 57. Figure 58 illustrates the technical specifications of the concept. A 3D-printed prototype was created, as shown in Figure 59.

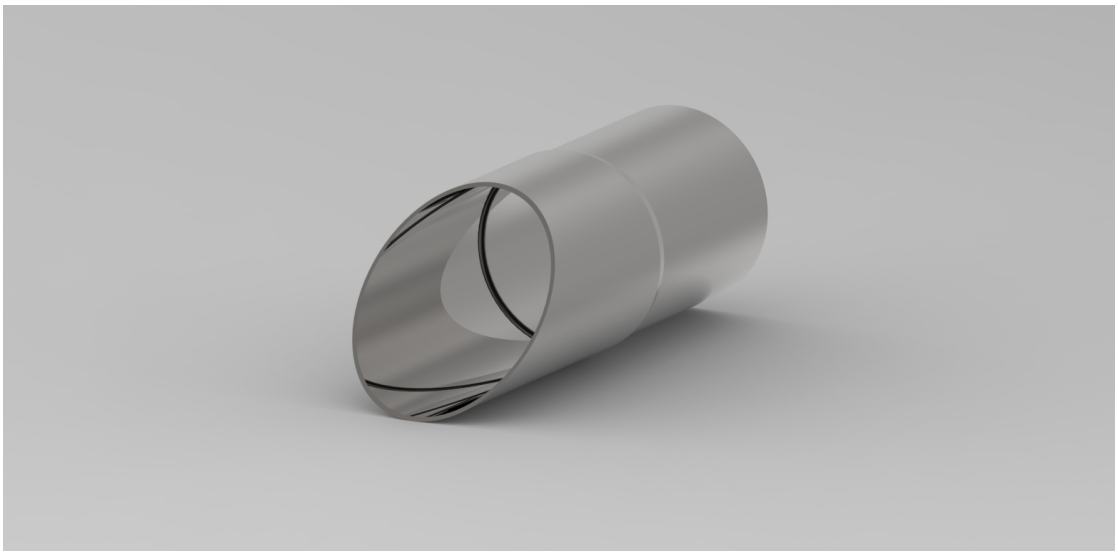


Figure 56: Rendered image of the VMC-25.



Figure 57: User case of the VMC-25.

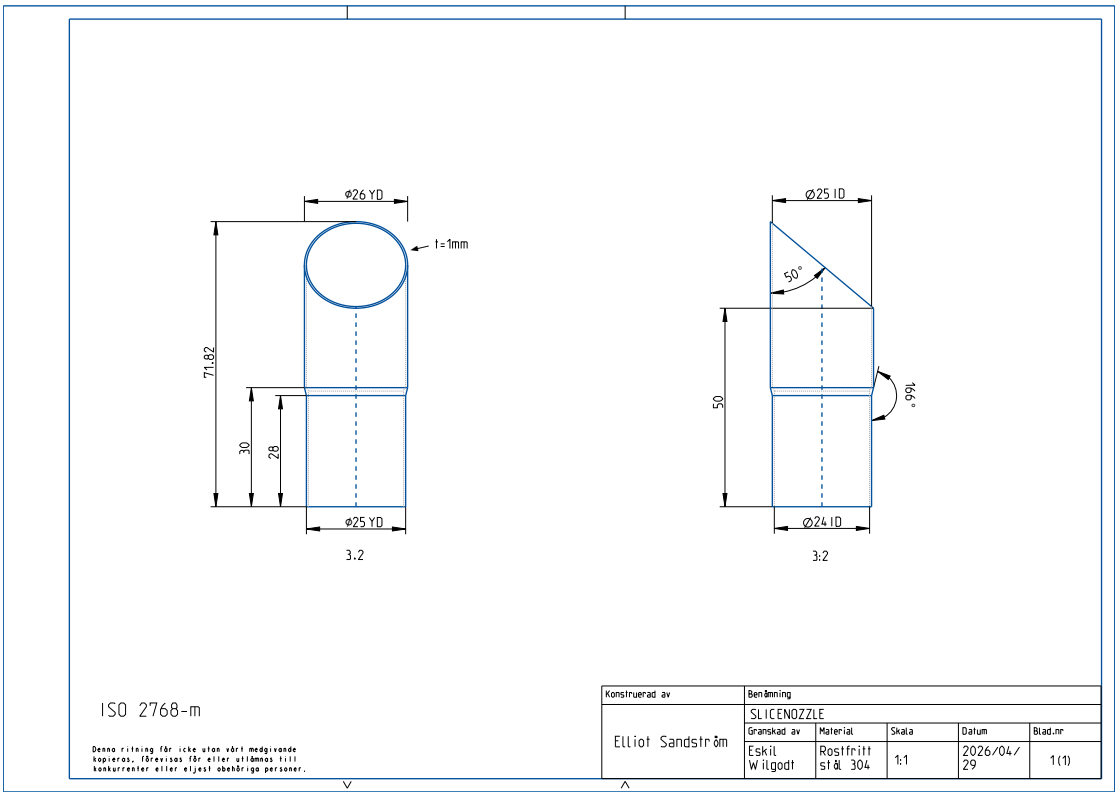


Figure 58: Technical drawing of VMC-25.



Figure 59: 3D printed prototype of the VMC-25.

7.1.2 Positioning

In addition to the measurements of the nozzles themselves, the positioning of the nozzles were also a major design consideration. The suggested positioning of the VMC-25 is illustrated in Figure 60.

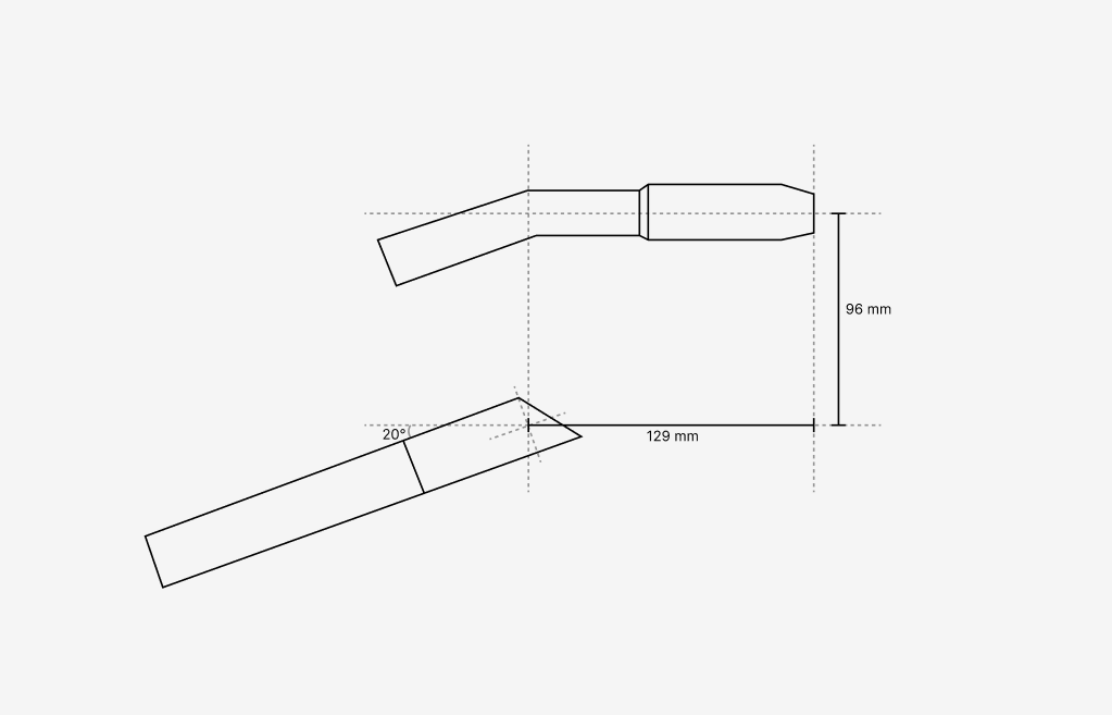


Figure 60: Suggested positioning of the VMC-25.

7.2 Concept 2: CMC-10

7.2.1 Images of product

The second concept was named **CMC-10**, and is illustrated in Figures 61 and 62. Figure 63 illustrates the technical specifications of the concept. As for the VMC-25, a 3D-printed prototype of the CMC-10 was created (Fig. 64).



Figure 61: Rendered image of the CMC-10.

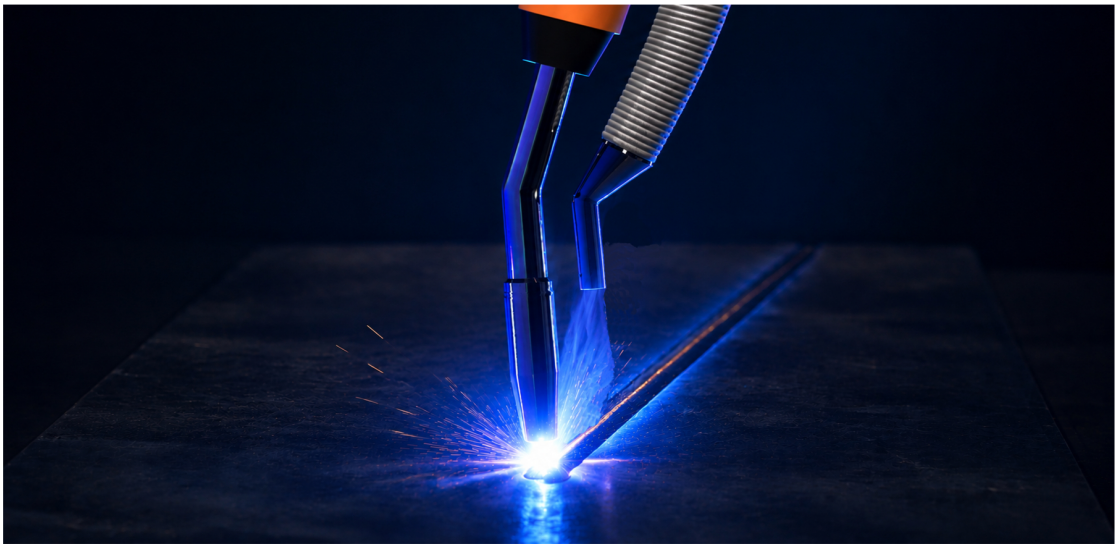


Figure 62: User case of the CMC-10.

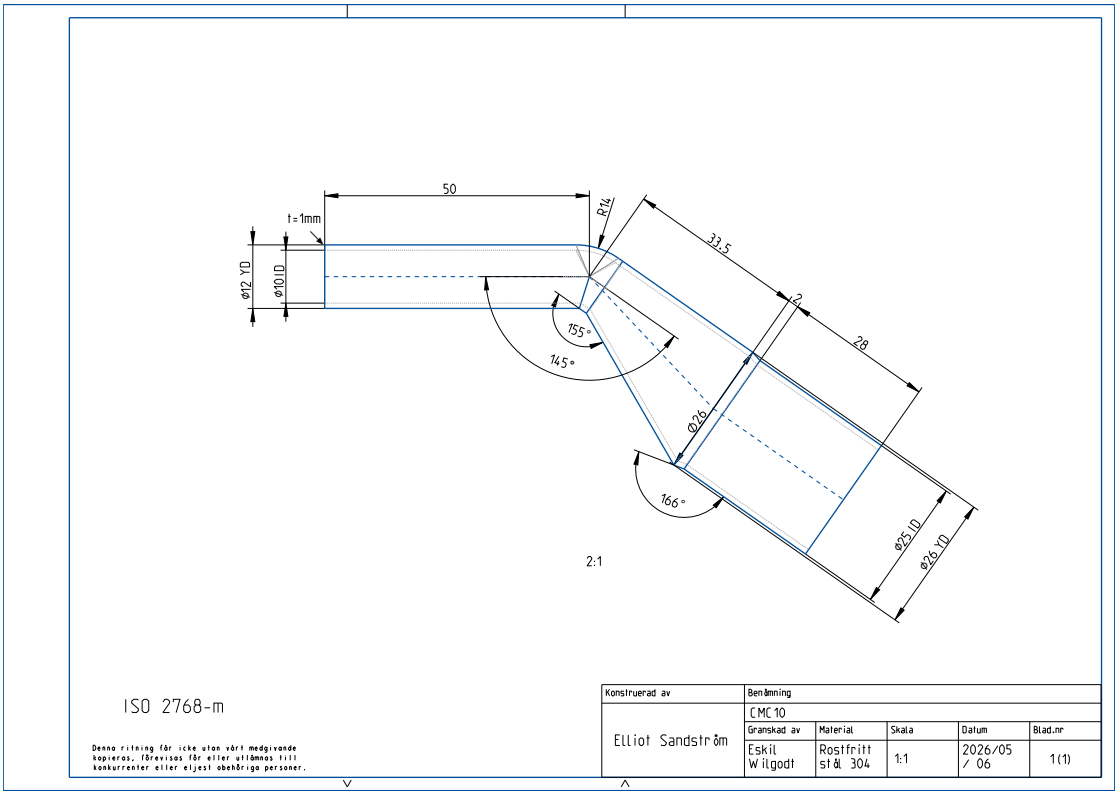


Figure 63: Technical drawing of the CMC-10.



Figure 64: 3D printed prototype of the CMC-10.

7.2.2 Positioning

The suggested positioning of the CMC-25 is illustrated in Figure 65.

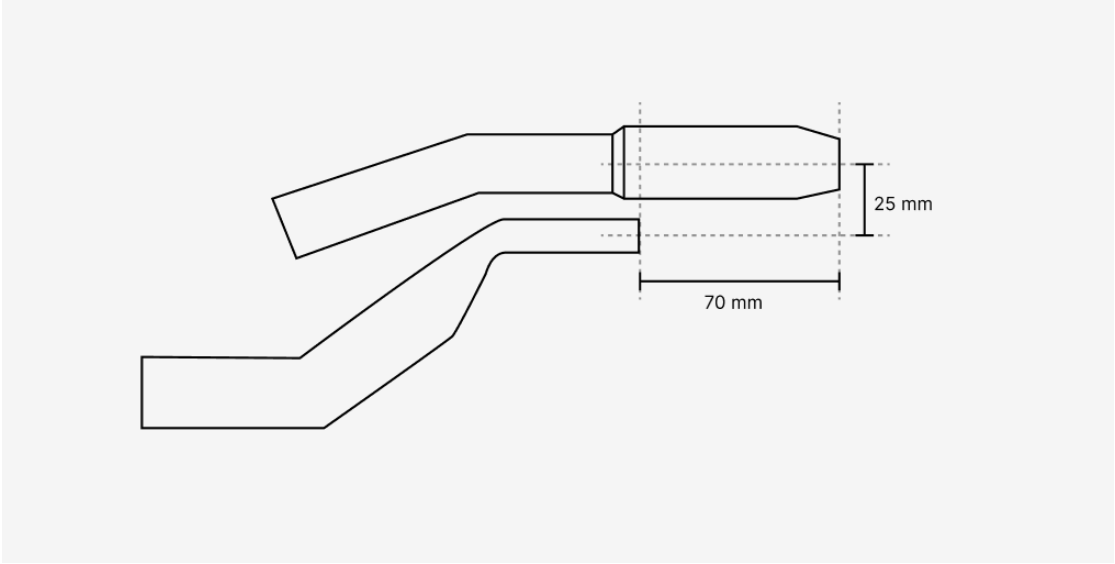


Figure 65: Suggested positioning of the CMC-10.

8 Performance of final concepts

In this chapter, the performance of the two final concepts is presented.

8.1 Calculation of working air volume flows

In order to visualize the performance of the final concepts, a suitable working air volume flow was calculated. This was achieved by measuring the lowest air volume which kept the extraction velocity above the ISO limit of 0.3 m/s in the welding spot. The welding spot was approximated to be placed 10 mm from the end of the welding gun and is illustrated as a red dot (see Fig. 66). Once the minimum air volume had been calculated, a suitable safety factor of 30% was applied, resulting in the respective working air volume flows. These ended up being 448.5 m^3/h and 162.5 m^3/h for the VMC-25 and CMC-10 respectively.

For the CMC-10, requests were made at Nederman to further analyze the operational range of the nozzle. Therefore, tests were performed with safety factors in the range of 0-150%, and the respective results were collected in a table (see Appendix C.2).

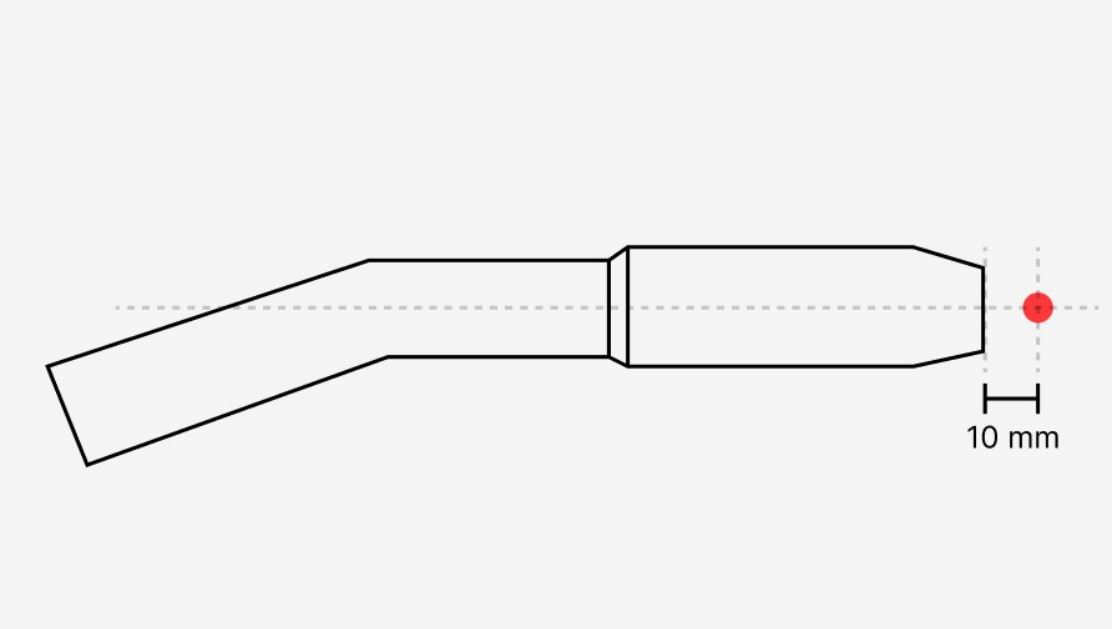


Figure 66: Positioning of the welding point.

8.2 VMC-25

8.2.1 Contour views

To illustrate the velocity distribution of the nozzle, contour views were created. The velocity distribution of the VMC-25 is illustrated in Figures 67 and 68. The results were obtained using the same settings as the original simulations.

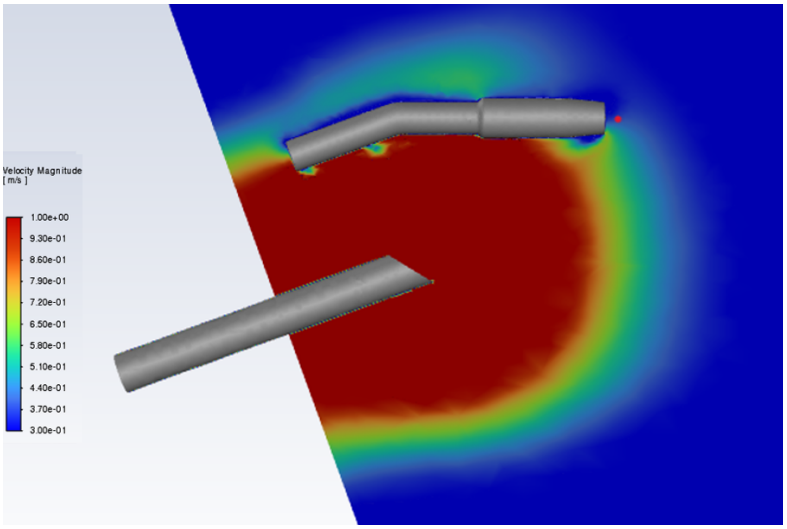


Figure 67: Side contour view of velocity distribution of the VMC-25.

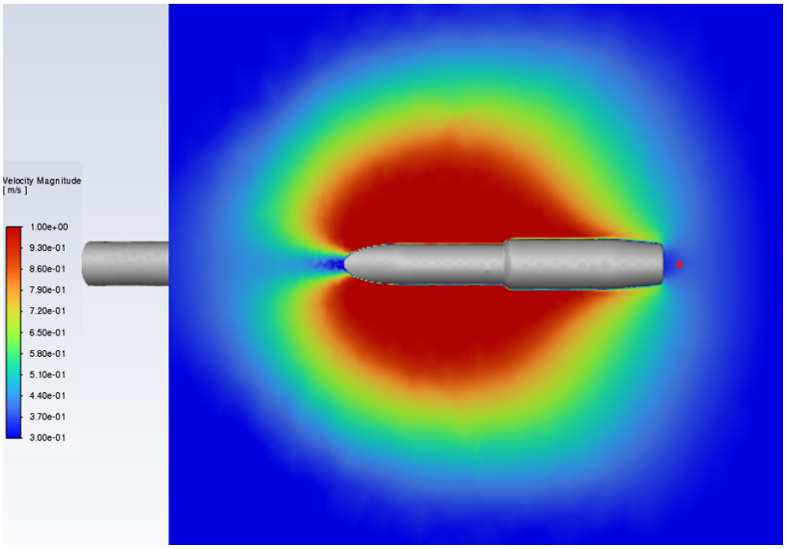


Figure 68: Top contour view of velocity distribution of the VMC-25.

8.2.2 ISO surface

In addition to the contour views, an ISO surface was created with the velocity of 0.3 m/s (Fig. 69 & 70).

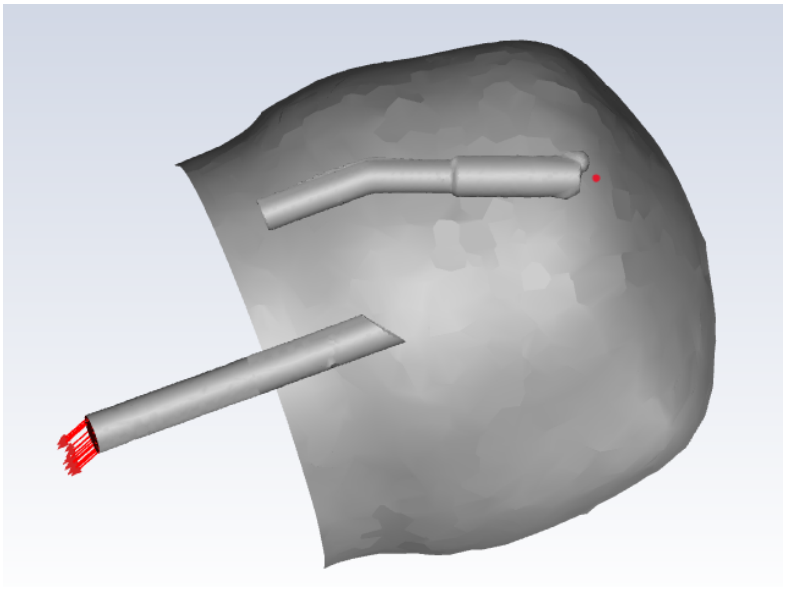


Figure 69: Side view of ISO surface with v=0.3 m/s for the VMC-25.

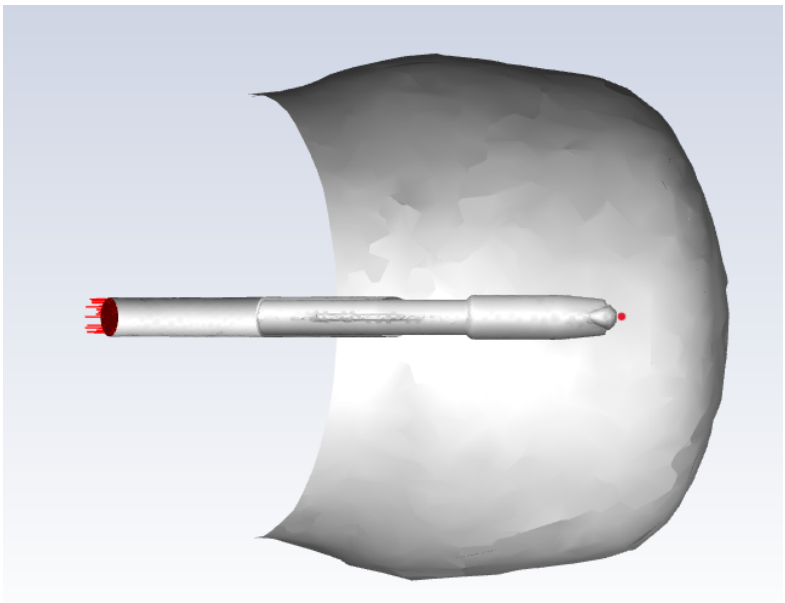


Figure 70: Top view of ISO surface with v=0.3 m/s for the VMC-25.

8.3 CMC-10

8.3.1 Contour views

The velocity distribution of the CMC-10 is illustrated in Figures 71 and 72. As for the VMC-25, the same simulation settings were used to obtain the results.

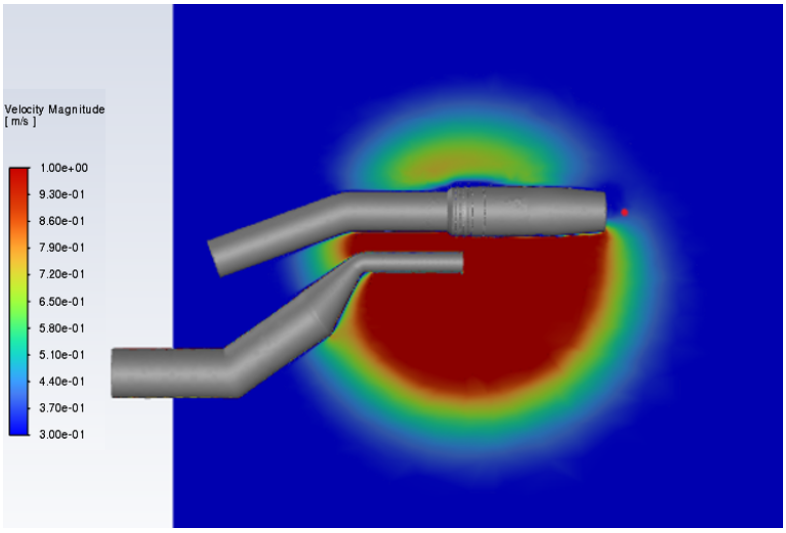


Figure 71: Side contour view of velocity distribution of the CMC-10.

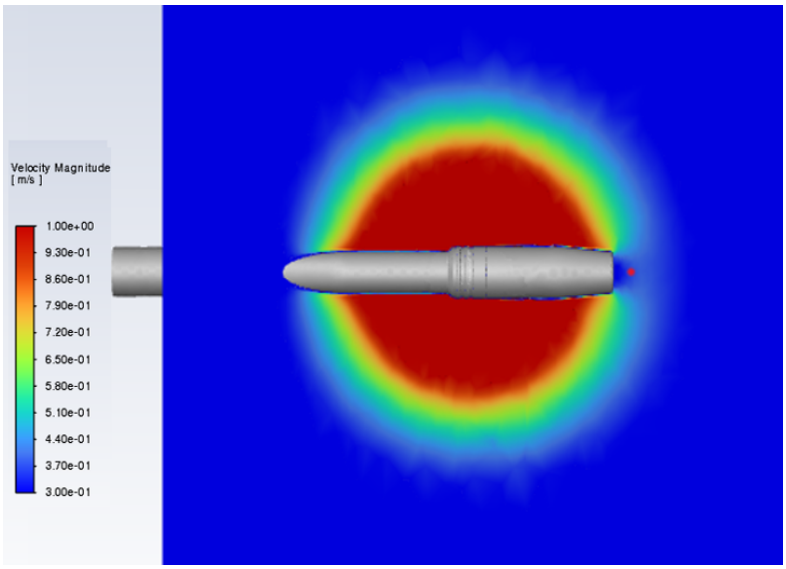


Figure 72: Top contour view of velocity distribution of the CMC-10.

8.3.2 ISO surface

As for the VMC-25, an ISO surface with the velocity of 0.3 m/s was created for the CMC-10 (Fig. 73 & 74).

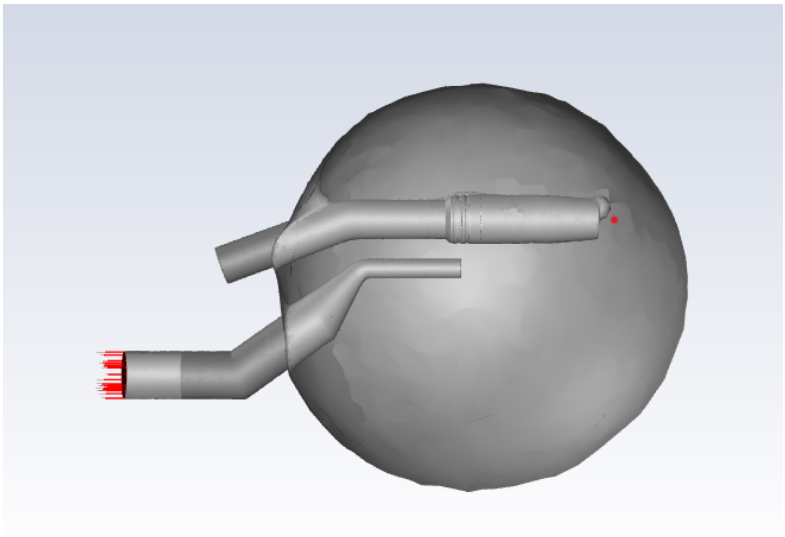


Figure 73: Side view of ISO surface with v=0.3 m/s for the CMC-10.

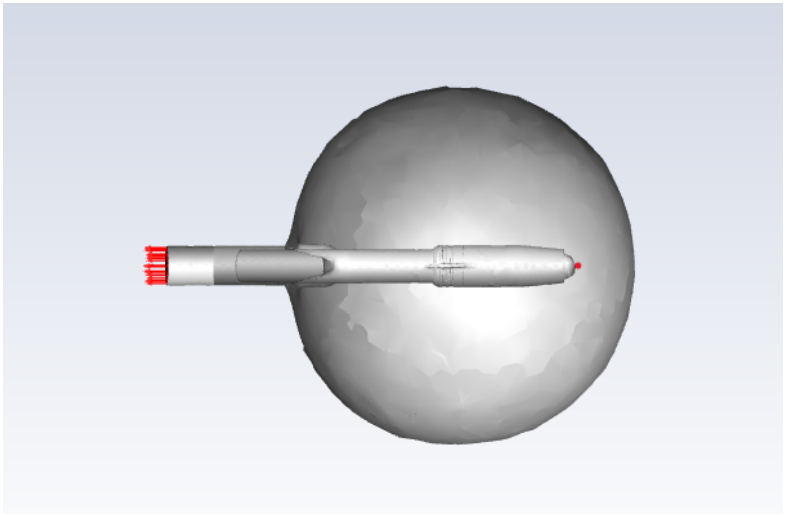


Figure 74: Top view of ISO surface with v=0.3 m/s for the CMC-10.

9 Discussion of Part 2

In this chapter, the development process, design choices and results from Part 2 of the study are reflected upon with regard to the problem breakdown and future development.

9.1 Development process

It was decided to follow the design process described by U&E. The primary reason for this was because it is an extensive development method, that is well suited to address known and unknown challenges. There exist alternative development methods, such as the "Double Diamond" or IDEO's "Design thinking". Because the main aspects of these can be found within U&E's development process, it was deemed more efficient to use.

Furthermore, the process allows for a high level of flexibility, and to tailor it in a way that fits each unique design project. Lastly, the study was well acquainted with U&E's development process. In addition to using the U&E process, utilizing a Human-centered design approach was central throughout the study, as described in Section 2.6.

Due to the fact that no functioning products exists in the chosen area of work, as well as the scope of Part 2, a great weight was placed on exploring several solutions. Therefore, altercations were made to the process.
The restructured design process is described in Subsection 6.4.1.

Firstly, a "Breakdown of challenges" was added to the "Clarifying the problem" step. The reasoning behind this was that it would help to provide more specific target specifications, applicable to the two challenges that the study chose to limit itself to. Hence, no evaluation was performed of the target specifications established in Section 6.3. Instead, the results were evaluated against the "Breakdown of challenges" specifications. Due to the scope of the study, no final specifications were set. The target specifications from Section 6.3 were included in the report as they could be useful to further development.

In addition to the results, Part 1 of the study provided a set-up for digital models that could be used to efficiently evaluate the performance of extraction nozzles. The ability to rapidly evaluate the performance of the nozzles, in combination with the desire to take a broad and iterative approach, led to the idea of creating design cycles.

The reasoning behind this was that the experience gained in Part 1 could be used as a starting point to brainstorm a large number of concepts, which would subse-

quently be evaluated and screened efficiently. By repeating this process iteratively, a transition could be made from a wide number of concepts toward the refinement of a smaller number of high-potential concepts, see Figure 75.

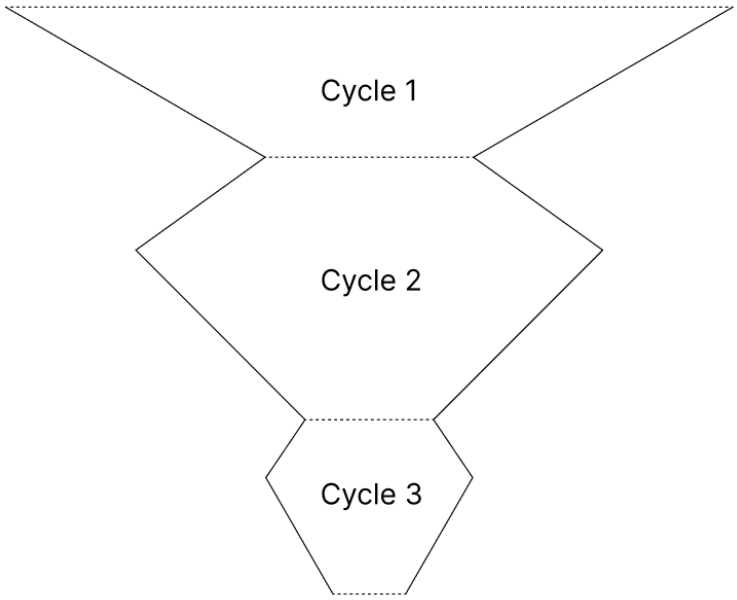


Figure 75: Visualiztion of how cycles help transitioning from wide exploration towards refinement of high-potential concepts.

Ideally, a larger number of cycles would have been used. This would have allowed for broader exploration and sharper refinement. However, considering the scope of the study, three cycles were deemed as sufficient to provide a basis for further development.

Using the "Cycles" and "Breakdown of challenges" was to take a step away from the process described by U&E. As previously stated, however, iteration and adaption of the process is common when developing a product. Therefore, the study still operated within the framework of the chosen design process.

9.2 Design choices

The design choices made were primarily based on the experience gained from the analysis part of the project. Furthermore, decisions were assisted by methods and approaches provided by the development process.

The aim of Part 2 was to generate concepts that provided a basis for further development to build upon. The focus was to solve the challenges of using reasonable volume flows and preserving the freedom of movement of the cobot. The findings from Part 1 indicated that the shape and position of a nozzle were the dominant factors affecting these challenges. Because of this, a concept was defined as the shape and positioning of a nozzle.

In order to get a manageable number of concepts to evaluate, the 38 concepts created at the beginning of Cycle 1 were summarized as seven concept families (see Subsection 6.4.3). These families were based on characteristics or features found among the original 38 concepts.

The first family, the "Mini TM-80" was created to evaluate how a smaller version of the TM-80 nozzle evaluated in Part 1 would perform. The second family was referred to as "Reference", in the shape of a cylindrical tube. The reason for including this family was that the data gathering suggested that tubes are sometimes used instead of a nozzle in the industry. The "Cone" family was created with the purpose of investigating the effects of a tapered geometry and smaller outlet area. The results of Part 1 showed the existence of backflow, i.e extraction taking place behind the nozzle. Therefore, a "Dog cone" family was created, incorporating a conical geometry surrounding the nozzle neck. The intention was to explore the possibility to better utilize the volume flow.

In order to investigate possible solutions to the "Preserve the freedom of movement of the cobot" challenge, a bent nozzle named "Banana" family was created. The results of Part 1 showed that a TM-200 nozzle could provide wider extraction zones. To further explore this, a "TM50" family was created. Lastly, it was deemed relevant to investigate the possibilities of utilizing the effect of a table for a cylindrical nozzle. Therefore, the "TM-Tilt" family was created.

The performance of the seven concept families was evaluated through the digital model, and then screened using a "Concept Screening Matrix" (Tab. 5). The screening matrix used five criteria: Ease of positioning, "Extraction reach", "Access of tight spaces", "Aesthetics" and "Ease of manufacture". All nozzle families were evaluated on whether they were worse, better, or equal to the reference family in every criterion except "Ease of manufacture". For this criterion, the "Mini TM-80" was used as reference.

The "ease of positioning" criterion evaluated whether the nozzle design enabled an easier positioning than a regular tube would. The curved shape of the "Banana" was deemed beneficial while the rest were seen as worse or equal to the reference. Evaluation of the "Extraction reach" was conducted using the data from the digital

model. All concepts performed similarly, with the exception of the "Cone", which performed better. Moreover, "Access to tight spaces" primarily concerned the ability of a nozzle, positioned close to the weld gun mouthpiece, to not hinder the cobot accessing tight spaces. The "Banana" performed better than the reference concept, the "Cone" and "TM-tilt" were seen as equal to the reference, and the rest were deemed worse. "Aesthetics" were evaluated through comparing the concepts to the existing product portfolio at Nederman, as well as how suitable they would be in a cobot environment. The "Cone", "Banana", "Mini TM-80" and "TM-tilt" concepts performed better than the reference, while the "Dog cone" and "TM50" were worse. The "Ease of manufacturing" criterion was included to ensure that the concepts would not be too difficult or expensive to produce. Although some concepts would likely be easier to manufacture than others, this was not seen as a major concern for any design. The study chose to continue to develop all concepts that had received a positive net score. The other concepts were deemed unsatisfactory, and therefore left behind when entering Cycle 2.

It was decided to use a concept combination table (Fig. 54) in order to systematically explore new concepts consisting of combined features from the seven families. Furthermore, it was considered interesting to investigate nozzles applied in areas outside of fume extraction. The intention was to explore whether any findings could be applicable to the studied area. Four nozzle types were found, and out of them, one was generally deemed as the most efficient. Therefore that one was evaluated in the digital model. The result showed that it did not perform better than the reference, and therefore the remaining three were not considered.

Ten concepts were evaluated in the same concept screening matrix used in Cycle 1, (Tab. 6). Three of the concepts performed equally well, and following discussions with sales experts at Nederman, it was decided to dismiss the remaining concepts and focus on the top three.

Entering Cycle 3, the three concepts chosen from Cycle 2 was initially seen as sufficient. In order to challenge any existing assumptions and not overlook any good solutions, it was decided to use the three concepts to create four relatively new ones. Two of the concepts were created with the primary aim of requiring reasonable working volume flows, whilst the other two were centered around keeping the freedom of movement of the cobot. Although the concepts were based primarily on solving one of the two identified challenges, substantial work was put on fulfilling the remaining requirement as well.

The final concept selection was performed using a Concept scoring table, see Table 7. The criteria used where: "Aesthetics", "Non-intrusive", "Flexibility of positioning", "Cost of operation", "Potential of development" and "Secondary ap-

plications". The "Aesthetics" criterion was the same as in the screening matrix. The "Non-intrusive" and "Flexibility of positioning" criteria were used to evaluate how well concepts kept the freedom of movement of the cobot. "Cost of operation" was evaluated based on the required air volume flow, as measured using the digital model. "Potential of development" was used since it was evident that two concepts had more possibilities of development than the other two. Since the aim of Part 2 was to provide a basis for further development to build upon, this was seen as an important factor. Lastly, in interviews at Nederman, a general demand for products with secondary applications was identified. Therefore, "Secondary applications" was also included as a criterion in the matrix.

Lastly, the criteria were weighted. "Non-intrusive" and "Flexibility of positioning" was deemed most important, since they directly corresponded to the "Freedom of movement" challenge. Due to the exploratory nature of the project, "Potential of development" was deemed to be important, while "Cost of operation" was of lower priority. Following the reasoning of the project being exploratory, "Aesthetics" and "Secondary applications" were also prioritized lower.

The reason for choosing two final concepts was that the study tasked itself with providing a direction in which further development could take place. Due to this, it was deemed disadvantageous to prematurely limit future development by choosing a single final concept when two of the concepts were deemed to have future potential. Instead, the study aimed to present the findings objectively and create a foundation to build on.

9.3 Evaluation of breakdown of challenges

The two concepts were evaluated against the demands and guidelines presented in Subsection 6.4.2. These were then compared to each other, as shown in Table 8.

The evaluation shows that none of the nozzles prevents servicing of the weld gun mouthpiece. The VMC-25 is located at a greater distance from the weld point, thereby preserving accessibility to tight spaces. Meanwhile, the CMC-10 is more intrusive and would in some situations prevent access to tight spaces, which resulted in a negative evaluation for this criterion. The VMC-25 is expected to be slightly better at following welding patterns since it does not occupy any side of the weld gun body. However, the demand was that it should only occupy one side, consequently, the CMC-10 still has a good ability to follow patterns. The VMC-25 does not satisfy the demands regarding volume flows and standard machines will not be able to provide the required air volume flow. Therefore, the VMC-25 becomes a costly solution. The CMC-10, on the other hand, requires a volume flow well within the interval.

Table 8: Evaluation comparison against the demands and guidelines set in Subsection 6.4.2.

VMC-25	CMC-10
+ Full access to service	+ Full access to service
+ Good access to tight spaces	- Limited access to tight spaces
+ Very good ability to follow patterns	+ Good ability to follow patterns
- Q = 450 m3/h	+ Q = 160 m3/h

9.4 Conclusions

The purpose of Part 2 was to create a foundation for future development. Consequently, no results should be viewed as final, rather as early stages of a direction in which further development could take place.

Though the study has been careful not to limit any future solutions, three out of the five challenges presented in Subsection 6.4.2 have not been addressed. However, the CMC-10 could benefit from an alternating attachment allowing it to occupy different sides of the weld gun, making it more adaptable to different situations. Furthermore, the study has taken into account that the mouthpiece of the nozzle requires the possibility to be unscrewed and serviced. Due to this being an important and regular occurrence, the study chose to consider this by keeping the mouthpiece clear from intrusion by any nozzle. Although this approach addresses this problem, further development is needed to determine a complete solution.

Due to the limitations of the study, the current findings are insufficient to support a universal solution. Today, the findings suggest that the solution lies in combining several different solutions and tailor the extraction process in a way that optimizes air volume flow and accessibility.

The main finding is that there is a trade-off to be made between reasonable volume flows and the freedom of movement of the cobot. In order for the cobot to access tight spaces and to weld complex patterns, it is important that the extraction nozzle does not obstruct the welding gun. Placing the nozzle further back mitigates this issue, but requires substantially higher air volume flows leading to increased operating costs. Since no fully functional extraction nozzles exist in the chosen field of study, it was deemed unclear which of the two aspects would be regarded as the most important in the future.

Overall findings are that greater volume flows result in a greater safe zone as well as a more conical shape. This aligns with the previous findings at Nederman. Additionally, the results indicate that the main factor for the performance of the

nozzle is the outlet area. Furthermore, the results suggest that the geometry of the outlet area should stay consistent a couple of centimeters before the nozzle body changes shape. The findings suggest that outlet volume is the dominant factor for nozzle performance.

9.5 Further development

Since no fully functional product currently exists in the area of study, further testing and research will still be required in the future. As previously mentioned, only two of the five identified main challenges were properly addressed in the study, and even among these, further considerations need to be made regarding the relative importance of the respective needs.

Depending on future industry requirements, it might be possible to position the extraction nozzle close to the welding gun, substantially decreasing the operating cost. This would likely result in a design resembling the geometry or positioning of the CMC-10 model. On the contrary, further importance may be placed on the freedom of movement of the cobot, allowing for operating air volume flows above the current industry standards. In that case, the VMC-25 may be a more suitable solution to base further development on. Lastly, it is very possible that future development may include aspects of both models or a third solution from the previous concept selection process. One way of evaluating the performance of different positions and geometries is by performing a Design of Experiments (DOE). During this process, the relevant measurements are set as parameters, and iterations are performed at varying intervals until the most efficient designs are created.

Regardless of which direction the development may take in the future, there are several factors that need to be considered. As previously mentioned, the attachment of the nozzle, integration of the tube, and cleaning and maintenance of the cobot are areas of the design that need to be explored in order to fulfill the requirements.

There are also additional factors that have not been considered regarding the proposed solutions, as they were deemed to fall outside the scope of the study. One simplification during the digital modeling was to neglect energy losses of the flow. In reality, a nozzle with sharp edges and a rapidly changing geometry may cause large thermal energy losses, which could complicate matters. In addition to this, the operational noise level of the nozzles is an important factor to consider since some designs could cause distress for the user and their surroundings. The risk that was deemed most likely is that the small outlet area would cause the nozzle to behave like a whistle, producing a sharp and unpleasant sound during

use.

Other factors that need to be considered are the material and manufacturing methods. The nozzles were originally assumed to be made out of bent and welded sheet metal in order to align with the existing high-vacuum nozzles from Nederman. Another reason for this decision was to ensure that manufacturing of the new concepts would not have a negative environmental impact, as covered in Section 1.6. Because of the differing measurements and geometries, however, this may need to be explored further. The same is true for any additional components that may be required for a fully functional product, such as an attachment for the nozzle to the cobot.

10 Reflections of study

In this chapter, the study as a whole are reflected upon, regarding the working process and how the findings contribute to the chosen field of work.

10.1 Work process

As described in Section 1.9, a Gantt chart was created in order to ensure a clear and structured work process (Fig. 76). Throughout the study, this was continuously changed when required, resulting in the revised Gantt illustrated in Appendix A. This, in addition to the "to-do" list and the continuous check-up meetings with supervisors, ensured that the work process remained structured and that any unexpected issues could be dealt with efficiently.

10.2 Contribution to field

Based on the findings from the two parts, it is evident that the study contributed towards the chosen field of study in a sufficient way. From Part 1, the previous experiments conducted at Nederman was expanded upon, in addition to suggesting a change in setup of the TM-80 and TM-200 nozzles. Furthermore, the study adds to the existing ISO standard by introducing the concept of a "Work zone".

From Part 2, it was explored whether the current extraction methods in cobot welding could be changed from extraction torches to extraction nozzles. The findings provide future researchers with new data on which to build on in further development. In addition to the findings, the restructured design process contributes to the concept development area as a whole. Through concretizing the iterative approach suggested by U&E, the study provides a structure well suited for development in unexplored areas.

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Appendix A

A.1 - Original Gantt chart

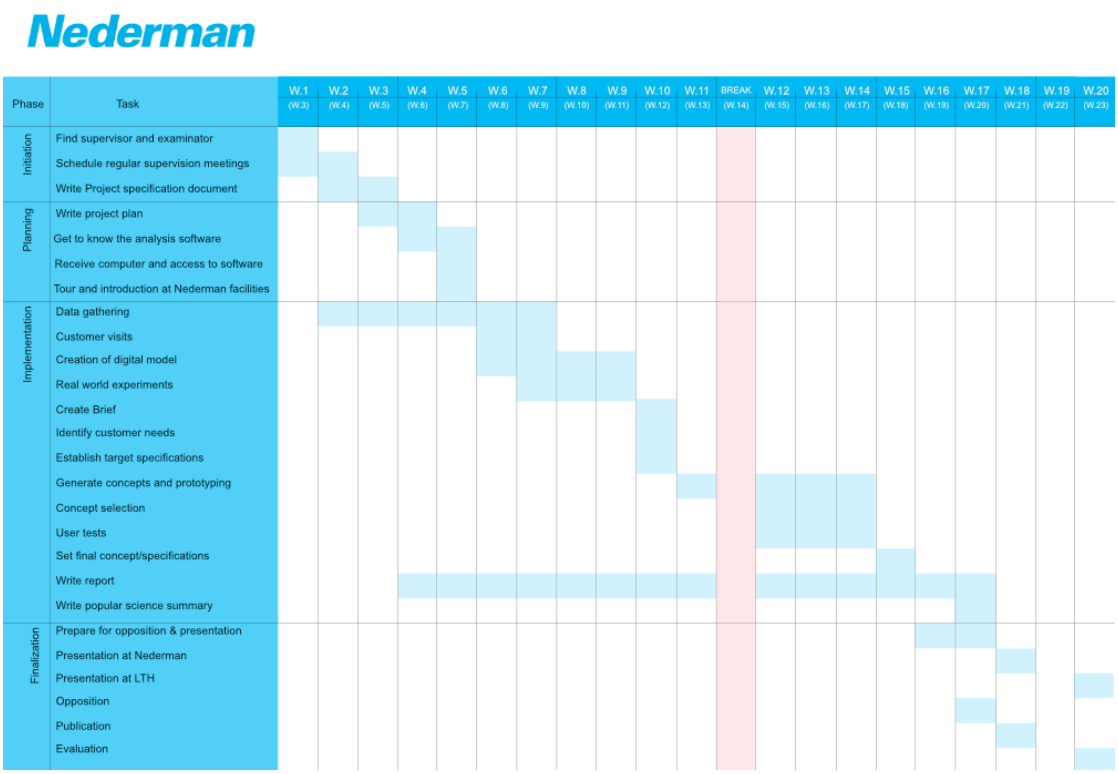


Figure 76: Original Gantt chart.

A.2 - Revised Gantt chart

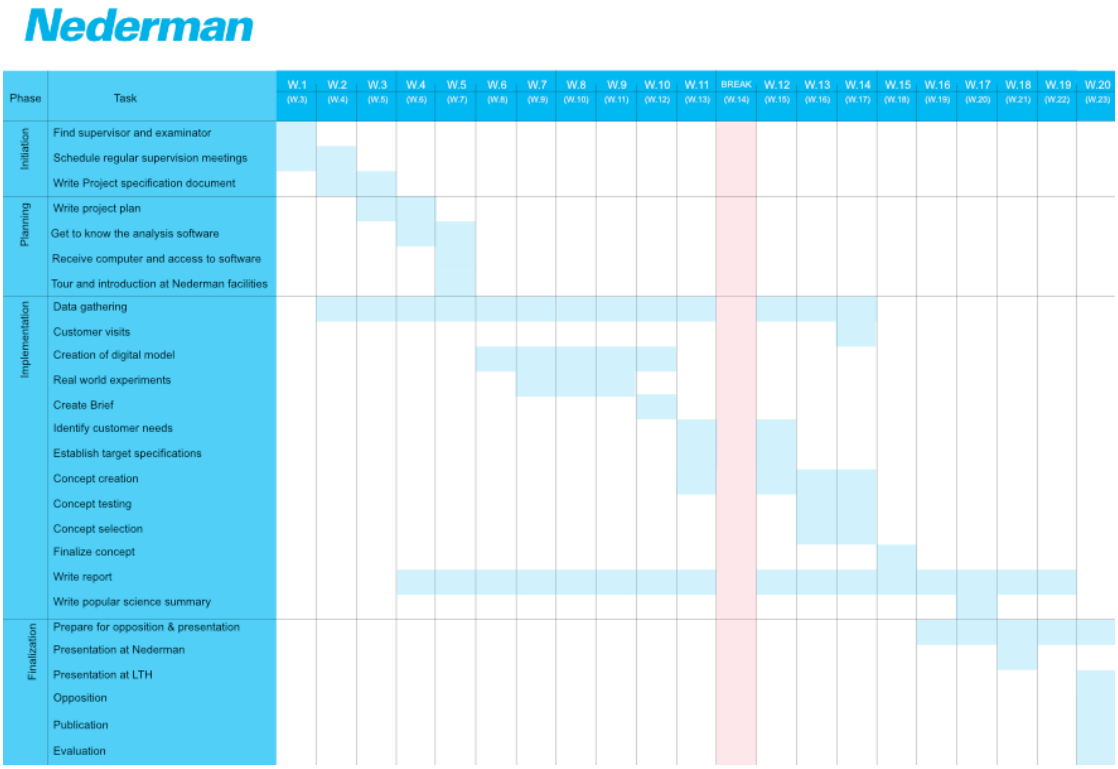


Figure 77: Revised Gantt chart.

A.3 - "To-do"-list



Vecka 9:		Aktivitet:	Status:
Måndag	Fm	Import CAD model + Material Assignment + Meshing	Slutförd
	Em	Meshing + bekräfta bra mesh	Slutförd
Tisdag	Fm	Meeting with Thommie?	Slutförd
	Em	Assign Boundary conditions	Slutförd
Onsdag	Fm	Run Tests || Prepare for experiments	Slutförd
	Em	Run tests, ex start test cycle 2	Slutförd
Torsdag	Fm	Test cycle 2 or 3	Slutförd
	Em	- || - > Prepare experiment for next week	Slutförd
Fredag	Fm	Buffert (Hopefully sufficient model)	Slutförd
	Em	Skriva Teori: Iso & pre.exp Nederman, ev. börja med Ung	Slutförd

Vecka 10:		Aktivitet:	Status:
Måndag	Fm	Resolve TM200 issues	Slutförd
	Em	Write report	Slutförd
Tisdag	Fm	Experiment 1 Setup continuation + Status meeting	Slutförd
	Em	Resolve TM200 issues + Experiment continuation	Slutförd
Onsdag	Fm	Experiment 1 run	Slutförd
	Em	Resolve TM200 issues	Slutförd
Torsdag	Fm	Get results from digital model TM80	Slutförd
	Em	Begin part 2	Slutförd
Fredag	Fm	Write report	Slutförd
	Em	Get results from digital model TM200	Slutförd

Vecka 11:		Aktivitet:	Status:
Måndag	Fm	Write report	Slutförd
	Em		Slutförd
Tisdag	Fm	Model impact of table	Slutförd
	Em	Get results from digital model TM200 + Continue w	Slutförd
Onsdag	Fm	CWMT + Summarize Results and make presentable	Slutförd
	Em		Slutförd
Torsdag	Fm	Summarize Results and make presentable +	Slutförd
	Em	continue verification of TM200	Slutförd
Fredag	Fm	Write report	Slutförd
	Em		Slutförd

Vecka 12:		Aktivitet:	Status:
Måndag	Fm	Analyse results from part 1	Slutförd
	Em	Start other data gathering	Slutförd
Tisdag	Fm	Work with part 2	Slutförd
	Em		Slutförd
Onsdag	Fm	Prepare presentation	Slutförd
	Em		Slutförd
Torsdag	Fm	Work with part 2	Slutförd
	Em		Slutförd
Fredag	Fm	Present results from part 1	Slutförd
	Em	Write report (theory+method+results)	Slutförd

Vecka 13:		Aktivitet:	Status:
Måndag	Fm	Write report	Slutförd
	Em	Write report	Slutförd
Tisdag	Fm	Analyse previous data gathering(part1) -> Set needs	Slutförd
	Em	Set needs + Prepare for further data gathering	Slutförd
Onsdag	Fm	Needs -> Target specifications	Slutförd
	Em		Slutförd
Torsdag	Fm	Perform and transcribe interviews -> Needs	Slutförd
	Em	Set target specifications	Slutförd
Fredag	Fm	Write report + Concept generation	Slutförd
	Em		Slutförd

Vecka 14:		Aktivitet:	Status:
Måndag	Fm	PÅSKLOV	Slutförd
	Em		Slutförd
Tisdag	Fm		Slutförd
	Em		Slutförd
Onsdag	Fm		Slutförd
	Em		Slutförd
Torsdag	Fm		Slutförd
	Em		Slutförd
Fredag	Fm		Slutförd
	Em		Slutförd

Vecka 15:		Aktivitet:	Status:
Måndag	Fm		Slutförd
	Em		Slutförd
Tisdag	Fm	Concept generation 1	Slutförd
	Em	Interviews ->Needs	Slutförd
Onsdag	Fm	Customer visit?	Slutförd
	Em	Elicit needs -> Target specifications	Slutförd
Torsdag	Fm	Concept generation 1	Slutförd
	Em		Slutförd
Fredag	Fm		Slutförd
	Em		Slutförd

Vecka 16:		Aktivitet:	Status:
Måndag	Fm	Write report	Slutförd
	Em		Slutförd
Tisdag	Fm	Concept testing + hitta lösning på CAD problem	Slutförd
	Em		Slutförd
Onsdag	Fm	Solving CAD issues. Simulate 7 first concepts	Slutförd
	Em		Slutförd
Torsdag	Fm	1st Concept screening	Slutförd
	Em	Creating refined CADs and better simulations	Slutförd
Fredag	Fm		Slutförd
	Em		Slutförd

Vecka 17:		Aktivitet:	Status:
Måndag	Fm	Generate nzl head concepts	Slutförd
	Em		Slutförd
Tisdag	Fm	Generate nzl head concepts	Slutförd
	Em	Start overall comcept generations	Slutförd
Onsdag	Fm	Skapa och få data för 5 concept	Slutförd
	Em	Skapa och få data för 5 concept	Slutförd
Torsdag	Fm	Färdigställ de 5 koncepten	Slutförd
	Em	Färdigställ de 5 koncepten	Slutförd
Fredag	Fm	Write report	Slutförd
	Em	Write report	Slutförd

Vecka 18:		Aktivitet:	Status:
Måndag	Fm	Write report	Slutförd
	Em	Write report	Slutförd
Tisdag	Fm		Slutförd
	Em	Write report	Slutförd
Onsdag	Fm	Concept scoring	Slutförd
	Em	Finalize choosen concept	Slutförd
Torsdag	Fm	Finalize choosen concept	Slutförd
	Em	Finalize choosen concept	Slutförd
Fredag	Fm	Write report	Slutförd
	Em	Write report	Slutförd

Vecka 19:		Aktivitet:	Status:
Måndag	Fm	Prepare presentation	Slutförd
	Em	Write report	Slutförd
Tisdag	Fm	Collect & evaluate print. Order tube? Case for Nozz	Slutförd
	Em	Case for Nozzles. Bilder positionering(Elliot), contou	Slutförd
Onsdag	Fm	Prepare presentation	Slutförd
	Em	Prepare presentation	Slutförd
Torsdag	Fm	Customer visit - Prepare presentation	Slutförd
	Em	Prepare presentation	Slutförd
Fredag	Fm	Finished preperation presentation at Nederman	Slutförd
	Em	Write report	Slutförd

Vecka 20:		Aktivitet:	Status:
Måndag	Fm	Slutta rapport	Slutförd
	Em	Mål: Hela dispositionen färdig. Vem skriver vad?	Slutförd
Tisdag	Fm		Slutförd
	Em		Slutförd
Onsdag	Fm	Work on presentation	Slutförd
	Em		Slutförd
Torsdag	Fm	Work on presentation	Slutförd
	Em		Slutförd
Fredag	Fm	Skicka in first draft rapport Nederman	Slutförd
	Em		Slutförd

Vecka 21:		Aktivitet	Status:
Måndag	Fm		Slutförd
	Em	Final presentation at Nederman 13:00	Slutförd
Tisdag	Fm		Slutförd
	Em	Report writing	Slutförd
Onsdag	Fm		Slutförd
	Em		Slutförd
Torsdag	Fm	Report writing	Slutförd
	Em		Slutförd
Fredag	Fm	Deadline lämna in rapport Nederman	Slutförd
	Em		Slutförd

Vecka 22:		Aktivitet:	Status:
Måndag	Fm	Report writing	Slutförd
	Em		Slutförd
Tisdag	Fm	Report writing	Slutförd
	Em		Slutförd
Onsdag	Fm	Report writing	Slutförd
	Em		Slutförd
Torsdag	Fm	Report writing	Slutförd
	Em		Slutförd
Fredag	Fm	Report writing	Slutförd
	Em	Deadline lämna in rapport LTH	Slutförd

Vecka 23:		Aktivitet:	Status:
Måndag	Fm	Work on presentation + opposing	Slutförd
	Em		Slutförd
Tisdag	Fm	Work on presentation + opposing	Slutförd
	Em		Slutförd
Onsdag	Fm	Work on presentation + opposing	Slutförd
	Em		Slutförd
Torsdag	Fm	Work on presentation	Slutförd
	Em	Attend presentation of opposing group	Slutförd
Fredag	Fm	Final presentation at LTH 5 Juni	Slutförd
	Em		Slutförd

Figure 78: "To-do" list.

Appendix B

B.1 - Calculations of Safe zone for TM80

B.1.1 - Q = 250 m^3/h

Table 9: Digital experiments of TM80 with Q = 250 m^3/h at a 0° angle.

TM80, 250 m^3/h, 0°					
Distance	**-x (cm)**	**+x (cm)**	**-z (cm)**	**+z (cm)**	**Result (cm)**
10 cm	13.8	13.4	13.8	13.4	**∅27.2**
12.5 cm	13.1	13.2	13.2	13.1	**∅26.3**
15 cm	12.5	12.5	12.6	12.4	**∅25.0**

Table 10: Digital experiments of TM80 with Q = 250 m^3/h at a 45° angle.

TM80, 250 m^3/h, 45°					
Distance	**-x (cm)**	**+x (cm)**	**-z (cm)**	**+z (cm)**	**Result (cm)**
10 cm	9.6	10.7	10.5	10.5	**∅20.3**
12.5 cm	6.7	7.8	7.4	7.3	**∅14.5**
15 cm	-	-	-	-	*v<0.3 m/s for all points*

Table 11: Digital experiments of TM80 with Q = 250 m^3/h at a 90° angle, with and without a table.

TM80, 250 m^3/h, 90°					
Distance	**-x (cm)**	**+x (cm)**	**-z (cm)**	**+z (cm)**	**Result (cm)**
No Table	(0)	15.3	14.9	14.8	**15.3 x 29.7**
W. Table	(0)	16.7	15.9	15.7	**16.7 x 31.6**

B.1.2 - Q = 200 m^3/h

Table 12: Digital experiments of TM80 with Q = 200 m^3/h at a 0° angle.

TM80, 200 m^3/h					
Distance	**-x (cm)**	**+x (cm)**	**-z (cm)**	**+z (cm)**	**Result (cm)**
10 cm	12.1	12.1	12.1	12.1	**∅24.2**
12.5 cm	11.8	11.5	11.8	11.5	**∅23.3**
15 cm	10.9	10.7	10.9	10.8	**∅21.6**

Table 13: Digital experiments of TM80 with Q = 200 m^3/h at a 45° angle.

TM80, 200 m^3/h, 45°					
Distance	**-x (cm)**	**+x (cm)**	**-z (cm)**	**+z (cm)**	**Result (cm)**
10 cm	7.7	8.6	8.6	8.4	**∅16.3**
12.5 cm	3.6	4.0	3.9	3.7	**∅7.6**
15 cm	-	-	-	-	*v<0.3 m/s for all points*

Table 14: Digital experiments of TM80 with Q = 200 m^3/h at a 90° angle, with and without a table.

TM80, 200 m^3/h, 90°					
Distance	**-x (cm)**	**+x (cm)**	**-z (cm)**	**+z (cm)**	**Result (cm)**
No Table	(0)	15.3	13.5	13.1	**15.3 x 26.6**
W. Table	(0)	15.5	14.4	14.4	**15.5 x 28.8**

B.1.3 - Q = 150 m^3/h

Table 15: Digital experiments of TM80 with Q = 150 m^3/h at a 0° angle.

TM80, 150 m^3/h					
Distance	**-x (cm)**	**+x (cm)**	**-z (cm)**	**+z (cm)**	**Result (cm)**
10 cm	10.5	10.4	10.5	10.4	**∅20.9**
12.5 cm	9.9	9.6	9.8	9.7	**∅19.5**
15 cm	8.8	8.7	9.0	8.8	**∅17.5**

Table 16: Digital experiments of TM80 with Q = 150 m^3/h at a 45° angle.

TM80, 150 m^3/h, 45°					
Distance	**-x (cm)**	**+x (cm)**	**-z (cm)**	**+z (cm)**	**Result (cm)**
10 cm	5.2	5.8	5.8	5.7	**∅11.0**
12.5 cm	-	-	-	-	*v<0.3 m/s for all points*
15 cm	-	-	-	-	*v<0.3 m/s for all points*

Table 17: Digital experiments of TM80 with Q = 150 m^3/h at a 90° angle, with and without a table.

TM80, 150 m^3/h, 90°					
Distance	**-x (cm)**	**+x (cm)**	**-z (cm)**	**+z (cm)**	**Result (cm)**
No Table	(0)	12.1	11.4	11.2	**12.1 x 22.6**
W. Table	(0)	13.1	12.3	12.4	**13.1 x 24.7**

B.1.4 - Q = 100 m^3/h

Table 18: Digital experiments of TM80 with Q = 100 m^3/h at a 0° angle.

TM80, 100 m^3/h					
Distance	**-x (cm)**	**+x (cm)**	**-z (cm)**	**+z (cm)**	**Result (cm)**
10 cm	8.8	8.2	8.3	8.2	**∅16.5**
12.5 cm	7.4	7.3	7.4	7.3	**∅14.7**
15 cm	6.2	6.1	6.0	6.3	**∅12.3**

Table 19: Digital experiments of TM80 with Q = 100 m^3/h at a 45° angle.

TM80, 100 m^3/h, 45°					
Distance	**-x (cm)**	**+x (cm)**	**-z (cm)**	**+z (cm)**	**Result (cm)**
10 cm	-	-	-	-	*v<0.3 m/s for all points*
12.5 cm	-	-	-	-	*v<0.3 m/s for all points*
15 cm	-	-	-	-	*v<0.3 m/s for all points*

Table 20: Digital experiments of TM80 with Q = 100 m^3/h at a 90° angle, with and without a table.

TM80, 100 m^3/h, 90°					
Distance	**-x (cm)**	**+x (cm)**	**-z (cm)**	**+z (cm)**	**Result (cm)**
No Table	(0)	10.0	9.6	9.5	**10.0 x 19.1**
W. Table	(0)	10.3	10.1	9.9	**10.3 x 20.0**

B.2 - Calculations of Safe zone for TM200

B.2.1 - Q = 250 m^3/h

Table 21: Digital experiments of TM200 with Q = 250 m^3/h at a 0° angle.

TM200, 250 m^3/h					
Distance	**-x (cm)**	**+x (cm)**	**-z (cm)**	**+z (cm)**	**Result (cm x cm)**
10 cm	16.8	16.8	11.7	11.6	**33.6 x 23.3**
12.5 cm	16.0	16.1	11.2	11.0	**32.1 x 22.2**
15 cm	15.2	14.9	10.4	10.1	**30.1 x 20.5**

Table 22: Digital experiments of TM200 with Q = 250 m^3/h at a 45° angle.

TM80, 250 m^3/h, 90°					
Distance	**-x (cm)**	**+x (cm)**	**-z (cm)**	**+z (cm)**	**Result (cm x cm)**
10 cm	18.8	12.1	10.0	9.9	**30.9 x 19.9**
12.5 cm	17.3	7.2	7.6	7.6	**24.5 x 15.2**
15 cm	11.8	-0.4	3.9	3.7	**11.4 x 7.6**

Table 23: Digital experiments of TM200 with Q = 250 m^3/h at a 90° angle, with and without a table.

TM200, 250 m^3/h, 90°					
Distance	**-x (cm)**	**+x (cm)**	**-z (cm)**	**+z (cm)**	**Result (cm)**
No Table	(0)	13.1	17.6	17.3	**13.1 x 34.9**
W. Table	(0)	19.6	21.6	21.3	**19.6 x 42.9**

B.2.2 - Q = 200 m^3/h

Table 24: Digital experiments of TM200 with Q = 200 m^3/h at a 0° angle.

TM200, 200 m^3/h					
Distance	**-x (cm)**	**+x (cm)**	**-z (cm)**	**+z (cm)**	**Result (cm x cm)**
10 cm	15.2	15.2	10.1	9.8	**30.4 x 19.9**
12.5 cm	14.4	14.4	9.3	9.1	**28.8 x 18.4**
15 cm	13.3	13.0	8.5	8.2	**26.3 x 16.7**

Table 25: Digital experiments of TM200 with Q = 200 m^3/h at a 45° angle.

TM200, 200 m^3/h, 45°					
Distance	**-x (cm)**	**+x (cm)**	**-z (cm)**	**+z (cm)**	**Result (cm x cm)**
10 cm	18.0	9.3	8.0	8.0	**27.3 x 16.0**
12.5 cm	15.1	2.8	5.5	5.5	**17.9 x 11.0**
15 cm	-	-	-	-	*v<0.3 m/s for all points*

Table 26: Digital experiments of TM200 with Q = 200 m^3/h at a 90° angle, with and without a table.

TM200, 200 m^3/h, 90°					
Distance	**-x (cm)**	**+x (cm)**	**-z (cm)**	**+z (cm)**	**Result (cm)**
No Table	(0)	11.6	16.6	16.4	**11.6 x 33.0**
W. Table	(0)	17.8	21.1	21.0	**17.8 x 42.1**

B.2.3 - Q = 150 m^3/h

Table 27: Digital experiments of TM200 with Q = 150 m^3/h at a 0° angle.

TM200, 150 m^3/h					
Distance	**-x (cm)**	**+x (cm)**	**-z (cm)**	**+z (cm)**	**Result (cm x cm)**
10 cm	13.8	13.6	8.0	7.7	**27.4 x 15.7**
12.5 cm	12.5	12.5	7.2	6.9	**25.0 x 14.1**
15 cm	10.4	10.1	5.6	5.6	**20.5 x 11.2**

Table 28: Digital experiments of TM200 with Q = 150 m^3/h at a 45 °angle.

TM200, 150 m^3/h, 45°					
Distance	**-x (cm)**	**+x (cm)**	**-z (cm)**	**+z (cm)**	**Result (cm x cm)**
10 cm	16.4	5.4	6.7	7.0	**21.8 x 13.7**
12.5 cm	11.5	-3.5	2.9	2.7	**8.0 x 5.6**
15 cm	-	-	-	-	*v<0.3 m/s for all points*

Table 29: Digital experiments of TM200 with Q = 150 m^3/h at a 90° angle, with and without a table.

TM200, 150 m^3/h, 90°					
Distance	**-x (cm)**	**+x (cm)**	**-z (cm)**	**+z (cm)**	**Result (cm)**
No Table	(0)	9.7	15.5	15.2	**9.7 x 30.7**
W. Table	(0)	14.7	18.6	18.2	**14.7 x 36.8**

B.2.4 - Q = 100 m^3/h

Table 30: Digital experiments of TM200 with Q = 100 m^3/h at a 0° angle.

TM200, 100 m^3/h					
Distance	**-x (cm)**	**+x (cm)**	**-z (cm)**	**+z (cm)**	**Result (cm x cm)**
10 cm	11.2	11.2	5.3	5.1	**22.4 x 10.4**
12.5 cm	8.5	8.2	3.7	3.2	**16.7 x 6.9**
15 cm	-	-	-	-	*v<0.3 m/s for all points*

Table 31: Digital experiments of TM200 with Q = 100 m^3/h at a 45° angle.

TM200, 100 m^3/h, 45°					
Distance	**-x (cm)**	**+x (cm)**	**-z (cm)**	**+z (cm)**	**Result (cm x cm)**
10 cm	14.6	0.4	4.2	4.2	**15.0 x 8.4**
12.5 cm	-	-	-	-	*v<0.3 m/s for all points*
15 cm	-	-	-	-	*v<0.3 m/s for all points*

Table 32: Digital experiments of TM200 with Q = 100 m^3/h at a 90° angle, with and without a table.

TM200, 100 m^3/h, 90°					
Distance	**-x (cm)**	**+x (cm)**	**-z (cm)**	**+z (cm)**	**Result (cm)**
No Table	(0)	7.2	13.9	13.9	**7.2 x 27.8**
W. Table	(0)	11.5	15.7	15.7	**11.5 x 31.4**

Appendix C

C.1 - Air volume flows of GoMax

100 mm pipe

Q = 33,873***dp**^0,48133

Setting (kPa)	dp (Pa)	Q (m3/h)
1,0	8,0	92,16
1,5	12,5	114,24
2,0	17,5	134,33
2,5	21	146,65
3,0	25,4	160,71
3,5	29	171,30
4,0	34	184,93
4,5	38	195,10
5,0	43	207,06
5,5	45	211,64
6,0	50	222,65
6,5	55	233,10
7,0	60	243,07
7,5	64	250,74
8,0	70	261,79

Figure 79: Calculated air volume flows of GoMax.

C.2 - Impact of safety factors for CMC-10

s_f (%)	Q (m3/h)	v (m/s)
0	125	0,303
30	162,5	0,399
60	200	0,484
90	237,5	0,574
120	275	0,666
150	312,5	0,769

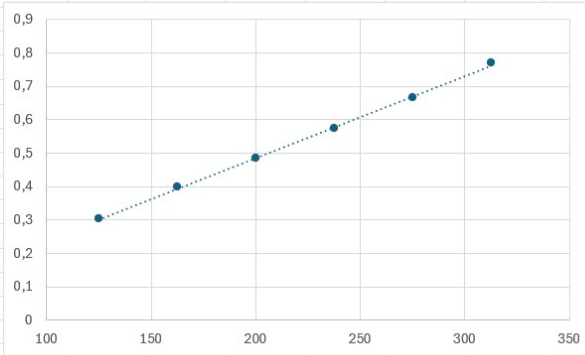


Figure 80: Calculated air velocities at different safety factors for CMC-10.

Appendix D

D.1 - Concept generation for Cycle 1

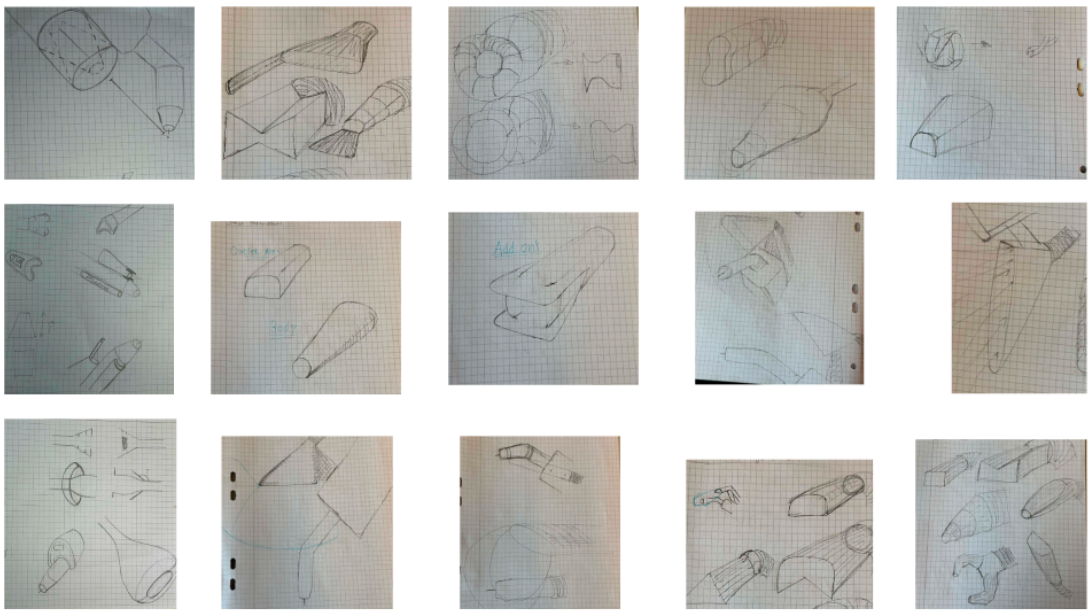


Figure 81: Initial 38 concepts from Cycle 1.

D.2 - Evaluation of concepts from Cycle 2

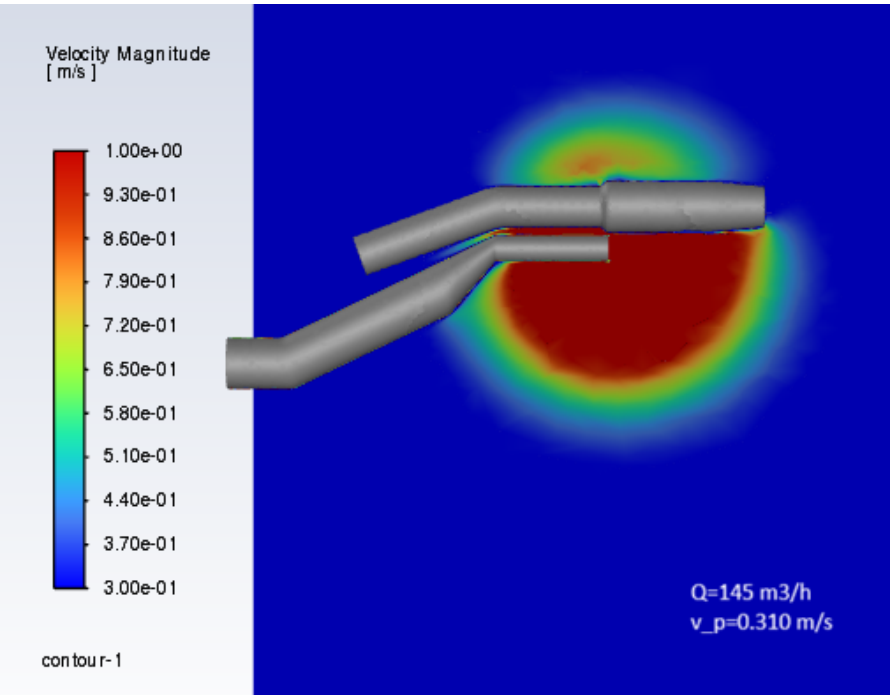


Figure 82: Performance of "Banana" concept .

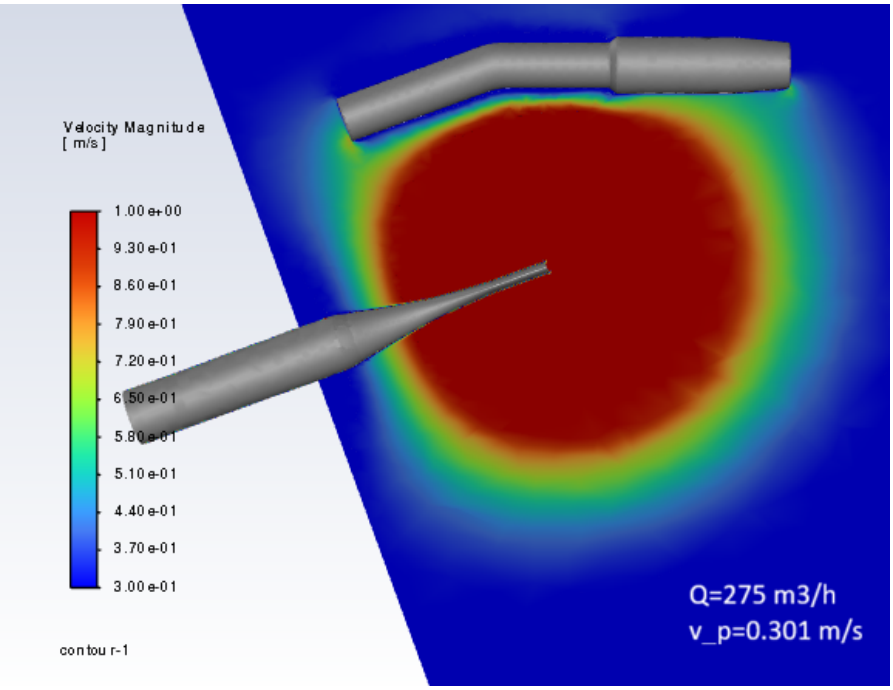


Figure 83: Performance of "Slot" concept.

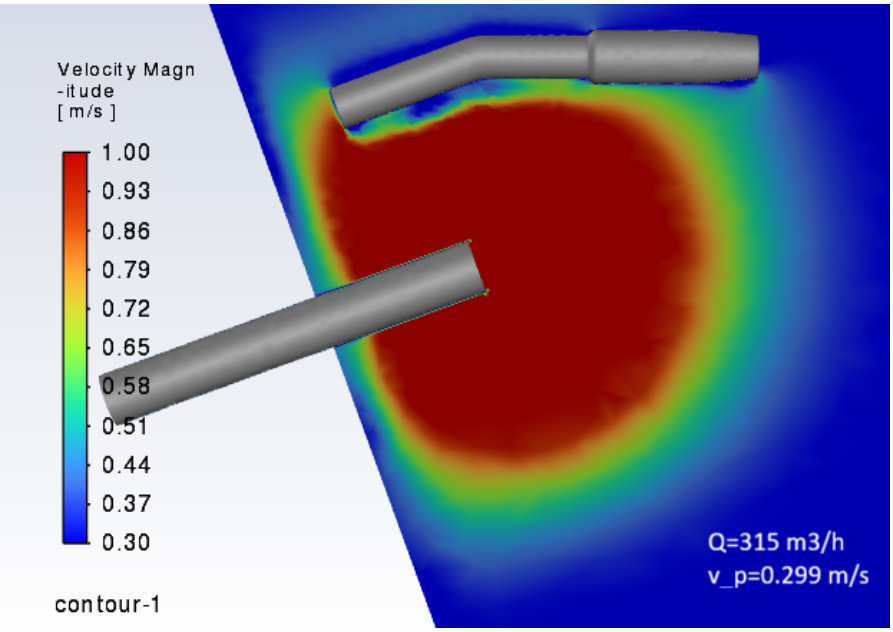


Figure 84: Performance of "Tube" concept.

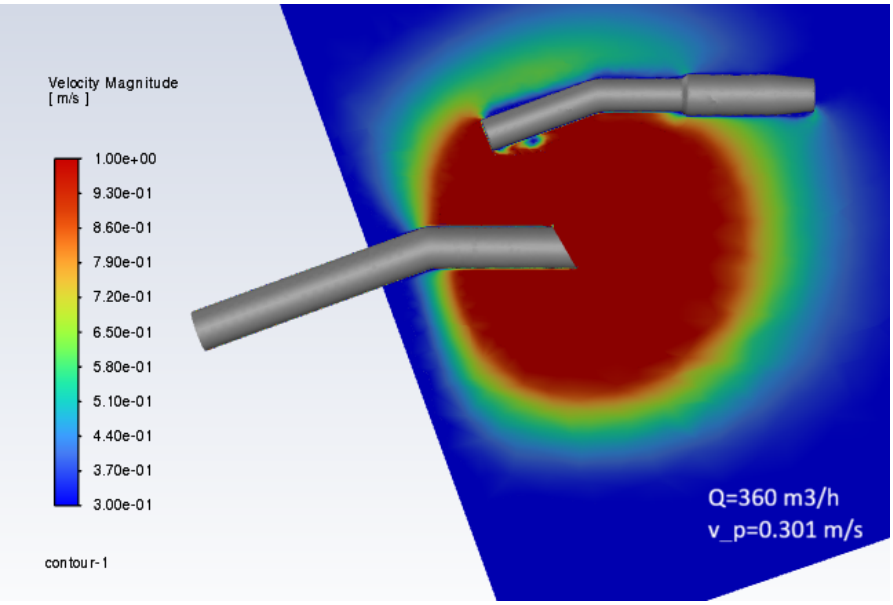


Figure 85: Performance of "TM-tilt" concept.

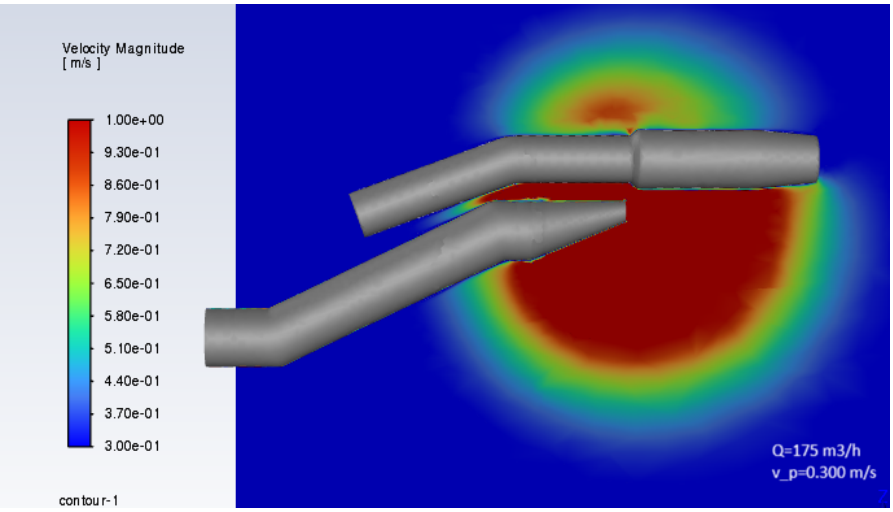


Figure 86: Performance of "Cone-close" concept.

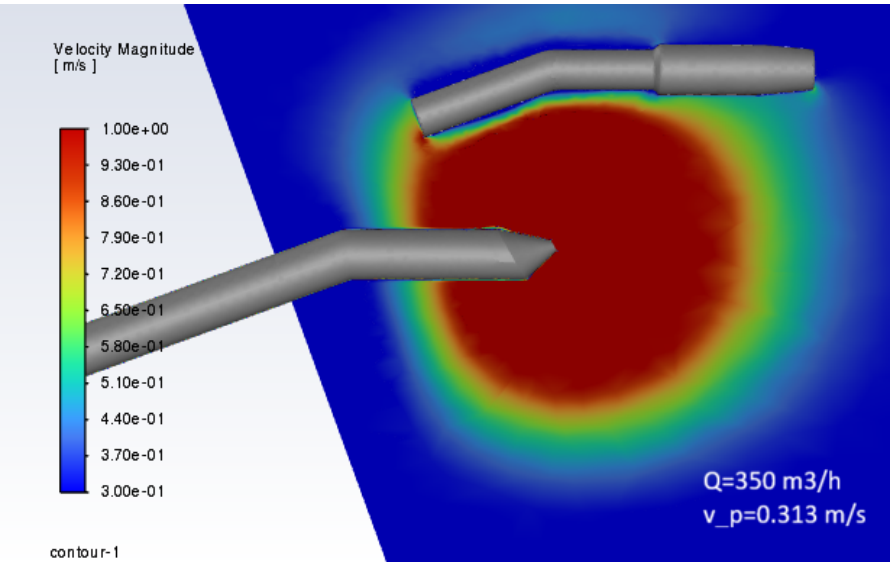


Figure 87: Performance of "Cone-far" concept.

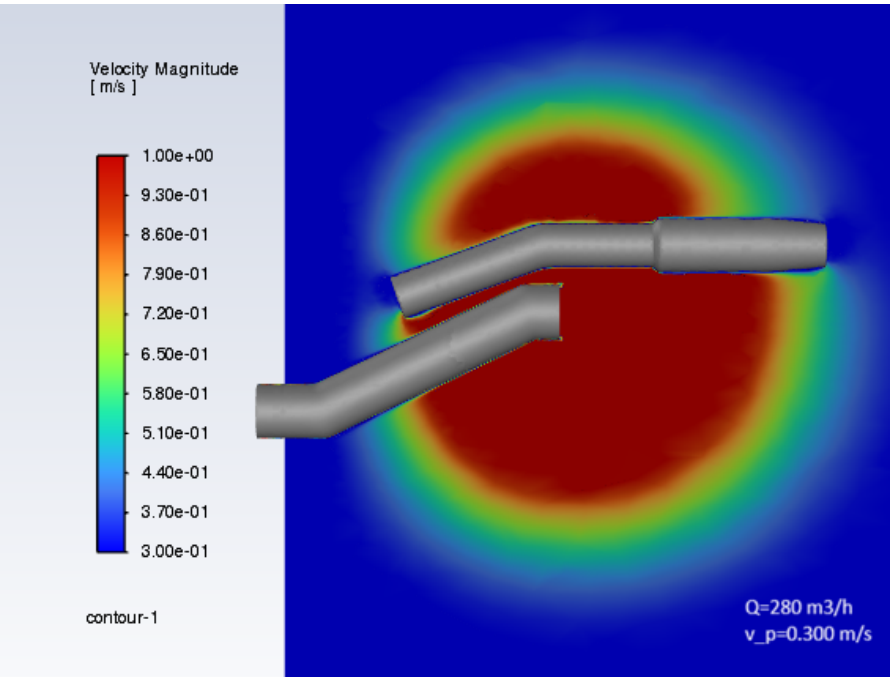


Figure 88: Performance of "Short" concept.

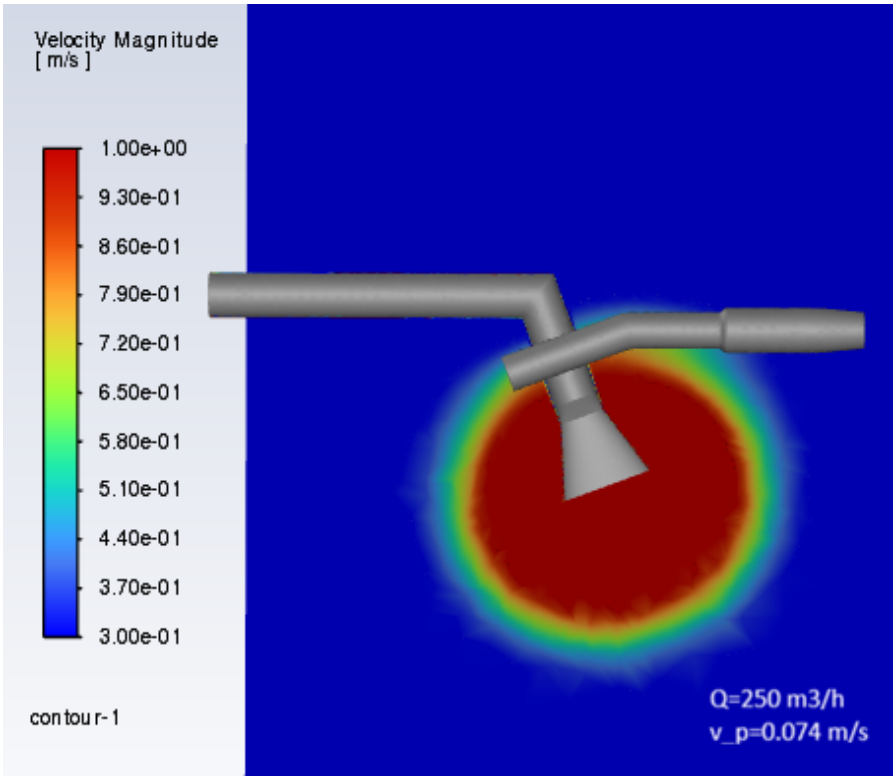


Figure 89: Performance of "TM50" concept.

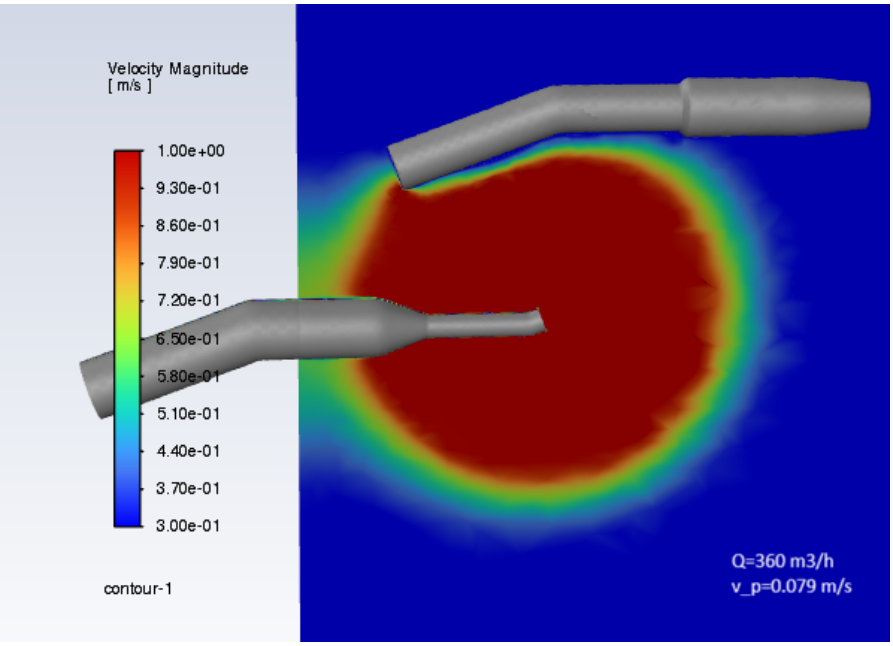


Figure 90: Performance of "Dentist" concept.

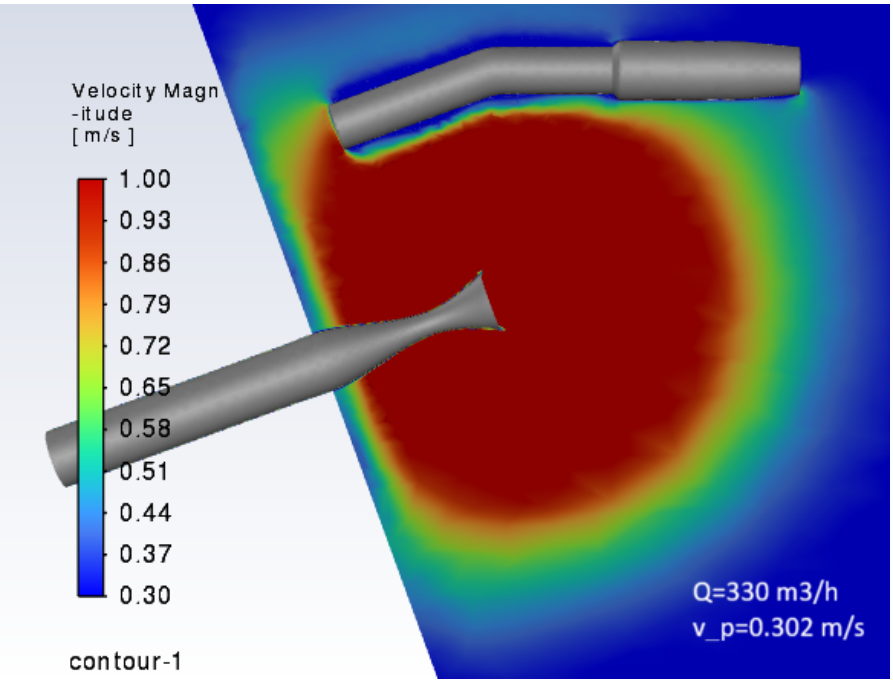


Figure 91: Performance of "Laval" concept.

D.3 - Evaluation of concepts from Cycle 3

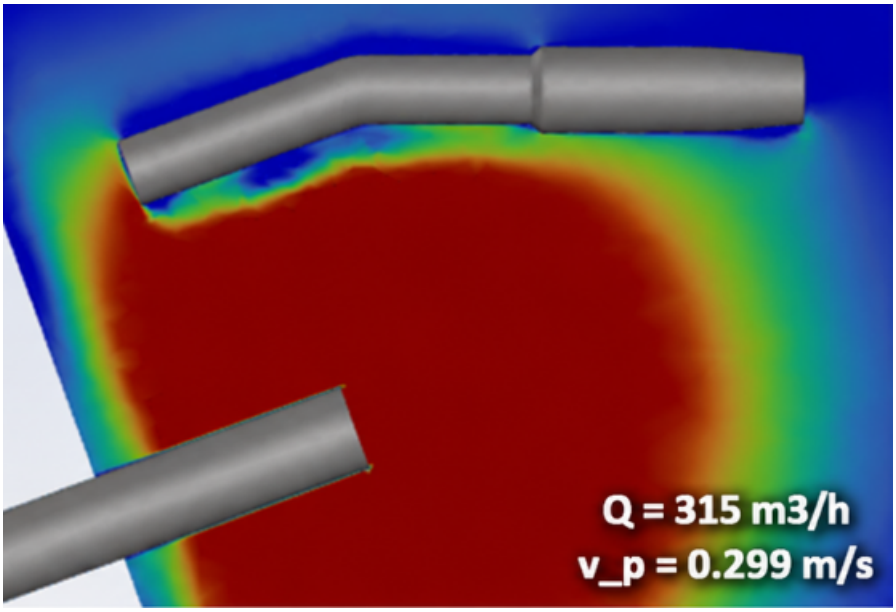


Figure 92: Final evaluation of "Tube" concept.

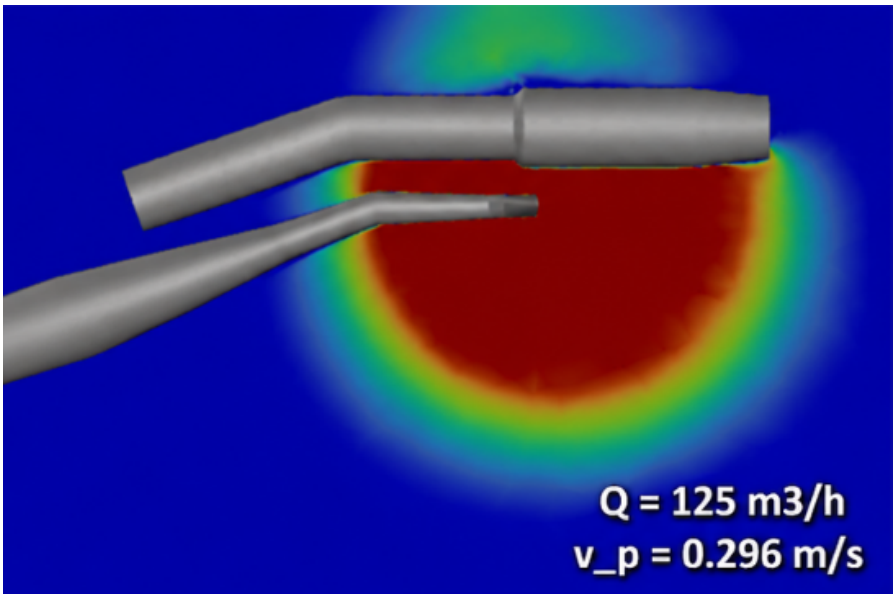


Figure 93: Final evaluation of "Cobra" concept.

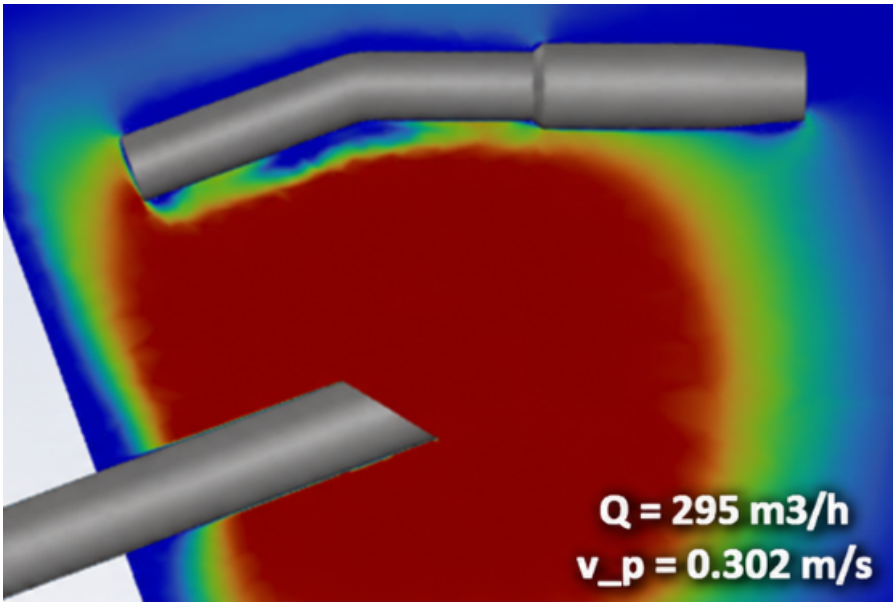


Figure 94: Final evaluation of "Slice" concept.

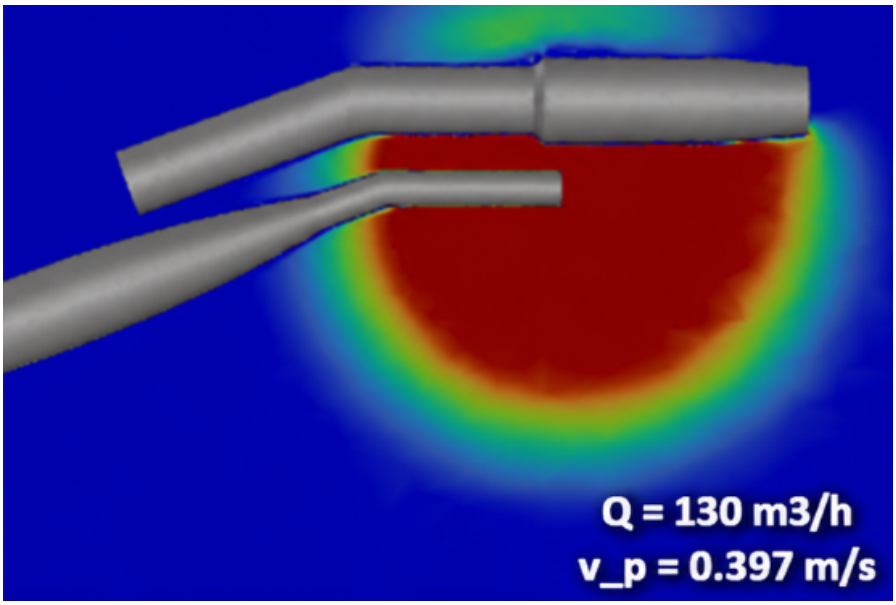


Figure 95: Final evaluation of "Banana" concept.

Appendix E

Questions for cobot welding:

What are important requirements/needs for a welding cobot?

What are its tasks?

What are the benefits of Cobot welding:

- *Precision?*

- *Cost (implementation and usage?)*

- *Time? (installation/education)*

What are the challenges?

How do you extract welding fumes today (for the Cobot)?

Who are you protecting?

In what situations do dangers arise?

Do you think that the industry today provides sufficient protection from these dangers?

What are today's solutions?

On the cobot?

What are the requirements for an extraction nozzle on a cobot?

What are the limitations of today?

Who are the customers?

What are their usual needs?

How is the human-cobot interaction?