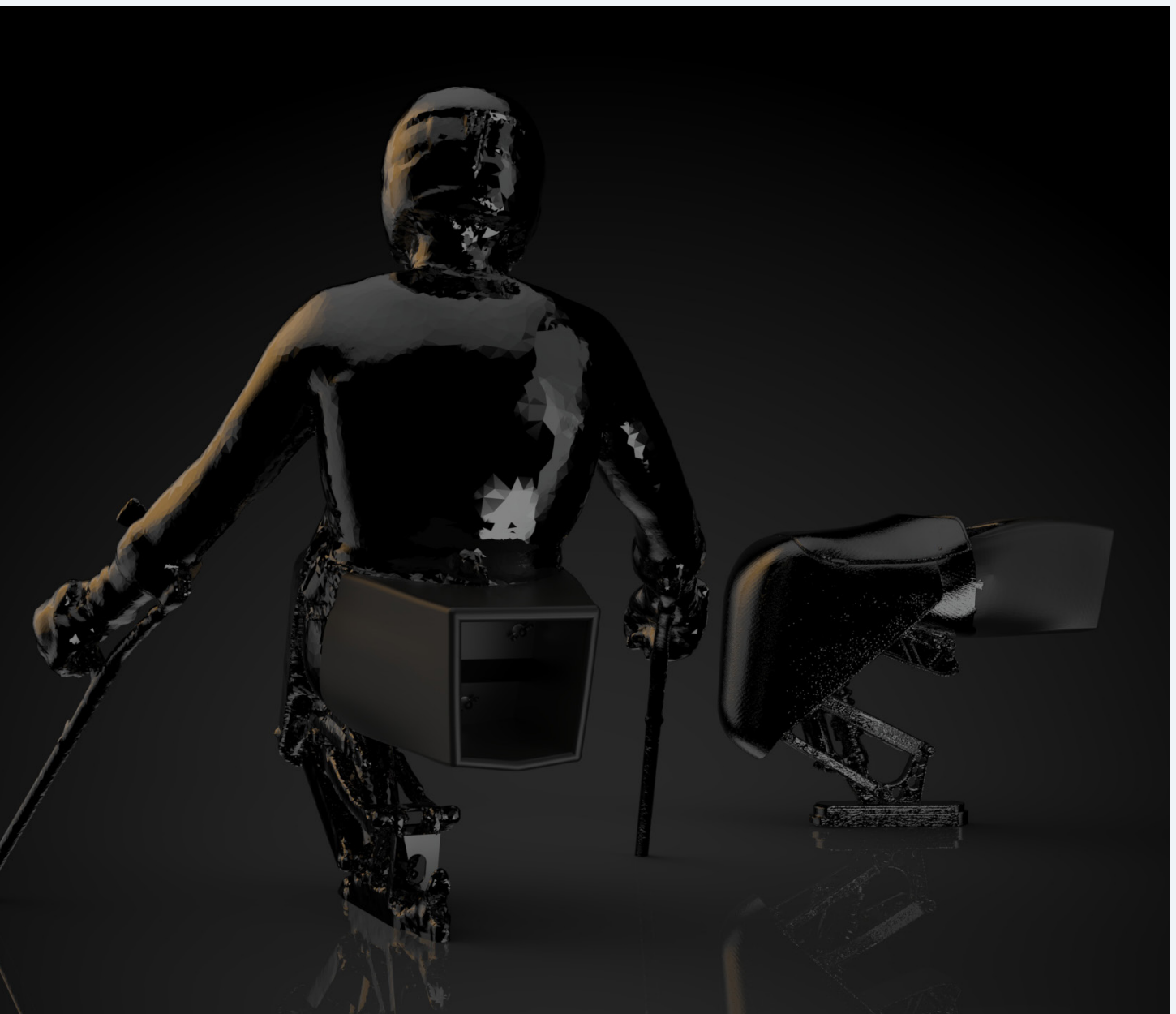


Master Thesis

By Brian Holtkamp

DESIGN FOR PARASKI

A new detachable aerodynamic shell component



DESIGN FOR PARASKI

A NEW DETACHABLE SHELL COMPONENT

MASTER THESIS BY BRIAN HOLTkamp

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Master Thesis

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PREFACE

This thesis is the final project of my Master's degree in Integrated Product Design at the faculty of Industrial Design Engineering at TU Delft. I dedicated 4 days of a week to this project from October 2024 to April 2025. Next to this master thesis I was working as a Junior Product Developer at VANMOKUM. This report offers an overview of the accomplished work in the past 7 months. During this project I learned how to work in a multidisciplinary project team and got to develop my CAD modelling skills. I learned surface modelling from scratch during this project. I was also able to apply and expand my knowledge and skills gained from my Bachelor's and Master's studies and extracurricular activities.

I want to express my gratitude to everyone who contributed to the success of this graduation project. A special thanks goes to my mentor, supervisors and collaborators of the entire project group. I would like to specifically acknowledge Toon Huysmans and Anna Ruiter for their support on the academic side. Their support helped me stay on track and find my place in this complicated project. On top of that, their expertise helped me in creating an extensive research overview, develop concepts and ensuring my process was scientifically sound.

I would also like to specifically thanks Wouter Terra and Roel van der Hooft for their ongoing support, setting up communication with the involved stakeholders and feedback on the project.

A special thanks to the coach and athletes for making this wonderful project possible.

Furthermore, I want to thank all the designers, researchers, students and experts who contributed to various activities of this project. Lastly, I want to thank my friends and family for their support.

I am very proud to present my thesis: 'Desing for paraski: A new detachable shell component.,

- Brian Holtkamp

ABSTRACT

This thesis presents the design and development of a new detachable shell component for paralympic sit skiers. The research is aimed at enhancing the aerodynamics of a sitski without compromising stability, safety, or the user's ability to control the ski. With user needs as a central focus, the design process began with an in-depth contextual and user experience analysis. This led to an extensive programme of requirements. By utilizing 3D scans of athletes in their ski, a CAD model of the shell was developed and iteratively refined using CFD simulations. 2 designs were tested in a wind tunnel, resulting in aerodynamic improvements of 8%. The final shell component is 3D printed in flexible TPU for a built-in safety mechanism in the event of a crash. To validate reproducibility, the design approach was successfully applied to a second athlete. The finalized CAD models are printed for snow testing.

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01

INTRODUCTION

- 1.1. Background information
- 1.2. Problem definition
- 1.3. Project team
- 1.4. Project timeline
- 1.5. Objectives and aims
- 1.6. Approach

1.1 BACKGROUND INFORMATION

When injured ex-servicemen of the Second World War returned to the sport they loved, skiing, a new sport was developed. Para-alpine skiing began in 1948 with the introduction of the first courses. Athletes with physical disabilities, such as spinal injuries, cerebral palsy, amputations, blindness, vision impairments, and other conditions, compete in this sport (Para Alpine Skiing - About the Sport, n.d.) Athletes are divided into three categories based on their functional abilities: vision impaired, standing and sitting. ("What Are The Three Categories in Para-alpine Skiing?", 2014)

The Paralympic programme consists of 5 different events combining speed and agility. These disciplines are ranked from high speed to high agility: Downhill, Super-G, Super Combined, Giant Slalom, and Slalom. (Para Alpine Skiing - About The Sport, n.d.) Each discipline has its own set of challenges and rules, as seen in Table 1 below. The Super Combined event consists of either a single downhill or super-G run and a single run of slalom. The combined time of these runs determines the final order of the event. (Stokke et al., 2023)

The Dutch sit-skiers are among the world's elite, reaching up to 120 km/h during downhill and super-G races. This project focuses on two Dutch athletes who have lost their lower limbs. They have full functionality in the remainder of their legs and upper body.

Table 1: Descriptions of para-alpine skiing disciplines.

Discipline	Downhill	Super-G	Giant Slalom	Slalom
Vertical drop (m)	450-800	400-600	300-400	140-220
Course setup	Longest and steepest course.	Second longest and steepest course.	Longer than slalom, with wider turns.	Shortest course.
# of gates	Least number of gates.	25m apart with 30 direction changes.	Determined by the vertical drop.	55-75.
# of runs	1 run, with one practice run.	1 run.	2 runs down different courses.	2 runs down different courses.
Type of event	Speed.	Combination of speed and technical.	Technical.	Most technical.

1.2 PROBLEM DEFINITION

As gravity is the sole propelling force on a slope, an athlete's weight is crucial in generating speed in straight descents. As the athletes are missing their lower limbs, they are missing weight and thus propelling speed compared to competitors with lower limbs. Air resistance is the most significant opposing force sit-skiers encounter during downhill and super-G races, accounting for as much as 80-90% of the total resistance acting on the skier. The current sit-ski shells (as seen in Figure 1) are not optimally streamlined, particularly the rear section. Any improvements made to the sit-ski's aerodynamics could have a big impact on a race result. (Elfmark et al., 2021)

To counter the aerodynamic force, a new shell component will be designed to streamline the rear section of the sit-ski. Prior projects, which will be discussed in Chapter 2.3.1, have focussed on streamlining the front of the sitski. This project addresses a critical issue: enhancing the aerodynamics of sit-skis without compromising stability, safety, or the user's ability to control the ski. The challenge lies in designing a component that integrates seamlessly with the athlete's existing sit-skis and meets the athlete's needs for competing for a gold medal. The shell component will be used in competition and possibly during training, meaning it must endure high speeds, crashes, and varying temperatures.



Figure 1: A sit-skier in action. (Redactie De Limburger, 2022)

1.3 PROJECT TEAM

This master's thesis is part of a bigger multidisciplinary project team. The project is funded by ZonMw and consists of a collaboration between Delft University of Technology, Actiflow, Roel van der Hooft Sports Engineering and The Dutch Ski Association (NSkiV). (ZonMw, n.d.)

The successful execution of this project relies on the collaboration of multiple stakeholders, each contributing their expertise to specific aspects of the process:

- Actiflow: Responsible for the aerodynamic design of the new component, ensuring optimal performance in reducing air resistance.
- Roel van der Hooft Sports Engineering: Manufacturer responsible for the test models and final component. He also functions as a client in this master's thesis, providing critical feedback on the design and production process.
- TU Delft researcher (Aerospace Engineering): Serves as the project lead. He also functions as a client alongside Roel, offering guidance and ensuring the project aligns with its objectives.
- TU Delft (Industrial Design Engineering): Responsible for the 3D scanning and modelling necessary in this project for aerodynamic simulations.
- NSkiV (Coach): The national coach of the paralympic athletes, who provides sport-specific knowledge.

The role of the designer (author) in this project is to combine the visions and needs of different stakeholders into a comprehensive programme of requirements and designing a detachable connection method for seamless integration of the new shell component.

1.4 PROJECT TIMELINE

As mentioned, this project is for a master's thesis and is carried out in around 100 working days. Due to the limited time, this project can contribute to part of the entire ZonMW project timeline. The focus for this project is therefore on creating a validated prototype for a connection mechanism combined with the final production method and material. Figure 2 shows the project timeline. The highlighted areas indicate the personal involvement and essential steps in the ZonMW project. The colours represent the design stages of a double-diamond approach, which will be discussed in Chapter 1.6. Green represents the Discover stage, light blue the Define stage, dark blue the Develop stage and purple the Deliver stage. The chapters in this report correspond with the numbers placed in the corners of the boxes.

ZONMW PROJECT

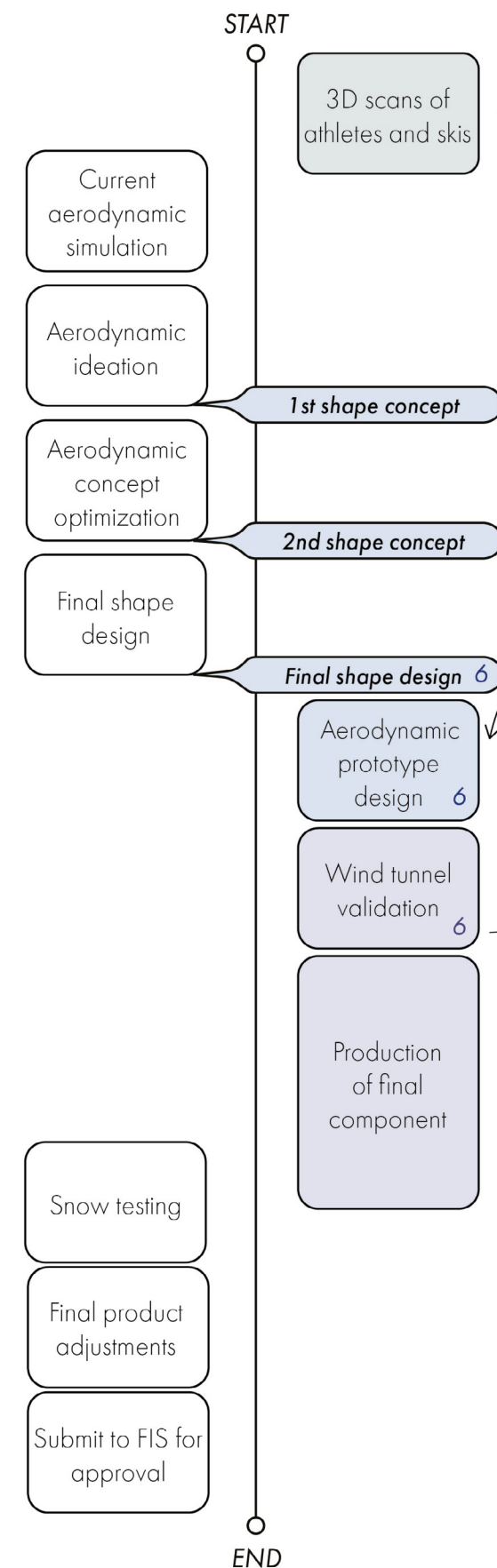
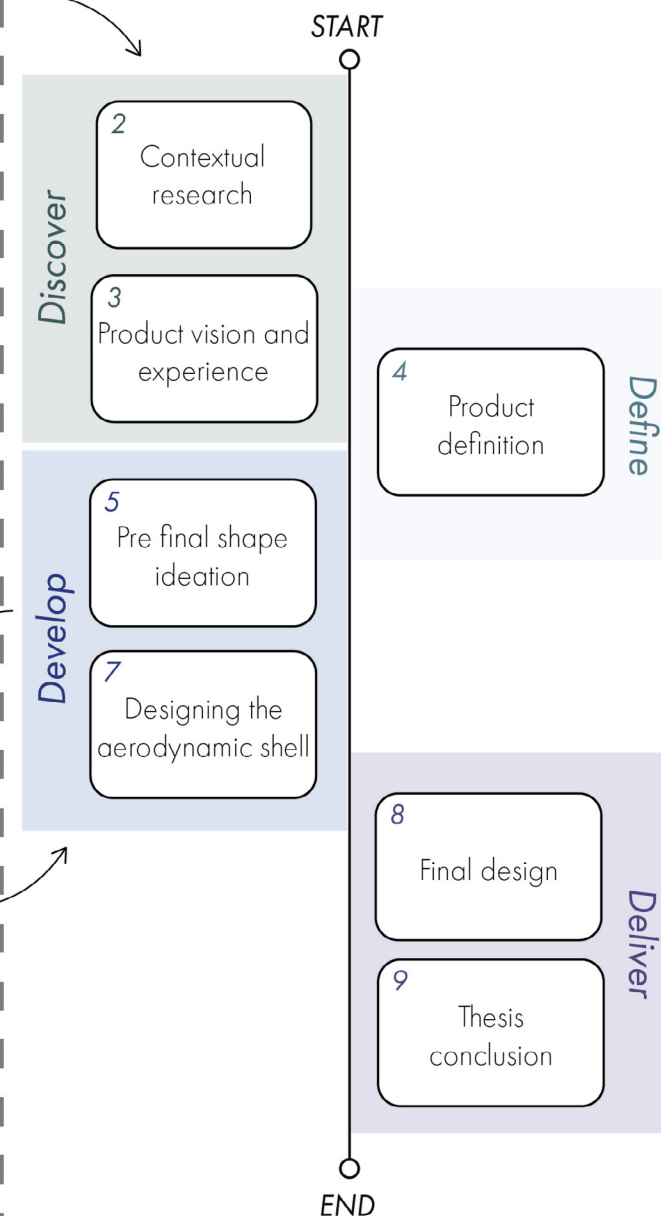


Figure 2: Project timeline.

MASTER'S THESIS



1.5 OBJECTIVES AND AIMS

The overall objective of this project is to design a new, detachable shell component for the back of the seat that significantly improves the aerodynamics of the current sit-skis, without compromising stability. The primary goal is to achieve a 10% reduction in air resistance, corresponding to saving over one second on a one-minute descent. It is important to note that two use cases will be defined during this project: wind tunnel use and actual product use.

As this new component is highly personalized, the athletes' needs are crucial in this project. This master's thesis focuses on the user experience, safety, and the seamless connection of the new shell component to the existing sit-ski. To achieve these aims, the following objectives have been defined:

- Enhance the overall aerodynamics of the sit-ski.
- Analyse the context in which the new component will be used and identify the user's needs.
- Develop a comprehensive programme of requirements for the aerodynamic shell component regarding the two use cases.
- Develop a prototype for testing and validating the aerodynamics in a wind tunnel.
- Design a detachable connection mechanism that allows the new component to be removed when not in use.
- Propose a production method for the new component and test functionality for actual use.

1.6 APPROACH

The approach used in this project is a double diamond model with elements of a human factors approach included. Human factors engineering focuses heavily on people and aims to reduce the risk of injury, increase performance, and increase desirability. This is achieved in an iterative cycle of understanding the people and context, creating solutions, and evaluating their effectiveness regarding the human factors aims. (Lee et al., 2017)

This project delicately balances performance, safety, and desirability. The design must be safe, personalised, durable, and user-friendly, allowing easy attachment and detachment for transport and use in competition while improving aerodynamic performance. The athlete's performance and needs are central to the approach. The research will be divided into the four phases of the double diamond approach: Discover, Define, Develop, and Deliver (Design Council, n.d.) Figure 3 shows the design approach used in the project timeline.

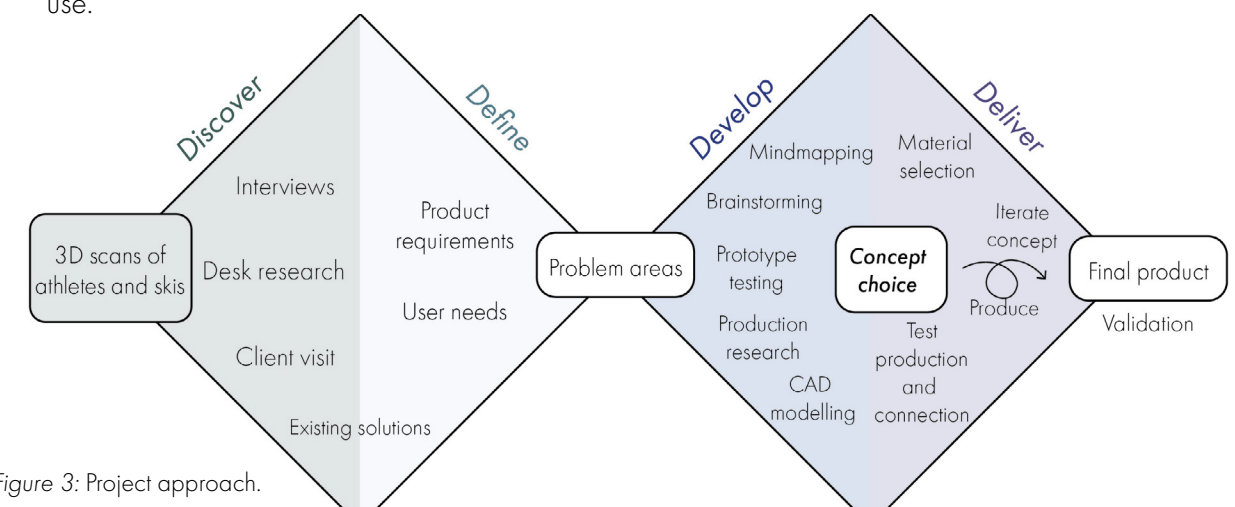


Figure 3: Project approach.

02

CONTEXTUAL RESEARCH

2.1. Method

2.2. Organisational context

2.3. Technical context

2.4. Usage context

2.5. Conclusions

This chapter lays the groundwork for the thesis by integrating desk research, semi-structured interviews and a client visit to present a comprehensive understanding of the context in which the new product will operate. The chapter begins with the methods used, followed by an organisational, technical and usage contextual analysis.

2.1 METHOD

The findings reported in this chapter are retrieved with a combination of desk research, semi-structured interviews and a client visit to the manufacturer.

2.1.1 DESK RESEARCH

Desk research was conducted to establish:

- A foundational understanding of Paralympic sit-skiing.
- Find regulations related to adaptive equipment.
- Gain knowledge about the aerodynamics involved in sit-skiing.

This included reviewing video footage of Paralympic skiing events, analysing organizational documents, and consulting research papers and supplementary resources. The research was conducted unstructured and guided by the previously mentioned themes.

2.1.2 SEMI-STRUCTURED INTERVIEWS

Two Paralympic sit-ski athletes and a coach were interviewed semi-structured to gather qualitative insights into the product's usage context and user experience. This flexible interview format ensured open-ended exploration while covering key topics of interest.

2.1.2.1 Paralympic athletes

The aim of the interviews with paralympic sit-ski athletes was to get a better understanding of the athletes' actions, perceptions, opinions, behaviours, and wishes regarding current and future sit-ski. The first interview had a broad focus, while the second delved deeper into user experience, bypassing certain contextual topics.

The interviews were formulated in a semi-structured way following a structure of different use cases, which can be seen in Figure 4.

The full details of questions can be seen in Appendix A1.

The interviews were conducted in person and in Dutch to accommodate participant's preferences. The duration of the interviews range between 1 and 1,5 hours and were performed in a private meeting room at the TU Delft. Participants were encouraged to bring their ski, to be able to portray certain actions and highlight discussed areas. Audio recordings supported a focus on active listening and follow-up questions in conversation. At times, the recording was stopped to capture a certain movement an athlete wanted to portray.

The results of the interview were thematically structured using the use cases. Findings are portrayed in the subsequent chapters.

2.1.2.2 Coach

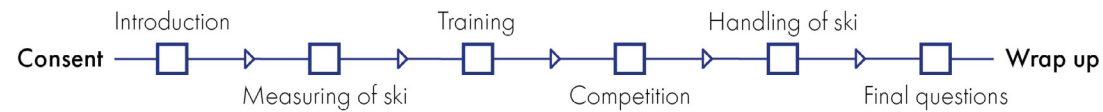
The results of the interview were thematically structured using the use cases. Findings are portrayed in the subsequent chapters.

The interview with the coach aimed to get a better understanding of the coach's vision, expectations, challenges, usage of the sit ski and technical aspects regarding the current and future sit-ski.

The interview was formulated in a semi-structured way following a structure of different themes, which can be seen in Figure 4. The full details of the questions can be seen in Appendix A2.

The interview was performed virtually and in Dutch. The duration of the interview was around one hour. Audio recordings were used for transcription and detailed analysis. The results of the interview were thematically structured. Findings are portrayed in the following chapters.

ATHLETE INTERVIEW STRUCTURE



COACH INTERVIEW STRUCTURE

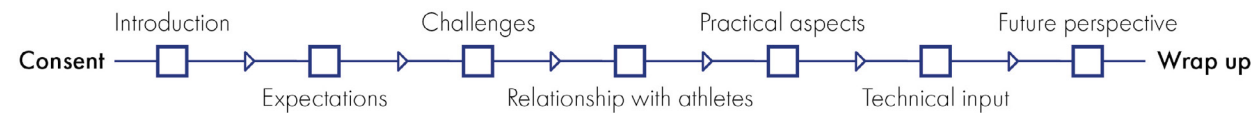


Figure 4: Athlete and coach interview structure.

2.1.3 CLIENT VISIT

The client visit consisted of a visit to the workshop of the manufacturer. This visit aimed to gain a deeper understanding of the production process through direct observation and a discussion. Specifically, the visit seeks to identify any challenges or inefficiencies in his current workflow and to explore his vision for the production of the new component.

Insights gathered from the athletes about the production process served as a foundation for guiding the discussion with the manufacturer. During the discussion, targeted questions were asked to uncover potential pain points and key considerations in the production process.

These discussions will be complemented by observations conducted within the manufacturer's workspace, enabling a comprehensive understanding of both the practical and contextual aspects of his production process. Relevant findings will be discussed in the following chapters.

2.2 ORGANISATIONAL CONTEXT

This part of the contextual analysis shows an overview of the involved stakeholders, a discussion of the relationships between the involved organisations and an overview of relevant regulations about Paralympic skiing.

2.2.1 STAKEHOLDERS

In this project, various stakeholders play a crucial role in the success and adoption of the new aerodynamic shell component. These stakeholders are categorized as main, direct, and indirect, as illustrated in Figure 5. Each stakeholder group has distinct roles, needs, and expectations that must be addressed during the project.

Actiflow is the company responsible for shaping the shell component's aerodynamics. Continuous collaboration with Actiflow ensures that the design meets both aerodynamic and functional requirements.

As the primary users, the athletes' needs and preferences are central to the project. Their involvement in decision-making ensures the component is user-centred and aligns with their expectations.

The national coach of the athletes has extensive experience and his expertise is crucial for evaluating the feasibility and acceptance of the design. His input guides decisions on functional elements and usability, enhancing the likelihood of adoption.

The manufacturer and a TU Delft researcher function as project clients. The manufacturer is responsible for the production of the wind tunnel prototype and final component. The TU Delft researcher is the project manager. Regular updates with both clients are necessary to stay aligned with the project goal and feasible production of the final design.

The IPC, FIS, NSKiV and NOCNSF are all abbreviations for organisations which will be discussed in Chapter 2.2.2.

STAKEHOLDER INVOLVEMENT

Direct

ZONMW - funding the project, need for innovation.
 IPC - Ensure a safe and fair paralympic event.
 FIS - Clear regulations on material, approve new component.
 NSKiV - Overall guidance of athletes, future product owner.
 NOCNSF - Overall application of athletes, possible regulations for product.

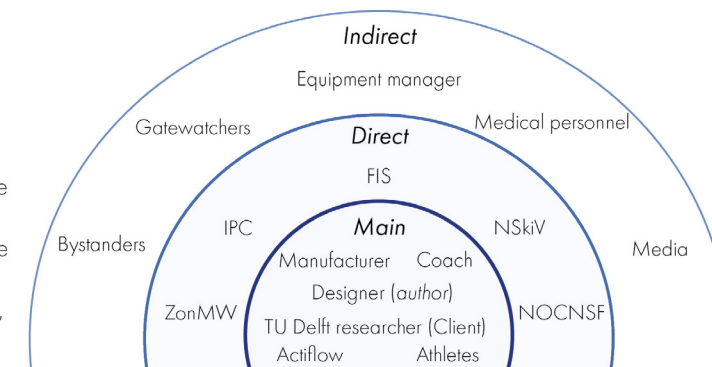


Figure 5: Stakeholder mapping and involvement.

STAKEHOLDER INVOLVEMENT

Indirect

BYSTANDERS - No risk in watching paralympics.
 GATEWATCHERS - Ensure a safe and fair event.
 EQUIPMENT MANAGER - handling and reparation of product.
 MEDICAL PERSONNEL - Ensure a safe event. Intervene in case of accidents or medical events
 MEDIA - influence on acceptance of product and framing of safety.

2.2.2 ORGANISATIONS

To ensure compliance with relevant regulations, an analysis of the involved organisations and their corresponding responsibilities has been conducted. Figure 6 shows the relationships and relevant responsibilities of the organisations.

The International Paralympic Committee (IPC) is the global governing body for the Paralympic Movement. It is a member-based organisation composed of National Paralympic Committees (NPCs), International Federations (e.g., the International Ski Federation), Regional Organisations, and other international bodies. (International Paralympic Committee, n.d.)

The NOC*NSF (Dutch Olympic Committee* Dutch Sports Federation) represents the Netherlands within the IPC. It unites various Dutch sports organisations and

sets broad objectives for sports development, while providing strategic guidance to sports associations. (NOCNSF, n.d.)

The NSKiV (Dutch Ski Federation), a member of NOCNSF, functions as the national governing body for skiing in the Netherlands and supports the development of elite skiing athletes. (Nederlandse Ski Vereniging, n.d.)

The International Ski Federation (FIS) is crucial in the technical organisation of skiing and snowboarding competitions. While the IPC manages the Paralympic Games, the FIS oversees events leading up to the Paralympics, such as World Cups and qualifying tournaments. FIS also develops sport-specific rules and regulations essential for ensuring compliance with international standards. (International Ski and Snowboard Federation, n.d.-a)

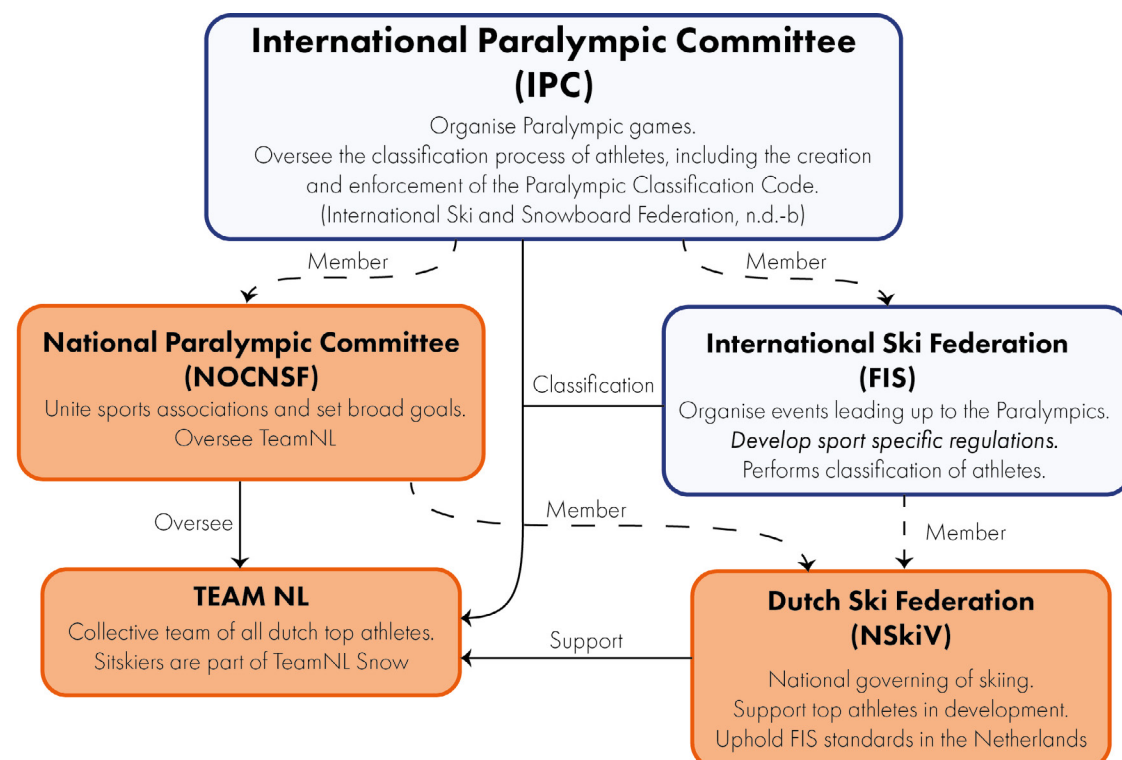


Figure 6: Relations and responsibilities of involved organisations.

2.2.3 REGULATIONS

The IPC has set up some general rules for adaptive equipment for the Paralympics. (IPC Medical Department & Scientific Department, 2011). These are:

- Safety (should not harm the athlete, spectators, or environment)
- Fairness (regulated in the rules)
- Universality (the principal components must be commercially available and affordable)
- Physical prowess (no motor, computer, robotically components)

The FIS is responsible for developing sport-specific regulations and has published a report outlining the specifications and regulations regarding para snow sports equipment. These specifications and regulations are divided into "Para Alpine skiing competition equipment" and "Para alpine skiing adaptive equipment". Regarding the competition equipment, multiple specifications are against improving aerodynamic properties; see Appendix B for further details. (INTERNATIONAL SKI AND SNOWBOARD FEDERATION, 2024)

Relevant specifications for adaptive equipment are:

- A sit-ski consists of a moulded seat mounted on a metal frame. A suspension system beneath the seat eases riding on uneven terrain and helps in turning by maximizing ski-snow contact. A metal or plastic block in the shape of a boot sole is the base that clicks into the ski's binding.
- A sit-ski can be used in Uni-Ski or Dual-Ski.
- A sit-ski needs a braking device on both sides of the seat. This device creates friction to prevent sliding.

It is important to note that while aerodynamic improvements are prohibited for most competition equipment, the regulations for sit-skis do not include any provisions that prohibit the addition of an aerodynamic shell component.

2.2.4 TAKEAWAYS

The contextual research highlights the importance of involving the athletes and coach of NSKiV throughout the design process to ensure the new component meets their needs and expectations. Compliance with FIS and IPC regulations is essential, as the component must adhere to their standards. Safety remains a critical consideration in sit-skiing and must be prioritised in the design. Emphasising safety not only addresses a core requirement but also provides a strong basis for obtaining approval from the FIS.

Important design element (this is not a requirement but a core pillar to take into consideration when designing the new shell component)

- Safety: The new component cannot endanger the athlete, bystanders, or the environment.

2.3 TECHNICAL CONTEXT

This part of the contextual analysis presents an overview of relevant aerodynamics followed by a function analysis.

2.3.1 AERODYNAMICS

Aerodynamics concerns the study of how gasses, in most cases air, interact with a body moving through this gas. The main forces concerned with aerodynamics are lift and drag. (Sadrehaghighi, 2023)

2.3.1.1 Basics of aerodynamics

Lift is the component of the aerodynamic force that works perpendicular to the direction a body is moving and drag is the component of force opposite to the direction of movement. (Rathakrishnan, 2013). As the sitski is attached to the ground, drag is the force that is most important for aerodynamic optimization. Lift cannot be neglected as this may alter the skiing experience, but is not something we will design for in this project.

Pressure drag is caused when there is a high pressure at the front of an object and a low pressure at the back of an object. The high pressure is caused by compressing air that hits the front of an object. The low pressure at the back is caused by air separating from the object. Due to this pressure difference, the air pushes harder on the front of an object than the back. (Causes of Aerodynamic Drag, 2011)

To counter the aerodynamic drag acting on an object, this lack of pressure at the back or wake needs to be minimised by streamlining the object. To streamline an object, the front of the object should be well rounded and the body should smoothly arch backwards from the midsection, narrowing towards the rear. (The Editors of Encyclopaedia Britannica, 1998)

2.3.1.2 Aerodynamics in Paralympic Skiing As mentioned in the introduction, aerodynamic drag can account for 80-90% of the total resistance acting on the skier. The most commonly used approach for studying aerodynamics on skiers has been the use of a wind tunnel. (Elfmark et al., 2021)

Research by Brownlie (2020) shows that any aerodynamic improvements made in paralympic sit skiing could be seen as “free speed” if this is permitted by the rules and regulations of the FIS. Brownlie states there are a few ways of reducing pressure drag for winter sports:

- Adopting a lower profile.
- Using streamlined equipment.
- Drafting behind another athlete, this is not relevant for sit-skiing.
- Wearing tight-fitting clothing.

For sitting skiers, Brownlie recommends aerodynamically improving the sit-ski, as this is allowed by regulations. A simple adjustment made in this research reduced the drag by 5-10%.

A study by Impey (2022) validates that making aerodynamic adjustments to the sitski is allowed and can improve the athlete's performance at high-speed events like Downhill and Super-G. In this study, a ‘Kamm tail’ was added to the ski of Corey Peters, which decreased the drag force by 7.1% at 60 km/hr. Figure 7 shows this Kamm tail integration. Corey later went on to win a gold medal in the Downhill event and a silver medal in the Super-G event with these improvements at the 2022 Paralympic Games.

Corey Peters won a bronze medal in the Downhill event and finished 11th in the Super-G event at the prior Paralympic Games in 2018. (PyeongChang 2018 - Alpine-skiing - Mens-super-g-sitting, n.d.)

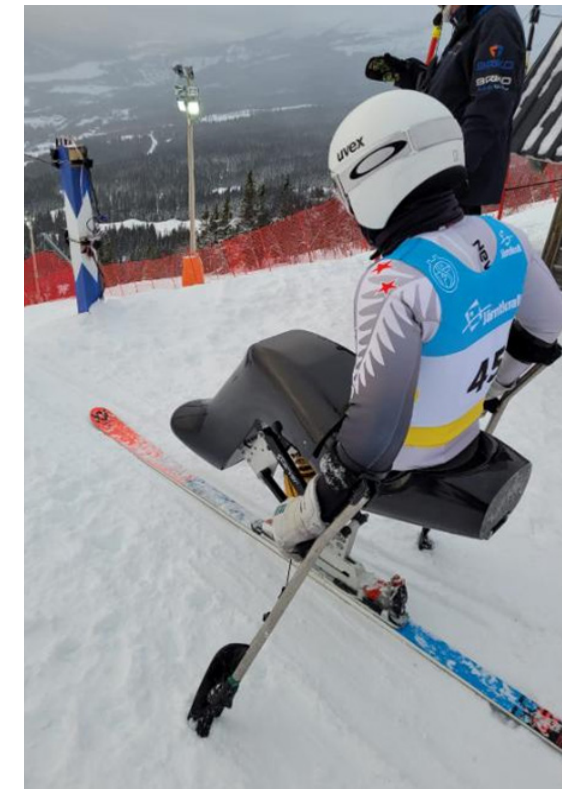


Figure 7: Corey Peters in action. (Canterbury Engineers Create World-leading Design for Kiwi Paralympic Skier, 2022)

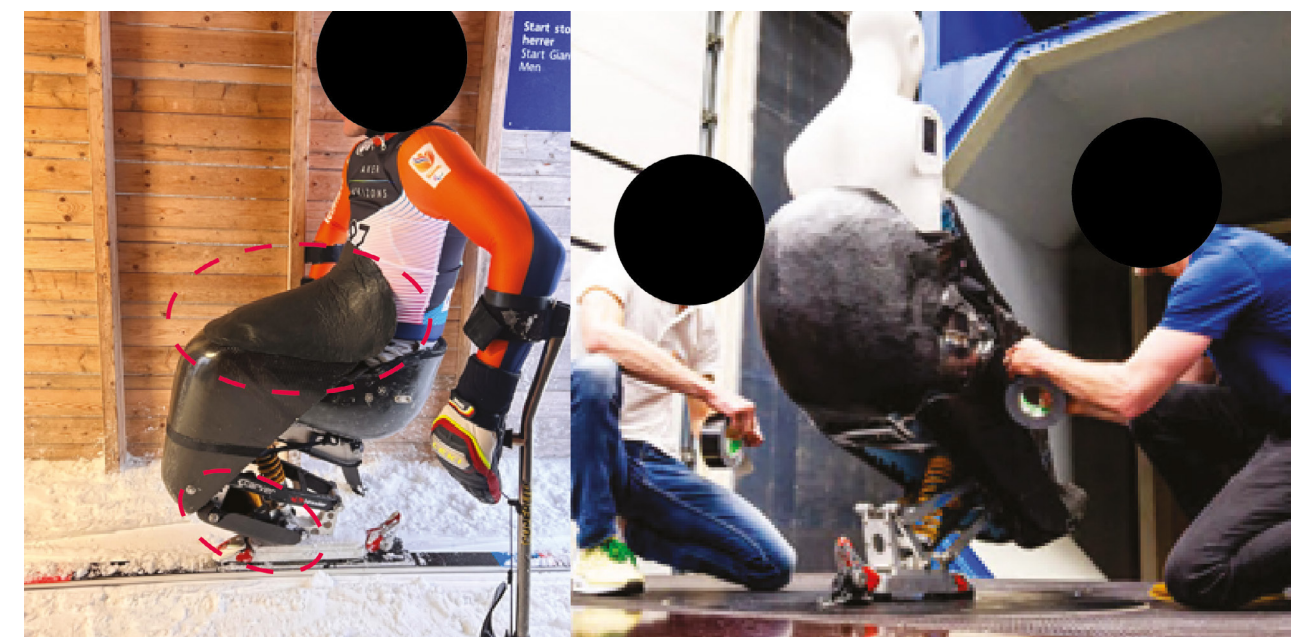


Figure 8: Prior aerodynamic optimisations.

2.3.1.2 Prior aerodynamic optimisation

Prior to this research, the Delft University of Technology, TeamNL, NSkiV and Roel van der Hooft Sports Engineering collaborated to improve the aerodynamics of the front of the sitski. This research included testing multiple aerodynamic postures per athlete and the design of an abdominal part and frame cover. The new components added up to an 8% reduction of aerodynamic drag. (Innovatie Helpt Paraskiërs in Jacht Op Eremetaal, 2022)

Next to these new designs, they tested prototypes and ideas for aerodynamic shaping of the back of the ski, setting the groundwork for this project. This new shell component on the back has been approved by the FIS, further validating the design of the new shell component of this master's thesis. Figure 8 shows the newly designed components on the left and the tested prototype for the back on the right.

During the interviews, the coach mentioned that he and the athletes noticed that the athletes would touch the foam abdominal part during use. Even though this might not limit the freedom of movement of the athlete, mentally this felt like a limitation. For the new shell component, it is important that the component does not interfere with the athlete's movements.

2.3.2 FUNCTION ANALYSIS

A sit-ski is a product composed of multiple parts, each with a specific function. The new shell component must integrate seamlessly with the existing sit-ski without interfering with or limiting necessary functions.

In Figure 9, the current components and their functions are shown. It is important to note that the belt tightener has been relocated to the back of the ski, as indicated by the arrow. This adjustment needs to be considered during the design process to ensure compatibility with the new component.

When designing the placement of the new shell component, there are a couple components that need to remain accessible. These components are:

- **Fastening belt:** This component is critical in tightening the sit-ski and securing the athlete during competition.
- **Brake screws:** Required by FIS regulations, this component is mandatory for use in competition.
- **Abdominal belt:** This component plays a crucial role in the athletes' skiing experience (see chapter 3.1) by providing additional stability and support.

2.3.3 TAKEAWAYS

Based on the aerodynamic analysis, the new shell component should reduce the pressure wake at the back of the ski. The air should stick to the ski as long as possible. The new component cannot limit the freedom of movement of the athlete. No issues are anticipated in obtaining FIS approval for the new component, given the prior aerodynamic optimisations and the approval of Corey Peters' ski.

The function analysis highlights the importance of the use and accessibility of the fastening belt, brake screws and abdominal belt. The new component cannot hinder this usability.

Requirements

- The product must reduce aerodynamic drag compared to the current ski design, measured through wind tunnel testing or CFD simulations.
- The product must fit seamlessly with the current sitski with gap tolerances of $\leq 5\text{mm}$
- The product must allow a full range of motion for the athlete.
- The product must not obstruct the fastening belt, brake screws, or abdominal belt, ensuring they remain fully functional and accessible without additional adjustments.

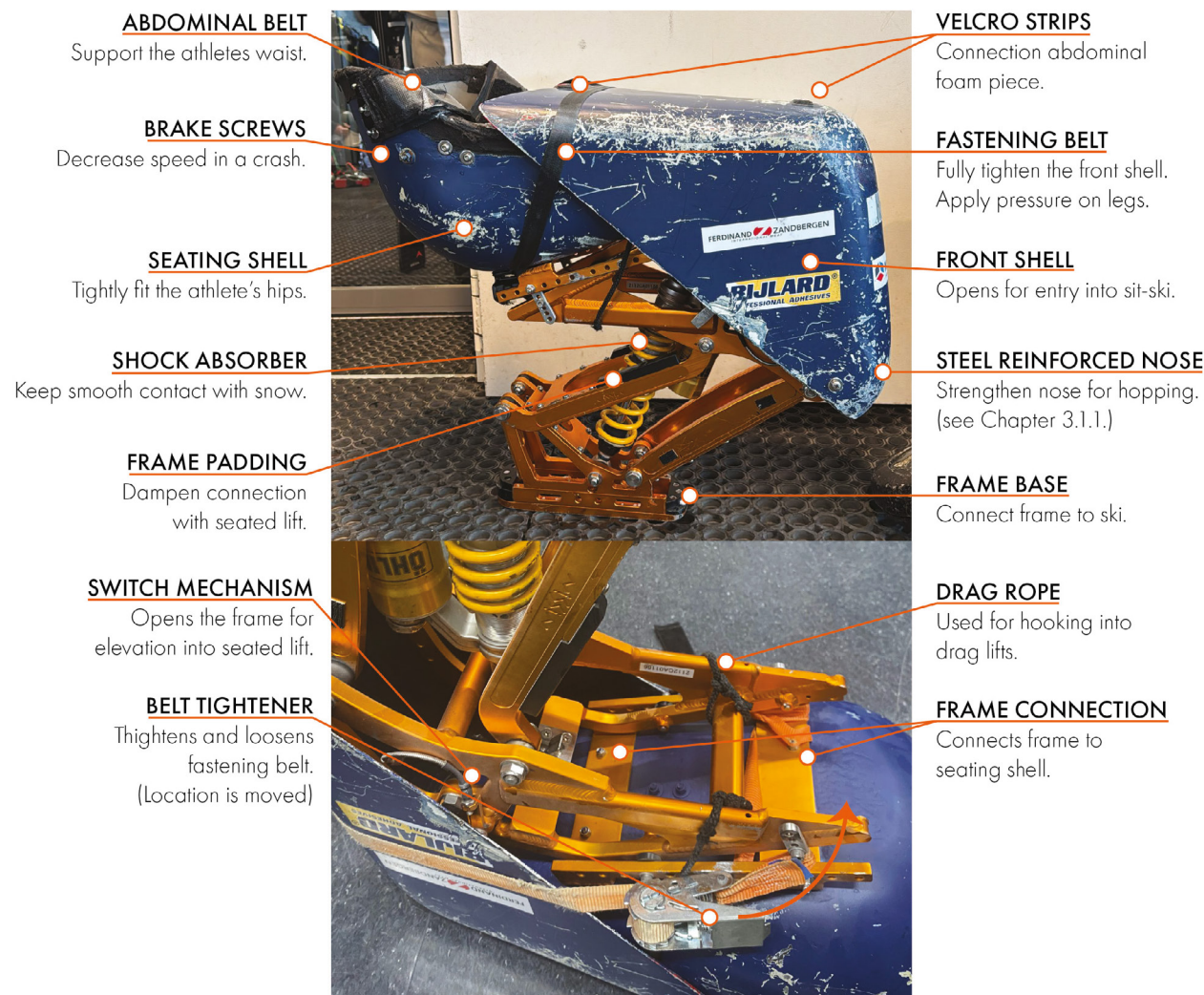


Figure 9: Sit-ski components and functions.

2.4 USAGE CONTEXT

In this part of the contextual analysis, a product journey map will be created and analysed along with environmental requirements.

2.4.1 PRODUCT JOURNEY MAP

To get a good overview of the full context of use a product journey map is made, based on the insights from the interviews. The product journey map covers the interactions, emotions and challenges the user experiences and creates opportunities for the design to add to the experience in each stage. This product journey map describes the process of measuring/producing the sit-ski, storage and maintenance, transport and use in training and competition. (Van Boeijen et al., 2013)

To better communicate the journey maps, they are separated into different figures. Figure 10 shows the production stage. Figure 11 shows the storage and maintenance and transport stages. Figure 12 shows the snow training stage and Figure 13 shows the competition stage.

The challenges section of this product journey map highlights problem areas or potential tension points for the new shell component in each phase. The opportunities section suggests actions or requirements for the new shell component to address these challenges and ensure the new shell component fits in the context of use.

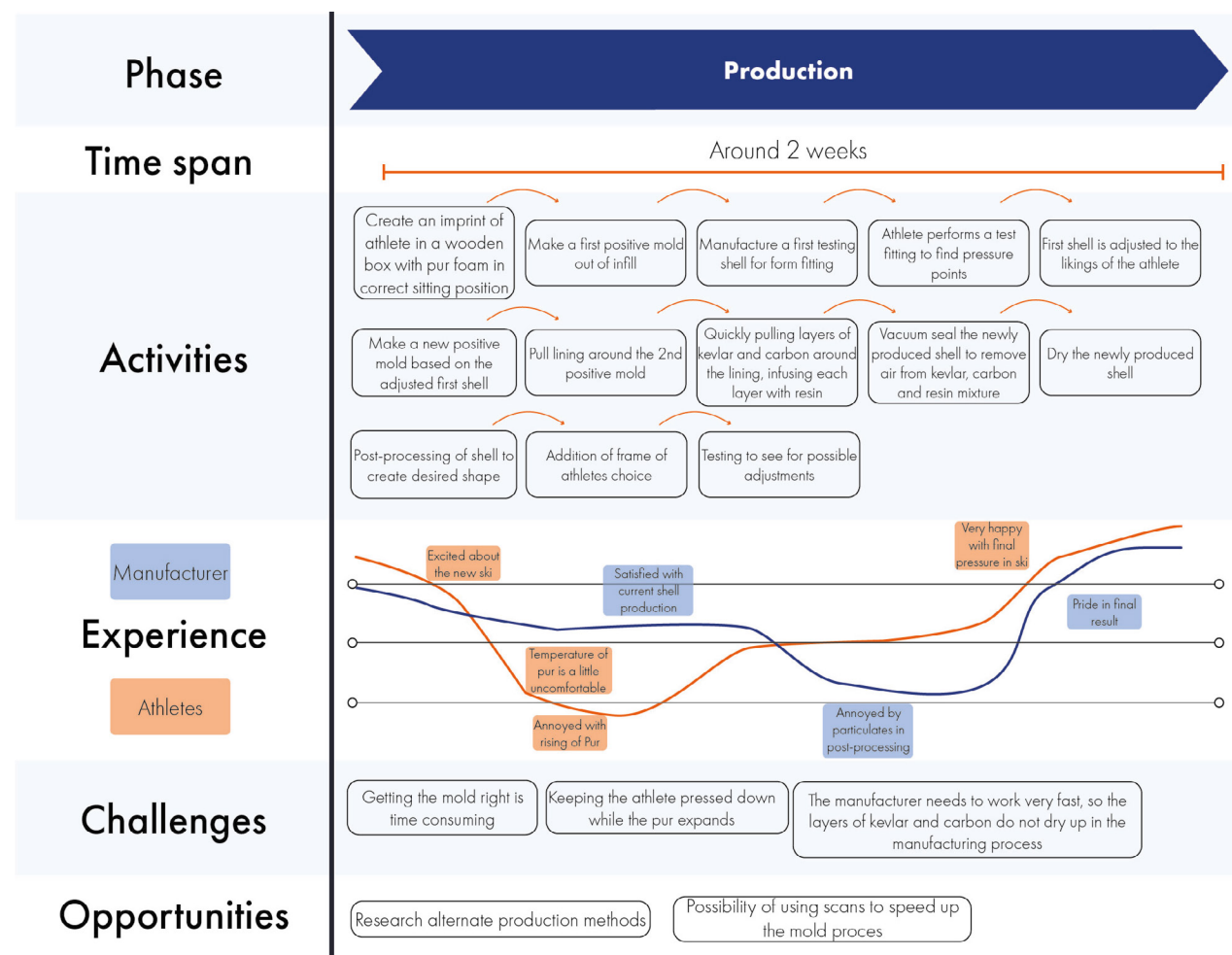


Figure 10: Product journey map - production.

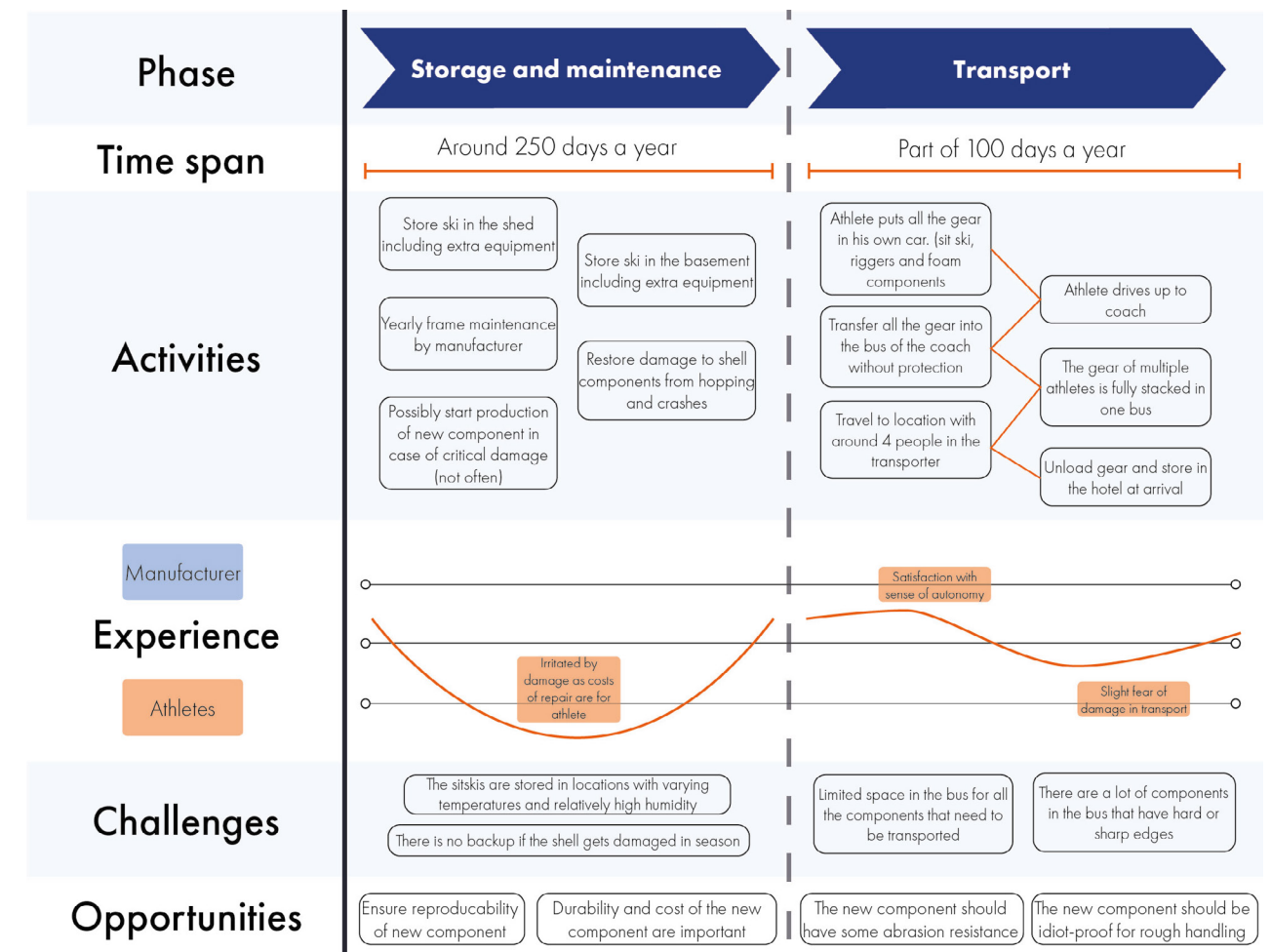


Figure 11: Product journey map - storage and maintenance and transport

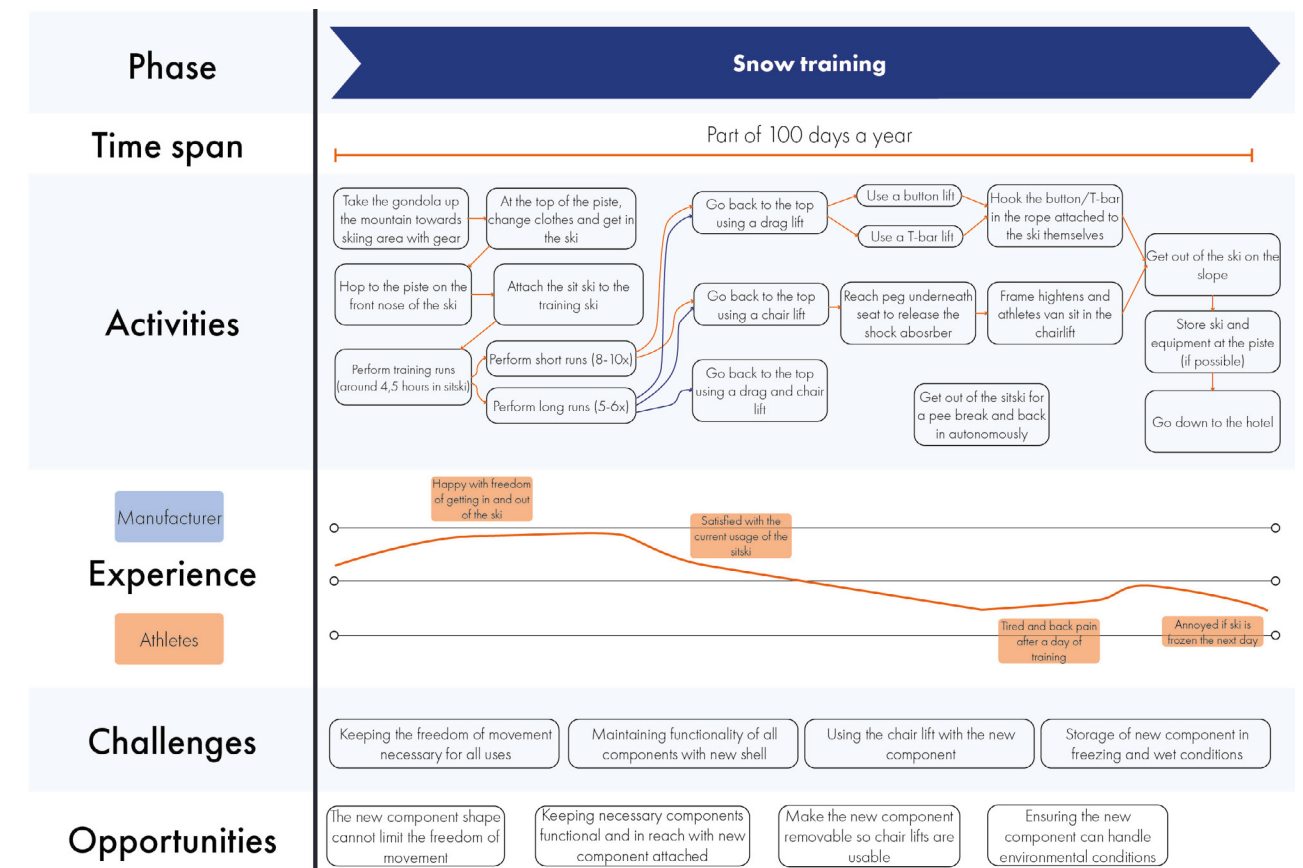


Figure 12: Product journey map - snow training

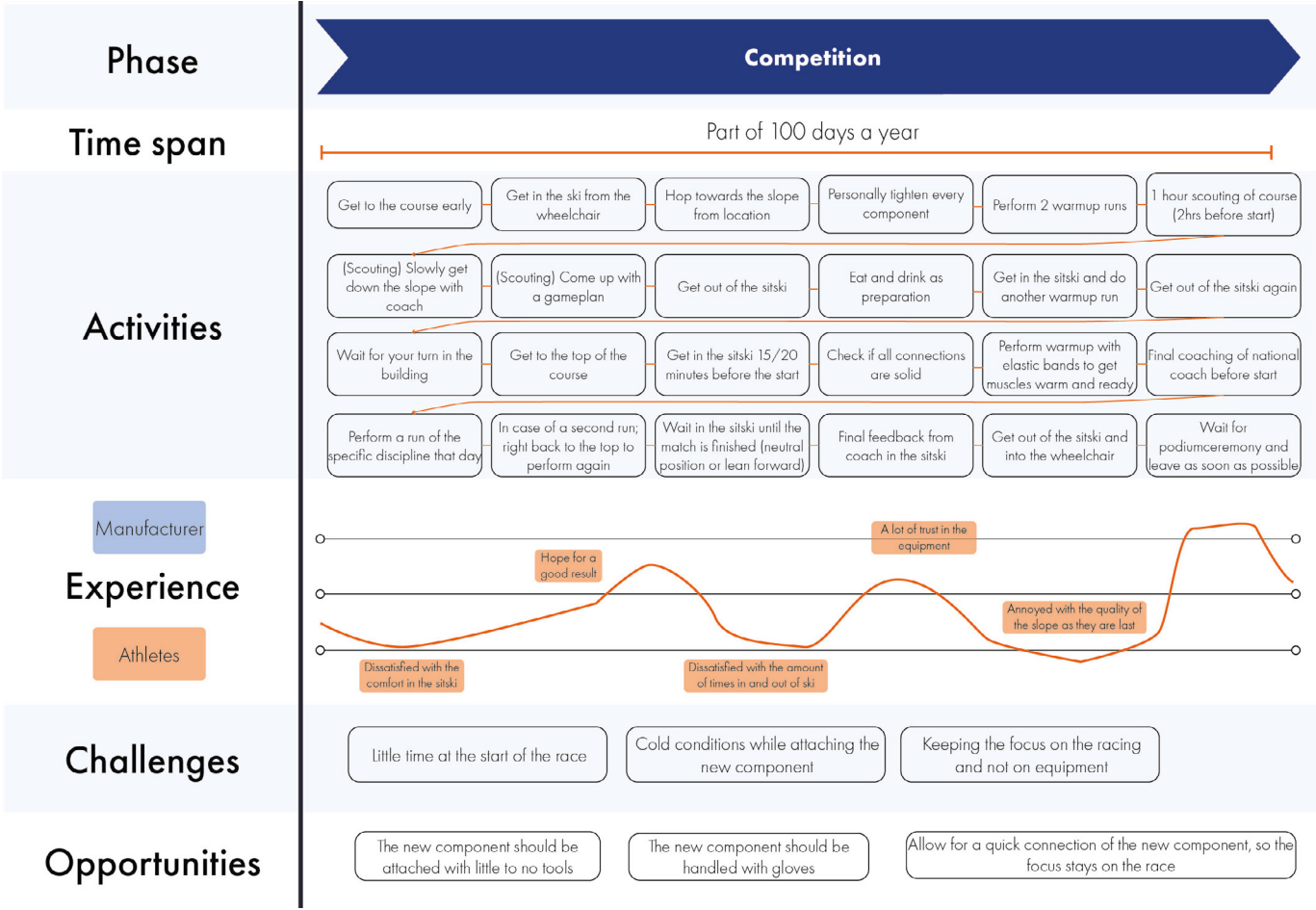


Figure 13: Product journey map - competition

2.4.2 ENVIRONMENTAL REQUIREMENTS

The FIS performed research about the effects of wind on the temperature experienced in combination with the prevention of cold injuries in snow sports. The FIS Medical Committee states that high-speed competitions like alpine skiing events should be cancelled at -20 degrees Celsius due to the wind chill effect at high speeds and the increased risk of hypothermia. (Lereim, 2007) The product should handle temperatures varying from -20 degrees Celsius to 20 degrees Celsius.

In case of warmer temperatures, racing slopes are sometimes prepared using salt to melt snow and create ice formation for the perfect racing slope. (Lubbinge, 2021) The product should be resistant to this salt exposure.

Lastly, the product encounters snow a lot. The shell component cannot freeze, as this would result in the product losing its desired impact resistance abilities.

Based on these environmental conditions the following product requirements are formulated:

- The product can withstand temperatures down to -20 degrees Celsius.
- The product can withstand exposure to moisture and salt without material degradation.
- The product must have a hydrophobic surface, preventing the formation of ice layers that could alter mechanical properties.

2.4.3 TAKEAWAYS

The product journey map reveals the need to research other production methods and materials for the final component than Kevlar and Carbon. There are 2 athletes involved in this project, so the design should fit both skis. As costs for the ski are for the athletes themselves, the final component should be durable. These are important criteria for the concept choice.

Furthermore, the components are typically stored in dark, cold, and damp conditions. These conditions need to be researched for further requirements.

On top of that, during transportation, they are often loosely placed in a bus, highlighting the need for the new component to be durable and able to withstand rough handling. The new component cannot limit the usage of the different types of lifts. Lastly, the shell component should be attached quickly while using gloves, with little to no tools, to keep the focus on the race.

Requirements:

- The product should be reproducible after the first production by either re-usage of a mould or using digital fabrication methods.
 - The product should be reproducible for a different athlete's ski.
 - The product has good abrasion resistance.
 - The product can withstand temperatures down to -20 degrees Celsius.
 - The product can withstand exposure to moisture and salt without material degradation.
 - The product must have a hydrophobic surface, preventing the formation of ice layers that could alter mechanical properties.
 - The product is idiot-proof. It should have no plastic deformation during transport.
 - Connecting and disconnecting the aerodynamic shell component requires no more than 1 standard tool.
- The product can be connected to the shell while wearing gloves.

Important design elements:

- Durability & cost: There should be a balance between costs and durability to accommodate the athletes.
- Manufacturing process: Manufacturing of the new component is quick and easy.

2.5 CONCLUSIONS

During the design process of the new shell component, it is important to involve NSkiV athletes and coaches to align with their needs. It must comply with FIS and IPC regulations, prioritising safety to gain approval.

Aerodynamic improvements should reduce the pressure wake without restricting athlete movement. The function analysis highlights components that need to remain accessible and usable.

Alternative materials and production methods for Kevlar and Carbon should be explored. Durability and cost-effectiveness are important elements for the new shell component and it should take the harsh storage and transport conditions into account. The component should also be compatible with various ski lifts and allow quick, tool-free attachment while wearing gloves.

The important design elements are not specific requirements for the final product. However, the product should take these design elements into account. These elements will be used to determine the concept in Chapter 7.5.

Important design elements:

- Safety: The new component cannot endanger the athlete, bystanders, or the environment.
- Durability & cost: There should be a balance between costs and durability to accommodate the athletes.
- Manufacturing process: Manufacturing of the new component is quick and easy and fits the requirements.

Requirements:

R-aero-1: The product must reduce aerodynamic drag compared to the current ski design, measured through wind tunnel testing or CFD simulations.

R-aero-2: The product must fit seamlessly with the current sitski with gap tolerances of $\leq 5\text{mm}$.

R-use-1: The product must allow a full range of motion for the athlete.

R-use-2: The product must not obstruct the fastening belt, brake screws, or abdominal belt, ensuring they remain fully functional and accessible without additional adjustments.

R-use-3: Connecting and disconnecting the aerodynamic shell component requires no more than 1 standard tool.

W-use-1: The product can be connected to the shell while wearing gloves.

R-man-1: The product should be reproducible after the first production by either re-usage of a mould or using digital fabrication methods.

R-man-2: The product should be reproducible for a different athlete's ski.

R-mp-1: The product can withstand temperatures down to -20 degrees Celsius.

R-mp-2: The product can withstand exposure to moisture and salt without material degradation.

R-mp-3: The product must have a hydrophobic surface, preventing the formation of ice layers that could alter mechanical properties.

R-mp-4: The product is idiot-proof. It should have no plastic deformation during transport.

W-mp-1: The product has good abrasion resistance.

03

PRODUCT VISION AND EXPERIENCE

- 3.1. User experience
- 3.2. Physical restrictions
- 3.3. Safety
- 3.4. Stakeholder points of view
- 3.5. Conclusions



3.1.1 SKI MOTIONS

To turn in skiing, fore-aft movement is crucial. To initiate a turn, the centre of mass needs to shift towards the front of the ski. This motion lets the front of the ski get into the snow and set a groove for the rest of the ski to follow. As the turn progresses, the centre of mass shifts backwards to move the rear of the ski. Figure 14 below, made by Ron LeMaster, shows the shift of the centre of mass in turns. (Wenzel, 2022)

3.1 USER EXPERIENCE

To design a component that enhances the performance of the athletes, it is important to get a good overview of the usage of the current sitski and the factors that are crucial for a good performance.



Figure 14: Photo sequence of Marcel Hirscher performing slalom turns. (Wenzel, 2022)

This shift of the centre of mass is just as important in turning in a sitski. The athletes describe that to make a turn, they first lean forwards turning their right shoulder inwards and shifting their body to the right in making a right turn and vice versa. After leaning in and initiating the turn, they move their body back to a neutral position and repeat the cycle to the other side. The fore-aft movements are crucial in the skiing experience. Figure 15 shows a sit skier at the apex of a turn. This turn shows that the hips touch the snow during a turn.

Next to normal skiing, the athletes described a movement they call "hopping". When the athletes get into the ski from their wheelchairs, they throw themselves forward, as seen in Figure 16 below, landing on the front nose and leaning on the riggers (the poles with skis attached).



Figure 15: Athlete at the apex of a turn. (Redactie Kidsweek, 2018)

The front shell has an aluminium reinforcement at this front nose to support this handling. By doing a crunch movement, they can hop towards the slope and attach the sitski to the ski to not damage the ski on rocky terrain.

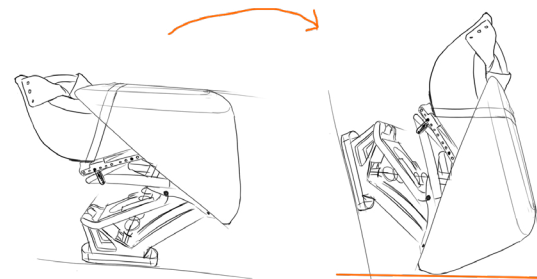


Figure 16: Visual representation of hopping.

3.1.2 PERFORMANCE FACTORS

The interviews with the two athletes provided insights into critical elements influencing the optimal performance with their current sitski. The following factors are essential in the skiing experience for maximising the athlete's performance:

- **Front-Back balance:** the sitski should be balanced over the foot that is connected in the ski binding to turn using the front-aft movement.
- **Pressure in the ski:** as much pressure in the ski as possible so the ski feels like an extension of the body. Furthermore, this pressure creates a feeling of security in the sitski.
- **Point of support at the back:** the backrest is a form of support. The athletes chose the height of the backrest. The athlete uses this point of support as a reference for a neutral and upright position. Moving the backrest any higher would decrease mobility and moving it lower would decrease control.
- **The abdominal belt:** the abdominal belt serves as a form of support at the trunk. The athlete uses the tension he feels from the abdominal belt as a reference for his front-back balance and can adjust his position in the ski according to the pressure he feels.
- **Feeling of freedom of movement:** the sitski must not make the athlete feel that he cannot make the necessary movements needed for skiing. On top of that, the athlete wants to be able to get in and out of the ski at their liking.

3.1.3 LIFT USAGE

In general, the athletes use either a drag lift or a chair lift to get to the top of the slope, as mentioned in the Product Journey Map in Chapter 2.4. There are two types of drag lifts: a button lift and a T-bar lift. For usage of both types of drag lifts, the athlete grabs the drag rope attached to the frame (normally covered under the front shell) and hooks the drag rope around the button or T-bar, as seen in Figure 17.



Figure 17: Drag rope hooked around T-bar. [athlete image]

If the athlete wants to use the chair lift, he needs to reach underneath the ski to open the switch mechanism, which unlocks the frame. The athlete can then lean forward and push themselves up using the riggers and land in the seat, as seen in Figure 18. The athletes mentioned that Corey Peters was sitting at the very tip of the chairlift with his improved sitski (mentioned in Chapter 2.3). On top of that, Figure 19 shows the minimal space for additional components the athletes have in a chair lift. To keep full functional use of the chairlift, the athletes want the new shell component to be removable.



Figure 18: Skier getting in the chair lift. [athlete image]



Figure 19: Athletes in chair lift. [athlete image]

3.2 PHYSICAL RESTRICTIONS

Maintaining the athletes' freedom of movement is critical for the design of the new shell component based on the previous chapters. Certain angles must remain unrestricted to accommodate the athletes' natural range of motion.

Based on the first iterations of Actiflow's aerodynamic shaping, the new component would fit above the top of the sitski and behind the back of the athlete, see Appendix C. Figure 20 illustrates a sit-skier executing a tight turn, with the upper body leaning at an angle calculated to be approximately 30 degrees. Figure 21 highlights the permissible area for the new component's design in green, ensuring the new component does not limit the athlete's freedom of movement.

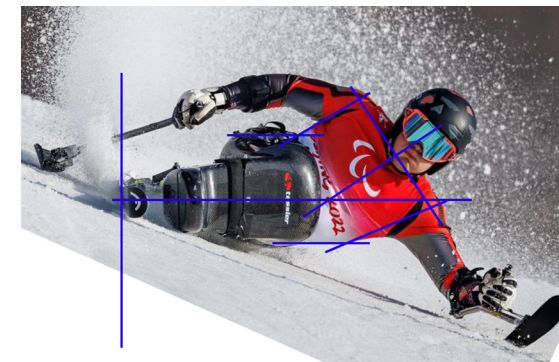


Figure 20: Athlete performing a tight turn.



Figure 21: Permissible area for shell.

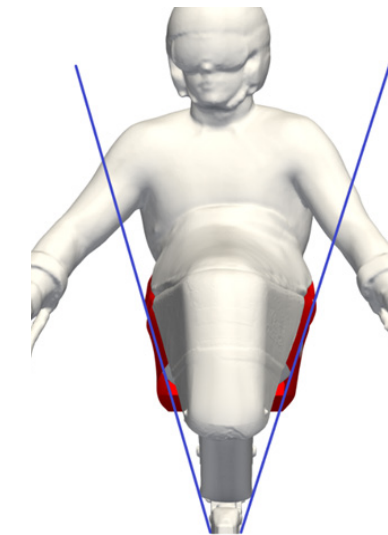


Figure 22: Maximum width.



Figure 23: Attachment lines shell.

Based on the user experience there are a few more physical restrictions. The sitski touches the snow in turns. To adhere to this freedom of movement, the shell component cannot widen the current ski at the hips. Figure 22 shows the widest possible area the new product can occupy. Furthermore, the fastening belt, braking screws, and the abdominal belt should maintain functional. Figure 23 shows the area behind which the new component should attach to the ski. This should be behind the red lines.

These physical restrictions lead to the following requirements:

The product can only go above the back support point if:

- The sides of the product run inwards at an angle of 30 degrees. (see figure 20)
- The front of the product follows the vertical axis of the back support with an angle of 30 degrees. (see figure 21)

The product cannot exceed the width of the current sitski.

The product should attach behind the abdominal belt and behind the fastening belt.

3.3 SAFETY

There are two ways an athlete can crash during skiing. The athlete either takes a turn too sharply and slides down the slope, or the athlete is launched into the air with flips due to a wrong landing after a jump or the ski catching snow unexpectedly.

The most positive sliding crash is one where the athlete possibly spins around but comes to a stop with the brake screws. The danger in a sliding crash lies in a component suddenly grabbing the snow and launching the athlete into the air. Figure 24 shows an example of a sliding crash with spin. In case such a sliding crash happens, the new component should not grab the snow and launch the athlete. Furthermore, the new component cannot become a loose projectile on the slope endangering the athlete and bystanders.

When an athlete is launched into the air with flips, other dangers can occur. Figure 25 below shows snippets of a crash from Tyler Walker at the Sochi 2014 Paralympics, where he landed badly after a jump. The athlete is launched into the air with multiple spins. The new product could further endanger the athlete if he lands on his back, creating a whiplash effect. To counter this, the shell component should have a form of impact absorption.



Figure 24: Athlete in a sliding crash with spin. [Athlete image]



Figure 25: Athlete getting launched in the air. (Paralympic Games, 2014)

3.4 STAKEHOLDER POINTS OF VIEW

3.4.1 ATHLETES

The athletes anticipate they will not notice significant improvements from the new aerodynamic component in their experience during skiing. However, they have identified several elements that are particularly important to their experience and expectations of the new component.

Firstly, both athletes do not see the necessity of training with the new component, as they do not expect to feel a difference in skiing with or without the component. They envision the use of the new component like the abdominal part. While there will be an initial adjustment period to become accustomed to skiing with the aerodynamic shell, like the abdominal part, training after this adjustment period will be performed without it to focus on technique and prolong the usage period of the aerodynamic components.

Secondly, the new component should fit in with the performance factors from Chapter 3.1 and should be removable to allow for the usage of seated lifts. In addition, athlete confidence in the equipment is essential, making a secure and reliable connection critical.

Lastly, the new component must not catch or drag on the snow during a crash. The athletes do not foresee any other safety concerns with the new component.

3.4.2 COACH

In an ideal scenario, athletes would have two different sit-skis: one tailored for speed disciplines (Downhill and Super-G) and another for technical disciplines (Slalom and Giant slalom). This would allow for a complete switch of the sit-ski instead of attaching a new component. However, this approach is unfeasible due to practical constraints, as athletes currently struggle fitting in a seated lift. Moreover, the production and maintenance of 2 sit-skis would be prohibitively expensive.

The coach refers to the new shell component as "the 1%". This new component will exclusively be used in competition and it should contribute to maximizing speed, with the remaining 99% relying on the skier's ability and technique. He prefers to handle the attachment of the new component himself, so the athletes can stay in their race focus. To accommodate this, the connection mechanism must be quick and easy to use, allowing him to focus on coaching the athletes. Furthermore, he strongly dislikes the usage of duct tape, as he experiences this as unsustainable and time-consuming. The abdominal part is currently taped to the shell.

The core elements to include in the design of the new shell component are:

- Durability
- Safety
- Freedom of movement
- Quick and easy connection

3.4.3 ACTIFLOW

Actiflow was provided with 3D scanned models of the athletes in their sit-ski to assist in the optimisation of the new component. Actiflow conducted CFD (Computational Fluid Dynamics) simulations across multiple wind angles to determine the most aerodynamic solution for the new component. Their view on the new component is:

- Design the most aerodynamically efficient shape possible on the scanned models.

In addition, the athletes' movements during skiing were communicated to Actiflow to be taken into consideration while designing the shaping of the final product (more elaboration will follow in Chapter 6). This ensures that the aerodynamic design and the athletes' actual positioning are aligned during competition.

3.4.4 MANUFACTURER

The current production method of the existing shell components is highly time-consuming. The manufacturer makes both a negative and positive mould by hand, repeating the process twice to adjust the first positive mould to properly fit the final design. The final shell component is constructed from a mixture of layers of Kevlar and Carbon. Kevlar is essential in the shell component for impact absorption, as it prevents the carbon shell from being dented on impact. The manufacturing goals for the final product are:

- Ensure the new shell component achieves the intended aerodynamic properties.
- Design the new shell component to fit the existing sit-ski seamlessly, optimising airflow.

An additional personal goal for this project is to streamline the production process of the new shell component, possibly by using a different production method for the final product.

3.4.5 STAKEHOLDER RELATIONS

Figure 26 shows an overview of the different visions of the stakeholders. The Figure highlights the importance of communicating ideas between the stakeholders to keep research findings and aerodynamic shape improvements aligned. The visions of the athletes and the coach are aligned regarding the usage of the new shell component. However, they prioritise different requirements for the new shell component. It is crucial for the success of the product that the manufacturer and Actiflow stay in contact with each other, to align ideas about the final product.

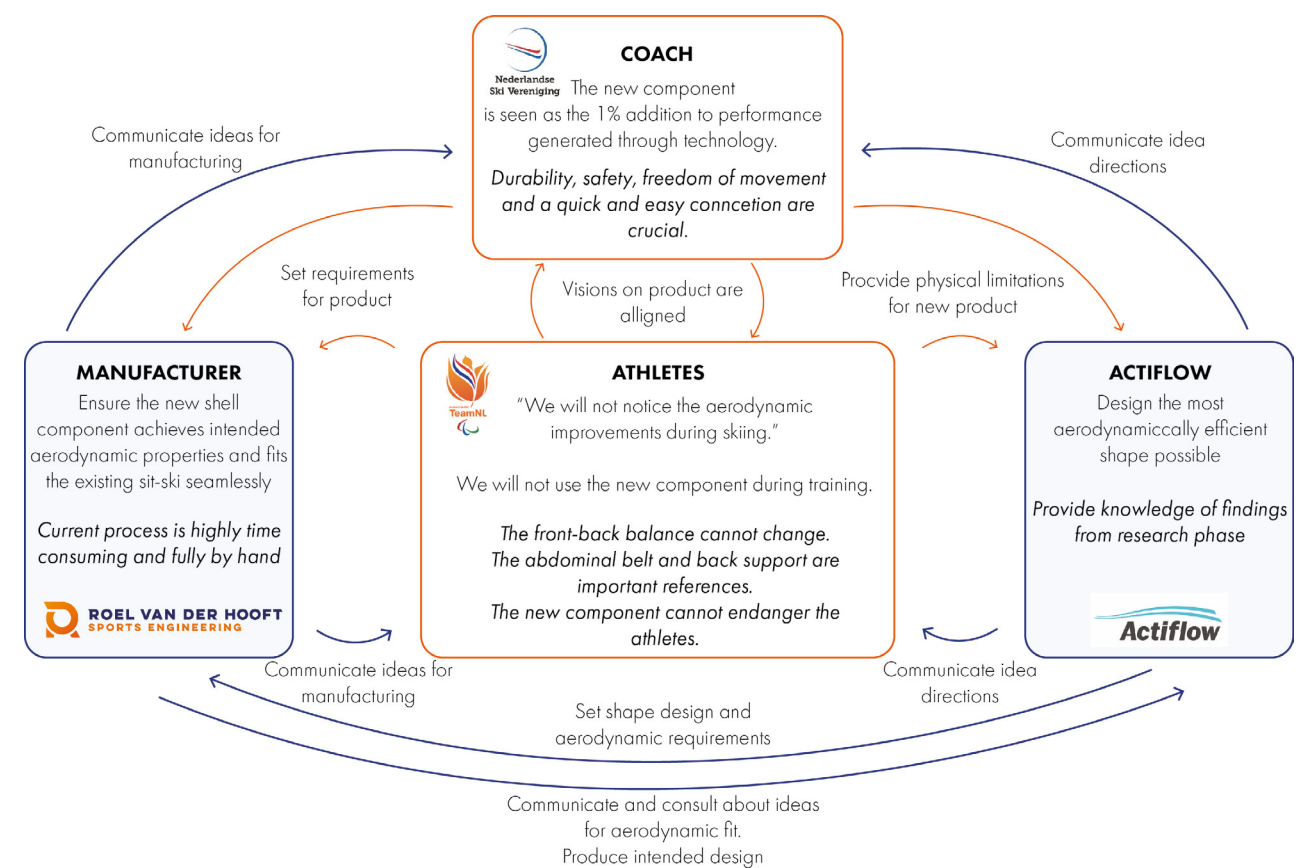


Figure 26: Stakeholder visions and communication.

3.5 CONCLUSIONS

The user experience gives a good overview of the different use cases of the sitski and the performance factors necessary for athletes. The front-back balance should be affected as little as possible, so the new product should be as light as possible, with much of the mass close to the centre of gravity. The back support point and abdominal belt are crucial in the skiing experience of the athletes, setting physical constraints for the aerodynamic shaping.

The component should be removable, aligning the usage of a chair lift with the visions of athletes and the coach for only using the component in competition during speed events. There is a possible need for removable added weight to the front of the sitski to keep the right balance. Safety is a critical aspect of the design. The component must not catch or drag on the snow in the event of a crash. This requirement aligns with the seamless connection needed to support the aerodynamic performance goals set by Actiflow. Furthermore, the materialisation plays a key role in ensuring safety and durability. The component should be designed to minimise potential risks in the event of a crash while maintaining structural integrity over time and under aerodynamic forces.

The connection mechanism for the new component must strike a balance between two key considerations: it must be strong and secure to ensure safety, while also being quick and easy to use for desirability from the coach. This creates a design spectrum with safety and strength on one end and simplicity and efficiency on the other.

Lastly, the freedom of movement creates certain physical restrictions. The product should touch the athlete as little as possible. These constraints are essential for Actiflow to consider in the design of the new component. Figure 19 shows the different stakeholders and the need for connecting their visions on the product.

Important design elements:

Lightweight: The product should be as light as possible to minimally affect the front-back balance of the sitski.

Seamless fit: A seamless fit of the product with the existing sitski is necessary to ensure safety and aerodynamic properties.

Simple and aerodynamic connection: The connection mechanism should be quick and simple to keep the focus on the race. The connection mechanism should alter the aerodynamics as little as possible.

Secure connection: The product cannot loosen in the event of a crash to ensure the safety of the athlete and bystanders.

Additional Requirements and Wishes:

R-aero-3: The product must have a smooth, rounded design with no sharp edges that could catch on snow or ice.

R-use-1.1: The product can only go above the back support point if:

- The sides of the product run inwards at an angle of 30 degrees. (see figure 20)
- The front of the product follows the vertical axis of the back support with an angle of 30 degrees. (see figure 21)

R-use-1.2: The product cannot exceed the width of the current sitski.

R-use-2.1: The product should attach behind the abdominal belt and behind the fastening belt.

R-use-4: The product should be removable.

R-use-5: The mounting mechanism must not interfere with the operation of ski lifts.

W-use-2: The product should be as light as possible.

R-mp-5: The product must be impact-resistant and designed to prevent shattering upon collision.

R-mp-6: The product must incorporate an impact absorption mechanism to reduce damage and ensure safety in the event of a crash.

R-mp-7: The connection mechanism is vibration-resistant, ensuring secure attachment during use.

04

PRODUCT DEFINITION

4.1. Users and needs

4.2. List of requirements and wishes

4.3. Success indicators

4.4. Preliminary aerodynamic shape

4.5. Problem areas



This chapter forms the foundation for the design process. It translates insights from the contextual and user analysis into concrete requirements and success criteria. Furthermore, the preliminary aerodynamic shape is discussed and problem areas are defined.

4.1 USERS AND NEEDS

The product will be used by athletes and the coach. They will not use the product in training. The new shell component must not limit the athletes and the coach in any way. The athletes need a couple of factors to perform well (see Chapter 3.1.):

- Front-back balance: The new product's weight needs to be as close to the centre of mass as possible:
- Pressure in the ski.
- Point of support at the back: The new product should not cover the point of support at the back.
- The abdominal belt: The new product should not limit the functionality of the abdominal belt.
- Feeling of freedom of movement: The new product should not touch the athlete.

Next to the athletes, the coach also has his specific needs for the new shell component, as he will be the one attaching the component at the start. Important needs from the coach are:

- Durability: The material is handled very roughly in transport and use.
- Safety: The new product cannot endanger the athletes.
- Freedom of movement: The new product should not touch the athlete.
- Quick and easy connection: The new product should be detachable and connectable quickly to ensure focus stays on the race.

4.2 LIST OF REQUIREMENTS AND WISHES

Aerodynamic shaping

R-aero-1: The product must reduce aerodynamic drag compared to the current ski design, measured through CFD simulations and wind tunnel testing. (Chapter 2)

R-aero-2: The product must fit seamlessly with the current sitski with gap tolerances of $\leq 5\text{mm}$. (Chapter 2)

R-aero-3: The product must have a smooth, rounded design with no sharp edges that could catch on snow or ice. (Chapter 3)

Sitski usage

R-use-1: The product must allow a full range of motion for the athlete. (Chapter 2)

R-use-1.1: The product can only go above the back support point if: (Chapter 3)

- The sides of the product run inwards at an angle of 30 degrees. (see Figure 20)

- The front of the product follows the vertical axis of the back support with an angle of 30 degrees. (See Figure 21)

R-use-1.2 The product cannot exceed the width of the current sitski. (Chapter 3)

R-use-2: The product must not obstruct the fastening belt, brake screws, or abdominal belt, ensuring they remain fully functional and accessible without additional adjustments. (Chapter 2)

R-use-2.1: The product should attach behind the abdominal belt and behind the fastening belt. (Chapter 3)

R-use-3: Connecting and disconnecting the aerodynamic shell component requires no more than 1 standard tool. (Chapter 2)

R-use-4: The product should be removable. (Chapter 3)

R-use-5: The mounting mechanism must not interfere with the operation of ski lifts. (Chapter 3)

W-use-1: The product can be connected to the shell while wearing gloves (Chapter 2)

W-use-2: The product should touch the skier as little as possible. (Chapter 3)

Manufacturing

R-man-1: The product should be reproducible after the first production by either re-usage of a mould or using digital fabrication methods. (Chapter 2)

R-man-2: The product should be reproducible for a different athlete's ski. (Chapter 2)

Mechanical properties

R-mp-1: The product can withstand temperatures down to -20 degrees Celsius. (Chapter 2)

R-mp-2: The product can withstand exposure to moisture and salt without material degradation. (Chapter 2)

R-mp-3: The product must have a hydrophobic surface, preventing the formation of ice layers that could alter mechanical properties. (Chapter 2)

R-mp-4: The product is idiot-proof. It should have no plastic deformation during transport. (Chapter 2)

R-mp-5: The product must be impact-resistant and designed to prevent shattering upon collision. (Chapter 3)

R-mp-6: The product must incorporate an impact absorption mechanism to reduce damage and ensure safety in the event of a crash. (Chapter 3)

R-mp-7: The connection mechanism is vibration-resistant, ensuring secure attachment during use. (Chapter 3)

W-mp-1: The product has good abrasion resistance. (Chapter 2)

Next to the requirements, that the product must fulfil, a couple of important design elements were developed. The design elements are not specific requirements. They are either crucial design aspects or elements the product should strive to fulfil as much as possible.

Important design elements:

Safety: The new component should not endanger the athlete, bystanders, or the environment. (Chapter 2)

Durability & cost: There should be a balance between costs and durability to accommodate the athletes. (Chapter 2)

Manufacturing process: Manufacturing of the new component is quick and easy and fits the requirements. (Chapter 2)

Lightweight: The product should be as light as possible to minimally affect the front-back balance of the sitski. (Chapter 3)

Seamless fit: A seamless fit of the product with the existing sitski is necessary to ensure safety and aerodynamic properties. (Chapter 3)

Simple and aerodynamic connection: The connection mechanism should be quick and simple to keep the focus on the race. The connection mechanism should alter the aerodynamics as little as possible. (Chapter 3)

Secure connection: The product cannot loosen in the event of a crash to ensure the safety of the athlete and bystanders. (Chapter 3)

4.3 SUCCESS INDICATORS

This master's thesis can be considered a success if these success indicators are achieved:

- All defined requirements are fully satisfied or there is a plan to test the requirements during field testing in the snow.
- Aerodynamics is improved by at least 8%, achieving 80% of the original goal of 10% improvement, validated in the wind tunnel.
- Feedback from athlete and coach shows satisfaction with fit, usability and performance.
- Functional prototypes are ready to be field tested on snow for both ski designs at the end of April.

4.4 PRELIMINARY AERODYNAMIC SHAPE

The preliminary aerodynamic shape provided by Actiflow was designated as "design wings V2." For a comprehensive overview of the aerodynamic shaping process by Actiflow, see Appendix C. As seen in Figure 27, this design extends above the point of support at the back. The region behind the back of the athlete was identified to be the most promising area to improve aerodynamics. However, this creates a conflict with the freedom of movement needs of the athletes.



Figure 27: Design wings V2.

4.5 PROBLEM AREAS

According to the conclusions of the research phase combined with the preliminary design of the new shell component shared by Actiflow, the following problem areas were defined:

Aerodynamic shaping vs freedom of movement: Aerodynamic shaping achieves the most gain behind the athlete's back (see Appendix C). From a usage perspective, the new component should not restrict the athlete's freedom of movement. Thus, in forward movements during turns, a gap is created between the athlete and the shell component, reducing the aerodynamic performance of the design.

Strong connection vs easy connection: As mentioned in Chapter 3, the connection mechanism must be strong and secure to ensure safety, while also being quick and easy to use for desirability from the coach. This creates a design spectrum with safety and strength on one end and simplicity and efficiency on the other.

Safety design for a crash: In the event of a crash, the new component cannot endanger the athlete. The component must include a form of impact absorption to ensure the safety of the athlete.

05

PRE-FINAL SHAPE IDEATION

With the preliminary design of wings v2 in mind, the first problem areas were defined, and the first ideation was performed, not taking physical limitations into account. This ideation process was performed in a short amount of time and interrupted by a new design of the shell component and wind tunnel validation, as explained in Chapter 6.

Designing for aerodynamics and a general motion of connection seemed the most pressing issues, as these influence the aerodynamic shaping the most.

For these first ideas, a brainstorming session was used to get preliminary ideas out on paper. Figure 28 shows an overview of these first ideas. This first ideation provided good insight into the complexity of trying to solve the first problem area. The difficulties in trying to solve this problem area and research findings were communicated with Actiflow in a progress meeting. This led to new designs that better fit the context and user needs, eliminating the first problem area.

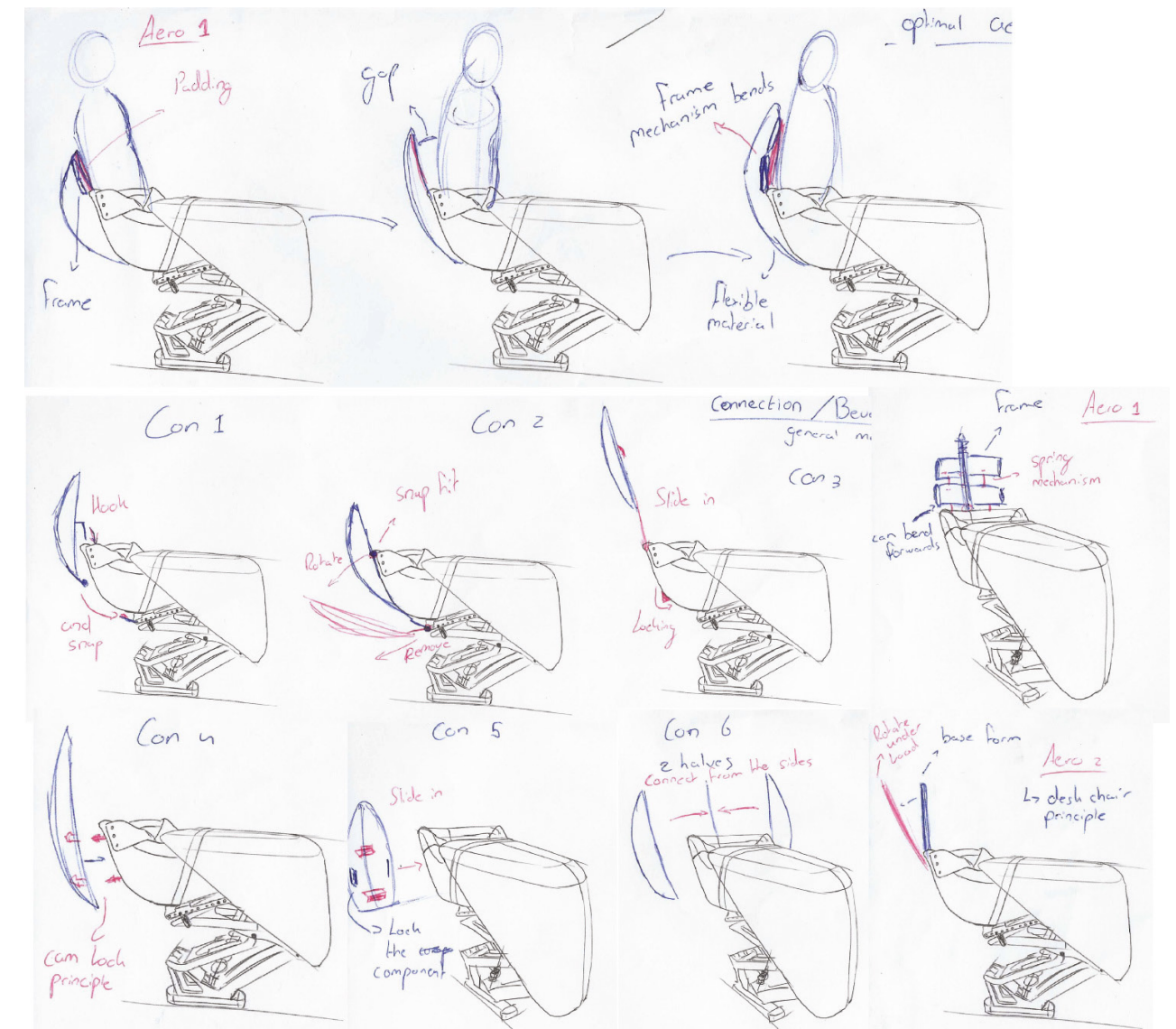
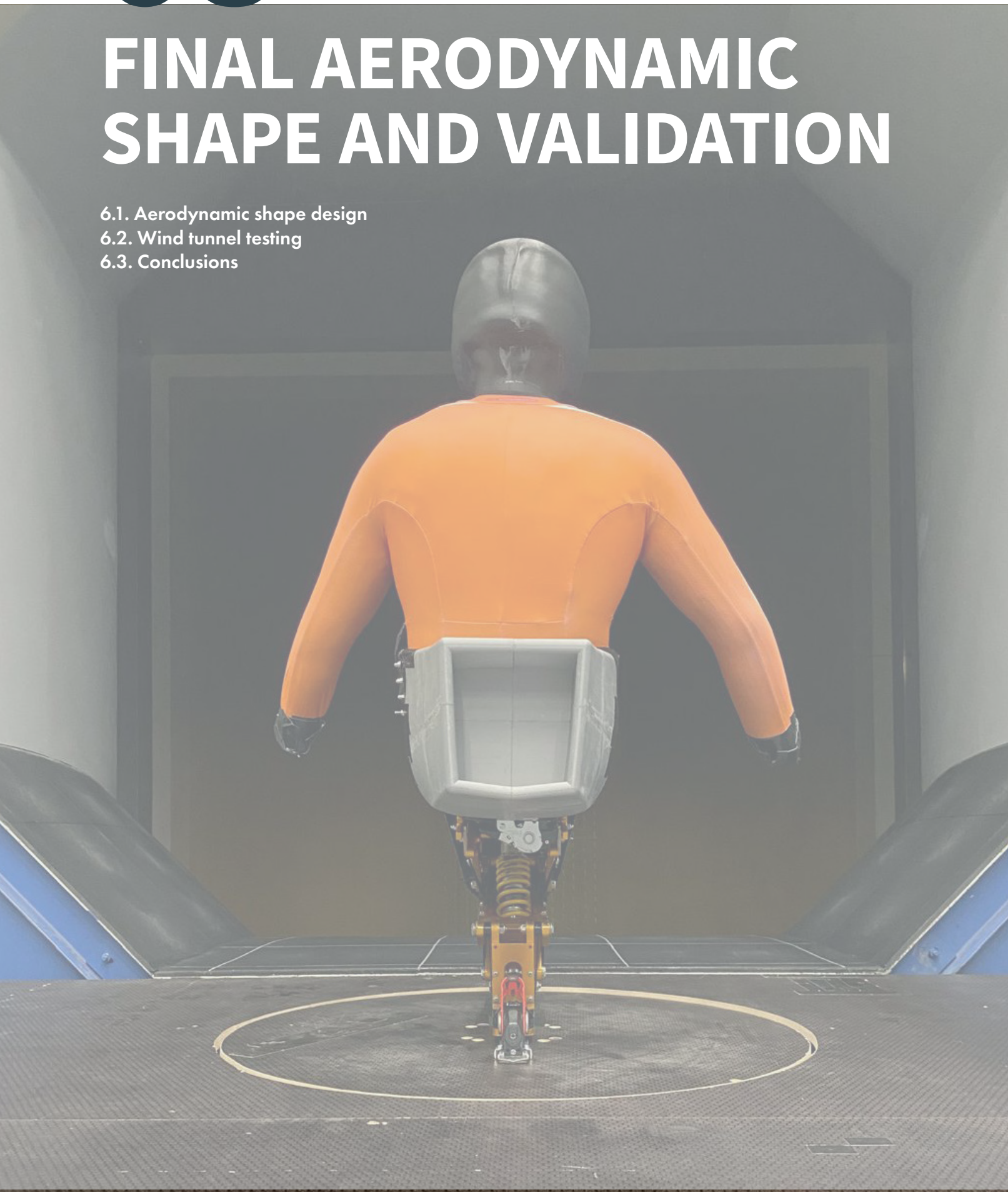


Figure 28: First ideation outcomes.

06

FINAL AERODYNAMIC SHAPE AND VALIDATION

- 6.1. Aerodynamic shape design
- 6.2. Wind tunnel testing
- 6.3. Conclusions



This chapter summarizes the final designs provided by Actiflow, followed by the process of validating the design in the wind tunnel and concludes with a final aerodynamic shape design. For the full process of creating and validating designs, see Appendices C and D.

6.1 AERODYNAMIC SHAPE DESIGNS

The design process for aerodynamic shaping was finalized taking feedback from the project team into account. Figure 29 presents the final designs. Designs 2.0 and 3.0 were tested with Computer Fluid Dynamics (CFD) simulations. Design 2.0 shows promising results with an aerodynamic improvement of around 10% without crosswinds. Design 3.0 seemed to taper inwards too aggressively, losing air flow and aerodynamic performances. The project team decided to produce designs 2.0 and 2.5 for the wind tunnel testing and validation.

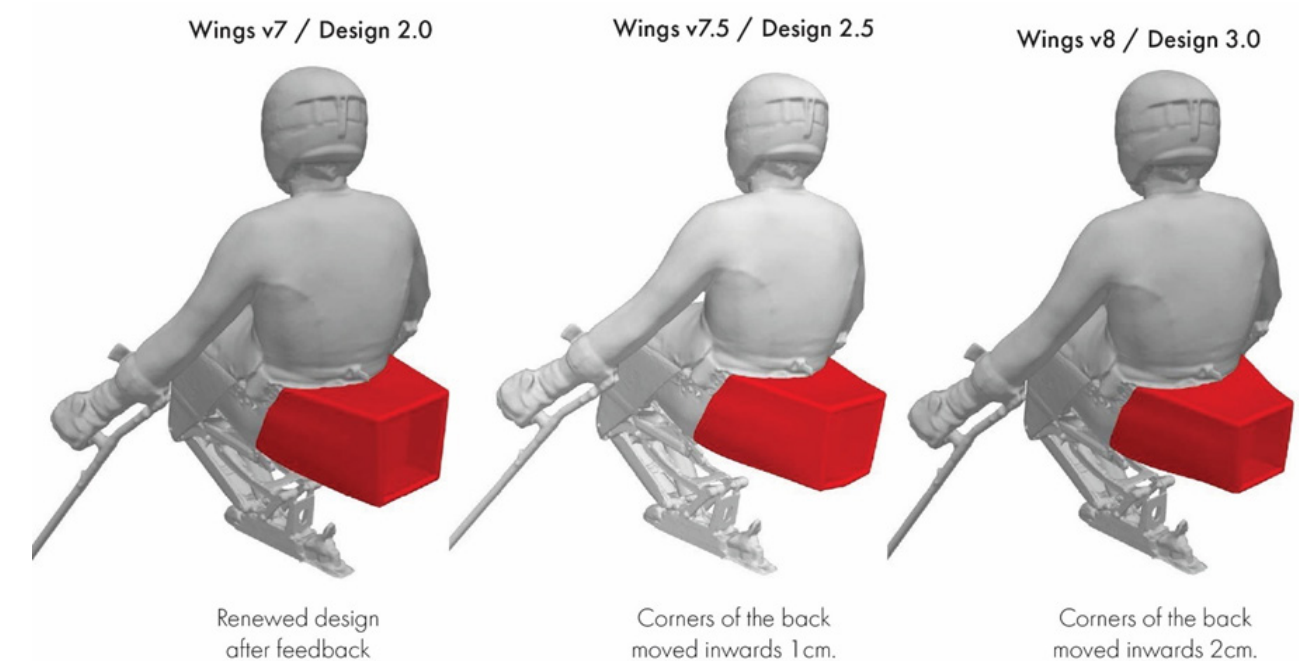


Figure 29: Final aerodynamic shape designs.

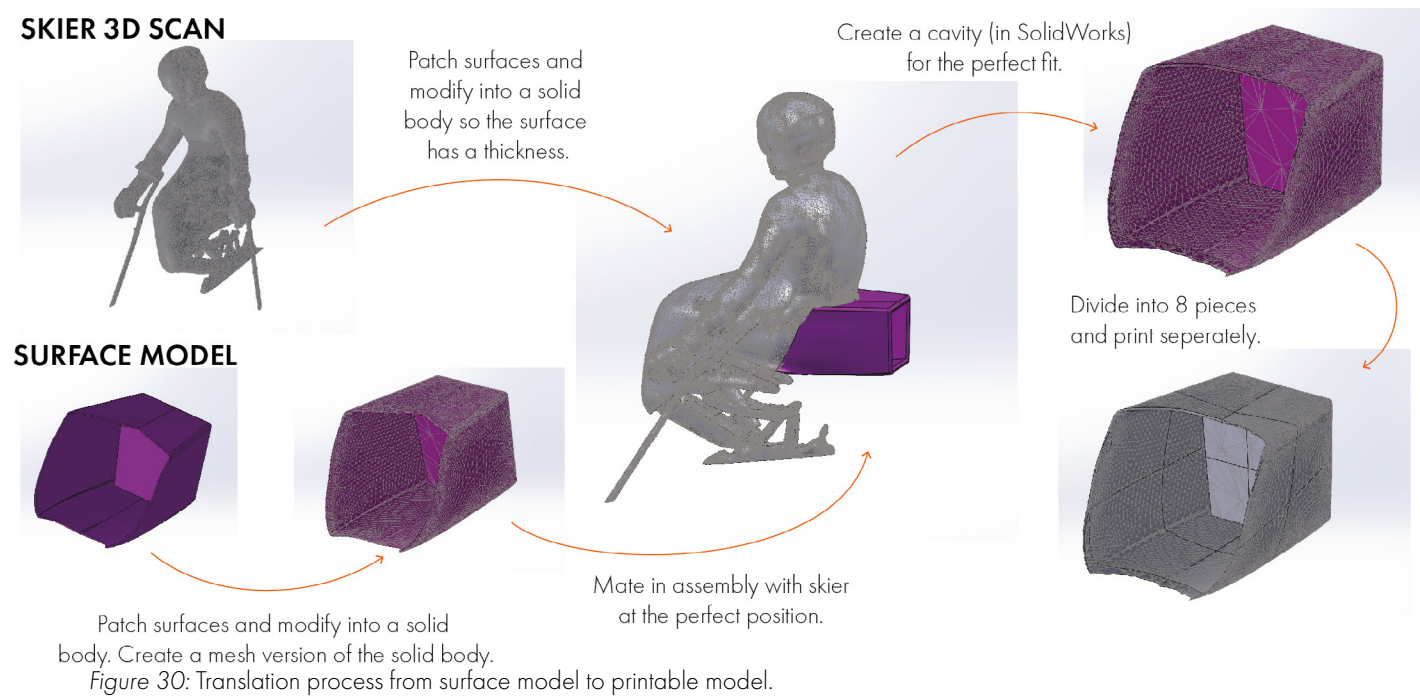
6.2 WIND TUNNEL TESTING

To test the designs in a wind tunnel, prototypes were developed using the 3D scans and surface models delivered by Actiflow. These prototypes were placed in a test setup using the athlete's ski and tested with multiple variations in the Open Jet Facility TU Delft.

6.2.1 PROTOTYPE DESIGN

The athletes anticipate they will not notice significant improvements from the new aerodynamic component in their experience during skiing. However, they have identified several elements that are particularly important to their experience and expectations of the new component.

Actiflow delivered the designs of the shell components as a surface model without the perfect fit on the current ski. To 3D print this component and to have it fit properly on the current ski, a couple of modifications had to be made. A surface model exists of surfaces with 0 thickness. To print such a volume, these walls need to have a thickness. Figure 30 shows the process of translating the surface model to a 3D printable model. The shell component was printed in 8 separate components, due to the print size, using standard PLA print filament. After printing, the components were glued together and sanded for a nice finish.



6.2.2 TEST SETUP

In the wind tunnel, the ski has been mounted into a ski binding, which was mounted to a turntable. The mannequin was wearing a competition suit (without hands) and was placed in the ski. The foam abdominal part and the aerodynamic frame cover from the prior aerodynamic optimisation project (see Chapter 2.3) were added to the setup. The designs of the new shell components were mounted to the ski using duct tape. It is important to note that the right side of the design did not properly connect to the ski because the design was made symmetrical. The ski was pressed down and locked with a tensioning strap to simulate the impact of the weight of the athlete on the shock absorber. Figure 31 below shows the setup of the model with design 2.5 connected to the ski.

After testing both design 2.0 and design 2.5, a couple of variations were tested to see their effect on the aerodynamics, as seen in Figure 32:

- Filling the square cavity of the designs.
- Improving the connection with the front cover using duct tape.
- Making the edges of the designs sharp using clay.

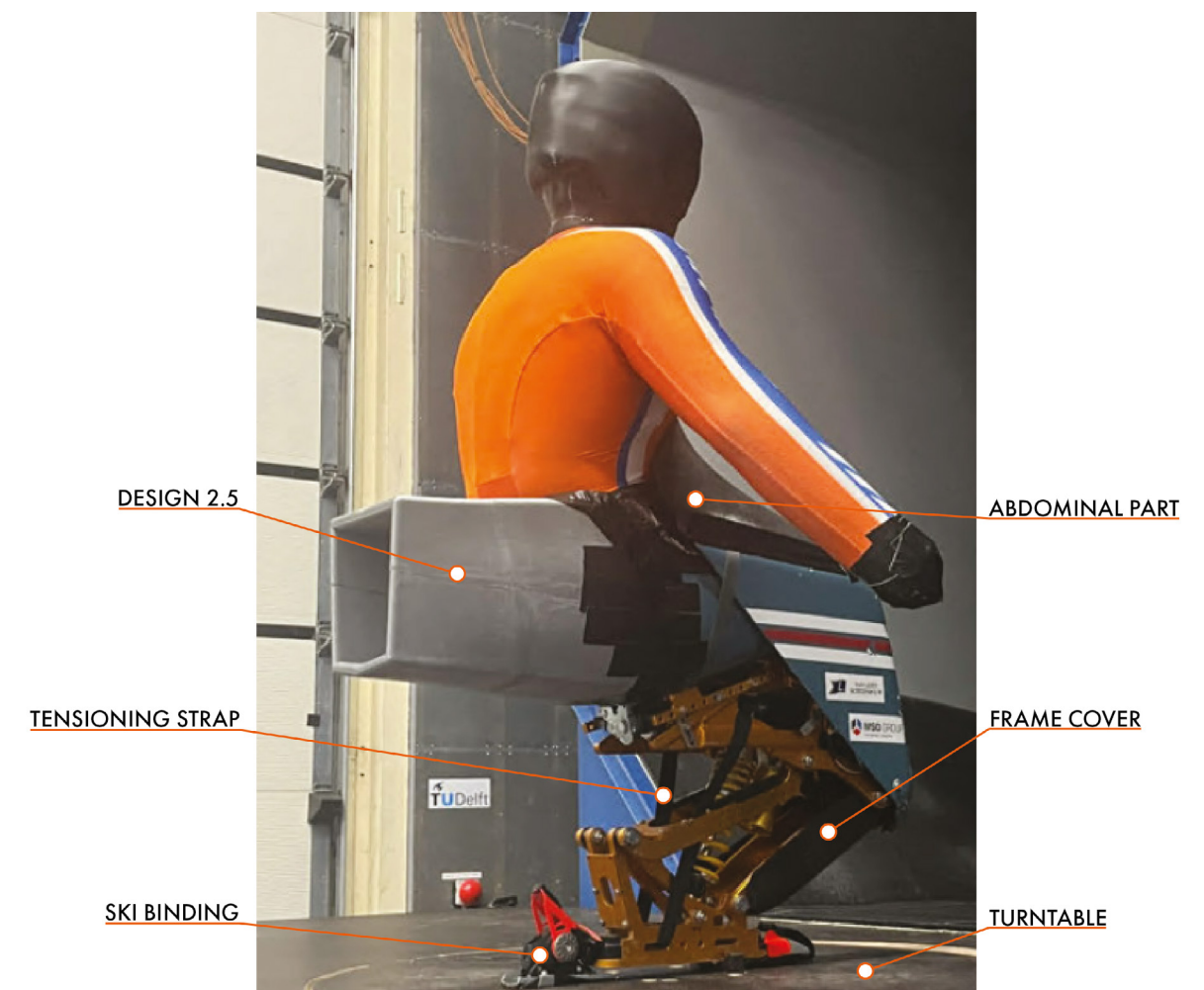


Figure 31: Wind tunnel setup.

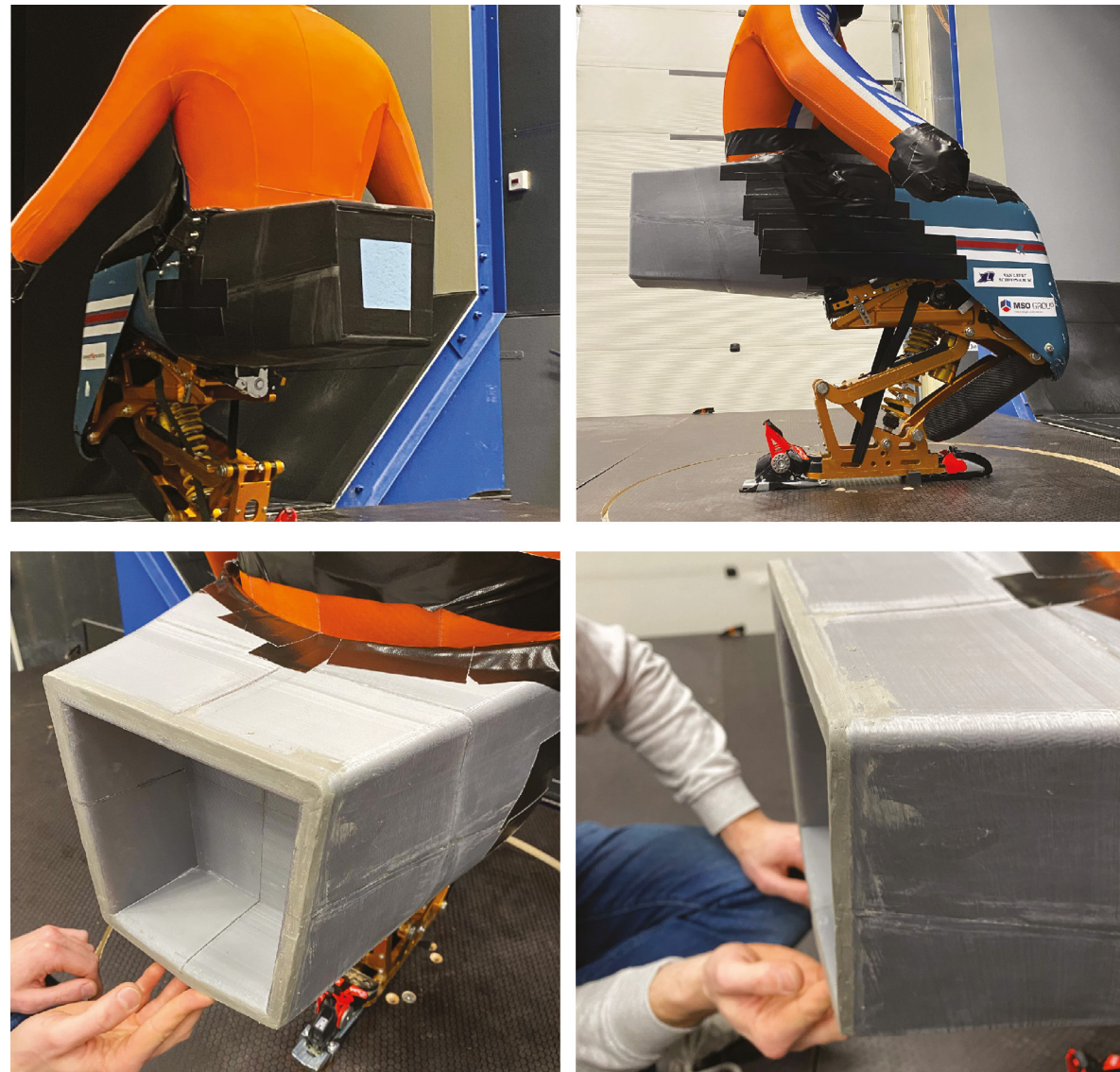


Figure 32: Wind tunnel variations.

6.3 CONCLUSIONS

For the full setup and results of the wind tunnel testing see Appendix D. This subchapter describes the conclusions drawn based on these test results.

Both designs show a decrease in aerodynamic drag of around 8%. At side winds, this improvement decreases to around 5% (yaw = 10 degrees) and 2% (yaw = 20 degrees). The lateral force slightly decreases with the new components. The moment around the vertical axis slightly increases.

Both designs perform relatively the same, with design 2.5 performing slightly better at higher speeds. Filling the square cavity at the back has no significant effect on aerodynamics. Both an improved connection to the front cover and sharper edges show a decrease of aerodynamic drag of about 0.5%.

This shows the new components function properly even without the perfect fit. Taking the safety aspects in case of a crash into account, design 2.5 has a lower risk of grabbing the snow with the back, due to the edges tapering in more at this design, as seen in Figure 33. Based on this combined with the slightly better results, the team has chosen to continue production with design 2.5.

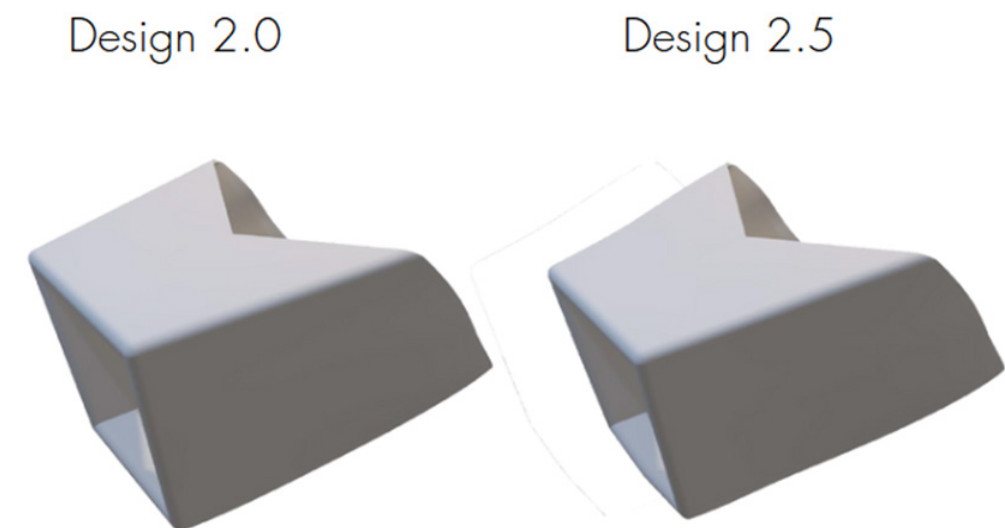


Figure 33: Design 2.0 and 2.5 side by side.

07

DESIGNING THE
AERODYNAMIC SHELL

7.1. Design areas

7.2. Additional manufacturing research

7.3. Ideation

7.4. Product concepts

7.5. Concept choice



This chapter describes the process of designing the aerodynamic shell component. It starts with revised design areas, followed by the ideation process. Some additional manufacturing research was performed to design product concepts and make a well-balanced choice.

7.1 DESIGN AREAS

To translate aerodynamic design 2.5 into a product, a few design areas were defined to create ideas for the final concepts considering prior research and requirements. These design areas are shape creation and a connection mechanism.

Shape creation

Shape creation indicates the translation from the aerodynamic shape into a real product. To achieve a shape-creation method that suits the usage of the product the following aspects are crucial:

Safety aspect: As requirement 5 of the mechanical properties state, the product should have a form of an impact absorption mechanism for safety purposes.

Aerodynamic sealing: To ensure that the aerodynamic purposes are fulfilled, some concepts will need a form of aerodynamic sealing to guide the wind along the shape.

Material usage and production technique: As this product is a highly personal product it is important to have a fitting production technique. Furthermore, selecting the right material plays a crucial role in fulfilling the mechanical property requirements.

Connection mechanism

This design area focuses on a couple of aspects to be able to add the newly created shape to the existing ski. These aspects are:

General handling: To start the design of a connection mechanism the general handling of the component and attachment needs to be defined. The general handling refers to the movement necessary to link the shell component and ski together. The shape of the product plays a crucial role in this decision-making.

Seamless connection: To ensure aerodynamic properties and ensure the product does not grab snow in the event of a crash, a seamless connection needs to be designed.

Specific types of connection: An overview of possible fasteners is necessary to connect the final product to the existing ski.

7.2 ADDITIONAL MANUFACTURING RESEARCH

Research by Nesheim et al. (2024) shows that using 3D-scanning, with generative design and 3D printing this design is a good method for quickly creating high-end user-specialized equipment. Combining the scanned data with the CAD model from the aerodynamic simulations sets a good basis for using 3D-printing for the final product.

Research by Conner et al. (2014) shows that 3D-printing is a suitable production solution for products with low volumes, high complexity and customization. This process fits the production of the current product, as it is complex and highly personal with a very low production volume. A perfect combination of the use of 3D-printing with energy absorption and lightweight volumes are lattice structures. Lattice structures reduce weight, and by varying densities, they can be used to create different stiffnesses in one object. (Shields, 2023)

Multiple pieces of research highlight the energy absorption qualities and customisation possibilities with 3D-printing lattice structures. On top of that, they highlight the lightweight property this lattice adds to the product. (Helou & Kara, 2017) (Hou et al., 2017) (Sun et al., 2021)

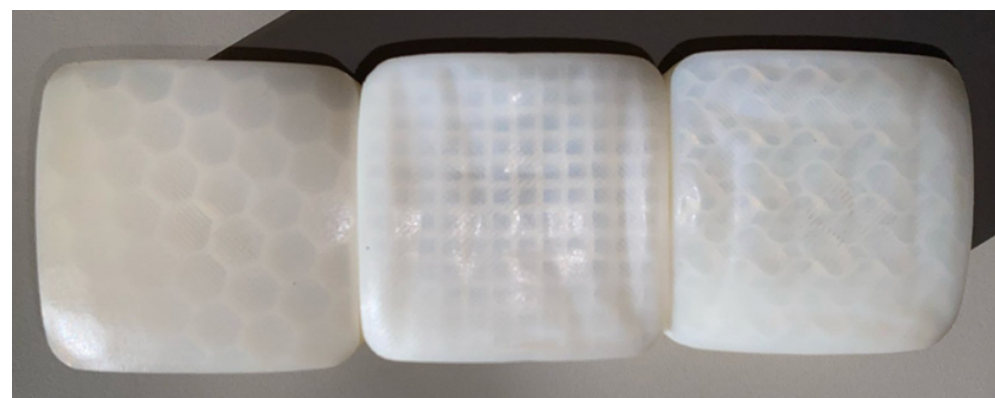


Figure 34: Hexagonal, 3D hexagon and gyroid infill TPE prints.

Using a flexible material to 3D-print lattice structures would make this a suitable solution for the current design challenges. There are two types of elastic filaments: TPE and TPU. TPU has a superior resistance to low temperatures and a good abrasion resistance, both qualities necessary for the final product, making it the most suitable flexible filament to use (Kent Elastomer, 2023). TPU is also hydrophobic, making it compatible with the snow environment (Francesco, 2022).

To test the possible use of a lattice structure and variation in elasticity, multiple test objects were printed using a TPE filament with a hexagon, 3D hexagon and a gyroid infill (Figure 34). The test prints showed potential for using this principle for the final product, with the gyroid infill creating the most universal stability and flexibility in all possible directions.

7.3 IDEATION

Handling the printed model in the wind tunnel eliminated a lot of options for the general handling of the component. Based on the shape and attachment point of the new product, only connecting the new component straight from the back was suitable. Figure 35 indicates the necessary motion with an arrow.

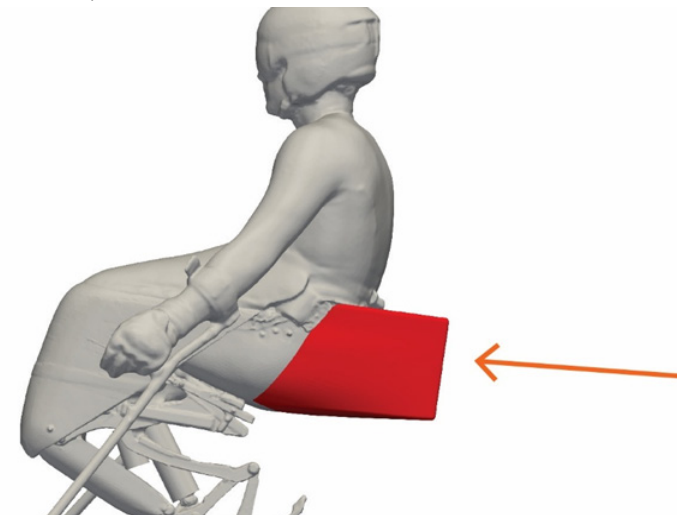


Figure 35: General handling of the component.

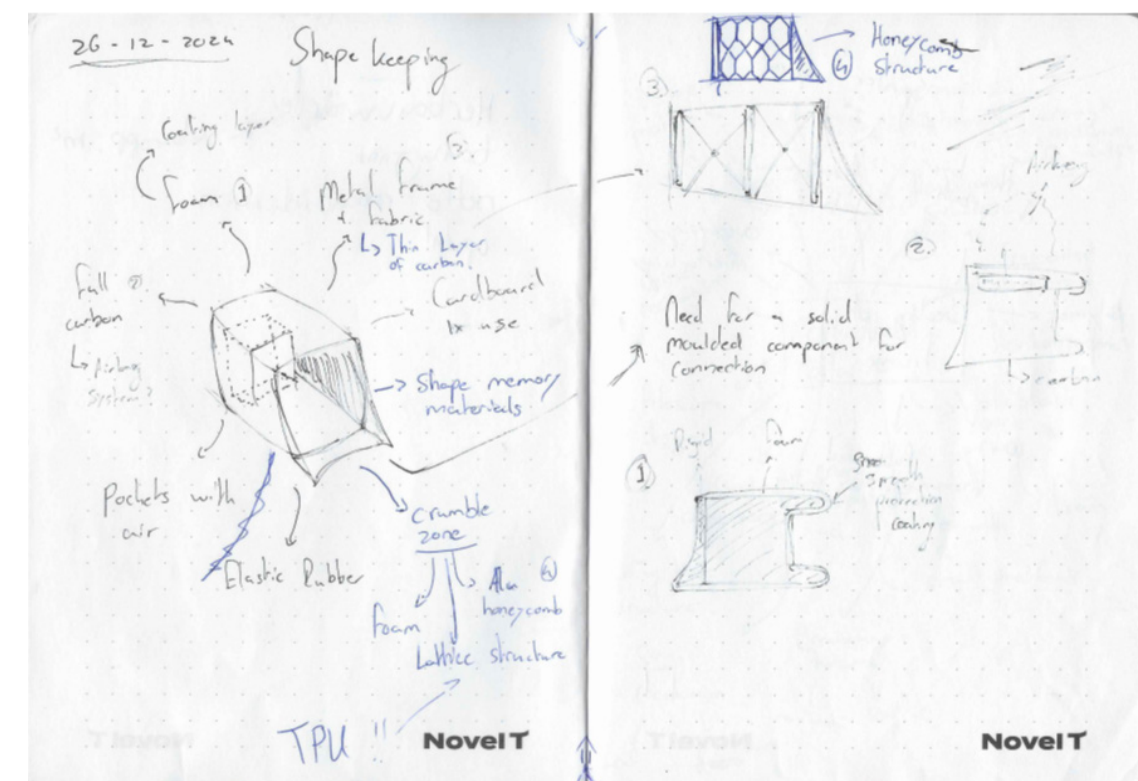


Figure 36: Shape creation ideation.

A combination of brainstorming, how-tos, mindmaps and desk research for existing solutions were used to generate ideas regarding the design areas (Van Boeijen et al., 2013). Figure 36 shows part of the shape creation design ideation and Figure 37 shows part of the seamless connection ideation. A full overview of all ideas generated can be seen in Appendix E.

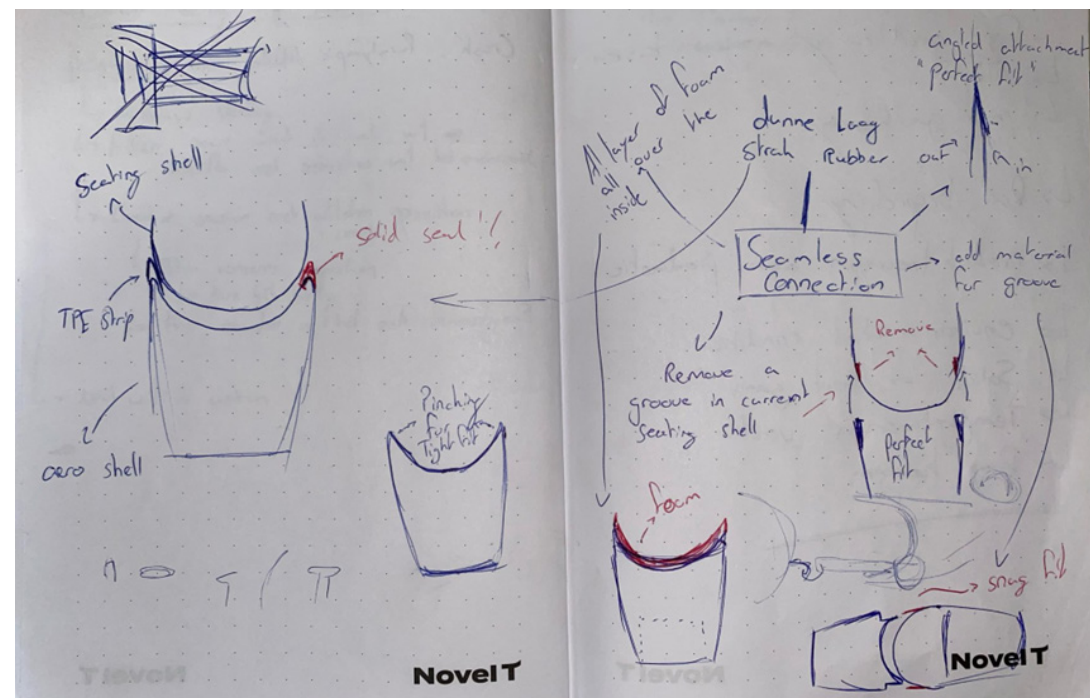


Figure 37: Seamless connection ideation.

These ideas for sub-areas were combined into concepts using a morphological chart method (Figure 38). (Van Boeijen et al., 2013)

In the morphological chart, routes were picked based on familiarity and durability (Blue), safety and weight (Green), and production method fitting the use of the CAD model (Orange).

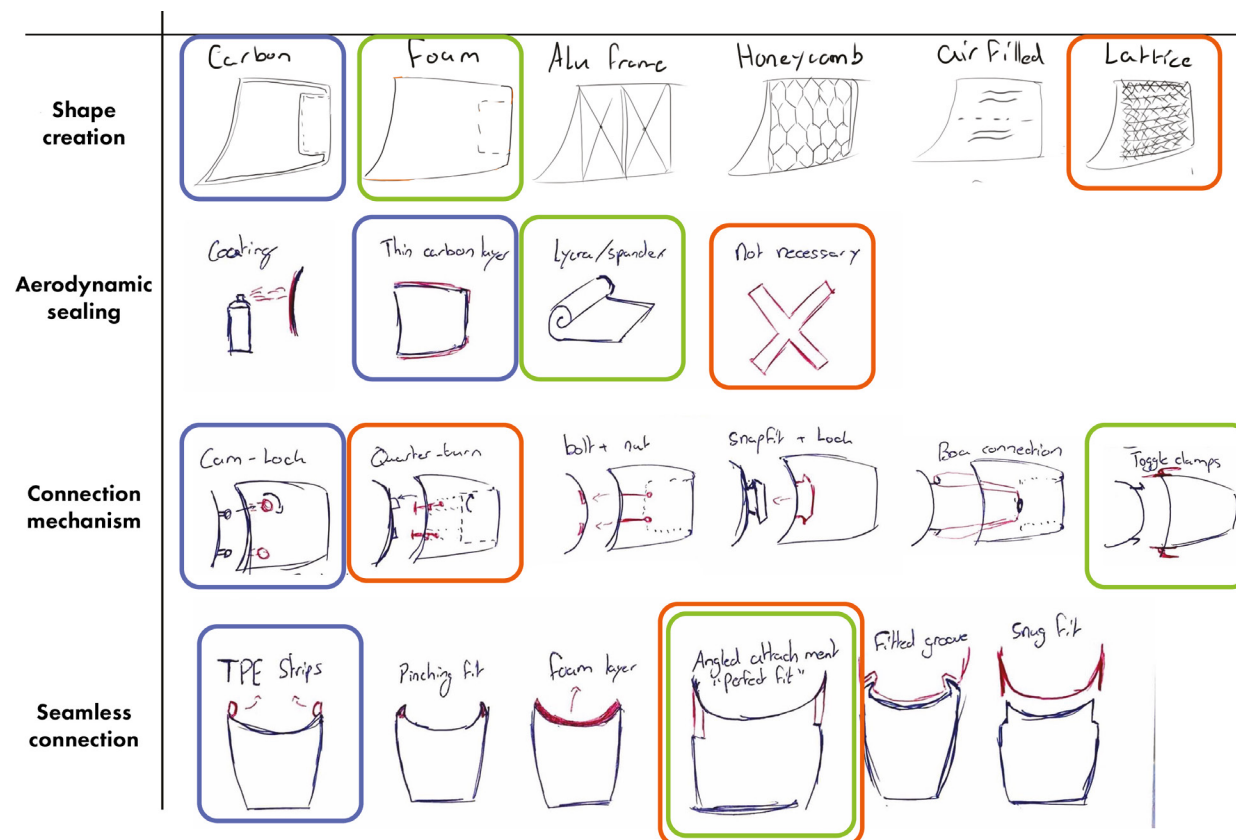


Figure 38: Morphologic chart.

7.4 PRODUCT CONCEPTS

The familiarity and durability route led to concept 1 (Figure 39). The concept makes use of a full Carbon fibre and Kevlar component, materials the manufacturer is very familiar with. Custom elastic strips are added to the front, to ensure a seamless fit and dampen the contact

between the ski and the new shell component. The connection mechanism used in this design is that of a F1 front wing: a CAM-Lock mechanism which can be turned from the top and bottom to keep the sides of the shell aerodynamically clean (Bhatnagar, 2016).

Concept 1: Carbon

Full carbon fiber shell produced with molds. Elastic strips on the sides for a seamless fit. Camlock attachments. No real safety mechanism included.

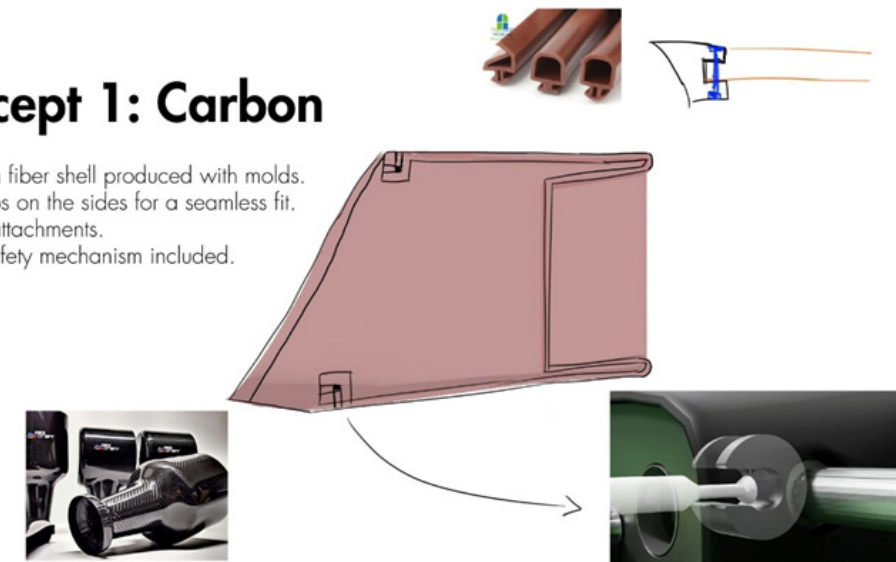


Figure 39: Concept 1.

The production method fitting the use of the CAD model route led to concept 2 (Figure 40). The concept is fully produced by 3D printing TPU. TPU is an elastic plastic that stays elastic in cold temperatures.

To tighten the fit between the ski and the new shell component, easy quarter-turn fasteners are applied that can be handled from the square cavity at the rear. The concept makes use of a lattice structure to absorb energy in case of an impact.

Concept 2: 3D print

3D printed TPU, single material. Automatic elastic seamless fit. Easy quarter-turn fasteners. Lattice structure for energy absorption.

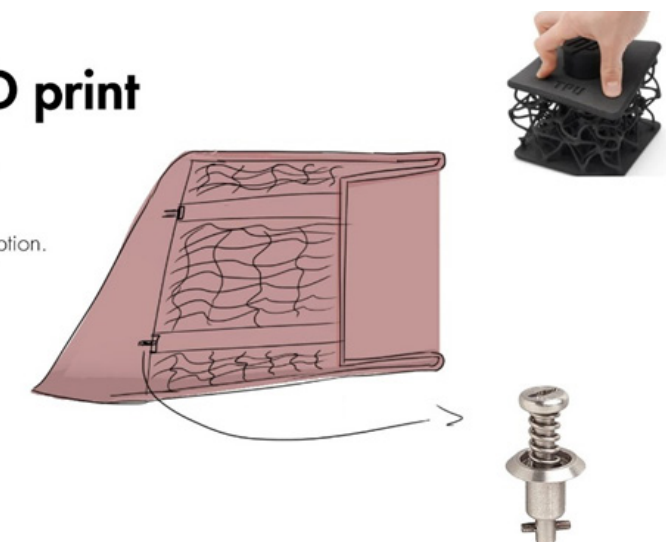


Figure 40: Concept 2.

The safety and lightweight route led to concept 3 (Figure 41). The concept is produced with flexible, cold-resistant foam enclosed in spandex/lycra, functioning as an aerodynamic sealing. The foam, together with a valve, functions as the energy absorption mechanism.

Concept 3: Foam

Flexible, cold resistant foam enclosed in spandex/lycra.
TPU printed base for elastic seamless fit.
Tension latch fasteners.
Foam with valve for energy absorption.

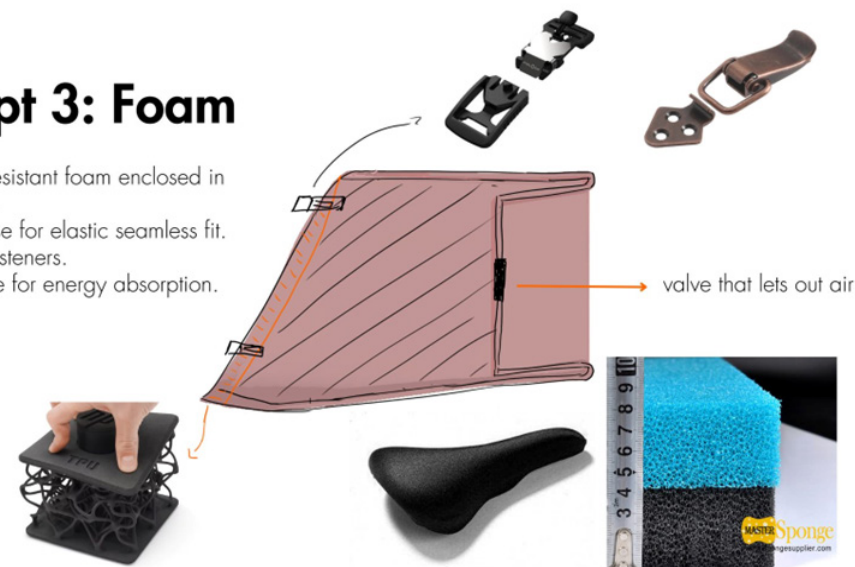


Figure 41: Concept 3.

7.5 CONCEPT CHOICE

The concepts were evaluated based on the eight important design elements (see Chapter 4.2) derived from Chapters 2 and 3 to identify the most promising concept and specific concept elements.

Safety: The new component should not endanger the athlete, bystanders, or the environment.

Durability & cost: There should be a balance between costs and durability to accommodate the athletes.

Manufacturing process: Manufacturing of the new component is quick and easy and fits the requirements.

To ensure a seamless fit with the existing ski and strengthen the point of connection, a 3D-printed TPU base is attached to the current ski. The product is connected using tension latch fasteners at the sides of the shell.

Lightweight: The product should be as light as possible to minimally affect the front-back balance of the sitski.

Seamless fit: A seamless fit of the product with the existing sitski is necessary to ensure safety and aerodynamic properties.

Simple and aerodynamic connection: The connection mechanism should be quick and simple to keep the focus on the race. The connection mechanism should alter the aerodynamics as little as possible.

Secure connection: The product cannot loosen in the event of a crash to ensure the safety of the athlete and bystanders.

A weighted objectives method is used to compare the concepts (Van Boeijen et al., 2013). This method was chosen because the overall score will represent the most promising concept and each specific criterion is evaluated separately, allowing for a possible combination of concepts after the concept choice. The weight of the criteria and scores for each concept were given in coordination with the manufacturer to benefit from his expertise. The coach and athletes were not available during this time of the project, due to a busy schedule of races. The insights were later shared with the coach and Athletes and they agreed with the results.

Based on the FIS regulations and the needs of athletes and the coach, safety and durability were prioritized most highly. Lightweight and seamless fit ranked next in importance as they heavily influence the skiing experience and aerodynamic performance. These criteria were followed by cost and secure connection as the project has a limited budget and the product cannot loosen for safety reasons. Finally, the manufacturing process and a simple and aerodynamic connection were ranked last as this influences the performance the lowest.

The weighted objectives method shows that the 3D-printed component is the most suitable solution for the new product (Figure 42).

The weighted objectives method shows concept 2 strikes a balance between safety, durability and lightweight compared to concepts 1 and 3. Furthermore, the manufacturing process perfectly fits the digital modelling performed in prior Chapters. Furthermore, the connection mechanism is rated similar to concept 1. For the development of the concept, it is useful to explore multiple specific fasteners but keep the connection points in the cavity.

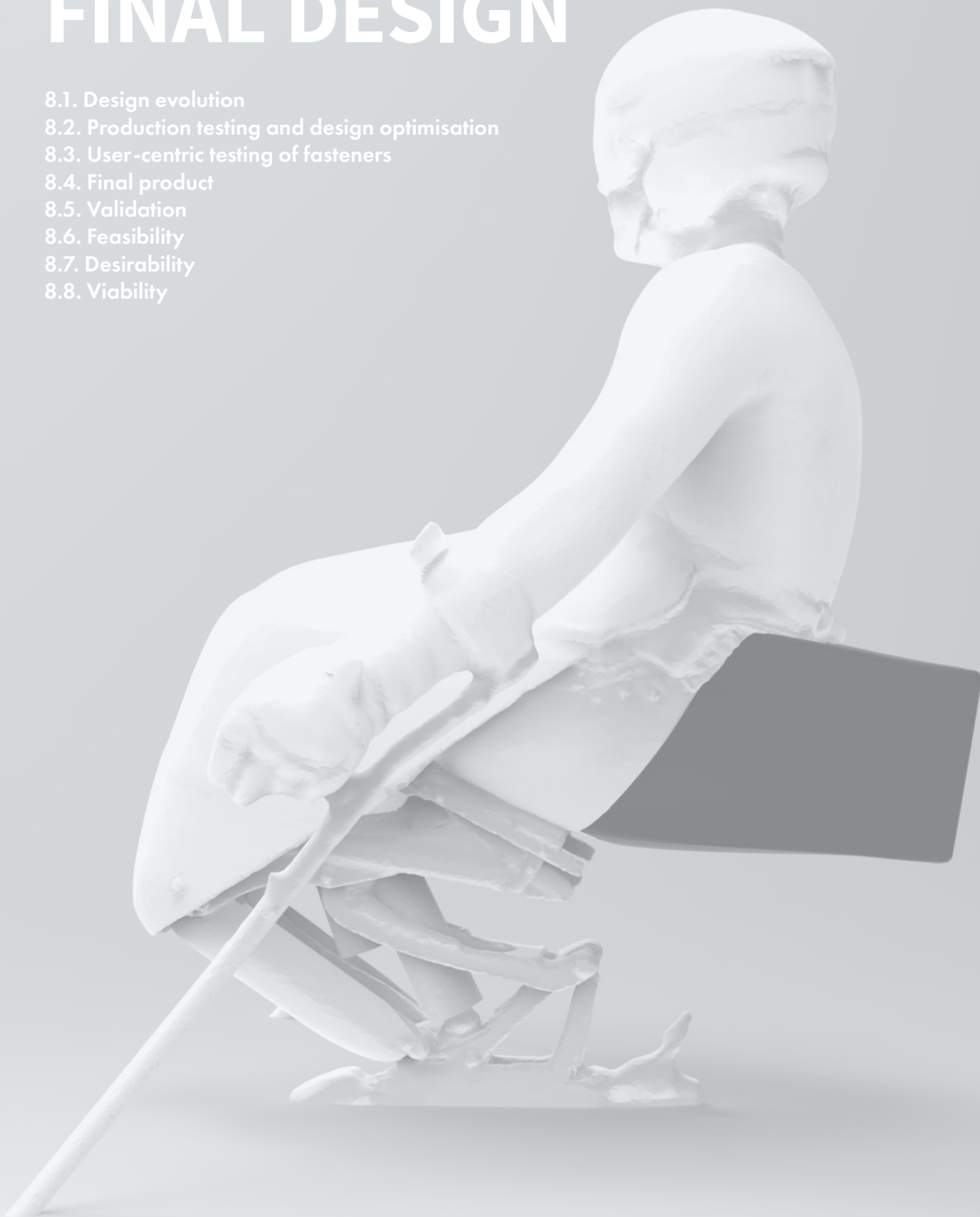
		Carbon Fibre		3D Print		Foam	
Criteria	Weight	Score	Weighted score	Score	Weighted score	Score	Weighted score
Safety	20	5	100	7	140	9	180
Durability	18	8.5	153	7	126	5	90
Cost	10	4	40	8	80	6	60
Manufacturing	8	5	40	10	80	7	56
Lightweight	14	5	70	7	98	9	126
Seamless fit	12	6	72	9	108	8	96
Simple+aero connection	8	8	64	9	72	5	40
Secure connection	10	9	90	8	80	6	60
Total score	100		629		784		708

Figure 42: Weighted objectives method.

08

FINAL DESIGN

- 8.1. Design evolution
- 8.2. Production testing and design optimisation
- 8.3. User-centric testing of fasteners
- 8.4. Final product
- 8.5. Validation
- 8.6. Feasibility
- 8.7. Desirability
- 8.8. Viability



This chapter describes the process of development from concept to final product. It starts with a design evolution to an improved product proposal, followed by testing production and fastening mechanisms. The chapter ends with a final product, which will be validated on the product requirements, feasibility, desirability, and viability.

8.1 DESIGN EVOLUTION

This subchapter shows the development from concept to proposed design before testing.

8.1.1 INITIAL CONCEPT

Based on the weighted objectives method, concept two seemed the most promising concept, see Figure 40 for a recap of this concept. It will be a 3D-printed TPU component, using lattice structures to strategically grant flexibility to the aerodynamic shell for impact absorption. It will be tightened from the back through the cavity using quarter-turn fasteners. Figure 43 shows the delivered 3D model of Actiflow that needs to be adjusted to fit the needs of 3D printing.

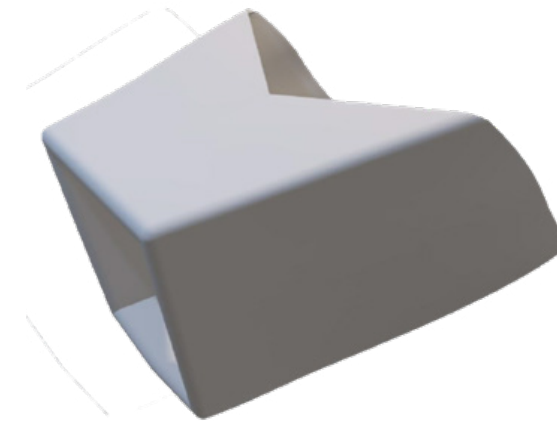


Figure 43: The 3D model of the shell component.

8.1.2 KEY ITERATIONS

This subchapter shows the key iterations in the design of the mounting mechanism and shell component.

8.1.2.1 Mounting mechanism

Since the current ski has a curved rear surface, a mounting plate was added to provide a flat interface that allows for a straight connection of the new shell component to the current ski. To ensure that the shell component is securely connected to the mounting plate and is fixed in all dimensions, three connection points were chosen instead of 1 or 2 connection points. Using three connection points is sufficient for functionality and reduces the amount of handling required to attach the component, compared to 4 connection points, making the process more feasible for the end users. The connections are placed as close to the edge as possible to fix the shell component as much as possible, as shown in Figure 44.

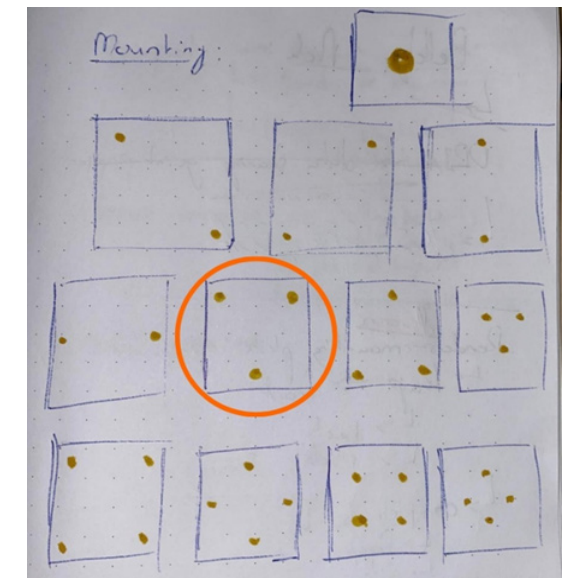


Figure 44: Possible connection points.

Figure 45 shows two schematic overviews of potential fastening methods using the rear cavity. To reduce the component's weight and enable multiple types of fasteners, the top sketch was selected for initial production, as this approach removes more material from the cavity. It also ensures a thinner fastening wall thickness for fastening and improved accessibility of the fasteners. If the design proves to lack sufficient stiffness, the bottom sketch will be adopted

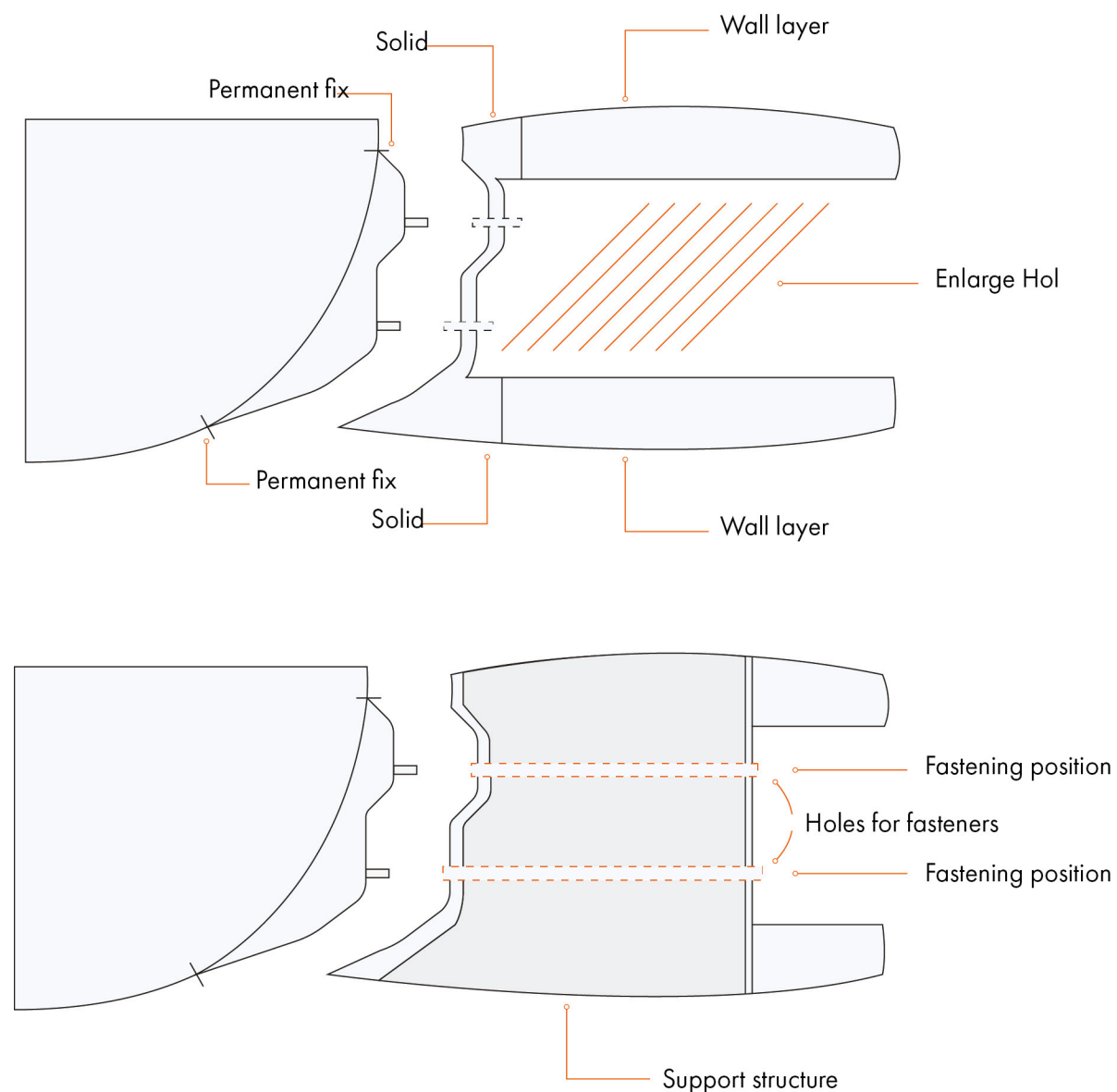


Figure 45: Possible connection solutions

Figure 46 shows the initial design of the shape of the mounting plate on the left, which was used to create the mounting cavity in the shell component. It also shows an improved version with connection areas on the right. The right version is scaled down to create some tolerance between the mounting plate and the shell component. This mounting plate has slots for sliding in and replacing square nuts.

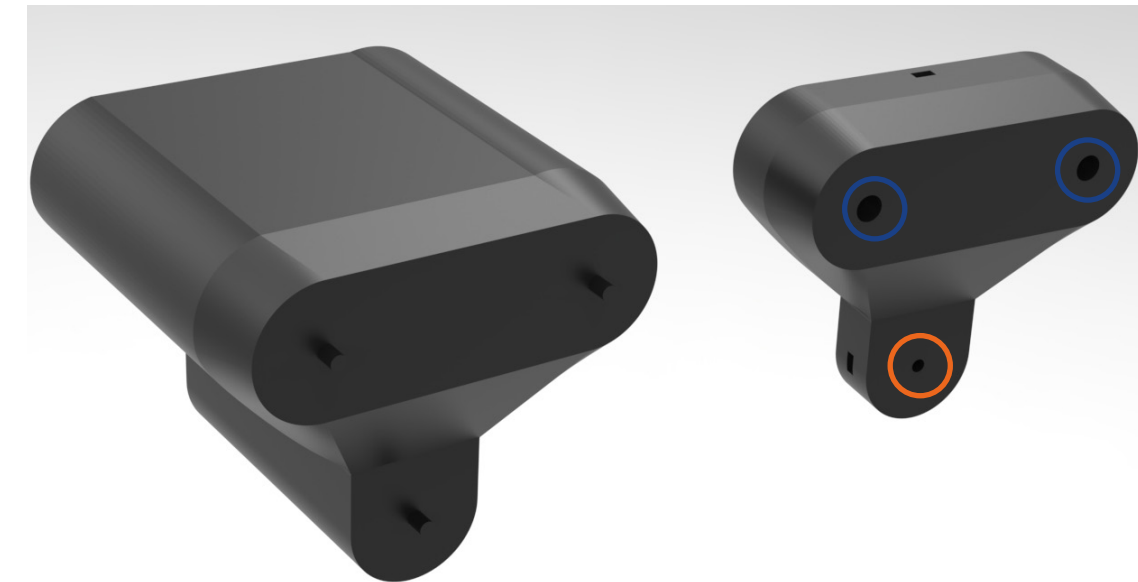


Figure 46: The base shape of the mounting plate (left) and an improved version with fasteners (right).

To enable the production of this mounting plate with 3D-printed TPU, several prototypes were created. First, the tolerances had to be checked for the fitting between the mounting plate and shell component and the fitting of receptors for the fastening systems.

Both tolerance prints were successful. Additionally, the size of the slot for the square nut needed to be tested. The print was successful without the use of support material. These prototypes are shown in Figure 47.

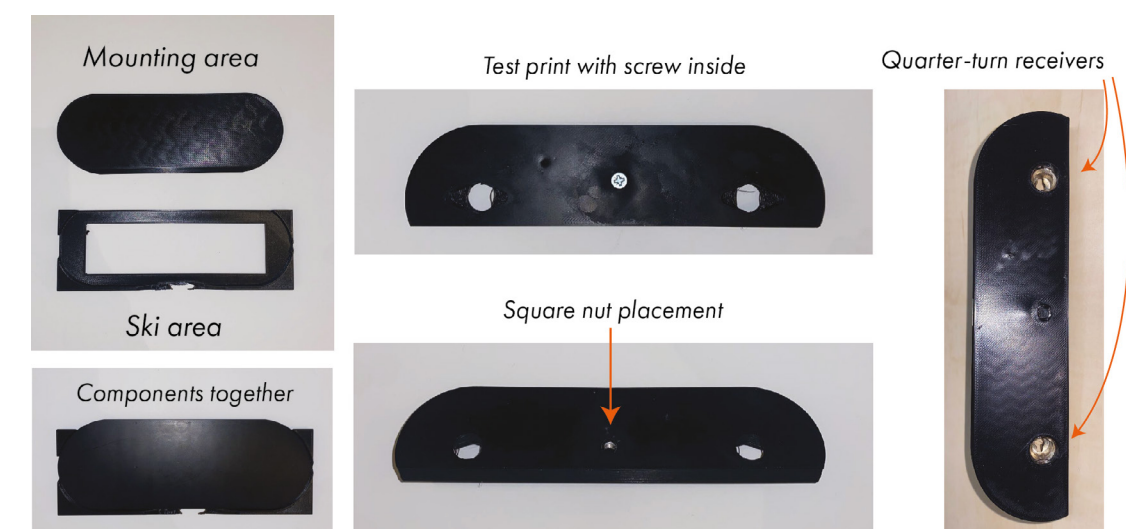


Figure 47: Tolerance test prints for mounting plate and shell component (left) and fastening receivers (right).

After testing for tolerances and printability of the square nut slots, the full mounting plate for fastening testing was printed in an upright position.

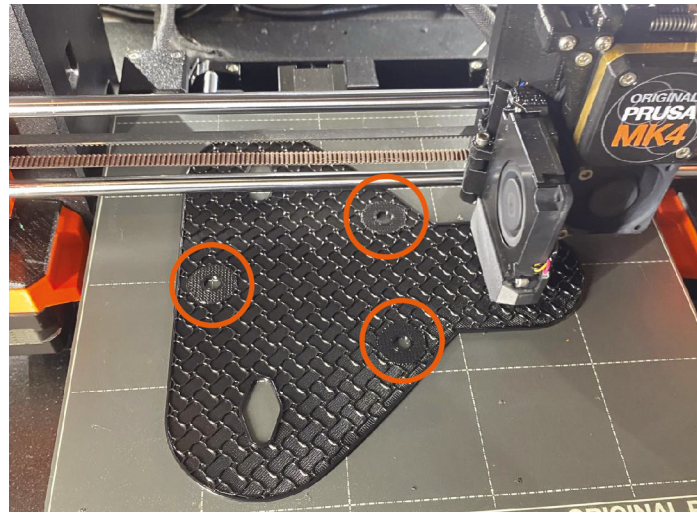
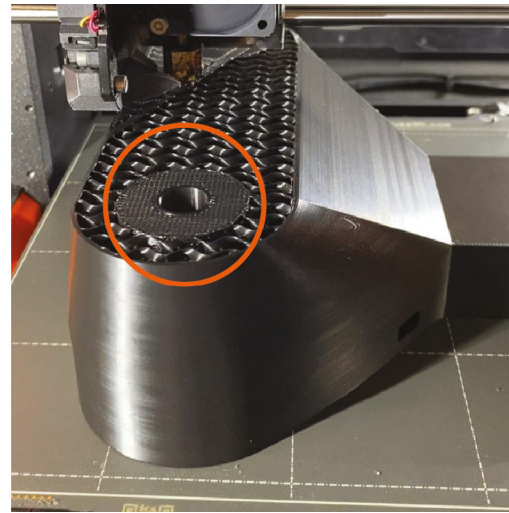


Figure 48: Printing mounting base with connection for wall (left) and strengthened connection area (right).

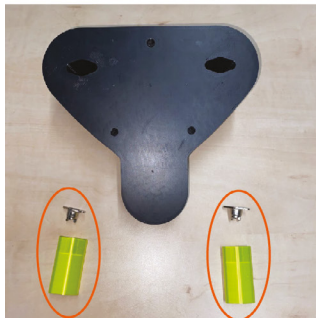
To finish the mounting plate, the receiving connectors were added and fixed into place. The quarter-turn fasteners were secured using a yellow printed part.

The print had strategically placed higher infill percentages for increased strength around connections. Figure 48 shows the print with the higher infill areas circled.



The square nuts were slid into place and secured driving screws into the TPU. Figure 49 shows the process of locking the fasteners into place.

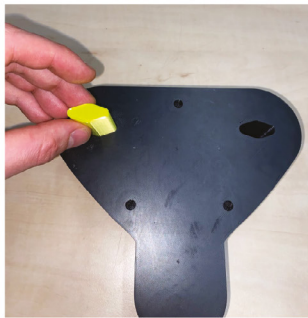
Place quarter-turn receivers in placeholders



Place components in designated area



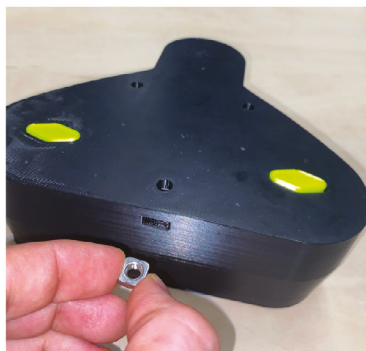
Repeat placement



Final result



Slide square nut into designated slots



Repeat the process with the other square nuts and slots



Lock the square nuts in place with screws



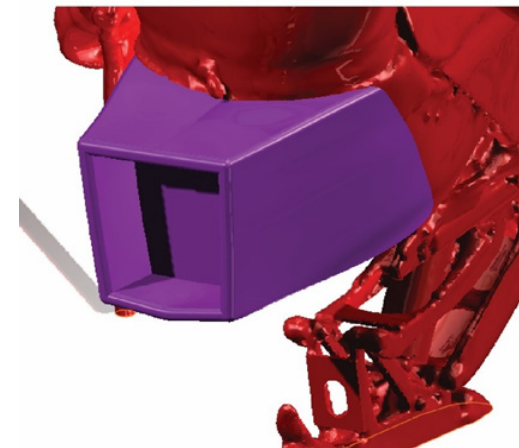
Figure 49: Assembly steps of mounting plate.

8.1.2.2 Aerodynamic shell evolution

The design of the CAD model has undergone several iterative modifications to improve aerodynamic fit, ensure 3D printability, and integrate a mounting system. The following steps outline the key stages in the model's development.

The initial design of the model for wind tunnel testing was developed symmetrically. During wind tunnel testing the team noticed the right side did not fit the ski properly. Based on this insight the geometry was adjusted from a symmetrical to an asymmetrical shape. This change improved the model's fit, as shown in Figure 50.

Initial design



Improved asymmetrical



Figure 50: Improved asymmetrical design for better fit on the right side.

To address issues of interference with the abdominal belt, the model was modified to sit behind the belt, preserving its functionality. A prominent protrusion on the right side of the design was removed, resulting in a smoother side profile. These changes provided a more seamless integration with the current ski. Additionally, the model was converted from a surface model to a solid body to facilitate 3D printing.

As part of this transition, the ski volume was removed to create a seamless fit between the new shell component and the current ski, streamlining the geometry. Figure 51 shows the old and new model next to each other, which shows the clear difference in the edges of the aerodynamic shell, marked in orange.

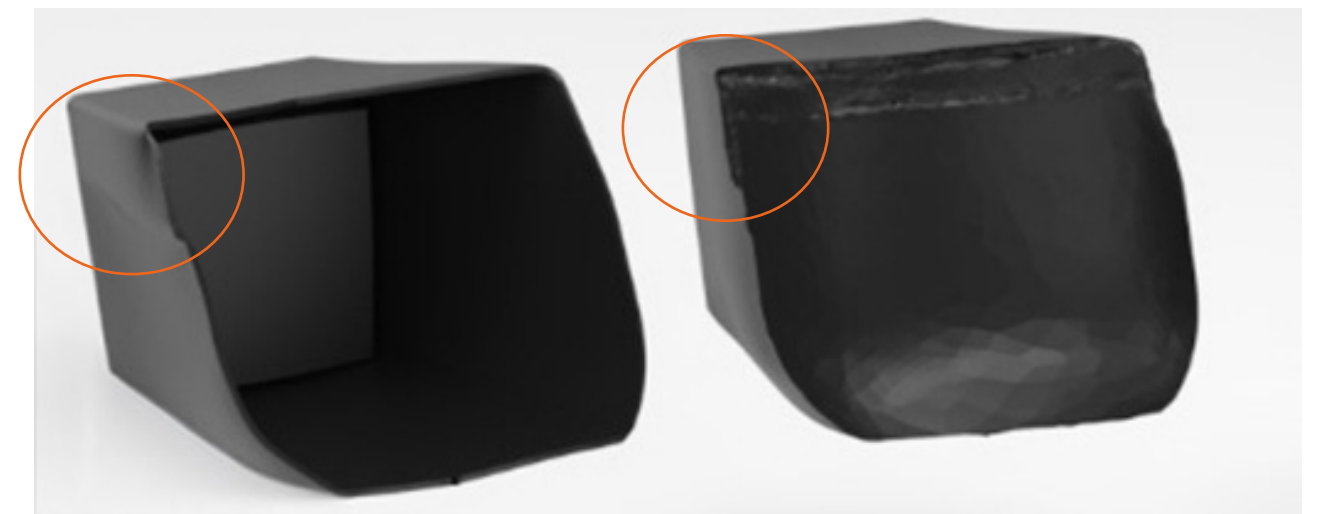


Figure 51: Old surface model (left) and new solid model (right).

Figure 52 presents the new design from multiple angles. The rear cavity was enlarged (right image). The mounting plate was removed from the front of the component (left image). Additionally, the bottom connection point has been repositioned further inward to maintain consistent wall thickness across the entire mounting area (right image).

These translations are marked in orange. The attachment points now feature circular countersinks to accommodate washers (Blue circles in the middle image). This modification helps distribute connection pressure more evenly over the surface area, reducing the risk of material deformation or failure under load.

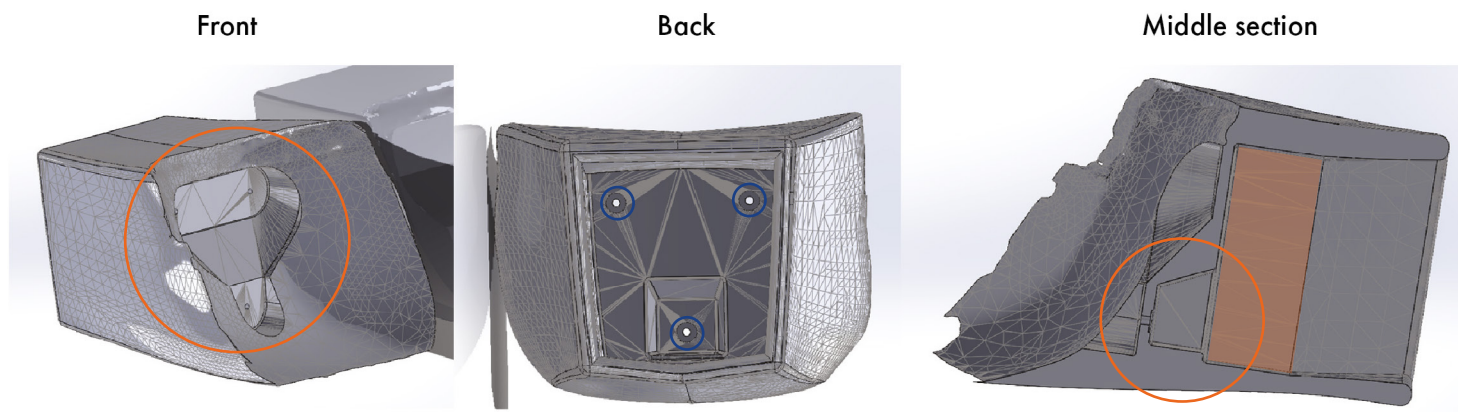


Figure 52: Improved design with a frontal mounting cavity, washers and enlarged rear cavity.

8.1.3 IMPROVED PRODUCT PROPOSAL

Both the improvements in the mounting mechanism and the CAD model led to an improved product proposal that is the starting point for the testing and validation phase.

The iterations of the mounting plate side by side can be seen in Figure 46. Figure 53 shows the iteration of the shell component side by side.

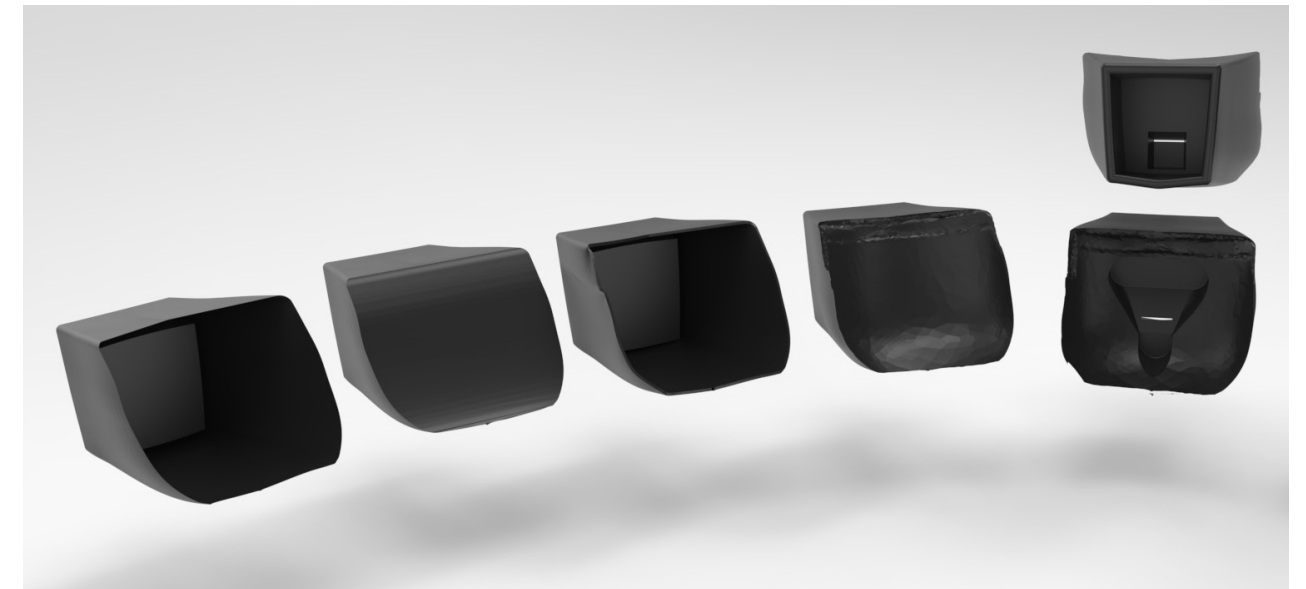


Figure 53: Evolution of the shell component model.

Figure 54 illustrates the side profile of the current ski assembly, showing the relationship between the key components. The ski is depicted in red, with the mounting plate positioned in the middle.

A semi-transparent version of the aerodynamic shell is shown that fits over the mounting plate and seamlessly on the current ski.

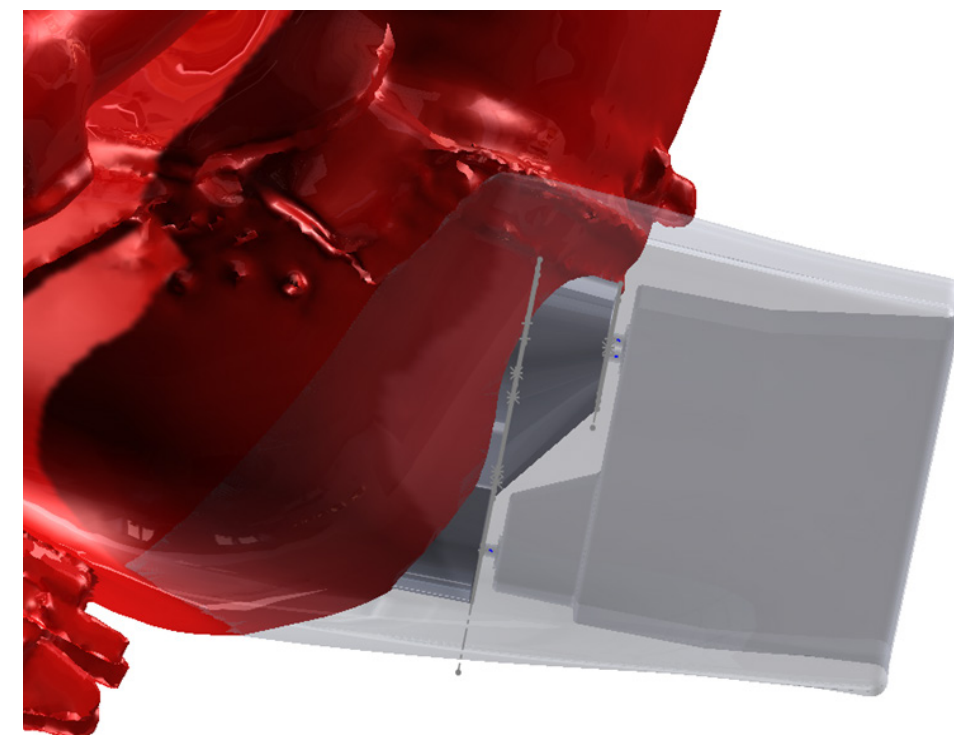


Figure 54: Side profile of the ski assembly.

8.2 PRODUCTION TESTING AND DESIGN OPTIMISATION

Throughout the development process, extensive testing with various 3D printing materials was essential to achieve a balance between mechanical performance, flexibility, and printability. This subchapter outlines the iterative approach taken to refine both material selection and part geometry to meet production and functional requirements.

8.2.1 INITIAL MATERIAL TRIALS

To print the final product, consisting of mounting plate and shell component, an external manufacturer has been consulted. To minimise weight and gain a better understanding of the material and its printing characteristics, the external manufacturer, project manufacturer, and the author agreed to produce the component without any infill. This approach results in minimal stiffness but achieves the lowest possible weight. This first test print created the possibility to determine the necessity of infills at specific placements and the material refinement necessary for achieving the desired print.

We began prototyping with **Ninjabflex 3D printer Filament (85A)**, a highly flexible material known for its elasticity and good abrasion resistance, both important qualities necessary for the product (Ninjabtek, 2025). (See requirements x-MP-x) This material was chosen based on the following properties (NinjabTek & Fenner Drives, Inc., 2016):

- According to the external manufacturer, Ninjabtek is a frontrunner in the flexible 3D printing scene. This material is readily available in the Netherlands and this will probably stay available over time.

- It has a shore hardness of 85A. Shore hardness refers to the flexibility of a material. This is the most flexible filament available. From this starting point, the shore hardness can be increased to enhance stiffness.
- It has a Glass temperature of -40 degrees Celsius, meaning it will stay flexible until -40 degrees Celsius and thus in all competition use (as competition gets cancelled at -20 degrees Celsius, see chapter 2.4).

Figure 55 shows that only a part of trying to print the entire shell component succeeded. However, the flexibility proved excessive for our application, leading to a failed print with structural holes.



Figure 55: Failed Ninjabflex 3D print.

This led us to test **DuPont Hytrel 3D4100FL NC010**, a material with a significantly higher Shore hardness of 60D (translating to around 100A) and a significantly lower nominal strain at break (DuPont, 2017). This was a flexible material ready to grab at the external manufacturer's workshop.

While this print offered improved stiffness, we encountered issues with warping, especially in sections with limited infill, as shown in Figure 56. The excessive rigidity also hindered the part's ability to flex as intended.

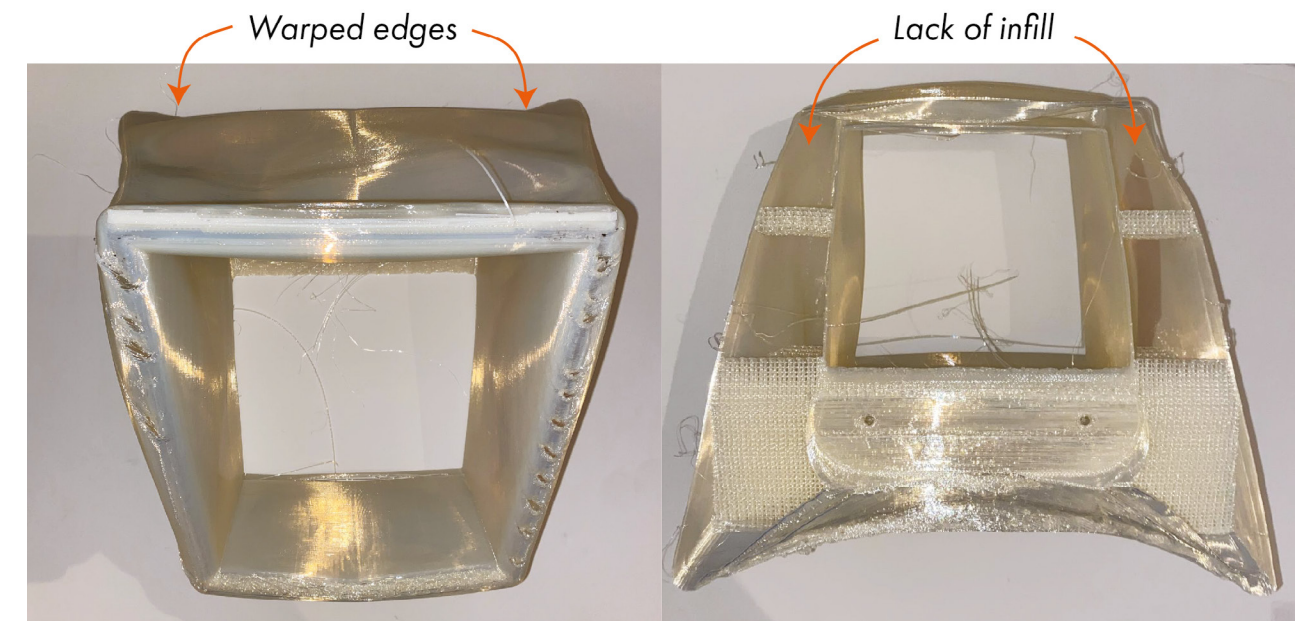


Figure 56: Failed Hytrel print.

8.2.2. MATERIAL AND PRINT STRATEGY REFINEMENT

The next iteration used **Ninjabtek Cheetah 3D printer filament (95A)**, which struck a better balance between flexibility and strength. It has a shore hardness of 95A, improved abrasion resistance and a glass transition temperature of -24 degrees Celsius (Ninjabtek, 2016). in figure FIXME.

To address earlier warping issues, we added a gyroid infill (from Chapter 8.2), which improved dimensional stability. However, due to the original print orientation, the wall thickness increased beyond optimal design tolerances, resulting in reduced flexibility. The original print orientation was tilted to be able to print the cavity in the design without the need for support material, as shown Figure 57.



Figure 57: First Cheetah print (left) with original print orientation (right).

To resolve the wall thickness issue, the print orientation was changed to an upright position, which reduced overbuilding on wall sections and preserved the intended material behaviour. A print to test the bridging qualities was conducted to evaluate whether certain spans could be printed without support structures. Bridging is the printing of filament over the air to create a bridge on which the rest of the component can be printed. This eliminates the need for excessive support material. The results were successful, paving the way for further design refinement.

8.2.3 DESIGN ADJUSTMENTS FOR MANUFACTURABILITY

In response to the new upright print strategy and successful bridging tests, modifications were made to the geometry of the final model. The modifications included adjustments to the internal cavity for improved printability and ease of post-processing. The cavity shape was restructured to ensure both connection point accessibility and support-free bridging, reducing material use and print time. As shown in Figure 58, the extra cavity at the bottom connection point was widened over the entire side to accommodate the bridging process. In addition, the cavity was straightened to accommodate the print orientation, reduce overhangs, and create an equal wall thickness at the top and bottom of the cavity.

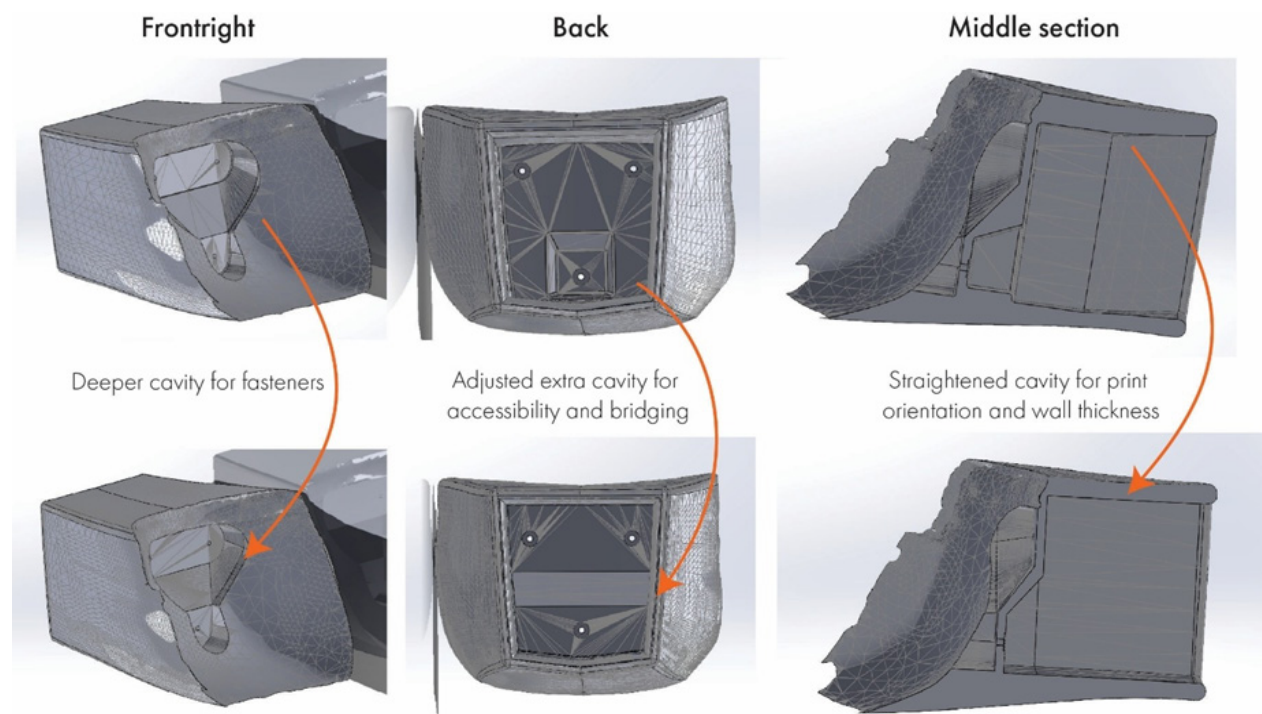


Figure 58: Improved design for printability.

8.2.4 LOCAL MATERIAL TRANSITION

To optimize production costs and streamline supply, we transitioned to **Colorfabb TPU 95A**. A material with mechanical properties nearly identical to Ninjatek Cheetah (ColorFabb, n.d.). Key advantages were its availability through a local supplier, bigger spool availability, and lower cost, which maintained the project's timeline and budget. Additionally, the external manufacturer had direct contact with Colorfabb's manufacturer, enabling efficient technical feedback and collaboration.

Both tests with support material and a bridging test were performed successfully. The supports can be removed neatly to create a neat surface (see Figure 59). The bridging test created a successful surface over air (See Figure 60). These tests confirmed the material's suitability.



Figure 59: Support material testing with a closeup of the edge.



Figure 60: Material bridging test result for creating an elevated print bed.

8.2.5 FULL-SCALE PROTOTYPING AND FINAL ADJUSTMENTS

The first full-scale prototype using Colorfabb TPU experienced a print nozzle jam due to carbonisation, likely caused by the extended print duration and material buildup. The print setup was adjusted to use a more direct drive extrusion system on a different printer, which



Figure 61: Final Hytrel and TPU print.

8.2.6 FINAL PRINT RESULT

The final prints were test-fitted directly onto the current ski setup, serving as the ultimate validation of both CAD design and print quality. The fit was seamless, as seen in Figure 62, and aligned exceptionally well with



Figure 62: Test fitting the shell component, 2 times right side and left side.

resolved the issue in the subsequent attempt. Due to this issue, we hedged our bets and opted to print with both Colorfabb TPU and Hytrel to make sure the shell component would be fully printed in time for the upcoming field-testing phase in snow conditions.

Both final prints were successful. Figure 61 shows the Hytrel print in white and the TPU print in black.



The Hytrel print seemed to be more robust than the TPU print as expected with the corresponding shore hardness. The TPU print shows some breaking of shape, probably due to a filament spool swap mid-print, as seen in Figure 63.

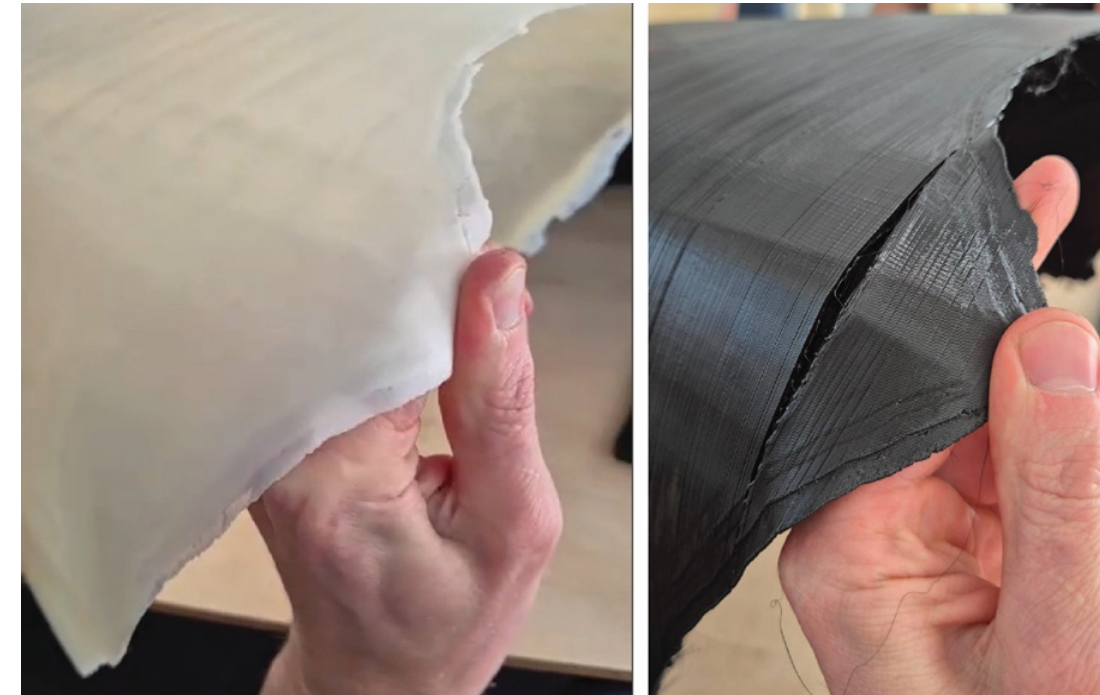


Figure 63: Hytrel print and breaking TPU print.

To further enhance performance and adaptability in future prints, the following adjustments are proposed:

- Change the print orientation by 90 degrees to better align material layers with flex directions.
- Reduce the infill percentage to allow greater elasticity and responsiveness under impact.
- Remove the inner wall of the cavity to introduce more internal deformation space, increasing flexibility without compromising external aerodynamic shaping.

While overall stiffness remained slightly higher than ideal, this was a valuable insight. For future iterations, we identified opportunities to improve flexibility and impact dampening through changes in the print setup.

The production tests validate the correctness of the CAD model and the possibility of printing the component with elastic energy absorption. Both prints will be field tested in snow conditions to get a feel for the skiing experience with the new component, test impact absorption, test the seamless fit during a simulated sliding crash, and validate remaining flexibility in cold conditions.

8.3 USER-CENTRIC TESTING OF FASTENERS

To ensure a strong and simple connection that evokes trust in the athletes, multiple connection mechanisms were tested with a mounting plate using gloves to create a real scenario.

8.3.1 FASTENER OPTIONS

All options used in the testing are fasteners that do not need tools to be fastened or released ensuring requirement FIXME is realized: "The product can be connected to the shell while wearing gloves and requires no more than 1 standard tool." The following fasteners were used in testing (see Figure 64):

- Nut and butterfly bolt to ensure proper fastening can be achieved.
- An excentric lever to fasten and tighten the connection.
- A big quarter-turn fastener for easy handling.
- A small quarter-turn fastener for easier access in small spaces.

8.3.2 METHODOLOGY

The objective of this test was to determine the most suitable fastener for the final design based on simplicity, trust, and handling with gloves. To measure these qualities the following measurements were set:

- Speed of handling the connection: Each connection mechanism is timed, both with and without explanation, to account for the learning curve.
- Perception of handling: A questionnaire was created to measure perceived handling and trust in the fasteners using a Likert scale, see Appendix F for an overview of the questions. The metrics were rated on a scale of 1 to 7, with 1 indicating a very negative result, 4 indicating a neutral result, and 7 indicating a very positive result.

The perception of handling was evaluated in the questionnaire and was created using the following categories:

- Handling, which addressed the general ease of use of the fasteners.
- Simplicity, which considered clarity and satisfaction during use.
- Trust, which captured participants' confidence in the fasteners' reliability and security.



Figure 64: Fastener options.

The test was conducted with ten participants affiliated with TU Delft, including both students and professors. Two additional key users, the coach and the athlete, were also included in the test. To reflect their practical involvement with the product, their results were weighted: the coach's feedback was counted three times, as he will primarily handle the product during operation, and the athlete's response was counted twice, due to his frequent interaction with the product. This brought the total number of weighted participants to fifteen (N=15).

Each participant began the test by signing an informed consent form, as seen in Appendix G. They were then asked to use each fastener for the first time without prior instruction. After completing this first round of fastening, participants repeated the same tasks after a brief explanation of the fastening mechanisms, particularly for connections 3 and 4, to take a learning curve into account. After completing both rounds of testing, participants filled out the questionnaire. The entire process was recorded on video to document verbal feedback, and the time required for each task.

To minimize order bias, the sequence of fasteners was rotated across participants. The first participant tested the fasteners in the order 1-2-3-4, the second in the order 2-3-4-1, and so forth, repeating this rotation for the remaining participants.

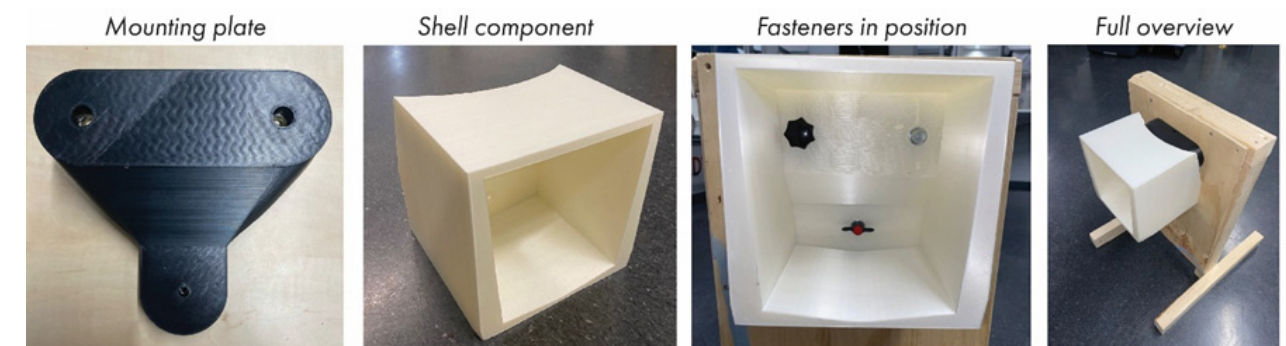


Figure 65: Mounting test prototypes.

Prototypes of both the mounting plate and the aerodynamic shell, as seen in Figure 65 were created to simulate the real-world scenario of fastening. The mounting plate was connected to a frame at the same height as the ski, as shown in Figure 66 indicated as X.

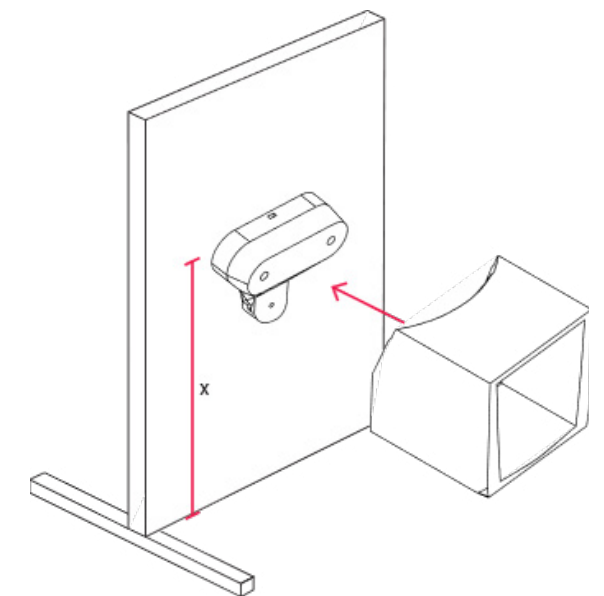


Figure 66: Test setup fastening test.

8.3.3 RESULTS

The performance metric for speed of handling was measured using videos. Figure 67 shows the results of the speed of handling of each fastener. For these results the second measurements after explanation were used, as multiple participants were not able to connect the quarter turn fasteners without explanation.

After explanation, participants were able to fasten connection 3 the fastest, with an average time of 7 seconds and a limited spread. Average connection times for connections 1, 2 and 4 were 17, 28 and 12 seconds respectively.

Figure 68 shows the visualization of questionnaire responses for the performance metrics, comparing connections 1, 2, 3 and 4. Both clarity and handling were evaluated before (A) and after (B) explanation. Average ratings are included in the plot.

Clarity

Connection 1 performs best on clarity with an average rating of 6.73 with responses heavily skewed towards “very positive”. Connection 2 has the second-highest rating with 6.20. Both quarter-turn fasteners performed badly before explanation with scores of 3.67 and 2.67, compared to 5.93 and 4.67 after explanation. Connection 3 has more positive answers but scores lower than connection 2 as more participants rated connection 2 very positive.

Handling

Connection 1 performs the best again with a rating of 5.80, which lowered to 5.60 after explanation. Connection 2 performs the second best before explanation with a score of 4.60. Both connections 3 and 4 score higher after explanation than before explanation with scores rising from 3.20 and 2.00 to 5.00 and 3.60. Connection 3 has a divide in positive and negative scores, creating a higher overall rating than connection 2 with a lower percentage of positive answers.

Connection handling

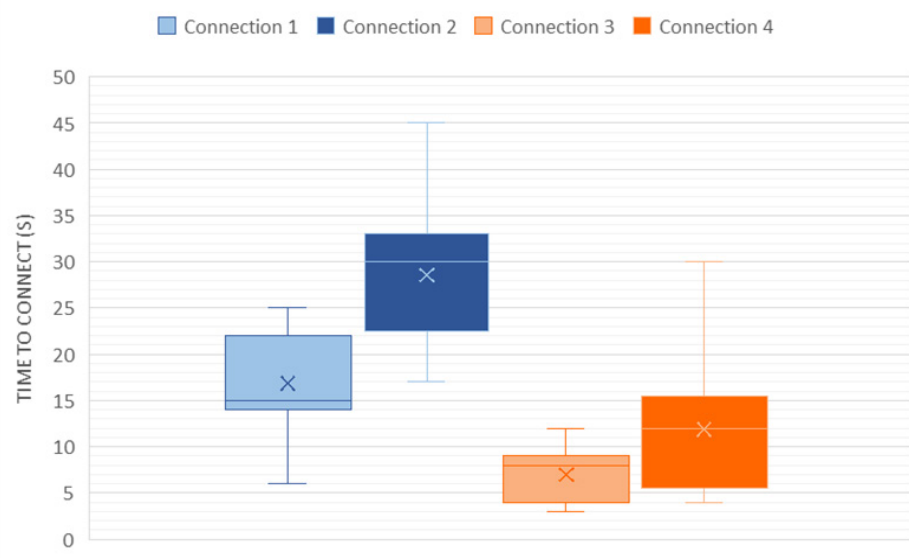


Figure 67: Plot of handling speed.

Likert Scale Plot

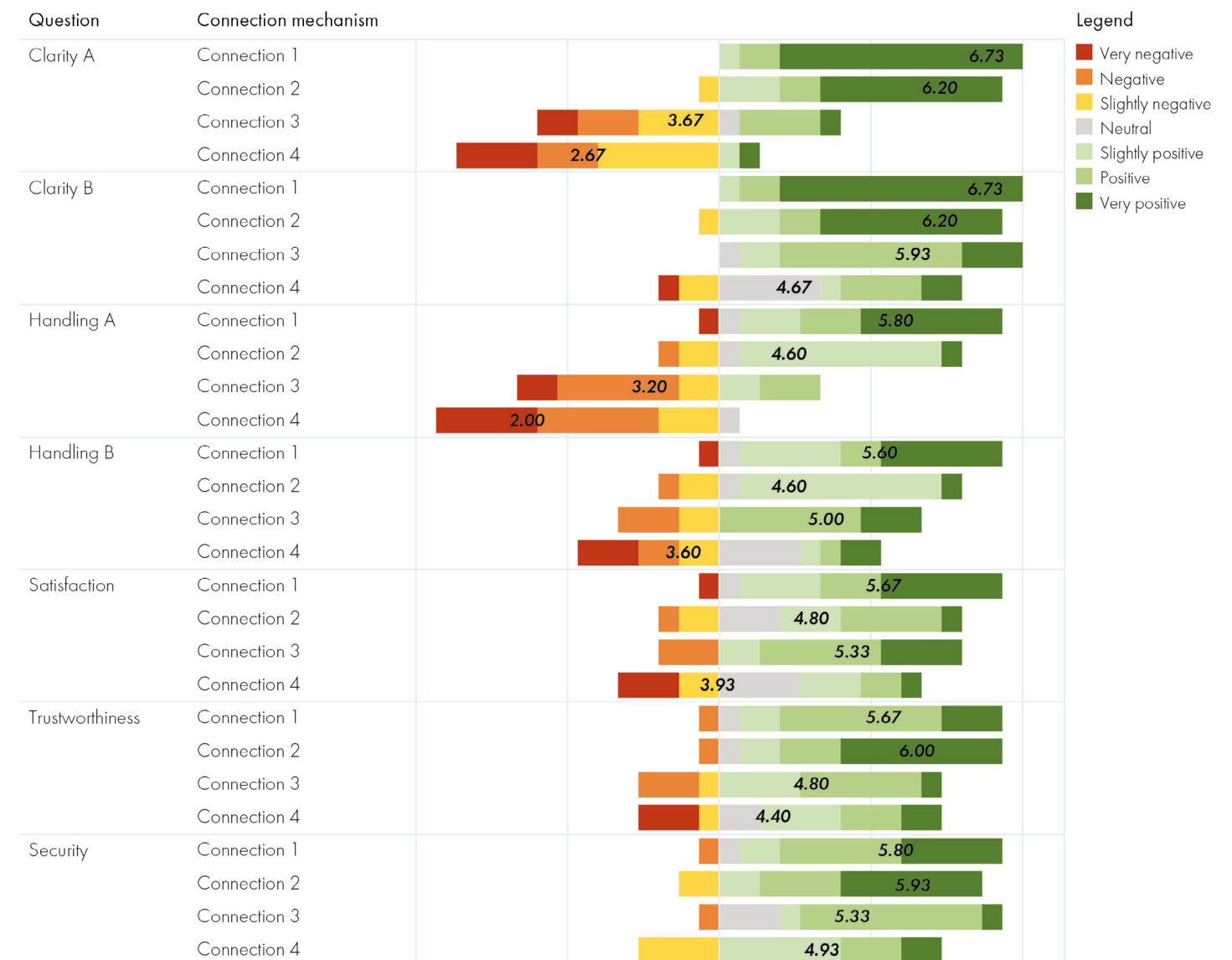


Figure 68: Plot of all Likert scale metrics.

Satisfaction

Connection 1 scores well again, with an average of 5.67. Connection 2 and 3 remain favourable with scores of 4.80 and 5.33. Connection 4 is the least satisfying and shows mixed reactions, with a strong negative component.

Trustworthiness

Connection 1 and 2 score well, with scores of 5.67 and 6.00. Connection 2 shows a very positive component. Connection 3 and 4 score 4.80 and 4.40, with connection 4 showing a very negative component.

Security

Overall, the connections score well, with connection 2 taking the lead with a score of 5.93. Connections 1 and 3 show a more positive balance than connection 2 with lower average scores of 5.80 and 5.33. Connection 4 scores the lowest with a score of 4.93 and shows a bigger slightly negative component.

When asked about the favourite connection, there is a 50/50 split decision between connections 1 and 3, with both the coach and athlete preferring connection 1. Further findings from the test show that loose components will fall and are difficult to pick up wearing gloves.

8.3.4 DISCUSSION

The evaluation of the four connection types across both objective and subjective performance metrics reveals notable differences in usability, perception, and overall preference. Among the tested options, Connection 1 consistently emerged as the most favourable, whereas Connection 4 showed several critical limitations.

Speed of Handling

Handling speed was assessed through timed observations, with Connection 3 showing the fastest average connection time (7 seconds) after explanation. This suggests that although initially unintuitive, once users are familiar with the quarter-turn mechanism, it offers clear advantages in operational efficiency. Conversely, Connection 2 was the slowest (28 seconds), indicating potential issues with the handle that could hinder rapid usage. Connection 1, while not the fastest, demonstrated moderate speed (17 seconds), aligning with its broader trend of reliable and balanced performance across other metrics.

Clarity and Ease of Handling

Clarity ratings were highest for Connection 1 (6.73), which was consistently described as intuitive and easy to understand. Connection 2 also scored well in this category (6.20), even though its low handling speed may indicate a difference between understanding and actual handling. Notably, both quarter-turn fasteners (Connections 3 and 4) performed poorly on clarity prior to explanation, with scores improving significantly afterwards. This highlights a steep initial learning curve for these mechanisms, as these are not commonly used fasteners, which could pose challenges at the start of a race.

Handling scores were very similar to the clarity scores. Connection 1 again led the category, while Connections 3 and 4 showed improvements post-explanation, but still scored lower overall. Connection 4 remained low-rated, indicating that even after instruction, users found it less ergonomic or more difficult to manipulate. Participants mentioned the button was difficult to turn and due to its small size difficult to press in deep enough.

User Perception Metrics

In terms of satisfaction, Connection 1 again stood out (5.67), closely followed by Connection 3 (5.33). This suggests that once users understood Connection 3, they found it pleasing to use, supporting its potential viability when getting accustomed to the fastener. Connection 4 had a high level of negative feedback and noticeably lower satisfaction scores, fitting the prior statements about the connection.

Trustworthiness and perceived security are critical for user confidence, especially in high-performance and safety-related contexts. Connection 2 was rated highest in trust (6.00) and security (5.93), indicating that despite its lower usability metrics, it inspired user confidence. This is probably due to the extra tension added to the connection after fastening it like connection 1. Connection 1 remained a close second in both areas, while Connections 3 and 4 scored lower, with Connection 4 again drawing strong negative perceptions, particularly in trust.

User Preference

When participants were asked to select their preferred connection, opinions were split evenly between Connections 1 and 3. However, both the coach and the athlete selected Connection 1, suggesting that when considering performance and professional usability, Connection 1 holds the highest practical value.

Limitations

In this test, all participants used the same gloves that were relatively big compared to some participants' hand sizes. This could have influenced the overall handling of the connections. Furthermore, connections 1 and 2 could only be connected at the top holes, with connections 3 and 4 solely fitting in the bottom connection hole. The placement of these holes and the space for handling could have influenced the scores.

8.3.5 CONCLUSION

Overall, Connection 1 offers the best balance of clarity, handling, satisfaction, and trust, making it the most reliable and broadly accepted option. Connection 3 demonstrates strong potential due to its speed and post-explanation performance, but requires better onboarding to be effective. Connection 2 is trusted and secure but lacks efficiency and user-friendliness, while Connection 4 consistently underperforms across most dimensions and may not be a viable choice.

Based on these results and the preference of the coach and athlete for connection 1, the butterfly bolt will be used in the final product.

8.4 FINAL PRODUCT

This subchapter shows the final product which includes final adjustments from the production and fastener testing.

8.4.1 MOUNTING PLATE

For the connection between the mounting plate and the aerodynamic shell, we have chosen to use butterfly bolts. This allows for easy manual fastening and removal without the need for additional tools. The mounting plate itself is fully removable, and all individual components are designed to be easily replaceable. Figure 69 shows the evolution of the test mounting plate to the final mounting plate.

One of the key modifications involves replacing the original square nuts with sliding nuts (see Figure 70). This change was implemented to prevent the nuts from rotating around their axis within the flexible material. Additionally, the slots have been removed to improve future printability and provide easier access to the nuts. The new sliding nuts are secured in place similarly to the quarter-turn receivers, using a locking mechanism with a seal.

We have also added six square nuts to facilitate the attachment of the mounting plate to the ski. These are accessible from the outside via holes that go through the entire mounting plate, allowing for straightforward assembly using bolts inserted from inside the ski. Figure 71 shows a semi-transparent version of the mounting plate attached to the ski. It shows the 6 square nuts around the edge of the mounting plate and the sliding nuts with placeholders at the attachment points.

Finally, the mounting surface has been positioned as close to the ski as possible, with a maximum distance of 42mm. This ensures compatibility with a sitting ski lift, allowing the mounting plate to remain attached to the ski during lift usage. Figure 72 presents the mounting plate attached to the ski from different angles.



Figure 70: Sliding nut. (RVS Paleis, n.d.)

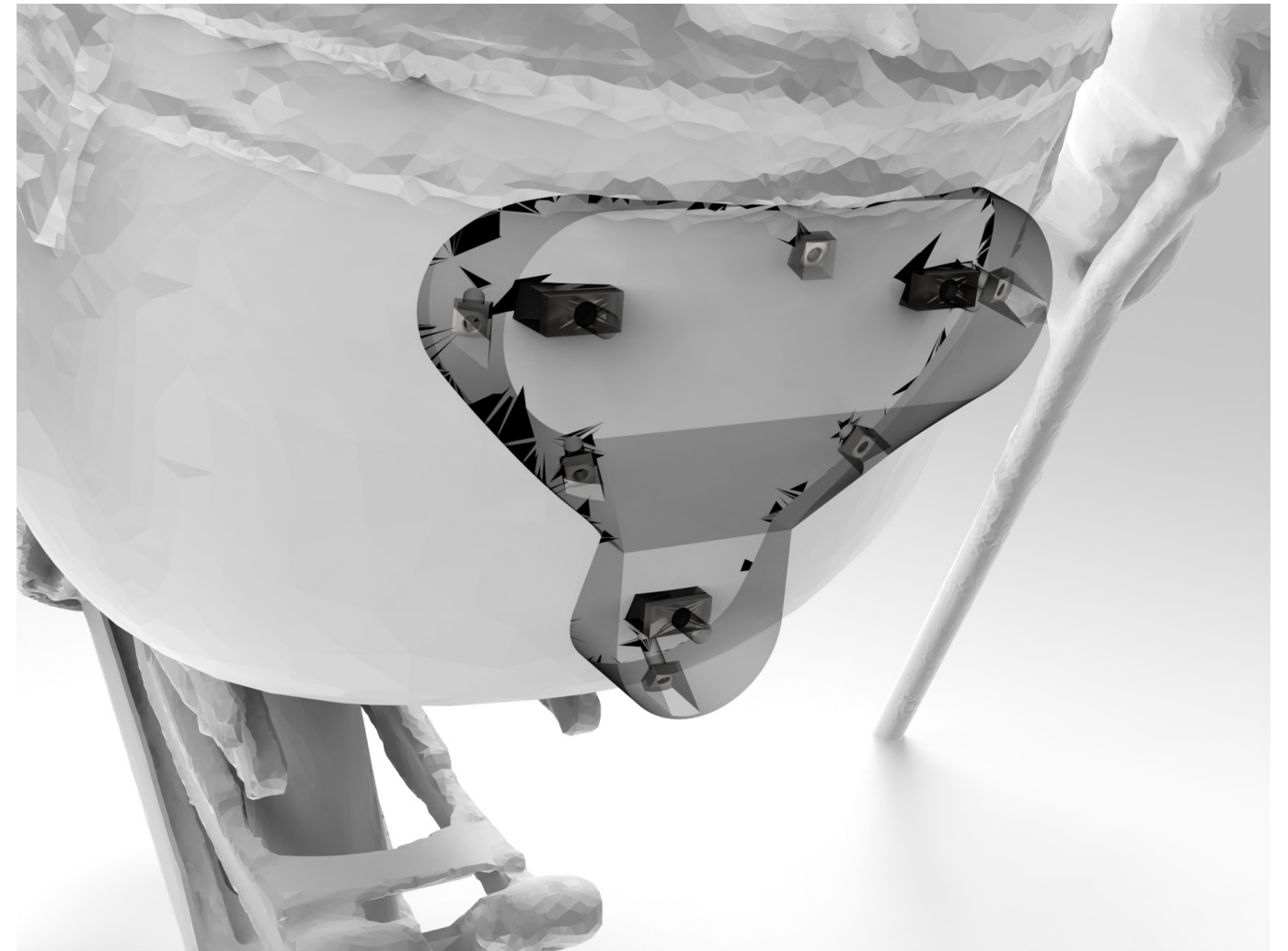


Figure 71: Final evolution of the mounting plate.



Figure 72: Final mounting plate from different angles.

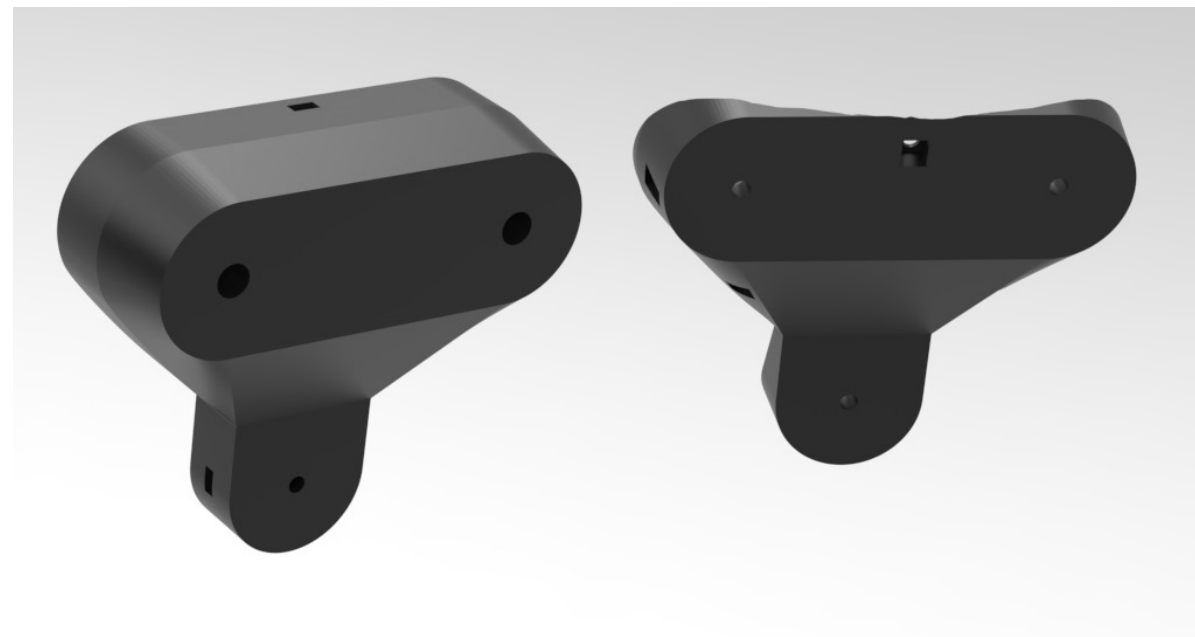


Figure 69: Final evolution of the mounting plate.

8.4.2 AERODYNAMIC SHELL COMPONENT

Figure 73 shows the evolution of the proposed aerodynamic shell to the final aerodynamic shell.

As outlined in the Chapter 8.2, several final adjustments were made to the aerodynamic shell to improve both functionality and manufacturability. The cavity design was modified to enhance the printability and accessibility to the bottom mounting point.

Additionally, the mounting plate and corresponding cavity were moved slightly upward and set deeper into the shell. This adjustment accommodates the fastening mechanism within the mounting plate and ensures compatibility of the mounting plate with sitting ski lifts. Finally, the holes in the shell were revised to precisely fit the selected fastening method, completing the integration of all components. Figure 74 presents the final shell component from different angles.



Figure 73: Final evolution of the aerodynamic shell.



Figure 74: Final aerodynamic shell from different angles.

8.4.3 COMBINED PRODUCT

Figure 75 shows exploded views of all the components of the combined product. The combined product is fully removable from the existing ski. The mounting plate, 3D-printed from the same material as the aerodynamic shell, will be attached to the ski using six m5 bolts. Inside the mounting plate are three sliding nuts that will be locked in place by 3D-printed placeholders. When the mounting plate is attached to the ski, the coach simply needs to place the aerodynamic shell component over the mounting plate and screw in the three butterfly bolts to secure the assembly. The washers between the butterfly bolts and the aerodynamic shell can be glued into place to avoid them falling on the ground during connection or getting lost during transport. The final product weighs under 2kg which is less than 10% of the weight of the ski.



Figure 75: Exploded view of all components

Figure 76 shows a semi-transparent aerodynamic shell in the full assembly. The material thickness of the shell component is 9mm.



Figure 76: Seethrough shell fitted over all the components.

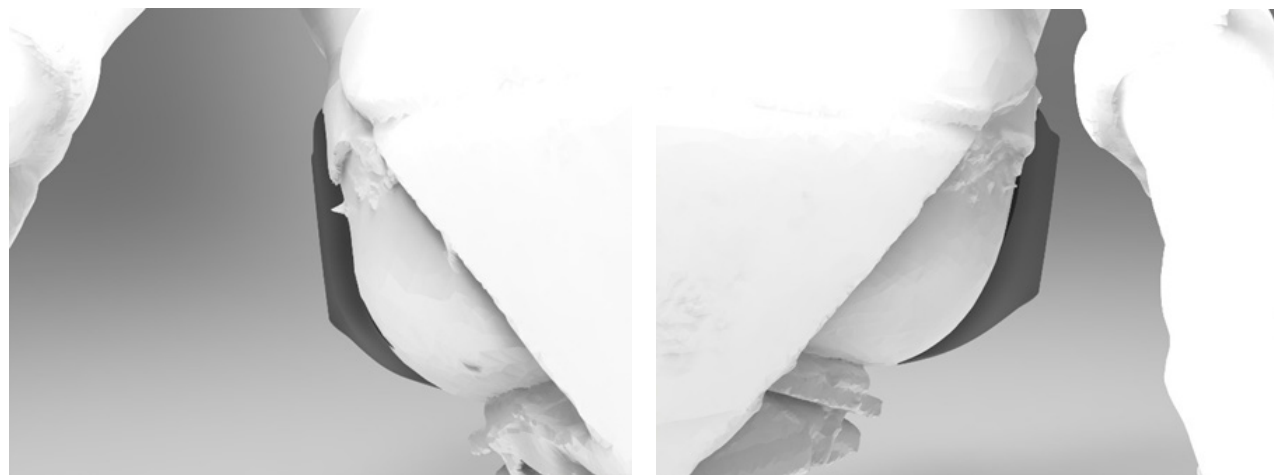


Figure 77: Seamless fit on the left and right side.

Figure 77 shows the seamless fit of the final shell component on the existing ski from the left and right sides.

8.4.4 REPRODUCTION FOR THE NEW SKI

As this product is highly personal due to its seamless fit, reproduction of the setup for a different athlete needs some adjustments. It can however follow most of the design philosophy. This will be demonstrated with a design created for a second athlete.

To reproduce the product for another athlete a high-quality, waterproof 3D scan of the athlete's ski is necessary. Ideally, the athlete should be in the ski during scanning for accurate positioning and subtracting the scan from the models for a seamless fit. Next to a high-quality scan, 3D models of the aerodynamic shell and mounting plate need to be created.

To model the aerodynamic shell the following steps are crucial:

- The square cavity needs to be placed at the same distance from the ski as the current design. Maintaining the same ratio between the shell width and the ski width is essential for consistency.
- Identify the widest point line of the ski and create a tangent surface that connects smoothly to the square at the back. This forms the base surface model of the shell.
- Define an intended contact point with the mounting plate and model the cavity to be 9mm from this contact point. Ensure the surface is parallel to the back surface.
- Create a solid version of the model and subtract the mounting plate and ski for a seamless fit.
- Add the final modifications of holes to finalize the model.

To model the mounting plate the following steps are crucial:

- Mark the desired connection points on the contact plane and model a triangular shape around it. If needed add another plane for the bottom connection to get as close to the ski as possible.
- Subtract the solid body from the aerodynamic shell.
- Scale the component to 99% to create the tolerances between the shell component and the mounting plate.
- Remove the ski from the mounting plate and add holes for the fastening elements.

This workflow was followed to recreate the design for a second athlete. The main differences between the designs for the second athlete and the first athlete are the shaping of the aerodynamic shell and the mounting plate. The mounting plate does not have a layered design due to a difference in curvature of the ski. Therefore, the cavity in the design of the aerodynamic shell does not need to be layered. Figure 78 show the second athlete's mounting plate attached to the ski, the aerodynamic shell, and the full setup attached to the ski.

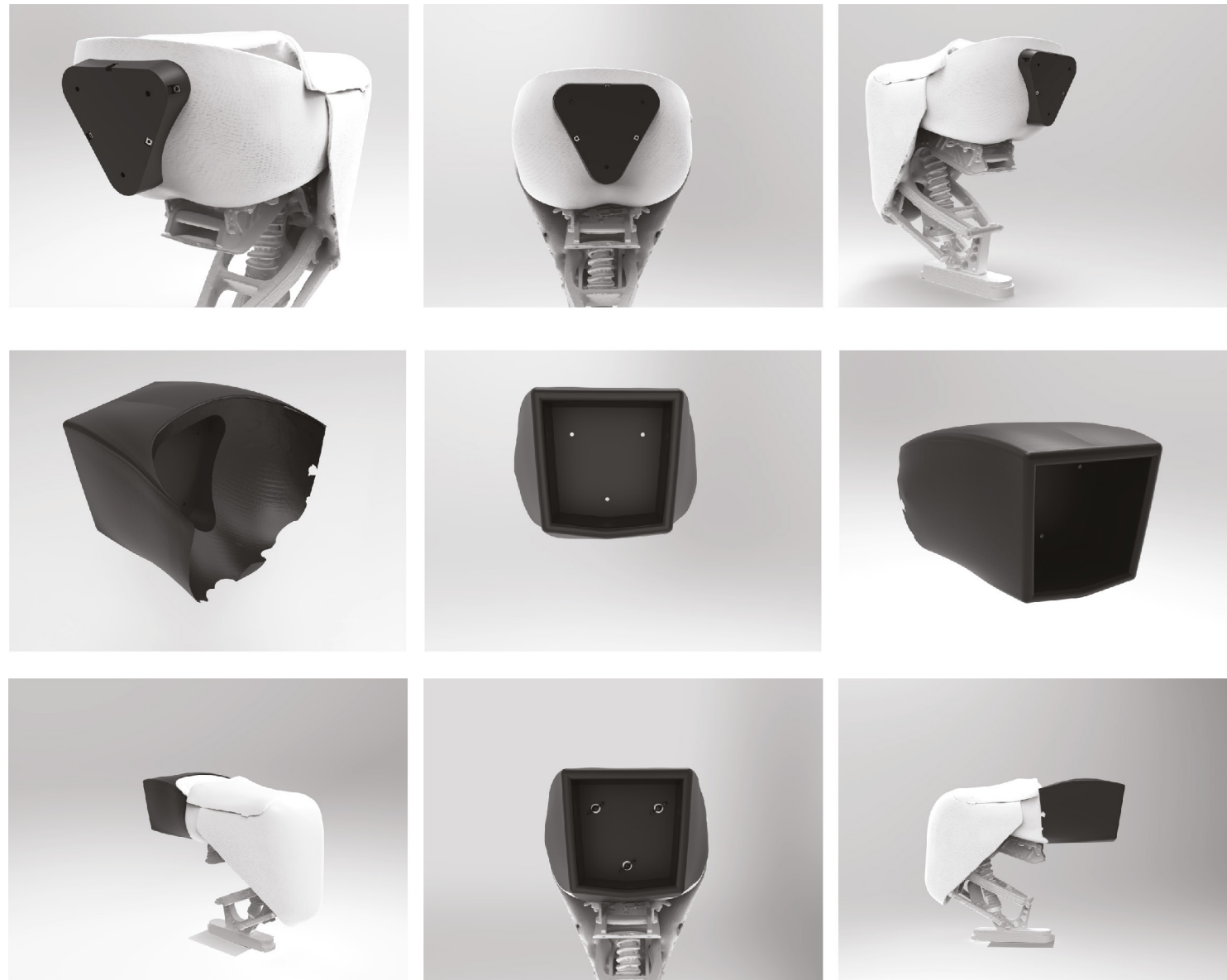


Figure 78: Overview of all the models for the second athlete.

8.5 VALIDATION

As the final CAD models are finished and ready to be printed, it is crucial to validate whether all the requirements have been met. The list of requirements is divided into 4 categories. These categories will be discussed with the corresponding requirement codes mentioned.

Aerodynamic shaping

The aerodynamic shell improves the aerodynamics by 8-10% according to the wind tunnel testing and CFD simulations (R-aero-1). The design is created using smooth rounded edges (R-aero-3) and fits seamlessly on the existing ski (R-aero-2), as seen in Chapters 8.2 and 8.4.

Sitski usage

The design of the aerodynamic shell component attaches at the back of the ski, behind the abdominal belt, brake screws and fastening belt (R-use-2). It does not go above the back support point and does not exceed the width, allowing the athlete a full range of motion (R-use-1). The aerodynamic shell component and mounting plate are fully removable (R-use-4). The aerodynamic shell can be attached without using tools, due to the butterfly bolts (R-use-3). The mounting plate has a maximum additional length to the ski of 42mm, which should allow full functional operation of ski lifts (R-use-5). This should be further validated during the snow testing.

Manufacturing

Both the aerodynamic shell component and the mounting plate are 3D-printed. As shown in Chapter 8.4, all models regarding these components are finished for both athletes ensuring reproducibility of the designs for a different athlete (R-man-2) and after the first production (R-man-1).

Mechanical properties

The material used for 3D printing the components is Colorfabb TPU 95A. This material has a glass transition temperature of -25 degrees Celsius ensuring functional use down to -20 degrees Celsius (R-mp-1). TPU itself is hydrophobic (R-mp-3), as mentioned in Chapter 7.2, but this needs to be further validated in snow testing to ensure there is no formation of ice layers. According to Ana (2024), TPU is highly resistant to UV rays and saltwater and the nuts and bolts used in the final product will be made from stainless steel (R-mp-2). Due to the elastic properties of TPU and the design of the aerodynamic shell component, the final product has an elastic impact absorption mechanism (R-mp-4, R-mp-5, R-mp-6). This should be further validated with a crash test in the snow testing. Finally, TPU is widely used in existing fasteners to make them vibration-resistant. As the mounting plate and shell component are both made from TPU, the connection mechanism should be vibration-resistant (R-mp-7). This will be further validated in the snow testing.

8.6 FEASIBILITY

The feasibility of a product refers to the manufacturability of a product with available tech, skills, time, and budget.

The production of the aerodynamic shell component and mounting plate has proven to be technically feasible, within the project constraints. A full-scale prototype has been successfully manufactured and fitted on the current ski. The fit of the shell component on the ski is seamless, indicating high dimensional accuracy of the print in comparison to the CAD model. The product is produced with 3D-printed TPU from a local supplier with whom the manufacturer has direct contact, ensuring the material will not run out. The elastic properties of the material offer impact resistance, crucial for the safety of the athlete and rough handling of the components.

3D models have been developed for both the athletes, with the print for the second athlete finishing in time for the snow testing at the end of April. This ensures the reproducibility of the design for new athletes. 3D printing shows not only reliability but also adaptability. By using different infills or print settings the manufacturer can finetune flexibility and weight distribution for the product. As the product is highly personal, there is no need for scaling up the production, making this a suitable production technique.

Nevertheless, some challenges remain. The printed components initially score well on environmental conditions and elastic behaviour. However, prolonged exposure to cold, moisture and repeated mechanical stress could hinder the durability of the product.

8.7 DESIRABILITY

The desirability of a product refers to the satisfaction of user needs and wants.

The design meets several user-centred needs as mentioned in Chapter 4.1. The product is designed to have the gross of its weight close to the user to keep the front-back balance relatively similar with and without the product. The placement of the aerodynamic shell does not limit the function of crucial components and reference points for the athletes. The product's elastic properties provide a safety feature by absorbing shocks in potential crashes and it enhances the durability of the shell component. Furthermore, the shell component can be attached in under a minute, while wearing gloves, without any tools for a quick and easy connection. This helps in keeping the focus on the race.

The product has been reviewed iteratively with direct input from the coach and athletes. Their feedback has been integrated into design choices. The coach and athletes were pleasantly surprised by the seamless fit and elastic properties of the final printed product, which strongly validates the product's desirability.

One potential negative for the final component is the skiing experience. This will be tested and validated in the snow tests and could possibly uncover specific needs that need to be

8.8 VIABILITY

The viability of a product refers to the ability of a product to survive in the market. As this product is highly personal, this chapter will discuss the advantages for the athletes with this product.

From a viability standpoint, the component creates a clear competitive advantage. The aerodynamic testing validated an 8-10% improvement in aerodynamics, which could make the difference between a silver and gold medal at the upcoming Paralympics.

Due to the product being highly personal, 3D printing provides a good solution for low-volume production economically. The material costs of approximately €100,- per unit are modest compared to the creation of moulds and other production alternatives.

A negative view of viability is the high personalisation of the product. For each athlete, a personal model needs to be created making it hard to speed and scale up the production of these components.

09

THESIS CONCLUSION

- 9.1. Conclusion
- 9.2. Recommendations
- 9.3. Personal reflection

9.1 CONCLUSION

The overall objective of this project was to design a new, detachable shell component for the back of the seat that significantly improves the aerodynamics of the current sit-skis, without compromising stability. The primary goal was to achieve a 10% reduction in air resistance. This Master thesis focused on the user experience, safety, and the seamless connection of the new shell component to the existing sit-ski.

To achieve these goals, a contextual analysis looking into the organisations, aerodynamics, component functions and usage context was performed. By interviewing the athletes and the coach their needs were determined. Combining these insights led to a comprehensive list of requirements and design areas for the final product.

By using brainstorming, mindmaps, how to's and a morphological chart three concepts were created. By using a weighted objectives method in collaboration with the manufacturer it was decided to produce the final product using 3D-printed TPU.

The aerodynamic shaping of the product has been validated through CFD simulations and wind tunnel testing. The final product delivers an 8-10% aerodynamic improvement.

A mounting plate has been added to translate the curved surface into a straight surface for proper connection. Fasteners and the mounting principle have been tested with students, professors, coach, and athletes. The aerodynamic shell component can be mounted to the ski without the use of any tool, through three butterfly bolts.

The production of the aerodynamic shell component was extensively tested, leading to a final full-scale print that was test fitted on the ski successfully. The shell component is elastic, introducing a safety feature for the athletes. Finally, the 3D models have been created for both athletes, validating the design philosophy. The final prints will be tested in the snow after this master thesis, which would fully validate the product.

9.2 RECOMMENDATIONS

Due to limited time in the project, some areas could use further research and improvements.

Perfect fit

The final aerodynamic shell component fits seamlessly onto the existing ski. However, the edges of the shell component are not fully fluent. To tackle this, the CAD model could use some adjustments or the final prints could use some post-processing for a perfect fit.

Future printing steps

As the current full-scale print has a tear in the edges due to the print orientation, further experimentation with print orientation and settings could improve the final product.

By playing around with the infill percentages, more flexibility and weight reduction could be achieved. This could improve the usability of the product.

Strength testing

The final fastening should be strength tested by performing a tensile strength test to see the maximum load before breaking.

By dropping a known weight from a fixed height on the shell component, an impact test can be performed to validate elastic behaviour and safety features.

Snow testing

The snow tests will be performed at the end of April. To fully validate the product a couple of areas need to be tested:

Test fitting in a seated ski lift to see if this is still comfortably functional with the mounting plate attached to the back of the ski.

Testing if the printed product does not freeze when used. If this does happen, a coating could make the print more hydrophobic improving the final product.

A simulated crash test should be performed to validate that the new shell component does not grab the snow in the event of a sliding crash. Furthermore, testing the elastic properties can give further information for improving the flexibility of the final product.

The athletes should ski with the new components attached to the ski to get a better feel for the skiing experience. On top of that, this could validate the vibration resistance of the mounting mechanism by marking the rotation of the bolt.

9.3 PERSONAL REFLECTION

As this project is ending, it is valuable to reflect on the project and personal learning ambitions set at the start of the project, see Appendix H.

First, I would like to start with the project complexity. This master thesis was part of a bigger multidisciplinary project team. It took some time for me to get used to the complexity of this project and to find areas to which I could contribute early on. After the final shape was determined I found myself being able to have a lot more impact on the project through consistent communication with the manufacturers involved with this project. I learned this constant communication is crucial for the success of such a complex project.

As my first learning goal, I wanted to improve my modelling and prototyping skills. During this project, I learned surface modelling from scratch and was able to successfully create the final 3D models that will be printed for the snow testing. I am very pleased with my development in this area, as this shape was very complex to model and a lot of issues were tackled during this project. This project helped me develop my modelling and communication skills

Finally, I was not aware of the sports engineering world as a path for my career. I enjoyed the combination of very technical elements with a human touch to it. On top of that, I got to meet incredible athletes.

10

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APPENDIX

Appendix A: Semi structured interview questions

Appendix A1: Interview questions athletes

Measuring of the ski:

- Je bent net bezig met het maken van een compleet nieuwe ski, hoe gaat dit proces in zijn werk? **Beschrijf het proces van Niels, vragen of dit hetzelfde werkt bij Jeroen.**
- Zijn er onderdelen in dit proces die je als niet prettig of vervelend ervaart? Waar komt dit door?
- Hoeveel invloed heb jij zelf op dit proces?
- Zou je graag meer bij willen brengen binnen dit proces of laat je dat liever in handen van de professionals?

Training schedule: (Just about in the snow)

- Hoe ziet een training er voor jou uit, kun je me eens door een gemiddelde training dag heen lopen? → In de sneeuw **Wat voor handelingen kunnen moeizaam verlopen binnen dit zit-skien?**
- Hoe lang zitten jullie in de ski op zo'n dag? Hoe bevalt dit?
- Kun je me eens praten door het proces van in de ski stappen?
- Hoe gaat het gebruik van de liften in een skigebied? Sleep en Zit
- Wat betreft het nieuwe kuipdeel, wat zijn je verwachtingen voor het trainen met dit onderdeel?
- Trainingskamp, hoe ziet dit er uit? Wat gebeurt hier allemaal?

Competitie:

- Neem mij eens mee door een wedstrijddag van start tot eind. **(Niels vermeldde dat ze zo kort mogelijk in de ski zitten omdat die niet zo lekker zit, hoezo?)**
- Ik vernam van Niels dat jullie jezelf vastzetten voor een wedstrijd, hoe is deze ervaring voor jou? Wil je dat dit zo blijft met het nieuwe onderdeel?
- Wat zijn jouw goede disciplines en wat zijn je wat mindere disciplines, waar komt dit door? Hoe verwacht je dat dit nieuwe onderdeel hierin steunt?
- Klim jij zelf onderaan de piste uit je zit-ski? Hoe ziet dat er hier uit?
- Wanneer voelt een zitski goed voor jou? Wat is ervoor nodig dat jij volledig in controle bent?

Opslag, transport en onderhoud:

- Wat gebeurt er met de zitski naast het gebruik van jullie?
- Hoe wordt deze schoongemaakt/onderhouden en door wie? Gaan hier dingen makkelijk/moeilijk?
- Waar wordt de zitski opgeslagen?
- Hoe wordt de zitski getransporteerd? Wie, waar, hoe?

Afsluitende vragen:

- Hoe vaak wordt een zit-ski gebruikt per jaar en wat is de levensduur?
- Niels zei dat jij wel eens een heel gat in je zitski hebt gehad door een crash, hoe is dit gebeurd? → stukje door op crashen.
- Waar moet de zitski fysiek aan voldoen om jou het best te kunnen laten functioneren?
- Ik vernam van Niels dat jouw binding van de ski op het moment veel problemen veroorzaakt, wat gaat er hier mis?
- Heb je verder nog pijnpunten binnen de algehele handeling van de zitski?
- Heb je zelf nog wensen voor het nieuwe onderdeel?
- Of zijn er nog restricties waarvan je zegt, dit mag absoluut niet gebeuren?
- Tot slot, is er beeldmateriaal van het gebruik van de zitski (alle scenario's) die ik zou kunnen ontvangen om observaties te doen over het gebruik?

Appendix A2: Interview questions coach

1. Introductie en algemene visie

- *Wat is jouw algemene indruk van het idee om een afneembare schaalcomponent toe te voegen aan de zitski?*
 - *Hoe denk je dat dit nieuwe onderdeel kan bijdragen aan de prestaties van de atleten?*
 - *Welke eigenschappen zie jij als essentieel voor een succesvol ontwerp van dit nieuwe onderdeel?*
-

2. Verwachtingen van het nieuwe onderdeel

- *Welke verwachtingen heb je van het afneembare kuipdeel wat betreft functionaliteit en prestaties?*
 - *Zijn er specifieke scenario's waarin je verwacht dat dit onderdeel een groot verschil kan maken voor de atleten (bijvoorbeeld wedstrijden, trainingen, specifieke weersomstandigheden)? **Waarin moet dit onderdeel gebruikt worden?***
 - *Hoe belangrijk is aanpasbaarheid of modulariteit van het onderdeel in jouw visie?*
 - *Zie je nog andere aspecten die belangrijk zijn voor dit onderdeel?*
-

3. Pijnpunten en uitdagingen

- *Zie je mogelijke uitdagingen of obstakels in het gebruik van een afneembare schaalcomponent, zowel technisch als in gebruik door de atleten?*
 - *Op wat voor manier verwacht jij dat dit kuipdeel de veiligheid van de atleet in gevaar kan brengen?*
 - *Zijn er eerdere ervaringen geweest met nieuwe onderdelen of innovaties die niet goed werkten? Wat kunnen we daarvan leren voor dit project?*
 - *Hoe denk je dat dit onderdeel getest moet worden om zeker te weten dat het aan de verwachtingen voldoet?*
-

4. Relatie met de atleten

- *Hoe verloopt het contact tussen jou en de atleten in? Op wat voor manier coach jij?*
- *Hoe werk jij samen met de atleten om hun behoeften en voorkeuren te begrijpen wat betreft het materiaal en ontwerp van de zitski?*

- *In hoeverre spelen de meningen en ervaringen van de atleten een rol in jouw visie op dit nieuwe onderdeel?*
-

5. Praktische aspecten en implementatie

- *Hoe denk je dat het nieuwe onderdeel geïntegreerd kan worden in de huidige training- en wedstrijdschema's?*
 - *Welke verwachtingen heb je van de duurzaamheid en onderhoud van dit onderdeel?*
 - *Hoe belangrijk is het voor jou en de atleten dat de schaal eenvoudig te bevestigen en te verwijderen is?*
 - *Zou het toevoegen van dit onderdeel invloed hebben op de manier waarop atleten trainen of wedstrijden skiën? Zo ja, hoe?*
-

6. Specifieke technische en tactische input

- *Zijn er technische beperkingen of regels vanuit competities waar wij rekening mee moeten houden in het ontwerp van dit onderdeel?*
-

7. Toekomstperspectief

- *Zie je andere trends of behoeften in de sport die invloed kunnen hebben op de ontwikkeling van dit soort onderdelen?*
 - *Heb je ideeën of wensen voor hoe dit project verder ontwikkeld en getest kan worden met input van jou en de atleten?*
-

8. Afsluiting

- *Is er iets dat we nog niet hebben besproken maar dat jij belangrijk vindt om mee te nemen in dit project?*
- *Zou je bereid zijn om in de toekomst betrokken te blijven bij het proces, bijvoorbeeld door feedback te geven op prototypes?*

Appendix B: Specifications for para alpine skiing competition equipment

These specifications are quoted from the FIS para snowsport equipment specifications 2024/2025. (INTERNATIONAL SKI AND SNOWBOARD FEDERATION, 2024)

RELEASE BINDINGS

Ski binding, which releases the boot from the ski, when during alpine ski racing conditions certain loads reach pre-set values.

RETENTION DEVICE

Retention device for alpine skiing is a ski brake which is designed to slow down a ski which has come off after the release of a ski binding. The use of skis without ski brake during competitions or unofficial training runs is prohibited. The functioning of the bindings release mechanism must not be compromised by the method of its mounting.

ANTI-VIBRATION PLATES INTERFACES (EG. PLATES, LIFTERS)

Functional component, mounted between skis and release bindings.

Interfaces can be mounted if the following conditions are taken into consideration:

Width of the interface: At each point of the interface, its width must not exceed the width of the running surface.

Maximum height: Maximum height (distance between the bottom of the running surface of the ski and the ski boot sole) for all categories is 50 mm (Women, Men).

SKI BOOTS

Ski boots are robust footwear developed specifically for skiing, offering protection against jolts and bumps as well as injury from ski edges and other external influences. The ski boot encloses the foot firmly, while at the same time allowing the movement necessary for skiing techniques, in that the ankle has the room it needs to flex, but at the same time facilitating the transfer of every steering movement completely to the ski. The relevant national and international guidelines and norms establish the requirements.

THICKNESS OF SKI BOOT SOLES

Distance between the ski boot sole and the base of the heel including all hard and soft parts:

Women, Men: maximum 43 mm

SKI POLES

The ski pole is an item of equipment, the function of which is to aid the skier and facilitate balance.

National and international rules establish the minimum requirements for ski pole tips, grips, shafts, baskets, straps, length, etc. Owing to the risk of injury, metal baskets are not permitted.

COMPETITION SUITS

Competition suits used in DH, SG and GS and clothing worn underneath, such as undergarments, etc., must have a textile surface on the inside and the outside. The surfaces may not be plasticised or treated by any chemical means (gaseous, liquid or solid) and must have a minimum permeability of 30 litres per m²/sec. Seams may only exist in order to join the portions of the suit. Outer tucks and darts are not allowed. The suits must be equally porous in all parts, both from the outside in and from the inside out. Minimum air permeability is established whereby the un-stretched fabric must show a medium air permeability of a minimum of 30 litres per m²/sec under 10 mm of water pressure (with a measurement tolerance of 3.0 litres per m²/sec).

Label attesting conformity with FIS specifications for competition suits (DH/SG/GS):

Fulfilment of requirements is to be attested by a specific standardized conformity label affixed in a non-removable way.



Width: **30mm**

Height: **45mm**

Label attesting conformity with FIS specifications for Alpine competition suits (GS/SG/DH).

CRASH HELMETS

The use of crash helmets is compulsory for all events. Only helmets specifically designed for Alpine ski racing with the embedded FIS sticker are permitted. Helmets must have a shell and padding which cover the head and ears. Only in Slalom events are soft ear helmets allowed. Helmets with edges that protrude are not permitted. Helmets cannot be modified.

**** Exception is use of certified full face cycle helmets for sit ski athletes in SL**

SKI GOGGLES

Ski goggles are devices protecting the eyes against weather and rays with optically correct lenses. Their aim is to guarantee good, contrast-free visibility in all weather conditions. The use of ski goggles is recommended. It is prohibited to reshape the ski goggles in order to obtain aerodynamic advantages.

SKI GLOVES

Gloves offer a protective covering against weather and external forces. The wearing of gloves is urgently recommended. Reshaping the glove, the application of a plastic coating on the outer surface, or the use of skai (imitation leather) with the aim of attaining more aerodynamic features, are not allowed. The glove must not reach beyond the elbow. Protective padding along the entire length of the glove is permitted. The use of protective guards in the form of shields, which are pulled over the glove, is permitted.

PROTECTORS

Competitors are allowed to protect all parts of the body with so called protectors in all events: It remains in the athlete's/NSA's discretion and responsibility to individually decide about the use of protectors.

In Downhill, protectors may not be integrated into the competition suit itself.

In all events these protectors must be worn underneath the conforming competition suit. (Exception forearm protection used in SG, GS and SL and shin protection used in SL)

Protectors must fulfil the 30 litre permeability measurement with a measurement tolerance of 3.0 liters per m²/sec with the exception of the shoulder, scapular region, chest, arms and legs. The anatomical body shape may not be changed.

Back protectors must adapt to the anatomical bend of the athlete's spine and lie flat against the body. The top edge of the back protector must be situated in the area of the spinal column and may not go above the 7th cervical vertebrae (C7). The maximum thickness must be in the middle part and may not exceed 45 mm; the thickness reduces at the edges of the back protector. Designs with the view to improve aerodynamic properties are forbidden. The back protector must be worn underneath the competition suit. It is strongly recommended to use protectors that are certified according to the latest EN 1621:2 standard.

Appendix C: Aerodynamic shaping process by Actiflow

1.1. Aerodynamic shaping – Actiflow

Actiflow started the aerodynamic shaping process with two scans. One detailed scan of the current sitski (figure 1) and a scan of the ski with the athlete (figure 2) with a less detailed frame to find the correct compression of the shock absorber in competition use.

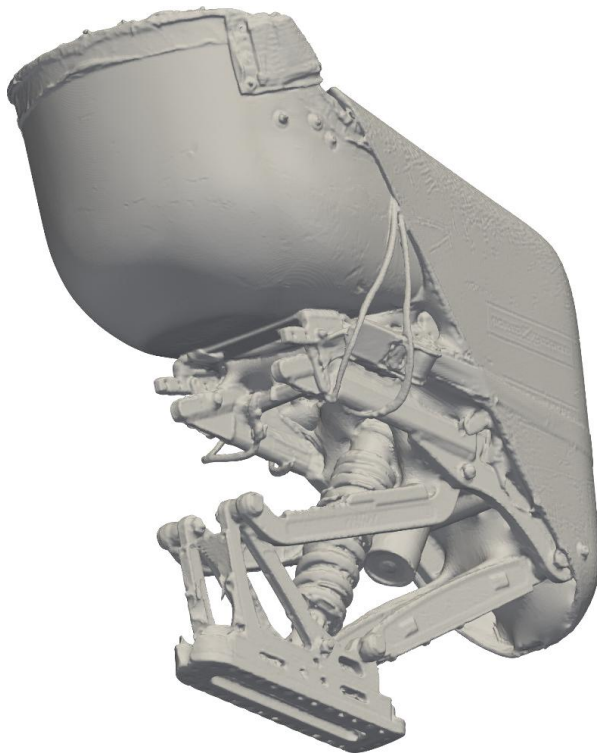


Figure 1: Detailed 3D scan of the current sitski.



Figure 2: 3D scan of less detailed frame with athlete.

By using surface wraps and manual CAD adjustments, Actiflow combined the two scans and refined the rough raw scan data into a 3D model ready for analysis, as shown in Figure 3. The model of the athlete has been placed in a domain of 45x20x10m (LxWxH). These dimensions were chosen to avoid unnatural accelerations around the athlete and to enable the use of the same calculation grid for calculations with side winds.

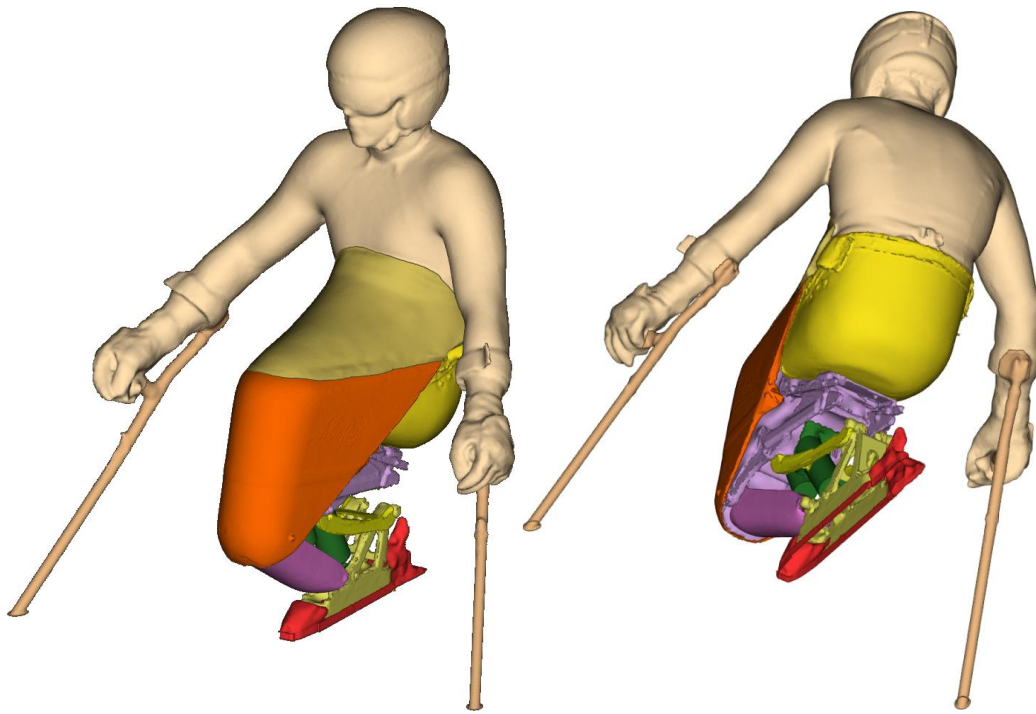


Figure 3: Improved 3D model for aerodynamic analysis.

Based on the first analysis, Actiflow started creating the first concepts freely, see Figure 24, with the goal of aerodynamic improvement. Wings v2 seemed to be the most promising concept, as the biggest pressure wake is placed behind the back of the athlete. On top of that, Actiflow concluded that the front of the ski is performing well and most aerodynamic drag is created by the athlete's posture.

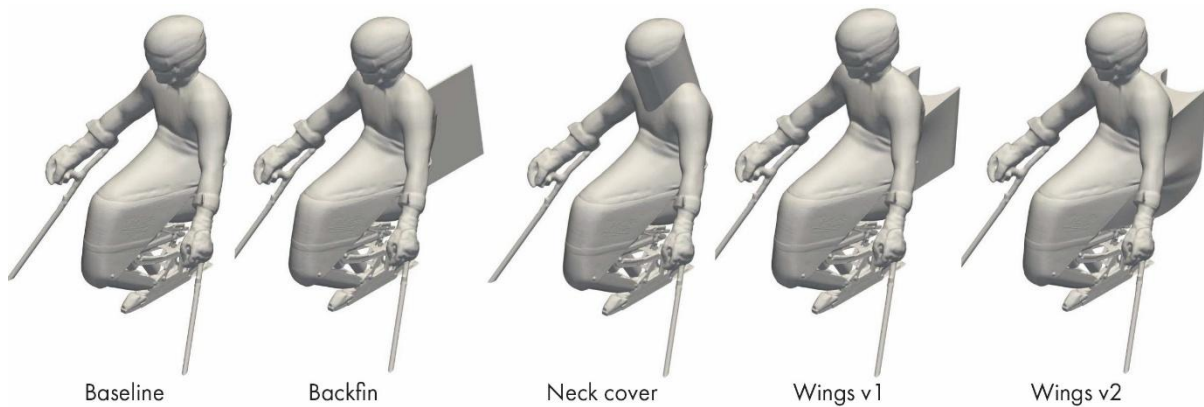


Figure 4: First aerodynamic concepts.

Based on the chosen concept direction multiple iterations were calculated regarding their aerodynamic properties. In total, 8 variations of the design were created and tested on performance. Figure 5 below shows the evolution and steps of the different variations. Wings v6 or Design 01 was the first design shared with the ZonMw project group.

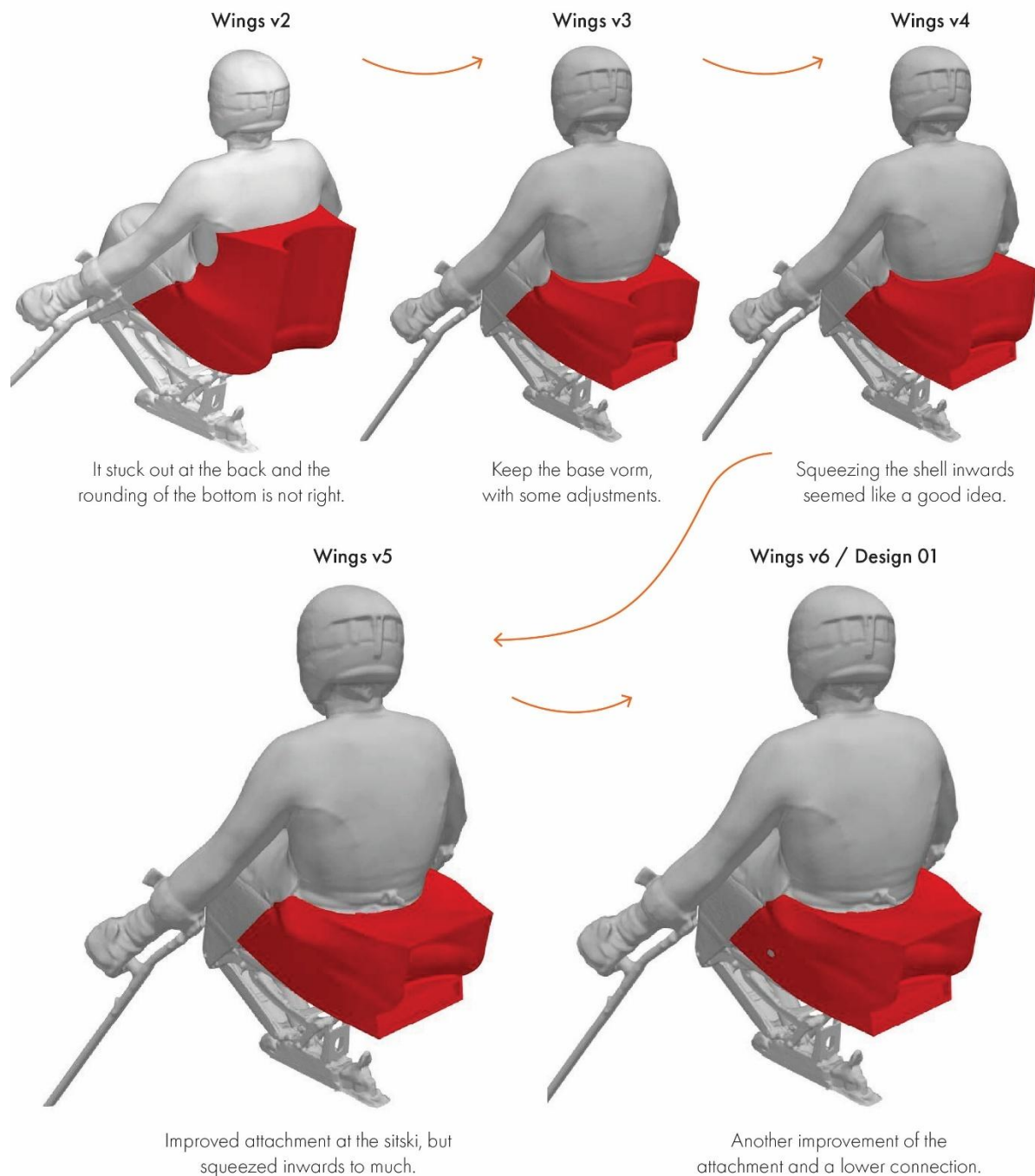


Figure 5: Wings design evolution.

Design 01 has been evaluated by the ZonMw project group to form the following feedback on the design:

1. The bottom of the design does not attach properly to the ski.
2. Why is the shape of the back rectangular at the bottom and rounded at the top? We want to round off the bottom as well.
3. The design is too wide around the hips based on the physical requirements. The shell now touches the snow first instead of the sitski.
4. The edges at the back of the design are too sharp. They should be rounded to prevent grabbing the snow.
5. The new shell component is not symmetric, probably due to the asymmetry in the current ski and abdominal part. Preferably, this new component is symmetrical.
6. Based on the physical requirements, The component is attached to far forwards. It should attach behind the abdominal belt and fastening belt.

This feedback round was a defining moment in the design process, as the new design did not touch the athlete anymore in any way. The problem area of aerodynamic performance vs freedom of movement was solved with this new design. With this feedback, designs 2.0 and 3.0 have been designed. Design 3.0 turned out to be too aggressive, so design 2.5 was created. The final designs are shown in Figure 6.

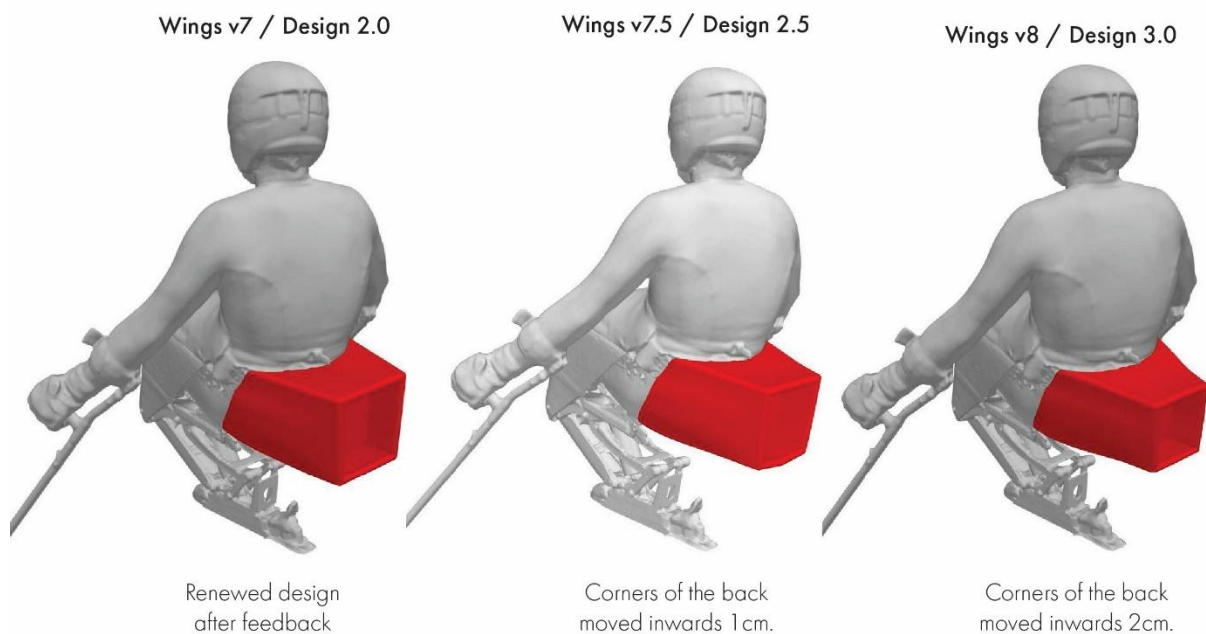


Figure 6: Final designs aerodynamic shaping.

This chapter starts with an overview of the new component's CFD simulations, followed by designing and manufacturing the wind tunnel prototypes. Furthermore, it entails the wind tunnel testing setup, method, and results. Finally, it concludes with a design choice.

1.2. CFD simulations - Actiflow

Actiflow ran computer fluid dynamics simulations to determine the best design with a baseline of the current sit ski and different added shell component designs and wind angles. From these, the expected aerodynamic gains of the new aerodynamic shell component can be theoretically approximated.

1.2.1. Simulation parameters

For the CFD simulations, a couple of important parameters were set. Figure 7 shows a visual representation of the following parameters. The average velocity for the measurements was 20m/s (72 km/hr). According to Actiflow, this is a good speed to design for.

The resistance is expressed as a resistance surface area (CDA). This is the frontal area A of the athlete and the ski times the coefficient of resistance C_D . This CDA is fairly constant with speed in turbulent flow. The flow itself also does not change significantly in this type of flow.

At the inlet, turbulence is also prescribed through a turbulence intensity (TI: 5%) and a length measure of turbulence (L: 2.5 cm). The chosen values are for some degree of free turbulence that can be expected with some wind or heat around the slope (due to crowd, front runners, wind etc.). For these parameters, a slight sensitivity in the resistance is to be expected. However, a design will also function under slightly different values.

An average kinematic reference pressure (P : 0 m²/s²) is specified on the outlet. This is an air pressure minus the atmospheric air pressure divided by the air density. Since air can be considered incompressible at speeds up to about 100m/s, this simplification is allowed.

Some simulations at crosswind were carried out. In these, the effective crosswind angle is 10 degrees, from the left.

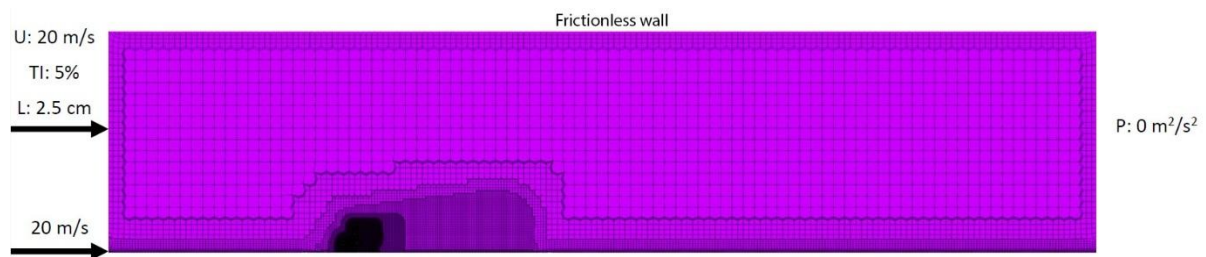


Figure 7: Visual representation of CFD simulation parameters.

1.2.2. Results

The resistance is lowest for sidewings v7 (design 02), as seen in Figure 8, with all the other sidewings v3-v8 relatively close. There is mainly an effect where the resistance force on the body and that on the wings differs. There are also small differences in the force on the undercarriage. At v7, there is a gain over baseline of almost 9.8%, at v8 this is 8.3%.

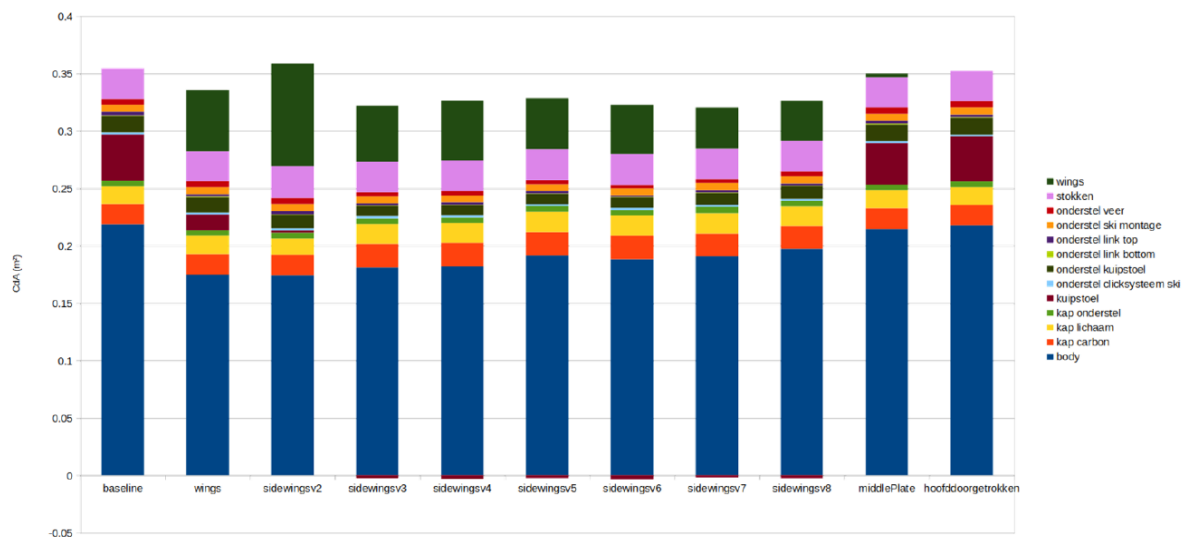


Figure 8: Resistance per part.

Figure 9 shows the pressure on the back of the athlete. Both designs show higher pressure on the athlete's back. In v7 this is higher than in v8. Also on the arms, v7 performs better than v8.

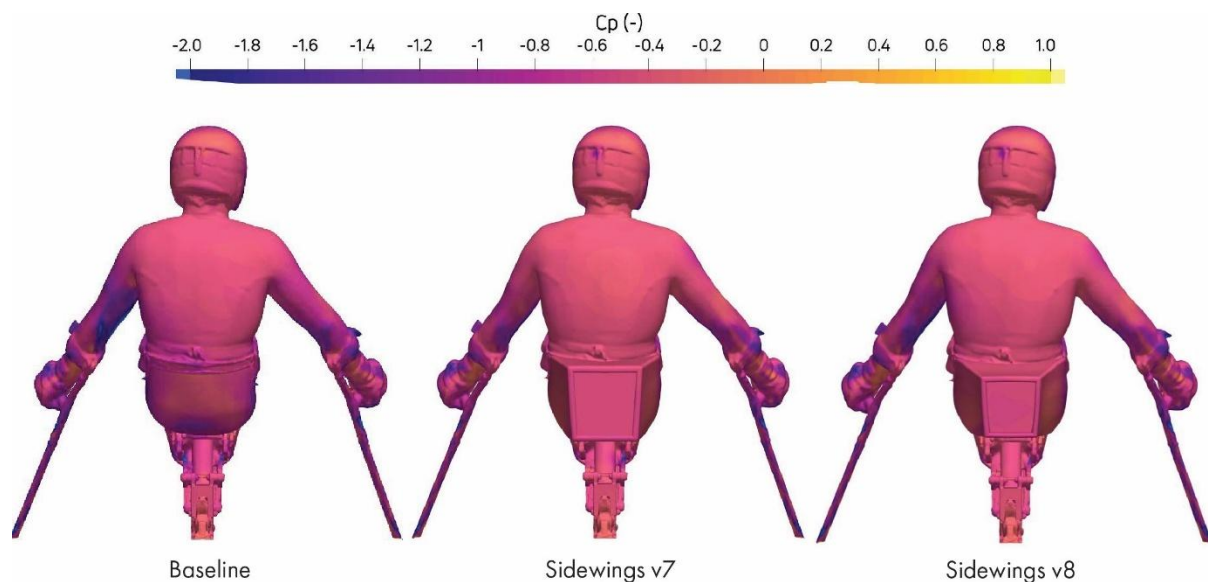


Figure 9: Pressure on the back of the athlete.

For wing versions V6 and V7, a simulation was also conducted under crosswind conditions and compared to the baseline situation. The wind was set at an angle of 10 degrees, with the goal of achieving some improvement at this angle. This corresponds to a wind speed of 3.5 m/s (12.6 km/h) coming from the athlete's left side. Figure 10 below shows that V6 achieves a gain of 3.8%, while V7 reaches 7.3%.

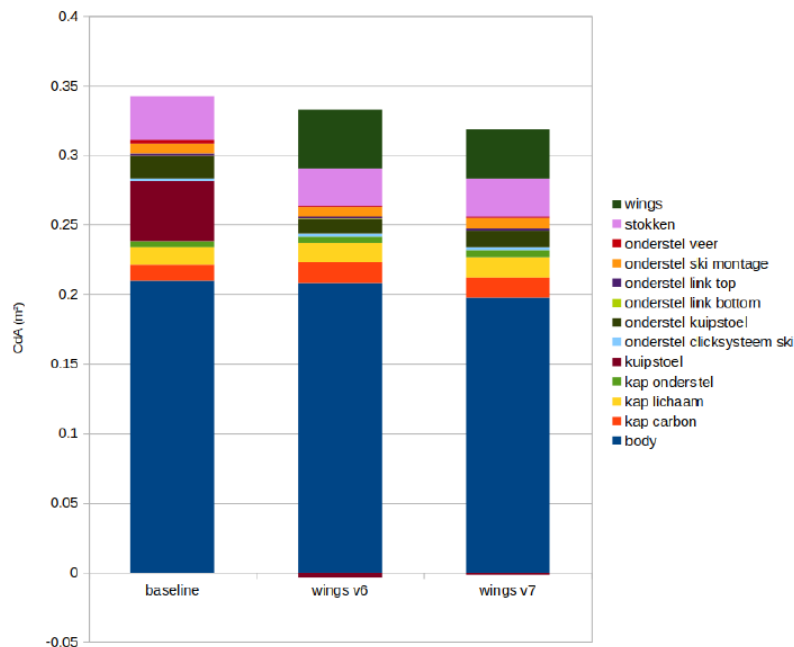


Figure 10: Resistance per part with a wind angle of 10 degrees.

Additionally, the aerodynamic moment around the vertical axis was examined, with the pivot point at the centre of the ski. For stability, it is important that this moment pushes the athlete back into the wind. At the same time, the moment should not become too large, as this would make quick directional changes more difficult. At a larger wind angle, the moment should become less positive or more negative.

The results, expressed as the moment coefficient multiplied by surface area and arm length, are shown in Table 1 below. In both cases, there is a small negative moment under direct airflow. The moment also becomes more negative at a larger wind angle. This is the desired behaviour, but practical experience will be important in influencing skiing dynamics.

Table 1: Aerodynamic moment under different angles.

Shape/Wind angle	0 degrees	10 degrees
Baseline	-0.0047	-0.0244
Wings v6 (design 01)	-0.0023	-0.0173
Wings v7 (design 02)	-0.0035	-0.0171

1.2.3. Conclusions

Design 2 shows promising results with an aerodynamic improvement of around 10% without crosswinds.

A more aggressive recoil of the sidewalls showed a higher risk of air detachment, for example, in crosswinds. For design 03, the rear vertices have been pulled inwards by 2cm. Perhaps a 1 cm shift (design 02.5) could improve aerodynamics.

For stability, designs 01 and 02 were studied under a crosswind angle of 10 degrees. They showed a similar effect as the baseline, with the new rear section resulting in a smaller moment around the vertical axis. Even at the larger wind angle, this moment was smaller with the new shape; the reduction was smaller in absolute terms but greater in relative terms. No significant effects on balance during skiing are expected, but some adjustments may be necessary.

According to these findings, design 02 shows the most promising results. The project group collectively decided to make prototypes of designs 02 and 02.5 for testing in the wind tunnel, as design 02.5 could possibly enhance the aerodynamic improvements.

Appendix D: Wind tunnel testing

1.1. Prototype design

For wind tunnel testing, prototypes of a mannequin and designs 02 and 02.5 have been produced to run multiple tests without the need for the actual athlete present.

1.1.1. Mannequin

The prototype of the mannequin has been developed based on the 3D scans made at the start of the ZonMw Project. The model has been simplified, removing the gloves and riggers attached to the scan. The arms, upper body and legs are printed separately for functional use in the wind tunnel and can be connected using a magnet system. The arms are removable and a split has been added in the legs in order to fit the mannequin in the racing suit. Figure 1 below shows the 3D scan and the printed prototype next to each other.



Figure 1: 3D scan and mannequin prototype.

1.1.2. Shell component

Actiflow delivered the designs of the shell components as a surface model without the perfect fit on the current ski. To 3D print this component and to have it fit properly on the current ski, a couple of modifications had to be made. A surface model exists of surfaces with 0 thickness. To print such a volume, these walls need to have a thickness. Figure 2 shows the process of translating the surface model to a 3D printable model. The shell component was printed in 8 separate components, due to the print size, using standard PLA print filament. After printing, the components were glued together and sanded for a nice finish.

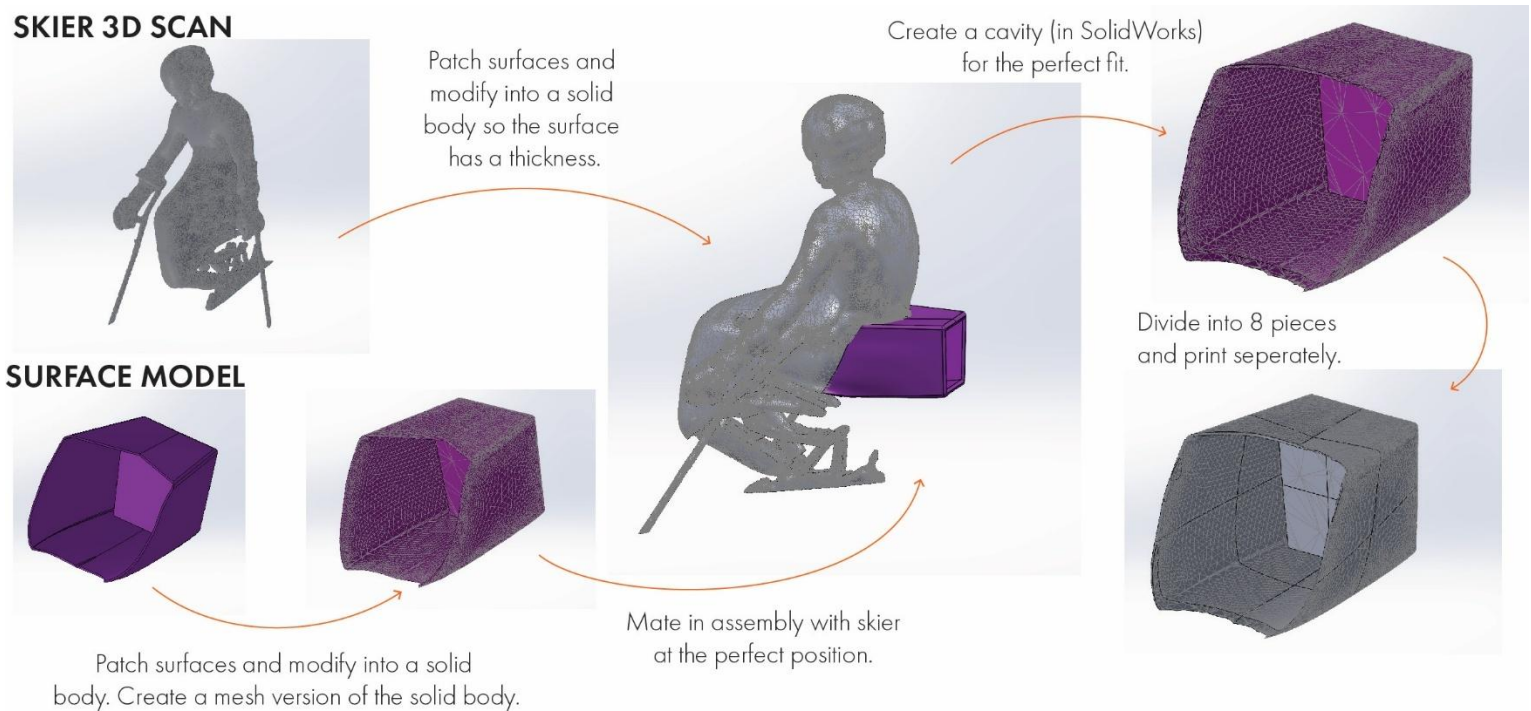


Figure 2: Translation process from surface model to printable model.

1.2. Wind tunnel testing

The prototypes have been tested in the Open Jet Facility TU Delft. The prototypes have been tested using the athlete's current sitski.

1.2.1. Setup

In the wind tunnel, the ski has been mounted into a ski binding, which was mounted to a turntable. The mannequin was wearing a competition suit (without hands) and was placed in the ski. The foam abdominal part and the aerodynamic frame cover from the prior aerodynamic optimisation project (see Chapter 2.3) were added to the setup. The designs of the new shell components were mounted to the ski using duct tape. It is important to note that the right side of the design did not properly connect to the ski because the design was made symmetrical. The ski was pressed down and locked with a tensioning strap to simulate the impact of the weight of the athlete on the shock absorber. Figure 3 below shows the setup of the model with design 2.5 connected to the ski.

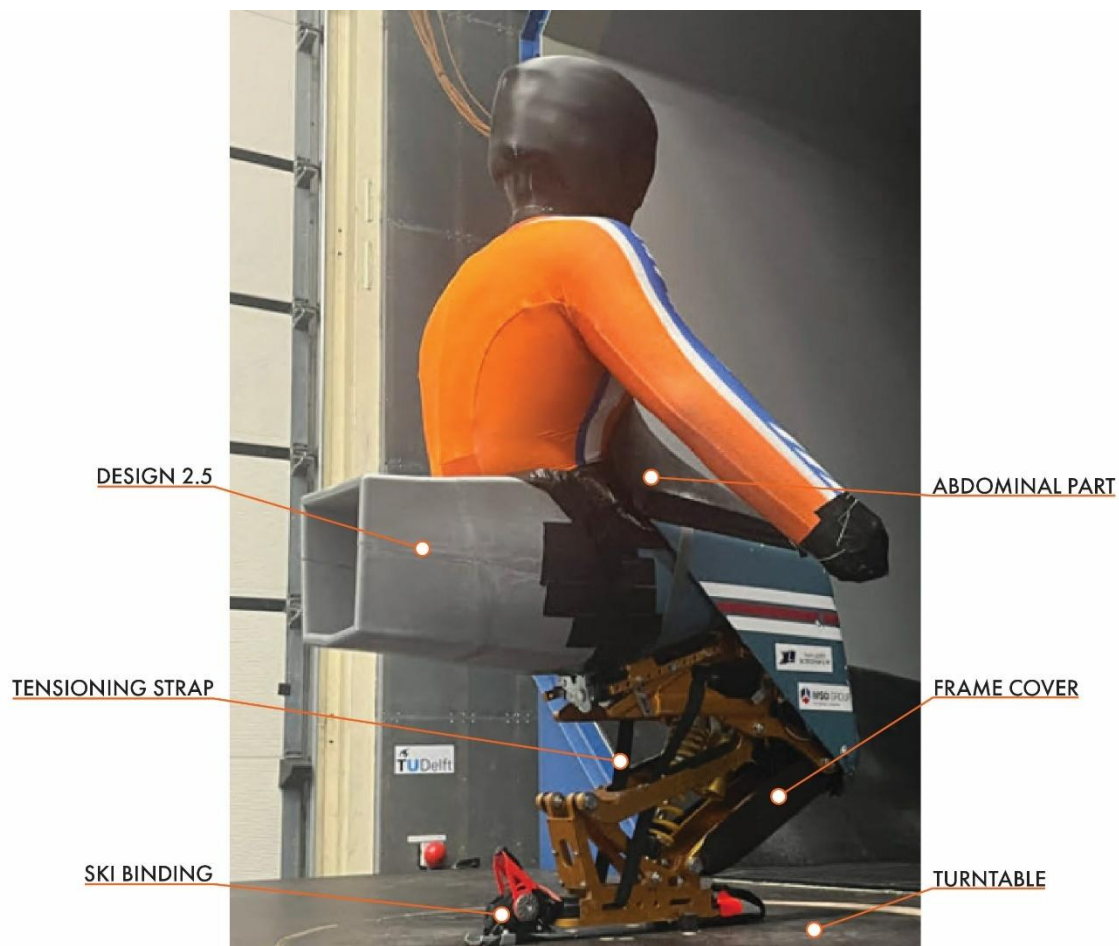


Figure 3: Wind tunnel setup.

1.2.2. Parameters

For the calculations a couple of parameters were set with Figure 4 visually showing these parameters:

- Aerodynamic drag force: F_x (D in results).
- Lateral force: F_y
- Moment around the vertical axis: M_z

To normalize the values the following calculations were used:

- $C_{F_x, F_y} A = F_{x,y} / 0.5\rho V^2$
- $C_{M_z} Ar = M / 0.5\rho V^2$

With ρ : air density [kg/m^3], V : velocity [m/s], A : frontal area [m^2] and r : torque arm from 'centre of pressure' to pivot ski [m].



Figure 4: Wind tunnel parameters.

1.2.3. Method

In the wind tunnel, a couple of variations have been tested. To start, a baseline measurement has been performed without any design attached. This baseline has been placed at a 0-degree angle (yaw), 10-degree angle and 20-degree angle.

These tests have been repeated with both design 2.0 and design 2.5. Afterwards, a couple of variations were tested to see their effect on the aerodynamics, as seen in Figure 5:

- Filling the square cavity of the designs
- Making the edges of the designs sharp using clay.
- Improving the connection with the front cover using duct tape.

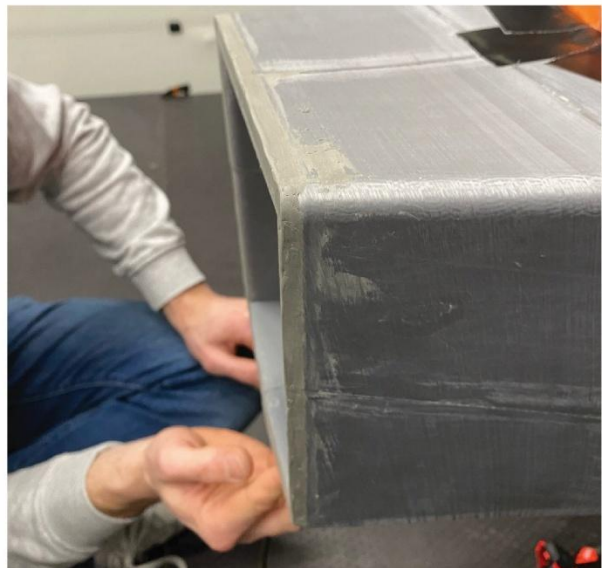
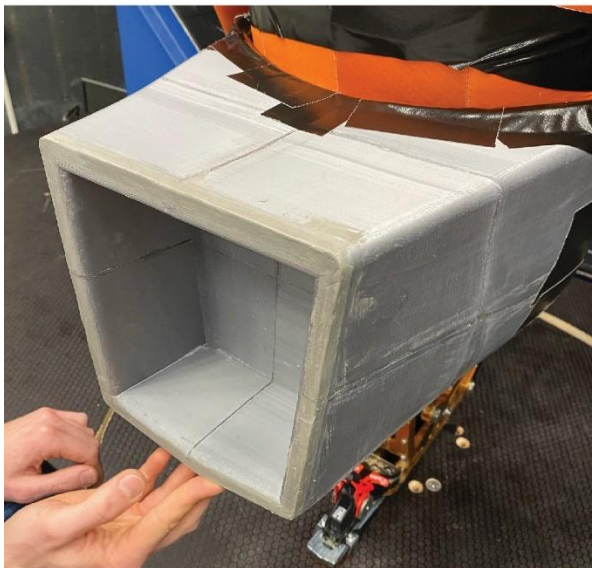
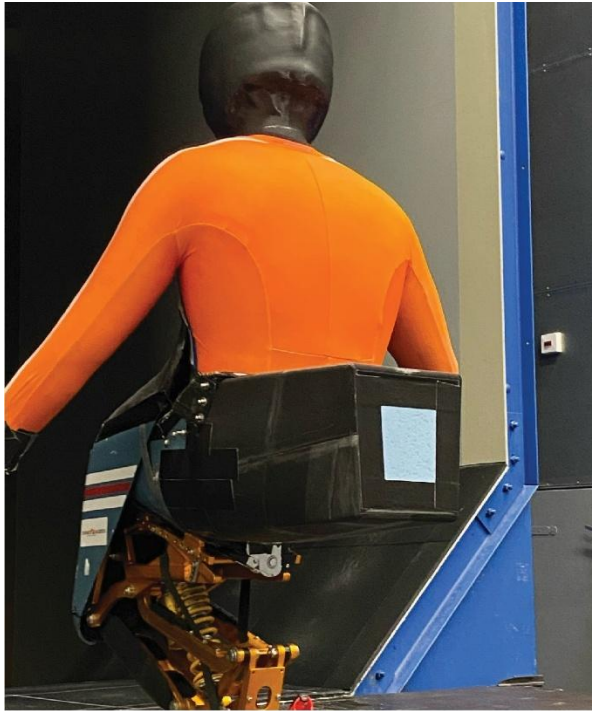


Figure 5: Wind tunnel variations.

1.2.4. Results

The baseline results, seen in figure 6, show the aerodynamic forces increasing with the velocity. The lateral force has a maximum force of 90N (yaw = 20 degrees and V = 90 km/h). The moment around the vertical axis, M_z , seems to be relatively small, with a maximum of 12 Nm.

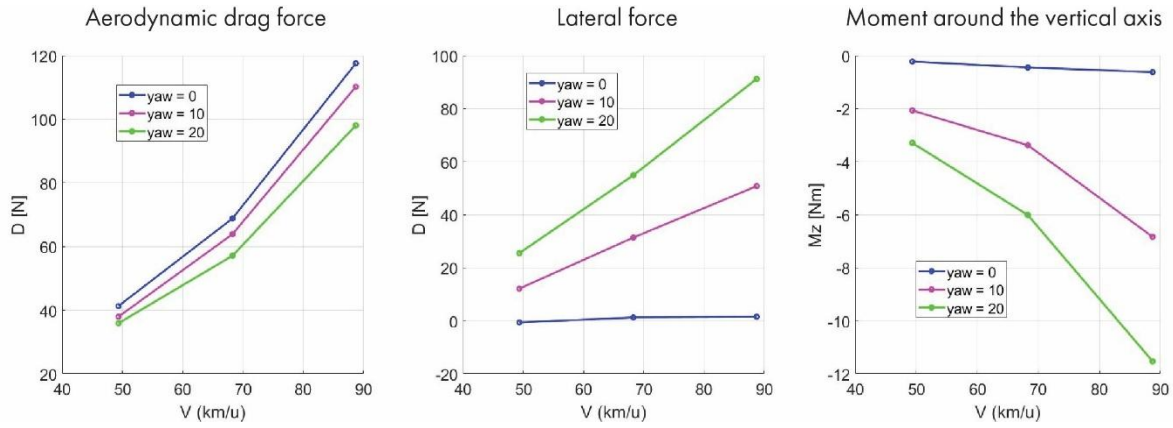


Figure 6: Baseline results.

For design 2.0 the forces of the baseline have been normalised to non-dimensional units for comparison. The baseline represents the 0 value in the following results. The difference between ski with and without the new design are expressed in $\Delta C_D A$ (delta $C_D A$).

$$\Delta C_D A = 100 \cdot \left(\frac{C_{DAmet}}{C_{DAzonder}} - 1 \right)$$

As seen in figure 7, design 2.0 results in an aerodynamic improvement of about 8% and 5% at yaw = 0 degrees and yaw = 10 degrees. The results are similar to the CFD simulations. At yaw = 20 degrees (very strong sidewind) the aerodynamic gain equals 2% at high speeds. At lower speeds we see an aerodynamic decrease of 2%.

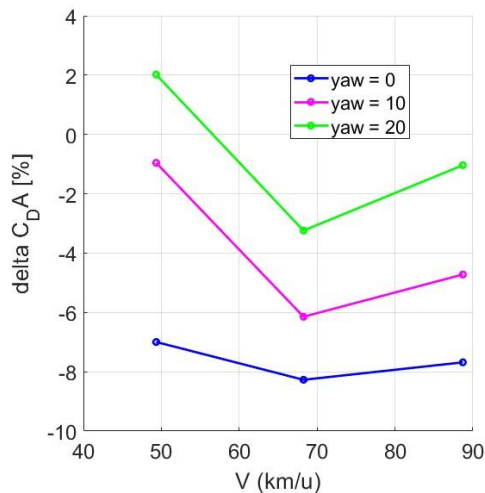


Figure 7: Results design 2.0

Figure 8 shows the results of design 2.0 vs design 2.5 (the dotted line) at different angles. The results in aerodynamic improvement are very similar. Design 2.5 performs slightly better at higher speeds.

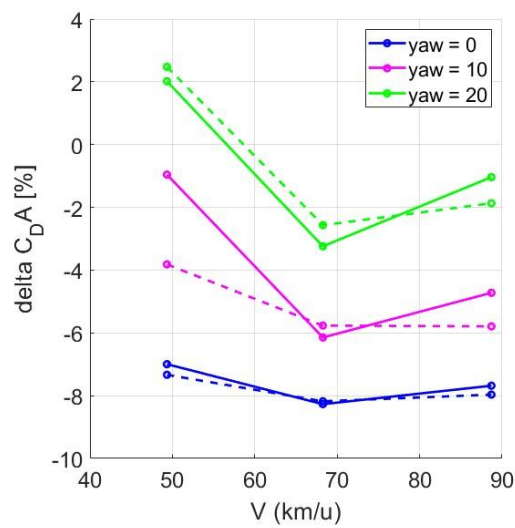


Figure 8: Results design 2.0 vs design 2.5

With both designs, as seen in Figure 9, there is a decrease of lateral force at yaw = 10 degrees, which is unexpected. At yaw = 20 degrees, the lateral force slightly increases to around 5%. The difference between the models is very small.

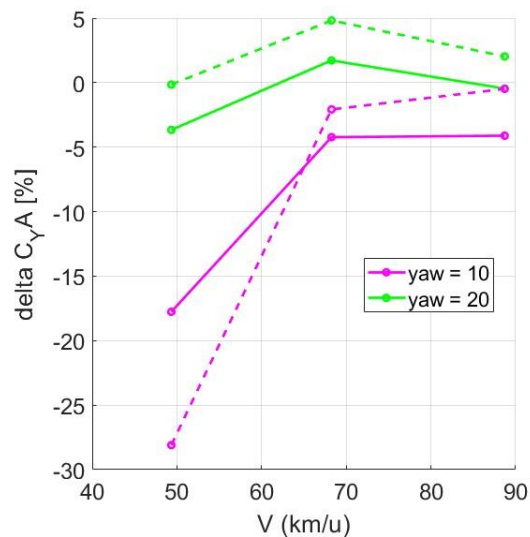


Figure 9: Lateral force results both designs.

For both designs the moment around the vertical axis slightly increases at yaw = 10 degrees, as seen in figure 10. This is also an unexpected result. This means the ski will probably be a little less stable at sidewinds. At yaw = 20 degrees, the moment around the vertical axis stays relatively similar to the baseline measurements. At higher speeds this moment around the vertical axis decreases.

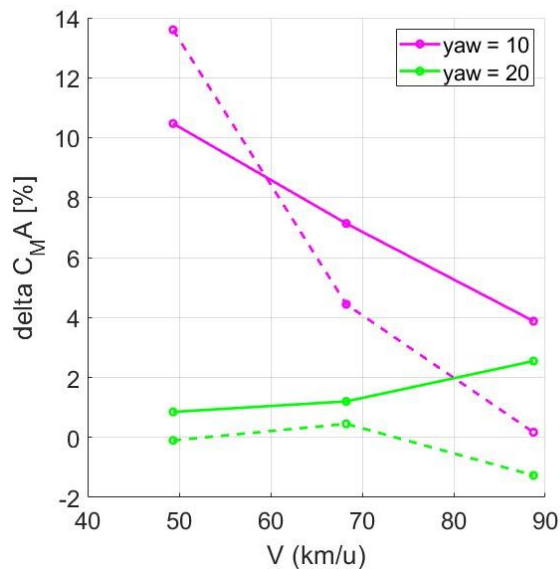


Figure 10: Moment around the vertical axis.

Design 2.0 with the filled in square cavity performs relatively similar to the design without the filling. Both the sharper edges and the improved connection to the front show about 0.5% improvement of aerodynamic drag, as seen in Figure 11.

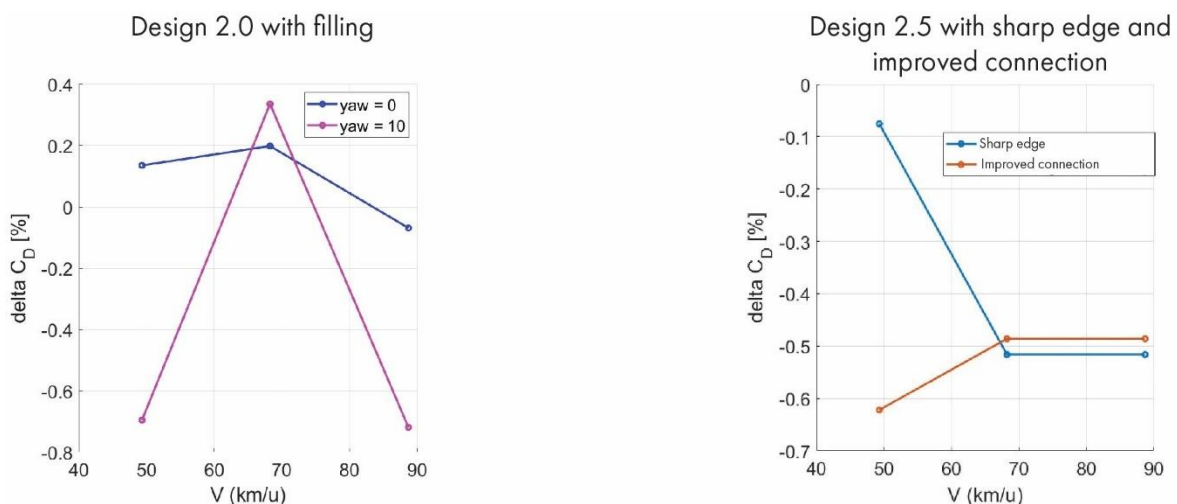


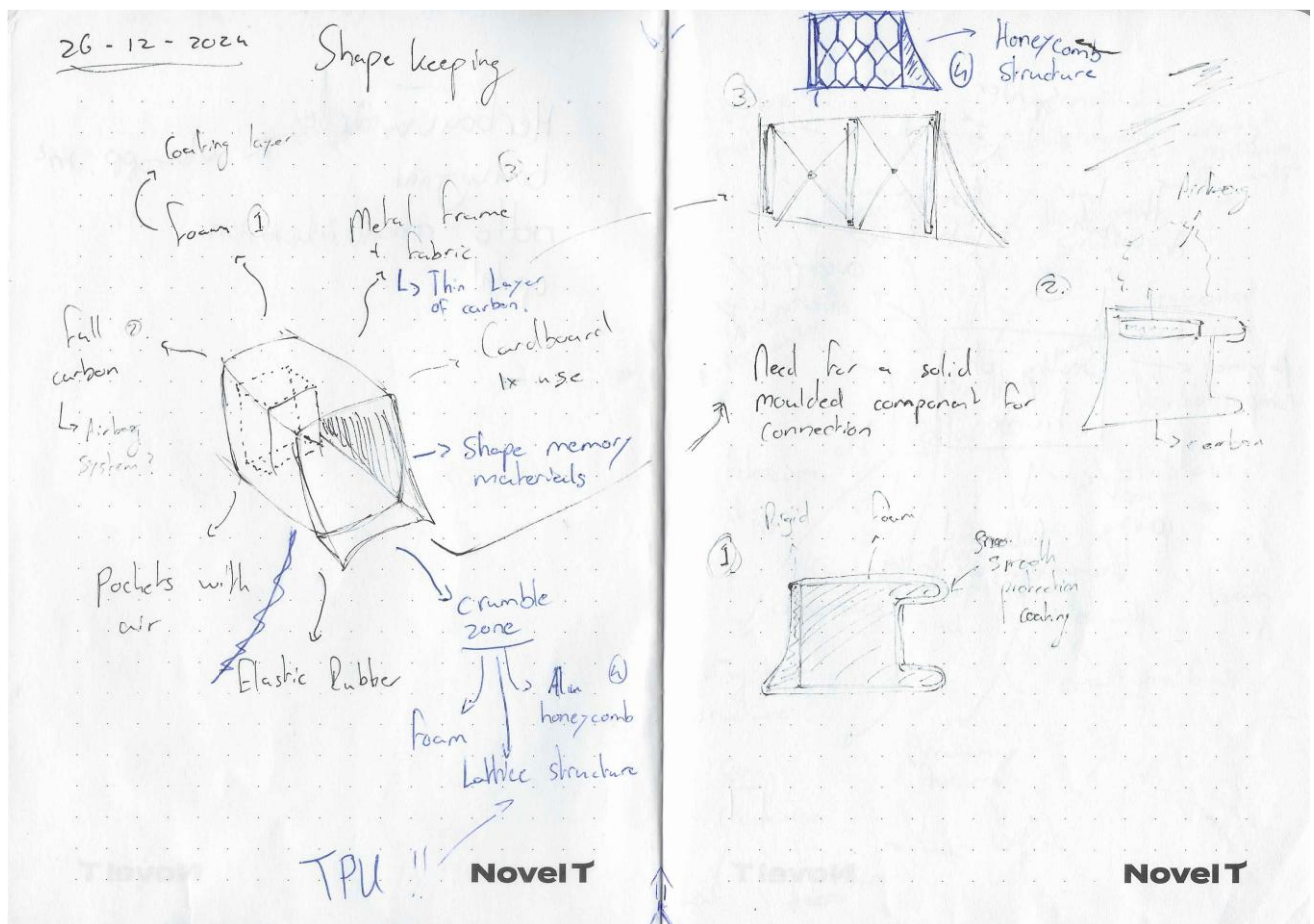
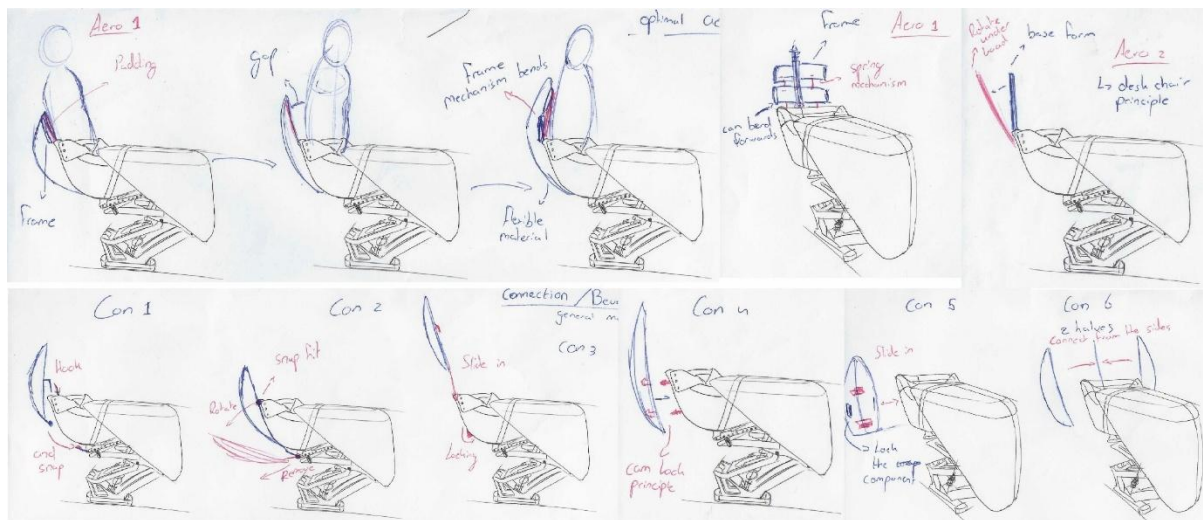
Figure 11: Results of variations.

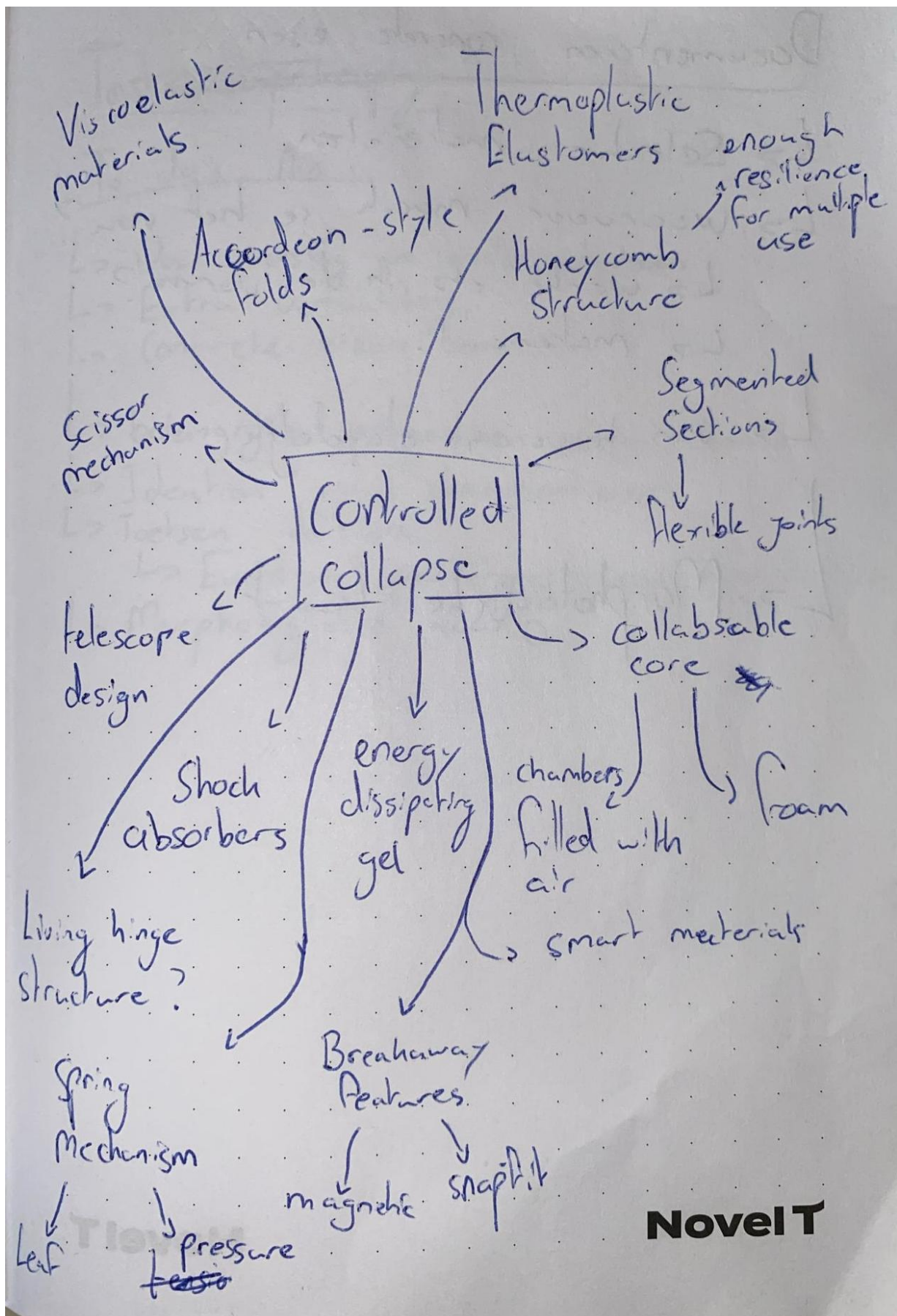
1.3. Conclusions

Both designs show a decrease in aerodynamic drag of around 8%. At sidewinds, this improvement decreases to around 5% (yaw = 10 degrees) and 2% (yaw = 20 degrees). The lateral force slightly decreases with the new components. The moment around the vertical axis slightly increases. Both designs perform relatively the same, with design 2.5 performing slightly better at higher speeds. Filling the square cavity at the back has no significant effect on aerodynamics. Both an improved connection to the front cover and sharper edges show a decrease of aerodynamic drag of about 0.5%.

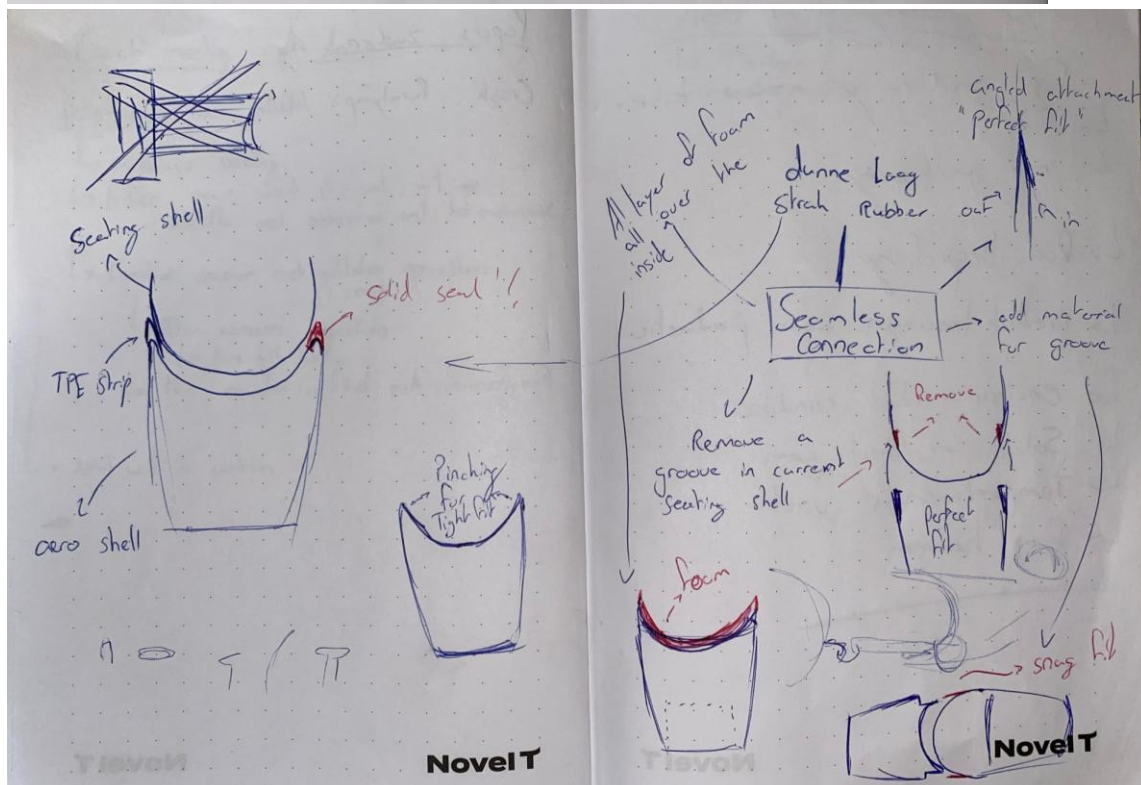
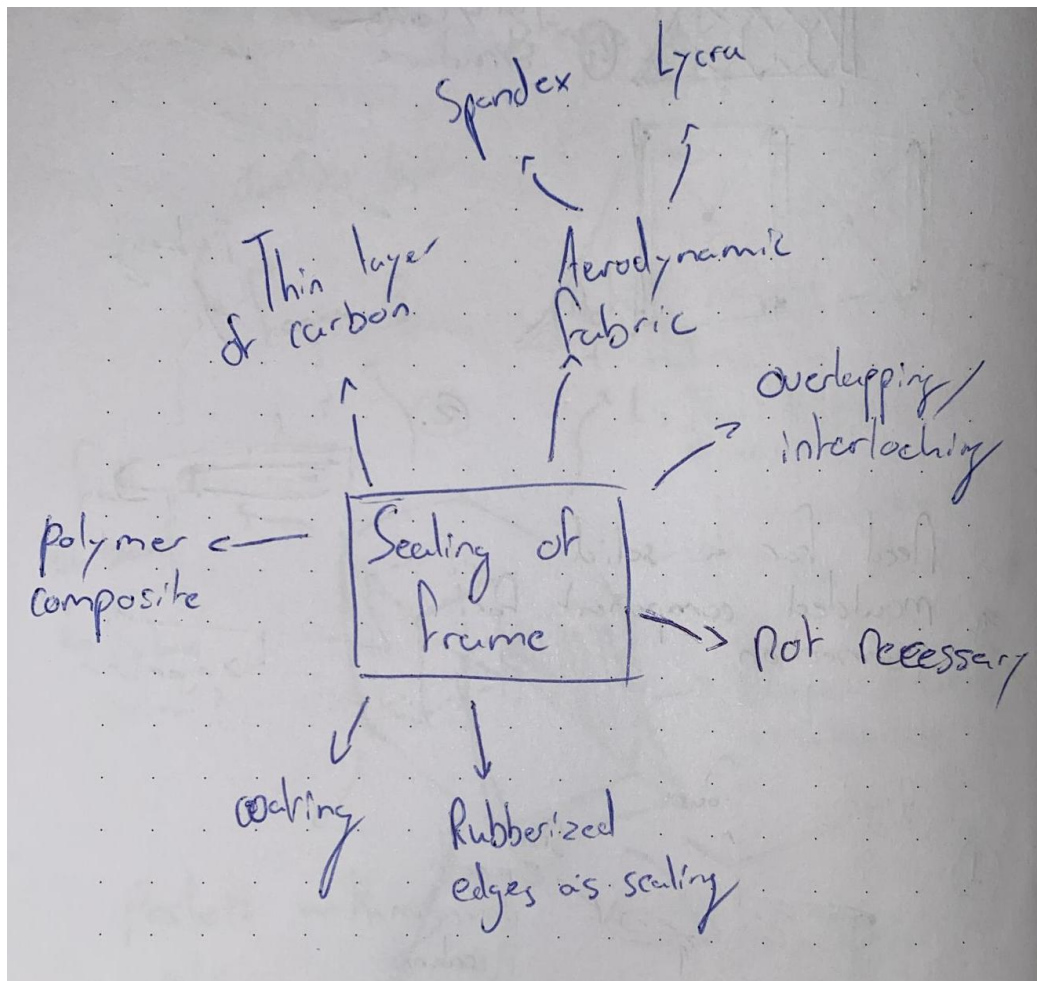
This shows the new components function properly even without the perfect fit. Taking the safety aspects in case of a crash into account, design 2.5 has a lower risk of grabbing the snow with the back, due to the edges tapering in more at this design. Based on this combined with the slightly better results, the team has chosen to continue production with design 2.5.

Appendix E: Ideation outcomes





NovelT



Bevestiging

→ Schroevendraaier binding
→ Handschoenen

↳ Taper

↳ Camlock Fasteners

282	
280	x
210	30

↳ Magnetic + mechanical stop

↳ Snap fit system

↳ Quarter turn fasteners

↳ Velcro + anchors

↳ Adhesive + Quick-Release clips

↳ Clamping design

Self-Tightening Fasteners

↳ Cam Lock fastener

↳ Toggle clamps

↳ Draw/tension latches

↳ Thumb screws + compression plates

↳ T-bolt fasteners

↳ Wedge locking system

↳ Over center clamps

↳ Screw with Captive Nut

NovelT

Appendix F: Questionnaire questions

[illegible]

Appendix G: Informed consent form

Research Design for Paraski

This research is conducted as part of the MSc study Integrated Product Design (IPD) at TU Delft. 3D scan information will be shared with the project group consisting of Actiflow, NSkiV and Roel van der Hooft Sports Engineering for designing the shell component.

Student: Brian Holtkamp

Informed consent participant

I participate in this research voluntarily.

I acknowledge that I received sufficient information and explanation about the research and that all my questions have been answered satisfactorily. I was given sufficient time to consent my participation. I can ask questions for further clarification at any moment during the research.

I am aware that this research can consists of the following activities:

1. 3D scanning of athlete and ski.
2. Interviewing for user experience.
3. Performing a low-fi test on a mounting system for a new shell component of a sit-ski.
4. Performing a high-fi test on a mounting system for a new shell component of a sit-ski.
5. Performing final product user testing in the snow.

I am aware that data will be collected during the research, such as 3D scans, notes, photos, video and/or audio recordings. I give permission for collecting this data and for making photos, audio and/or video recordings during the research. Data will be processed and analysed anonymously (without your name or other identifiable information). The data will only be accessible to the research team and their TU Delft supervisors.

The photos, video and/or audio recordings will be used to support analysis of the collected data. The video recordings and photos can also be used to illustrate research findings in publications and presentations about the project. In this case, the participant might be shown recognizable.

I give permission for using photos and/or video recordings of my participation:

(select what applies for you)

- ☐ not sharing/providing permission for data use, publications, and presentations about the project (default option)
- ☐ in which I am recognisable in publications and presentations about the project.
- ☐ in which I am not recognisable in publications and presentations about the project.
- ☐ for data analysis only and not for publications and presentations about the project.

I give permission to store the data for a maximum of 5 years after completion of this research and using it for educational and research purposes.

I acknowledge that no financial compensation will be provided for my participation in this research.

With my signature I acknowledge that I have read the provided information about the research and understand the nature of my participation. I understand that I am free to withdraw and stop participation in the research at any given time. I understand that I am not obliged to answer questions which I prefer not to answer and I can indicate this to the research team.

Last name

First name

___ / ___ / 2025

Date (dd/mm/yyyy)

Signature

Appendix H: Project brief



Personal Project Brief – IDE Master Graduation Project

Name student **Brian Holtkamp**

Student number **4,844,262**

PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT

Complete all fields, keep information clear, specific and concise

Project title **Design for paraski; a mounting mechanism for a new detachable aerodynamic shell component.**

Please state the title of your graduation project (above). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

Introduction

Describe the context of your project here; What is the domain in which your project takes place? Who are the main stakeholders and what interests are at stake? Describe the opportunities (and limitations) in this domain to better serve the stakeholder interests. (max 250 words)

The Dutch sit-skiers are among the world's elite, reaching speeds of up to 120 km/h during downhill and super-G races. The greatest opposing force they encounter is air resistance. The current sit-ski shells (as seen in figure 1) are not optimally streamlined, particularly the rear section, which causes significant drag. This project aims to reduce air resistance to enhance the chances of winning Paralympic gold in the winter Paralympics of 2026. Stability is taken into account for the design of the shell component. The shell component can not endanger the skier during crosswinds. Safety is a very important aspect in this project.

The shell component will be used in competition and during training, meaning it will have to endure high speeds, crashes and varying temperatures.

Involved stakeholders:

The project will be in collaboration with 2 athletes and coaches from the Para Ski Team (NSKiV), functioning as users of the product. As these athletes will have different body shapes and disabilities, the shells of the sit-skies need to be personalized. On top of that their needs for the usage of the product are important.

Actiflow is a company involved in the project, who are responsible for air resistance simulations and the aerodynamic shaping of the final component. We will collaborate to make sure the aerodynamic shape and connection of the new component fit.

Roel van der Hoofd will produce the prototypes for windtunnel testing and final components. He currently makes a lot of these components by hand.

→ space available for images / figures on next page

introduction (continued): space for images



image / figure 1 A paralympic sit-skier in action

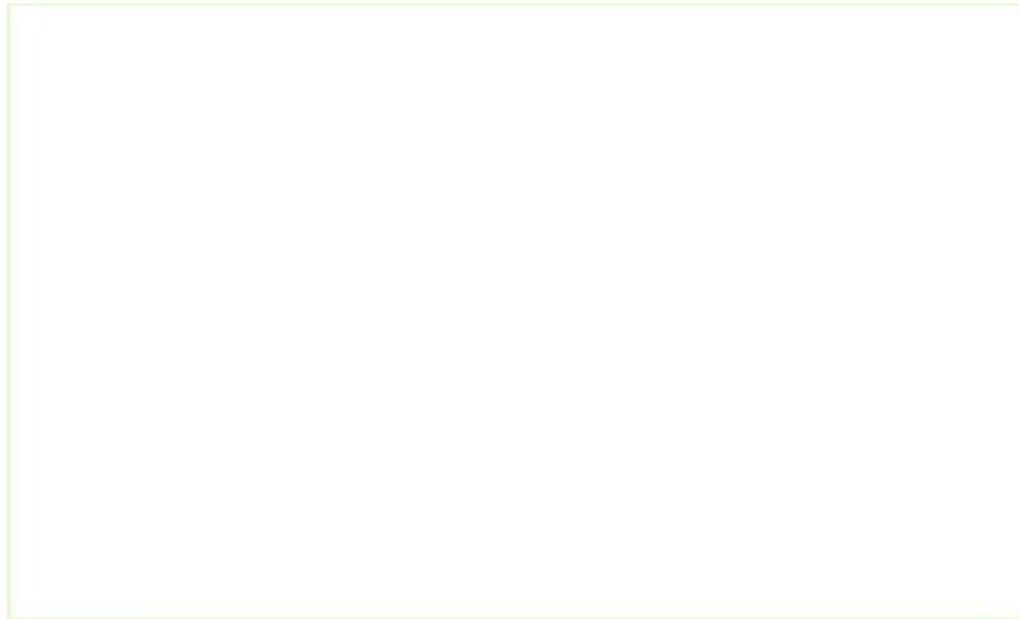


image / figure 2

Personal Project Brief – IDE Master Graduation Project

Problem Definition

*What problem do you want to solve in the context described in the introduction, and within the available time frame of 100 working days? (= Master Graduation Project of 30 EC). What opportunities do you see to create added value for the described stakeholders? Substantiate your choice.
(max 200 words)*

It is important to note my project is involved with 2 use cases: The creation of an aerodynamic shape for wind tunnel testing and the connection and use of the actual final component for the current sit-ski.

The general project goal:

The objective is to design a new, detachable shell component for the back of the seat that significantly improves the aerodynamics of the current sit-skis, without compromising stability. The goal is to achieve 10% reduction in air resistance, translating to over a second saved on a one minute descent.

Specific focus in this project:

This project needs a human factors approach, there is a delicate balance between performance and safety. The design must be safe, personalised, durable and user friendly, allowing easy attachment and detachment for transport and use in competition. The athlete's performance and needs are central in the approach.

As this project is multidisciplinary a good programme of requirements can ensure we are all on the same page.

On top of that digital fabrication methods could help improve the production process of the final pieces in making them more precise and to be able to produce the component for different athletes.

Assignment

This is the most important part of the project brief because it will give a clear direction of what you are heading for.

Formulate an assignment to yourself regarding what you expect to deliver as result at the end of your project. (1 sentence)

As you graduate as an industrial design engineer, your assignment will start with a verb (Design/Investigate/Validate/Create), and you may use the green text format:

Design a prototype of an easily detachable shell component for the back of the seat to improve the aerodynamics of the current sit-skis focusing on the usage and connection of the component for paralympic skiers in the 2026 winter paralympics.

Then explain your project approach to carrying out your graduation project and what research and design methods you plan to use to generate your design solution (max 150 words)

Familiarise and analyse: Conduct research on the competitors sit-ski's, analysing difference between the 2 current sit-ski's, contextmapping and customer journey mapping for the usage of the sit-ski, researching literature for ergonomics in sit-skiing, interviewing experts and stakeholders to formulate a solid programme of requirements.

Ideate, create and iterate: using design sprints on sub components to iteratively design and create multiple concepts regarding the connection of the shell component and ease of use. Building prototypes for testing. On top of the attachment of the new component I will make a suggestion for how to produce the final component.

Validate and evaluate: Conducting wind tunnel tests with athletes to measure performance improvements, testing attachment ease of use with prototypes and users. Make some adjustments when necessary and jump back to a design iteration.

Finalize: Document all the findings in a report and prepare a final presentation for the team to share results.

Project planning and key moments

To make visible how you plan to spend your time, you must make a planning for the full project. You are advised to use a Gantt chart format to show the different phases of your project, deliverables you have in mind, meetings and in-between deadlines. Keep in mind that all activities should fit within the given run time of 100 working days. Your planning should include a **kick-off meeting**, **mid-term evaluation meeting**, **green light meeting** and **graduation ceremony**. Please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any (for instance because of holidays or parallel course activities).

Make sure to attach the full plan to this project brief.
The four key moment dates must be filled in below

Kick off meeting	1 Oct 2024
Mid-term evaluation	10 Dec 2024
Green light meeting	25 Feb 2025
Graduation ceremony	1 Apr 2025

In exceptional cases (part of) the Graduation Project may need to be scheduled part-time. Indicate here if such applies to your project

Part of project scheduled part-time	✓
For how many project weeks	25
Number of project days per week	4,0

Comments:

I will be working 1 day a week to financially support myself during graduation. On top of that I will be on a vacation from 24-12-2024 to 2-1-2025.

Motivation and personal ambitions

Explain why you wish to start this project, what competencies you want to prove or develop (e.g. competencies acquired in your MSc programme, electives, extra-curricular activities or other).

Optionally, describe whether you have some personal learning ambitions which you explicitly want to address in this project, on top of the learning objectives of the Graduation Project itself. You might think of e.g. acquiring in depth knowledge on a specific subject, broadening your competencies or experimenting with a specific tool or methodology. Personal learning ambitions are limited to a maximum number of five.

(200 words max)

I enjoy sports a lot, especially pushing yourself past your limit during sports. To be able to contribute to a product that helps push the boundaries of paralympic skydiving speeds is immensely interesting to me. I know from first hand experience how hard it is to not be able to play the sport you love, which is why I am an immense fan the work paralympic athletes do to also inspire young people. Of course I like skiing a lot as well, to be able to contribute to such a high level of the sport is amazing.

During an internship at VANMOKUM last semester I figured out I really enjoy solving the puzzle of improving a current product within certain boundaries. I learned a lot about SolidWorks, Rhino and prototyping and I want to apply and improve these skills in this graduation project, especially my knowledge about simulations.

This specific context of sports engineering is new to me, however I have done a project with impaired people before. I really enjoy working on very specific solutions for them to be able to improve the things they do. In this project, helping the athletes seriously improve their time and making the product user friendly gives me a lot of satisfaction and I am looking forward to diving in their experience. I want to help these athletes as good as possible to be able to achieve the best results we can. On top of that this project is perfect for broadening my knowledge in the sports engineering world. A world in which I am very interested, but did not know how to enter.