Production optimalisation

Optimising the assembly by standardisation
for fully customisable wheelchairs

Master thesis Integrated Product Design
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I want to thank Pezy Group for giving me the opportunity to graduate at their place and work on a project they provided for me. I also want to thank my colleagues for their expertise, thinking-along and brainstorming talents, and the nice ping-pong breaks in between.

O4 Wheelchairs, where I immediately felt welcome and spent some long days closely analysing their production line. Especially Krein, Martin and René for always being happy to help and provide feedback.

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Although this project had its ups and downs, looking back at it, I see that it is a positive experience I will take with me for the rest of my life.

Summary

This master thesis was completed at the TU Delft in collaboration with Pezy Group for the company O4 Wheelchairs, with the goal of optimising the production and assembly of their wheelchairs, by standardising the wheelchair design.

In the field of fully customisable wheelchairs (ultra-personalised products), the conflicting interest of the need for customisability and standardisation to optimise production is prevalent. By standardisation of the wheelchair assembly, without compromising the needed customisability, the production time of O4 wheelchairs can be improved benefiting both the company and its stakeholders.
To achieve the goal of a shorter production time, the production at O4 Wheelchairs was analysed, and multiple opportunities were formulated. These opportunities were further elaborated by turning them into design questions, and their potential was assessed with brainstorming sessions and low-fidelity prototyping. From these opportunities, one direction for a concept was chosen to be fully developed in this project. In contrast, the others were formulated into a roadmap of specific steps for O4 to take to improve their production.
The chosen concept was further developed by prototyping and testing, ranging from cardboard and 3D printed models to fully laser-cut aluminium parts.
This led to a design proposal for a new fender assembly. This new fender assembly integrates the brake into the assembly and ensures exact fixation without the need for measuring. It is usable in all wheelchair configurations and with the three sold wheel sizes.
Testing the new fender assembly with assembly workers at O4 Wheelchairs resulted in an estimated time of 16 minutes, compared to the 37 minutes it takes to assemble the old fender assembly.
The improvement of 44% in time, a cost decrease of roughly €30 and the design being less error-sensitive due to the straightforward way of fixation, all add to the value brought to O4, with the design proposal.
This project provides multiple starting points for O4 Wheelchairs to further improve their production and product line. The design proposal also promises a substantial improvement to their current fender assembly.

This video presents the design proposal:
https://youtu.be/UXuV5QWDdHE

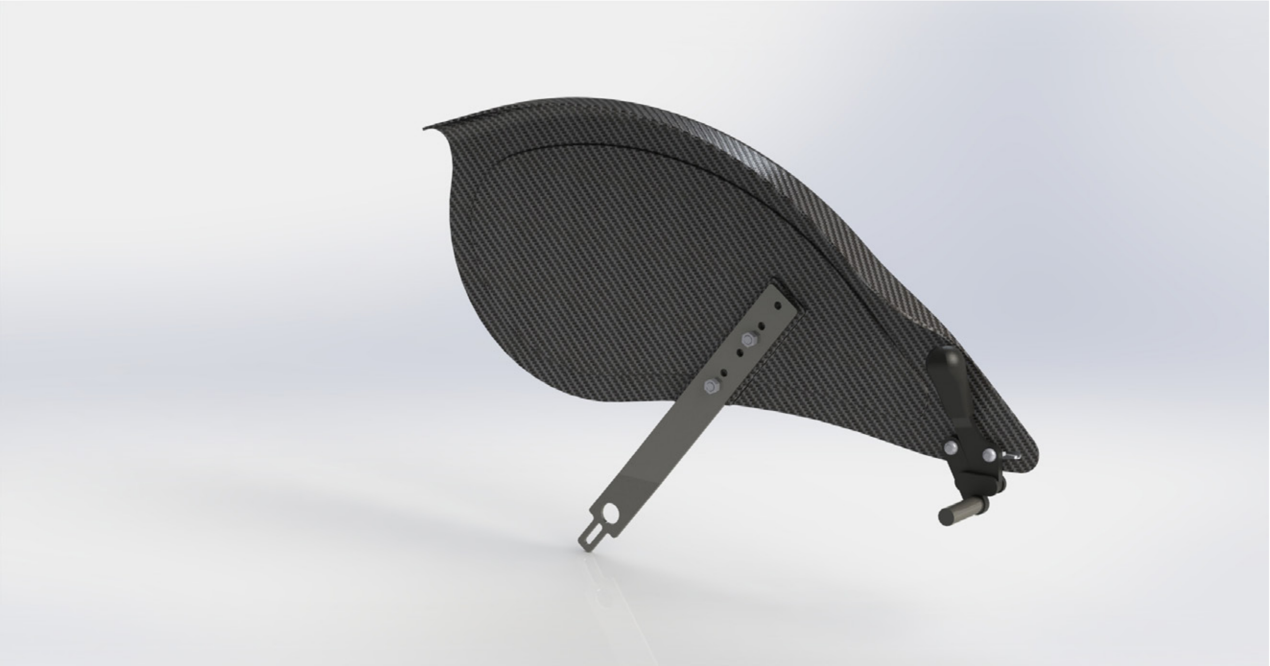


Figure 1, Design proposal

Contents

1. Introduction

In this chapter, the project is introduced, and the problem statement and design goal are defined. Then, the project scope is set in consultation with the project stakeholders to align the expectations. Finally, the relevance is substantiated to fulfil this project.

1.1 Project Introduction

In the world of rehabilitation and care for people, there are roughly 65 million wheelchair users and many more that need one (WHO, 2023). With numerous different users with different needs and interests, this market is good for 4.5 billion euros in 2022 and growing (Grand View Research, 2022). To put this into perspective, it is comparable to the global fire detector or global avocado market. (GlobeNewswire, 2023 & BusinessWire, 2020)
As the market is dominated by cheap and fast-manufactured wheelchairs for rehabilitating users, a smaller, yet more specialized segment is focussed on people who need a wheelchair every day, for example, people with a spinal cord injury or types of muscular disease like ALS (Savagea et al., 2019).
O4 Wheelchairs is a Dutch wheelchair manufacturer and seller that specializes in this target group. They develop wheelchairs with the unique selling point of being able to mechanically adjust the seat and back pitch during the day for an ergonomic and adaptable posture suited to the tasks at hand. The wheelchair's movement is shown in Figure 4.
O4 is currently the only company offering this specific kind of adjustability in Western Europe (O4 Wheelchairs, 2023).
As all users are different, all wheelchairs for this group need to be custom-made for the user to suit and function properly.

1.2 Problem Definition

In the field of ultra-personalised products, where wheelchairs are a good example, conflicting interests are at play. On the one hand, products (and thus companies) benefit enormously from making products in mass and standardising dimensions. The fewer different products or configurations you make, the more efficient (cheaper and faster) you can produce said products. On the other hand, in the wheelchair market described above, there is a need for 'perfect fitting' wheelchairs as it is essential for optimal performance and usage. This is an industry-wide problem that has no simple solution (ClickNL, n.d.). Wheelchair manufacturers often focus on fully custom wheelchairs, or wheelchairs that compromise a lot on the fit of the user and become very generic. This is often a fine solution as; people rehabilitating from a broken leg need a wheelchair for roughly 6-8 weeks. A perfect fit is not that important in such a scenario (NHS, 2024). Nevertheless, in case of a spinal cord injury, you need a wheelchair every day, forever, and compromises have a lot more impact on the user.
O4 Wheelchairs specialises in making custom wheelchairs exactly to the user's needs. However, the trade-off is that it results in long production times having a negative influence on, for example, the costs and satisfaction of their customers (O4 Wheelchairs, 2023). If their wheelchairs could be more standardised but still allow for the same customisation, a big step could be made, for both O4 as a company, their retail and assembly employees, resellers and the users themselves, as it would shorten the production time and decrease costs.

A summarised problem statement might be:
The conflicting interest in manufacturing custom wheelchairs perfectly adapted to the user's needs and the need for standardisation and quick production of these wheelchairs.

Design goal:
Create a substantiated overview of opportunities to improve production time, without compromising the customisation. By mapping out the production chain and assembly steps, a numerical image can be created to base potential improvements on.

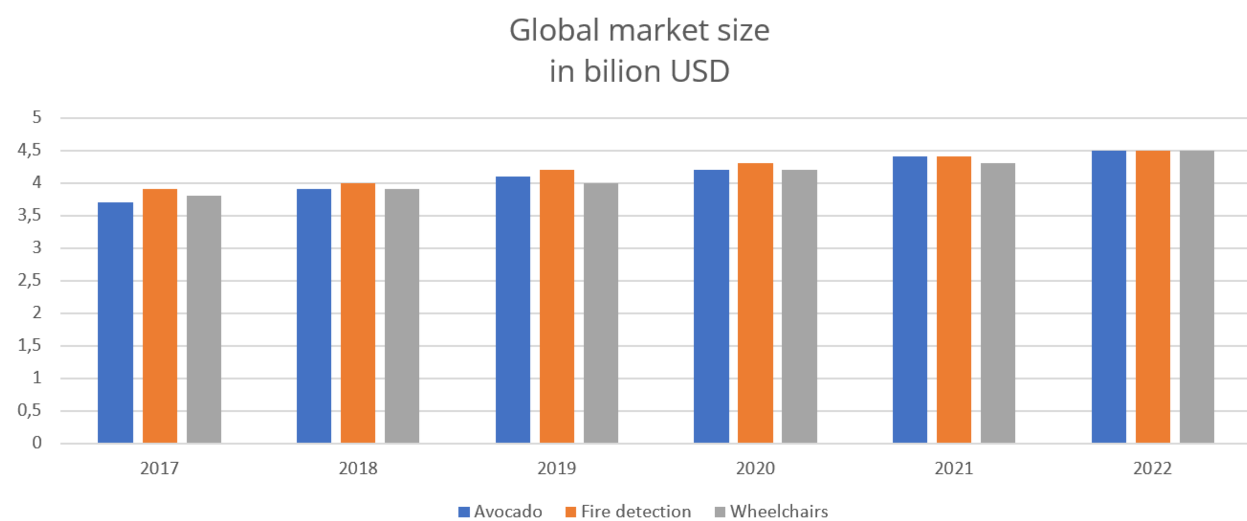


Figure 2, Market size comparison with global wheelchair market

1.3 Project Scope

The initial project is described as developing solutions for primarily challenges 1 and 2 (The need for standardisation without compromising the customisation and having a spread out and equal workload during the year (see chapter 2.2).
A direction would be to find which combinations of measurements have the most potential to be standardized and see if those wheelchairs can be redesigned to have fewer parts, with the same customizability.
This would add value by requiring fewer man-hours in assembly and more standardized manufacturing steps and parts in the production process, which would benefit the costs for O4 and the customer, as well as time to delivery.
Another (or combined) direction could be to investigate which parts and subassemblies of the wheelchair have the most influence on the assembly time and costs and see if the customisation steps can be done later in the assembly process to allow for more premade and standard sub-assemblies.
This would have the same benefits as the first opportunity plus O4 can have more sub-assemblies in stock that are usable for all wheelchairs, as well as the ability to schedule work more independently from wheelchair orders and the possibility to outsource some sub-assemblies.
These directions would lead to cheaper wheelchairs (that are faster made) and the spreading out of the workload.

Initial observations of the production process and conversations with different stakeholders (O4 management, production workers, university team and Pezy group designers,) lead to the specification of the project scope and a desired outcome.

One main goal stayed the same: make the wheelchairs quicker to produce. This would benefit the company and all its customers, and in itself, tackle the spreading out of the workload, at least for a bit, because order peaks will have less impact when they can produce more at the same time.
The project was narrowed down due to time constraints to analyse the whole production but to focus on only redesigning the wheelchairs. The findings from other parts of the production (for example, the layout of the factory) should be written down as recommendations for O4 to further develop.
A specific requirement was formulated based on challenge 4, which is that the redesign of (part of) the wheelchair must make assembly quicker, and thus, adjusting by second parties is easier. The reason for this focus was again the 'two birds with one stone' practice, as by making the assembly quicker, it would probably be also quicker for others and thus improve the brand image.
Aspects like the layout of the factory floor and the ergonomic circumstances for employees are left out of the scope, to focus on accomplishing the design goal by redesigning products (the wheelchairs). This is done to ensure a suitable project for the field of IDE and the small production volumes at O4 make it likely that improving on these aspects might not outweigh the (time) investment needed to improve them.

The newly agreed assignment statement was as follows:

Redesign and prototype (parts of) the wheelchair of O4, to minimise the need for all fully custom parts and thus reduce the production- and assembly time, while still accommodating the needed customisation for the target user.

1.4 Importance to O4 & Pezy

O4 Wheelchairs is a relatively small company with roughly 6 employees, that manufacture and sell wheelchairs. They are based in Varsseveld and sell their wheelchairs predominantly in the Netherlands, Germany and Belgium. They sell directly to customers, but a big part of their output goes to aid-providing organisations, that provide wheelchairs to people in their network. So a combination of the business-to-business and business-to-consumer model is used.
O4 was founded in 2004 and has been developing its wheelchairs and seating system in-house until the end of 2022 when Pezy Group (a design agency) acquired a majority interest in O4 Wheelchairs. Pezy Group started to take over the development of the wheelchairs, while O4 kept manufacturing and selling them.
Pezy Group is a large design agency with roughly 70 employees based in Eindhoven, Houten, Groningen, and Singapore. Founded in 1995, it provides industrial design services to other companies and sometimes starts strategic partnerships with innovative companies.

By fulfilling this project the hope is to deliver actionable recommendations and opportunities that could improve the overall production time of the O4 wheelchairs. By doing so, O4 benefits, and thus Pezy Group. I undertake this project from Prezy Group, as a designer, to further develop their products.

Why now? As said, Pezy Group has acquired a part of O4 in 2022. From that moment an internal reorganization was started, on the product level, but also operational-wise. At the moment, the product portfolio is largely simplified and the focus has changed more towards the direction of increasing sales instead of a large product portfolio (O4 Wheelchairs, 2023).

Concluding this chapter, it can be said that by fulfilling this project, substantial value could be gained for O4 and Pezy Group. The delivered product at the end of this project will consist of two parts. A design proposal backed with a prototype as stated in the assignment statement. Next to that, recommendations to O4 are likely to come up during the remainder of the product, so providing those in a clear way is the second way to provide value. This is all done in agreement with both O4 and Pezy Group.

2. Broad Context

In the following section, the current situation at O4, the stakeholders, the main challenges and current solutions are described. The section ends with the rephrasing of the project scope to how it is used for the rest of the project.

2.1 Current Situation

O4 Wheelchairs offers a series of four types of wheelchairs (see Figure 3) that have the unique feature of having an adjustable backrest and a seat. The combination of these two (as can be seen in Figure 4) makes them unique in the world of adjustable wheelchairs and interesting for specific users who need this easy adjustability.
To quickly describe the differences between the 4 wheelchair types: the Flow Active has adjustable seating and backrest, the Flow Original only has the adjustable backrest, and the Flow Relax offers adjustable feet support and a larger adjustable seat pitch. Finally, the Flow Mono is a lighter version of the Flow Original. All wheelchairs can be fully customised to the needs of the customer with for example: armrests, head support and different wheel sizes. Of course, all types of wheelchairs are made to fit the user, by changing roughly 15 measurements like seat width, depth and height, backrest height, and the position of the seat to the rear axle. Apart from all the options O4 offers, they also specialize in fully custom requests like the exact control lever position, one-hand operated brakes or the option for electrically powered wheels (O4 Wheelchairs, 2023).
O4 is a fairly small company and employs four people full-time (manager, assembly worker, welder and customer service) and four part-time. Apart from that, employees of Pezy Group mainly do the product and innovation projects. This means that there is a lot of in-depth knowledge about production by a small number of people. Being at O4, a quote from one of the employees was 'We always do it like this" and "I know how to do this because of my experience". According to Rothwell (2011), this can become a big risk to the company as the so-called 'knowledge workers' contain a lot of company value and when they leave that knowledge could easily be lost. Even so, the production of the wheelchair is not always straightforward and allows for human error to occur.

Figure 4, Double seat ajustability, unique to O4


Figure 3, Four sold types of wheelchairs at O4

The company sells about 170 wheelchairs annually, translating to an average of 3.5 per week (see Figure 5). There are peaks of 16 orders per week and weeks without orders.
However, because all wheelchairs need to be customised, it is very hard to pre-make wheelchairs or larger sub-assemblies to put in stock.
O4 uses an average time of 4 hours to produce one wheelchair, which means that theoretically, they can make 10 wheelchairs every week (without taking into account other peripheral matters). Their goal is to grow in the near future to an average of 5 orders per week. If the same fluctuation percentage is kept, it will result in peaks of roughly 27 weekly orders. In practice, the fluctuation will probably not be linearly the same, but it will still be a large number.

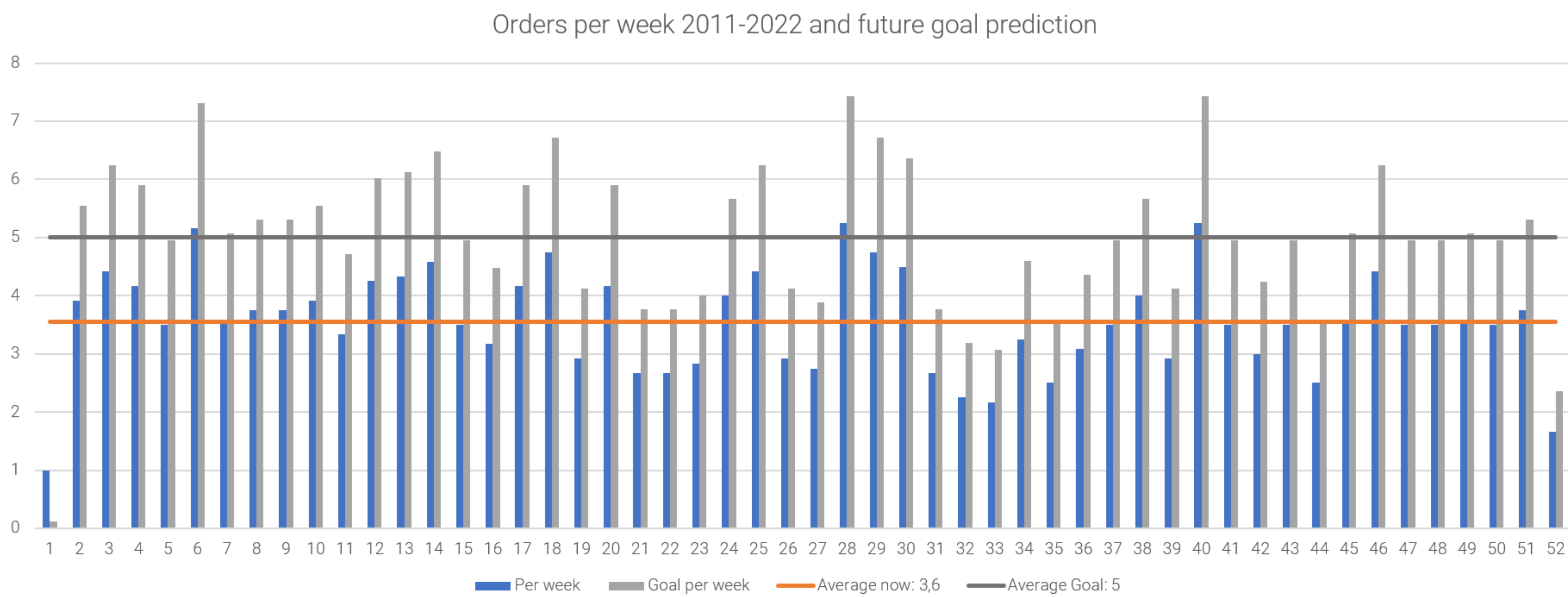


Figure 5, Orders per week & prediction

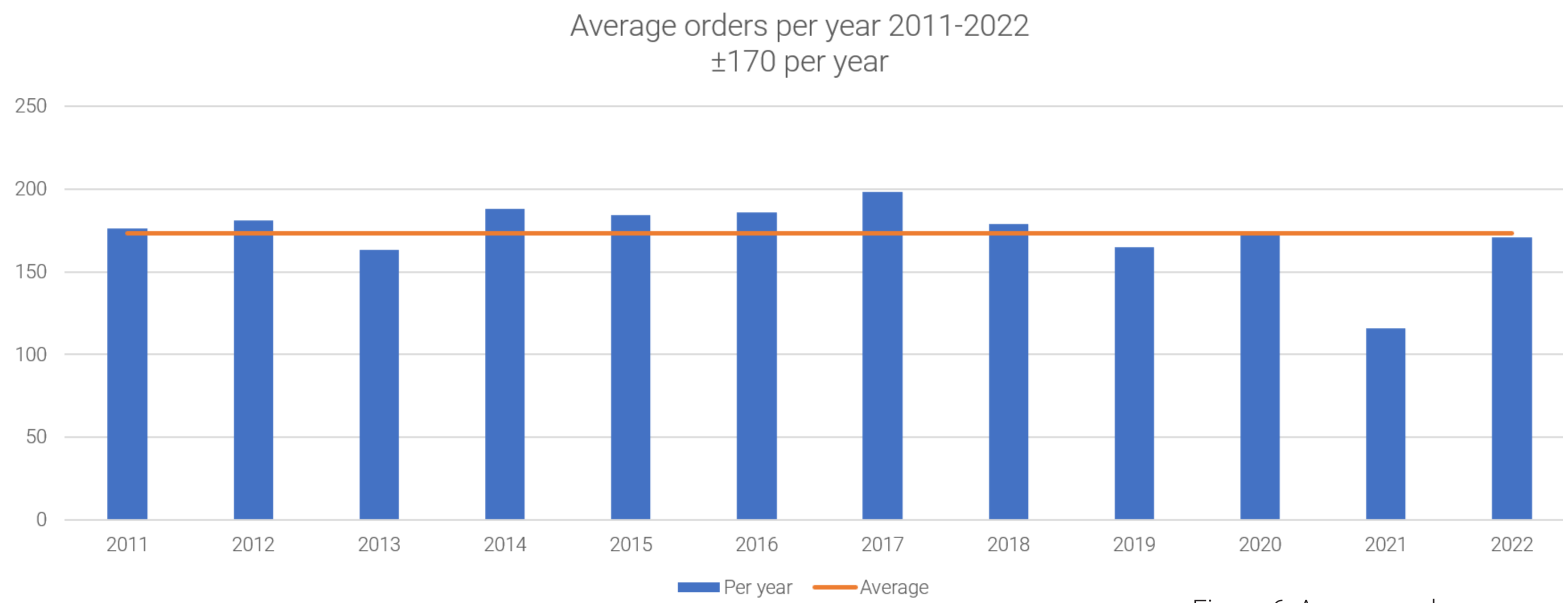


Figure 6, Average orders per year

O4 keeps a stock of certain sub-assemblies based on a rough idea of sales. For example, the tubes for the backrest are prebend in all sellable options. If a certain measurement is sold more often, and the employees notice it, then they make more of that measurement compared to others. The rest of the parts are kept in stock based on a 'kanban' system, that ensures that when a certain box of parts is almost empty, a signal is sent, and there is always enough left to bridge the delivery time of that part (Cimorelli, 2016).

At the company, almost everything is done in-house, from tube bending and welding to upholstering and assembly. The things that are outsourced are powder coating the frame, laser cutting assembly parts, and making the back cover. This allows for a lot of control over the process and short feedback loops but can become a drawback when production increases a lot (Kaya, 2011).

Figure 7, Pre-made stock at O4

2.2 Stakeholders

The most important stakeholders involved in the wheelchairs from O4 are listed in Figure 8. The way they influence the design of the wheelchair and their main concerns or functions are also listed.
Apart from the obvious end user of the wheelchairs, O4 has another large stakeholder that buys its product, in the form of resellers. These resellers are organisations that provide wheelchairs to people who need them. This system works via governmental allowances that anyone can request. In the Netherlands, there is a regulation (Wet maatschappelijke ondersteuning or WMO) that obliges municipalities to provide care to people in need of aid in and around the house (Rijksoverheid, 2015). This is often done in the form of a spendable allowance when someone needs a stairlift, walker or wheelchair. The height of this allowance depends on the severity of the disability one has.
The municipalities select specific aid-providing organisations like Medipoint or Welzorg where you can use this allowance on for example a wheelchair (Welzorg, 2023). It is in the aid-providing organisations' interest to provide the cheapest wheelchair possible so they can satisfy the obligation from the municipality (and government) and get the allowance that applies to the specific wheelchair user. This results in a big job for O4 of convincing these organisations that a perfectly fitted wheelchair is (in the long run) way better for the user.
Even so, the people who work for these companies and are involved in adjusting, prepping, and fitting the wheelchair to the user are influenced by their experience because they can recommend brands of wheelchairs or advise against them. After all, adjusting the wheelchair is very complicated, for example.
In short, there are a lot more interests at play apart from the needs and wishes of the end user.

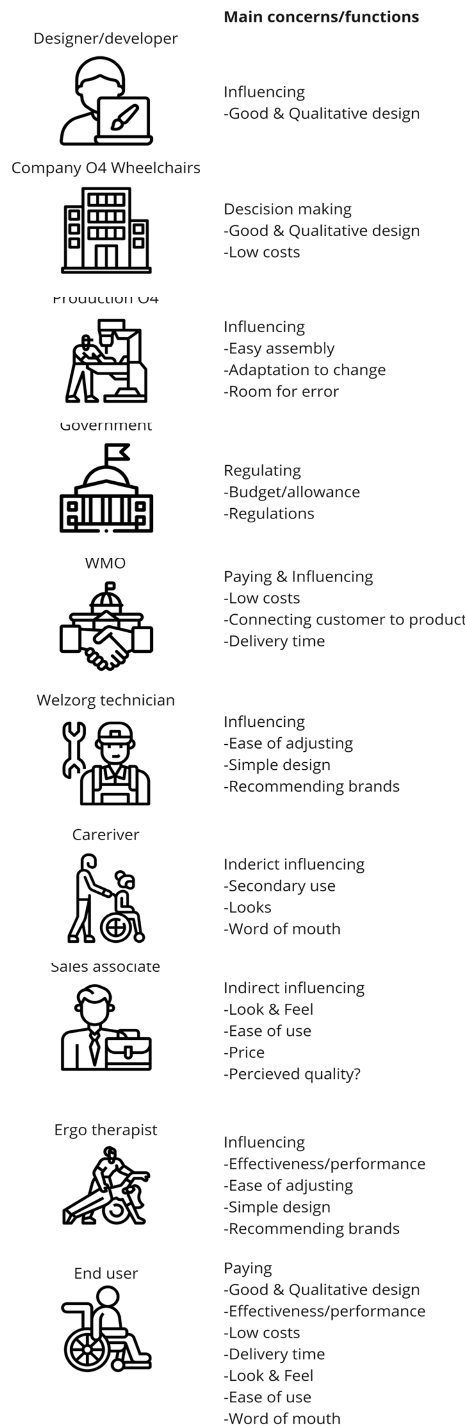


Figure 8, Main stakeholders with their influence and concerns

2.3 Main Challenges

Based on the context discussed above the following four challenges come to the surface:

1. The need for standardisation without compromising the customisation
2. Having a spread out and equal workload during the year
3. Become independent from in-dept knowledge of specific employees in the company
4. Keeping or improving a good image and easy experience for the resellers and technicians (quality assurance)

It is clear that these challenges are not easily faced or solved, but taking a step in the right direction already has many benefits. Many other companies probably face the same challenges, but solving them specifically for O4 requires an overall design approach, ideally from someone outside the company, so a neutral and unbiased image can be formed.

2.4 Current Solutions

With the current product line, O4 offers adjustability ranging from infinite to steps of 2.5 cm. The width of the frame for example is sold in 10 options. The position of the seat to the rear axle, on the other hand, can be set at any instance (between the two extremes). However, this still means there are more than 80 configurations and as O4 sells between 100 and 200 wheelchairs a year it is too costly to have all configurations stored, besides them not being sold equally often.

As already stated, the workload varies a lot from week to week. Now, the main mitigating action they take is to make as many sub-assemblies as possible in times of fewer orders. In practice, these sub-assemblies are very limited and just combine a couple of parts. A situation where, for example, the seat and the frame can be made separately in advance would be a huge benefit. Even more, hiring more assembly workers only helps so much, as a lot of the assembly steps need to happen consecutively.

The topic of preserving knowledge is a difficult one. One would need really good documentation (which takes a lot of work and upkeep) or the assembly of the wheelchair must be made easier to understand and not allow for human error but ideally the combination of both (Dalijono, 2006). At the moment, there is a large amount of old and messy documentation, and many steps in the production of wheelchairs are based on experience on how to do them instead of logic.

Finally, the experience for technicians and resellers is tried to be made positive by having good support via customer service and employees of O4 going to resellers to help if needed. This is, however, a time-consuming practice and could be solved by having a wheelchair design that allows for easy adjusting and prepping.

All in all, the context in which this project operates is mainly influenced by the balance between customisation and standardisation. O4 has a unique seat adjustment system and focuses on offering fully customisable wheelchairs, adapted to the end user. With a low sales output volume, a more spread-out workload is desired, and an optimised production time might help with that. The next step is to analyse the processes at O4.

Figure 9, Pre-welded sub-assembly stockat O4

3. Wheelchair production at O4

Here, an overview of findings and key insight into the current practice are described. Two analyses are done and the key takeaways are listed followed by recommendations to O4 Wheelchairs.

3.1 Assembly Analysis

The first step in solving the problem statement is an in-depth analysis of the whole production of the wheelchairs at O4. This gives a good understanding of the context and in-depth knowledge of the production process. Furthermore, the production process will be quantified. For this, a method of dividing the whole process into all the sub-steps, measuring the time it takes per step, and judging which steps a potential gain can be seen. The main question to be answered by this analysis is "What is the leadtime of the "average" wheelchair, and how is this leadtime divided?"
This analysis can be found in Appendix 11.1, and the most important findings are as follows.

- The total production time of the average wheelchair is 5:17 hours, of which 1:25 hours was welding, 32 minutes the manufacturing of the seat cushion, 3 hours of wheelchair assembly and 20 minutes quality control and packaging for shipment (see Figure 10). The subcategories in which the analysis is divided is not needed to be readable. For this, see Appendix 11.1).
- The step of 'checking the order bill and adding and adjusting the picked items' (the biggest orange pillar in Figure 10 took roughly 55 minutes. This is interesting as these 55 minutes were extra on top of the 10 minutes the initial order picking had already taken (the small orange pillar in Figure 10).
- The fender is connected to the frame using different brackets, depending on the type of frame, left and right side, and wheel diameter. These fenders are manually positioned and drilled to fit the wheel and bracket (see Figure 13).
- All the screwing and tightening is done manually and takes 17% of the total time of production.
- The activity (horizontal distance between the rear axle and seat) and the seat height are set at the same time but need to be measured multiple times because of the nature of the connection from the seat to the frame.
- The brakes can twist in two directions without it being necessary, as they are always mounted in the same way (see Figure 12).

Figure 11, Ajustability of seat activity (front & back position, over curved tube, seat height changes with it

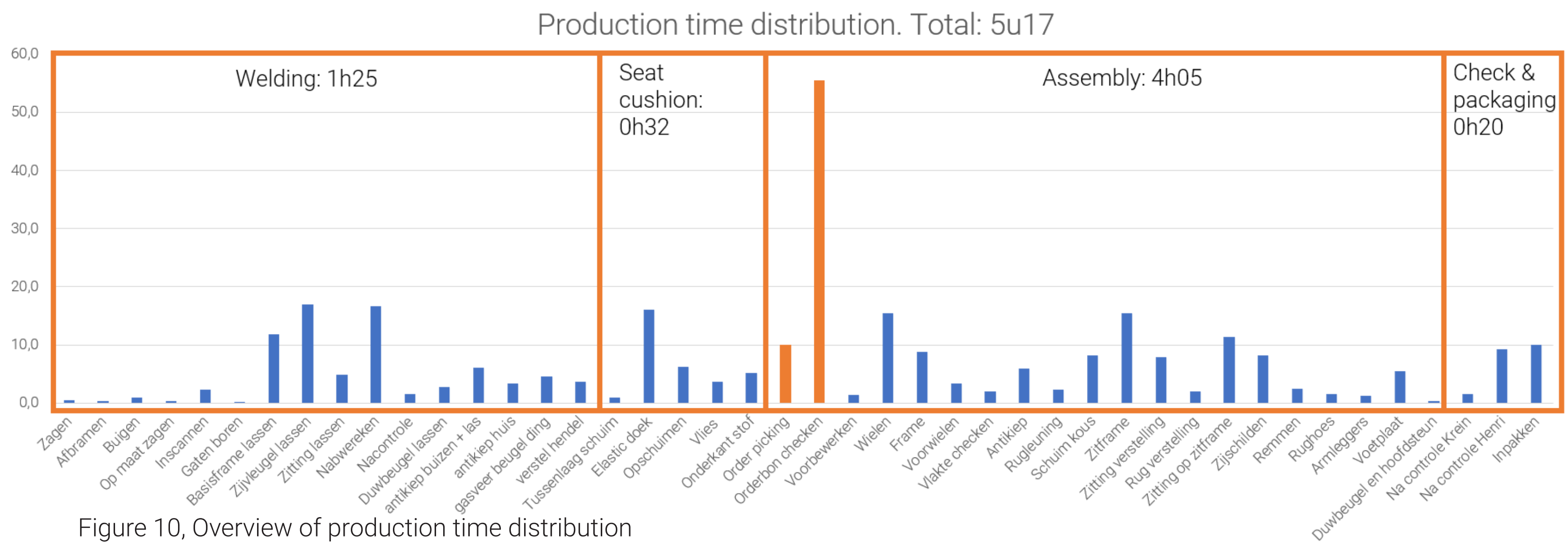


Figure 10, Overview of production time distribution

- The foam tube on the backrest is custom-made for every wheelchair, but it is almost every time the same (see Appendix 11.1, Figure 11).
- The anti-tip wheel on the back of the wheelchair rattles during use and is scratch-sensitive (see Appendix 11.1, Figure 9).
- Entering the client's wishes into the order bill system is sensitive to human error. It goes from paper to digital to paper again.

Recommendations to O4 to further look into but are out of scope for this project are:
- It is absolutely necessary to look into the process step of order picking. This takes almost an hour and should be doable in roughly 10 minutes. Preventing mistakes in the order bill and order picking should be evaluated on a process level, with probable easy time gain.
- It can be useful to look into the process of entering client-specific wishes in the order bill. At the moment mistake sensitive intermediate steps are done that seem unnecessary. Improving this can mean a radical change in the way of working but also potentially a great time gain.

This production analysis gives a quantified basis to substantiate future (design) choices. Apart from a detailed understanding of the whole production process and steps taken, it also familiarised my presence at the company and the benefits of my project for the employees. This can be of significant value added to acceptance when presenting solutions or recommendations to the company.
It has to be noted that the observations of the production are done for roughly 2 wheelchairs, causing the chance of coincidences in observations to be somewhat higher than with a larger sample size. Time-wise, this was the most effective way to get a good understanding and quantifiable data from the production process.
More limitations can be found in Appendix 11.1.

Figure 12, Double turnable brake assembly

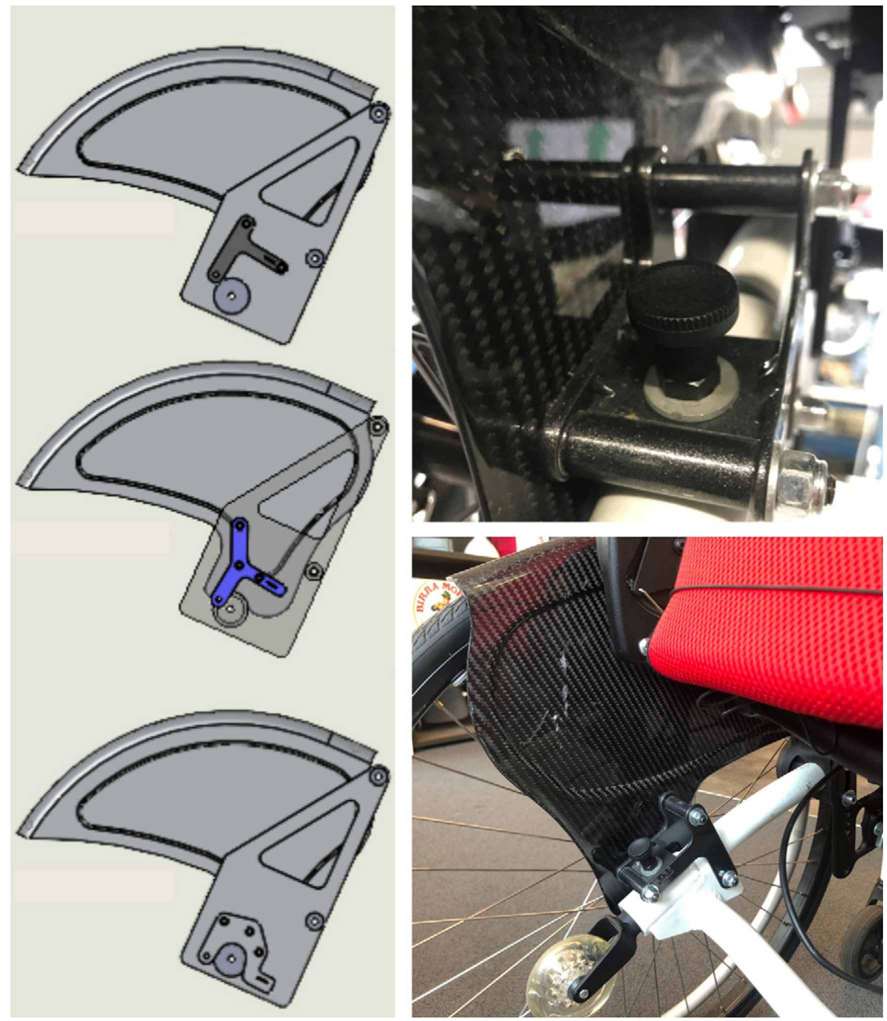


Figure 13, Collage of the current fender brackets, manualy aligned and drilled

3.2 Sales Data Analyses

Of all the wheelchairs that are being sold at O4, there are hardly any two wheelchairs that are the same. Therefore there is a need for an understanding and quantification of the distribution of the different options a wheelchair from O4 offers, and how often certain options are being sold. By analysing the sales data, design choices can be made in the field of 'design for all' or in selecting a percentage of all sales a solution might cover. If a solution for example is beneficial for only one out of three wheel sizes, but that one wheel size is sold 80% of the time, the benefits are larger than when all wheel sizes are sold equally. The main question that is answered in this analysis is: "What is the distribution of the different wheelchair configurations sold at O4".

Appendix 11.2 contains the full sales data analysis, and the most important findings are as follows.
-The categories that are based on human measurements like seat width or back height are normally distributed (see Figure 15).
-The categories that are non-human things, like the type of front wheel, are mono-dominantly distributed and have mostly one and sometimes two options that are sold roughly 80% of the time (see Figure 14).

The most important recommendation to O4 regarding a sales data analysis is that it is expected that when specific sales data gets combined, for example, seat width and depth, a nominal distribution will show up. This can be easily used to determine what sub-assemblies could be made in advance of orders and be the basis of precise inventory management. For this to work, O4 should look into what sub-assemblies exist and what measurements (or options) are influencing these sub-assemblies. Next, all these parameters should be combined to quantify what combinations get sold most. This could help in flattening the workload throughout the weeks but requires some investment to have more sub-assemblies in stock. A downside to this is that predicting the future (even though it would be based on past sales) always entails some uncertainties and risks.

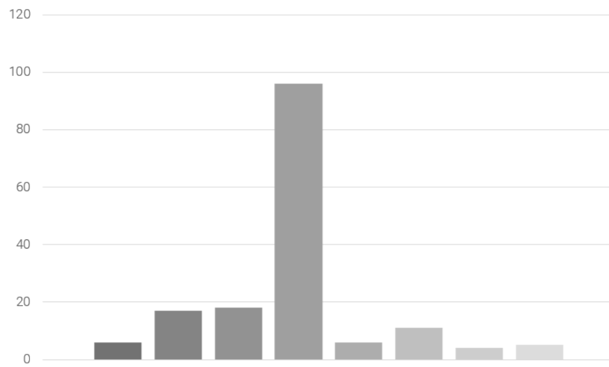


Figure 14, Mono-dominantly distributed sales, e.g. wheel type

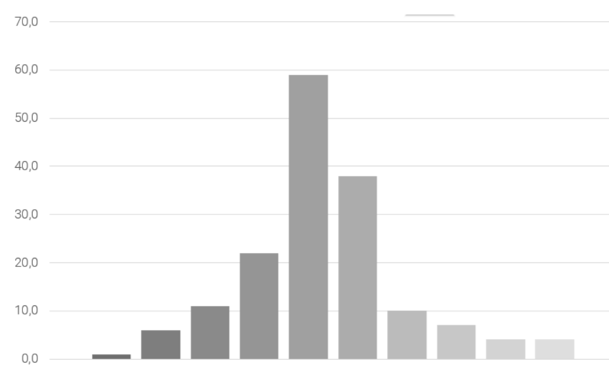


Figure 15, Normally distributed sales, e.g. seat width.

The two analyses concluded this chapter by providing numerous insights and presenting a basis for further development. A thorough understanding of the production process also aids the understanding of the product itself. The current situation at O4 was analysed, and the shortcomings and opportunities are listed in the form of recommendations. Acting upon these recommendations could improve O4's production and products.

4. Design directon and Recommendations

In this chapter, the program of requirements is created and used in combination with the findings from Chapter 3 as a starting point for ideation and the development of concepts in an iterative process. The chosen design direction is stated and recommendations for O4 are presented in a roadmap.

4.1 Program of Requirements

Based on the design goal and the findings from Chapter 3, a list of requirements is made, divided by overall requirements and sub-assembly-specific requirements, which can be seen in Appendix 11.3. Below the most important requirements for this stage are shown.

- The redesigned wheelchair should have a faster assembly time.
- The costs of the redesigned wheelchair should at least be the same or lower
- The redesign should work in as many wheelchair configurations as possible
- The redesigned wheelchair should at least be the same weight or lighter
- The redesigned part should be as easy and comprehensible to assemble as possible
- The redesign should allow for at least the same amount of adjustability as the current situation

The requirements and design goal shape the scope of the project and the space in which ideation takes place. It is clear that the concept is going to be a redesign of a part of the current wheelchair itself. The following chapter goes into how the project moved from creating ideas to choosing one concept.

4.2 Ideation and Concepts

The ideation process was done in a couple of phases. The first was to formulate design questions, based on the findings from Chapter 3. Next, a brainstorming and co-creation session was hosted to ideate on the formulated questions and elaborate the most promising ones into concepts. Finally, 3 ideas were further elaborated and a concept was chosen.

4.2.1 Design Questions

Based on the findings from Chapter 3, seven interesting opportunities were formulated into design questions. This was done by selecting findings and recommendations based on their potential to decrease production time if accomplished. This was intuitive, as during analyses, this goal was kept in mind, and everything that stood out as 'potentially improvable' or 'this can be done quicker' was noted down. They were complimented with two that can be perceived as 'bad design that could be simply fixable'.

- How can we prevent the need for customisation of the fender to the control lever
- How can we make the attachment of the fender workable in more solutions
- How can we decrease the total tightening time
- How can we make setting up the seat height and activity more easy
- How can we simplify the brake sub-assembly
- *How can we improve the design of the foam tube*
- *How can we prevent the rattling of the tip-prevention tube*

The goal of these design questions is to explore the potential of all seven opportunities, generate a selection of ideas, and develop a couple of concepts that will lead to one concrete design direction.
The relevance of these 7 opportunities was assessed by presenting and discussing them with O4's head of development. This ensured that the direction of ideation aligned with O4's development vision and would potentially benefit them.

4.2.2 Brainstorming

To explore the potential of all 7 design questions, a brainstorming session was held with five designers and engineers from Pezy Group. This was done to generate broad and unprejudiced ideas, as these colleagues were not necessarily involved in working for O4, and five people can do more than one. Figure 16&17 shows an impression of the brainstorming session and the results. The general thought steps went in the direction of combining one solution to fix multiple design questions, as this would be more efficient than several solutions. The standardisation aspect also sparked interest; how standardised can we go, without compromising customisability. Lastly, many ideas were built upon the use of tools and jigs to make assembly itself more straightforward, and less error-sensitive. If the design did not allow for misinterpretation, assembly would be easier. A more detailed overview of the generated ideas can be seen in Appendix 11.4.
At the end of this phase, the promising aspects of the ideas were gathered using dot-voting, a method where dots are placed on the ideas or combinations that were perceived as the most promising. This method ensures an intuitive but also democratic approach to assessing ideas, based on the judgement of experienced designers and engineers. This method led to 19 concrete ideas to further develop that can be found in Appendix 11.4.
It is to be noted that the last two of the seven design questions formulated in the previous chapter 4.2.1 (in italics) were left out of the scope for the remainder of the project because of time constraints and the importance to O4. This decision was made in consultation with the lead developer of O4, based on what is to be expected from this project and the feasibility combined with the usefulness for O4. It is therefore recommended that O4 looks into the last two design questions themselves in the future, as it is expected that solving these design questions improves the user experience and overall design of the wheelchair. The ideas that were created for these two design questions can be seen in Appendix 11.4.

Figure 16, Brainstorm with colleagues

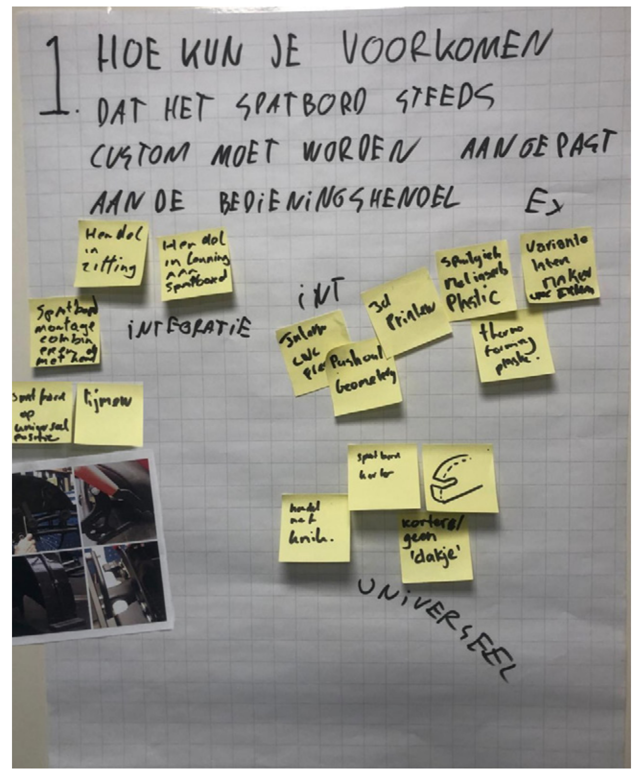
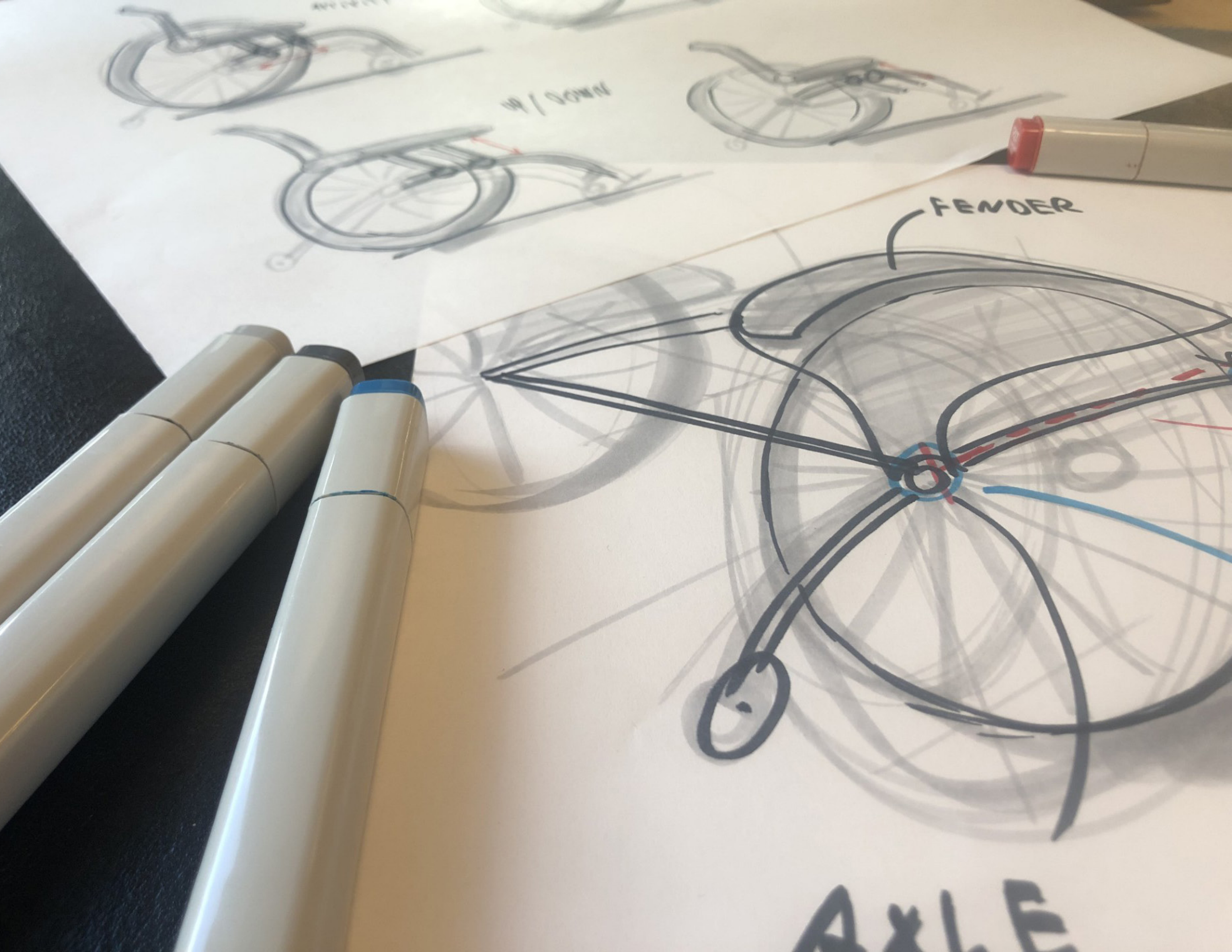


Figure 17, Impression of the results


FENDER
AXLE

4.2.3 Elaboration

In the next phase, 19 promising ideas and combinations from the dot-voting were elaborated on in the same 30 minutes. This was done to ensure roughly the same status and to evaluate these ideas as equally as possible.
The evaluation of these 19 ideas was done based on how a concept scored in different categories, on a scale from - - to ++ and everything in between. This was chosen as it is hard to quantify how 'viable' something is so it was based on knowledge and insight from me and the lead product developer of O4. An example of this can be seen in Figure 18.
The categories assessed were: the Viability of the concept, Desirability, Reliability, (based on research from Griffin's (1996) assessment methods for new product development, and Hamida's (2017) assessment under uncertainty) combinability and meeting the requirements. A detailed overview of this scoring result can be seen in Appendix 11.6.
This method was used to choose ideas 2.4, 4.1, and 5.3. The next paragraph explains these ideas in more detail and explains why this decision was made.

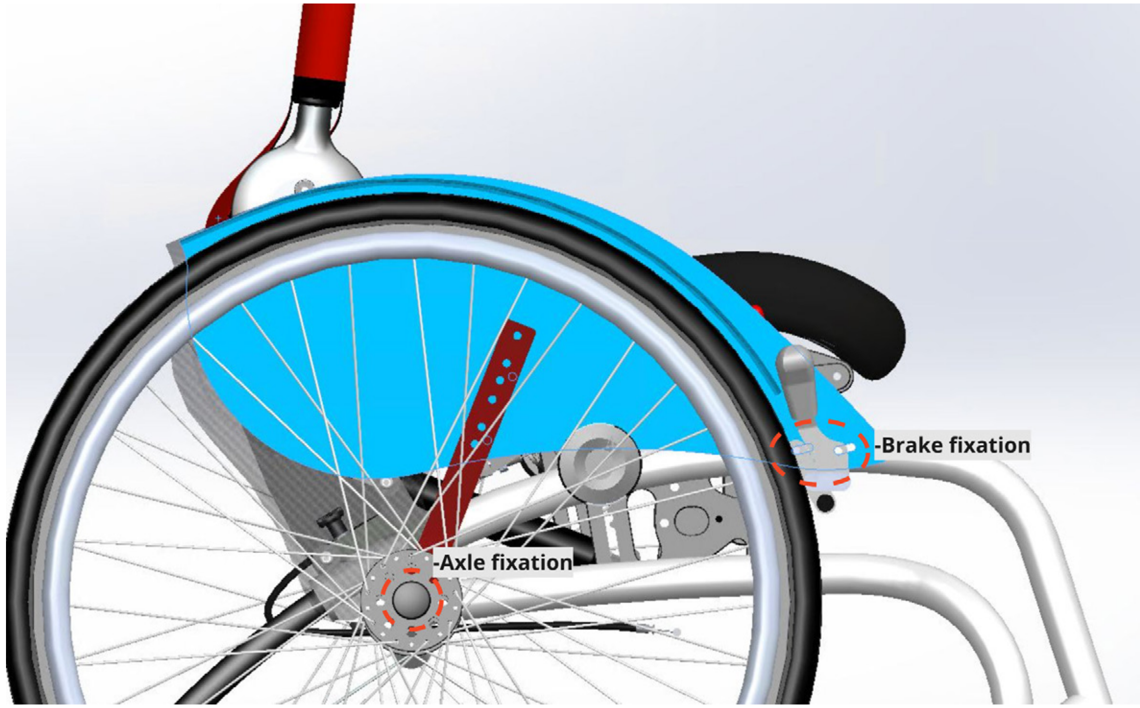


Figure 19, Overview of locations of importance

Concepts	Viability	Desirability	Reliability	Requirements met	Combinable with other concepts	Result
Fender-control lever						
2.4 To axle and brake	+	+	++	+	++	7
4.1 Visual indicating position	++	-	++	+	++	6
5.3 Brake on the fender	+	+/-	+	++	++	6

Figure 18, Example of the used grading system

Idea 2.4 Fix the fender to the frame in two positions.

This idea solves the hassle of how the fender is positioned in the current situation. First, the assembly worker manually holds the fender in the position he thinks looks good. Then he marks where to drill holes through the fender to attach it to the bracket. Then he screws it down and adjusts it a little to look nice. This process is done for each individual fender for each wheelchair.

A solution to standardise this process is to standardise the position of the fender with a set of fixed holes. As the distance of the wheel to the axle and the distance of the brake to the axle is always known, these would be logical positions to fixate the fender to the frame. At the axle, a strip with 3 holes is used to attach the fender for one of the 3 wheel sizes. The second point of fixation is to the frame where the brake is located. This would make the use of the current bracket from Figure 20, 21 & 22 redundant. Next to that, the assembly worker does not need to judge themself if the fender is in the right position, as it automatically is done by the fixed holes in the axle strip (see Figure 24).

Figure 22, Current fender bracket, left & right specific

Figure 21, Complicated version of the bracket

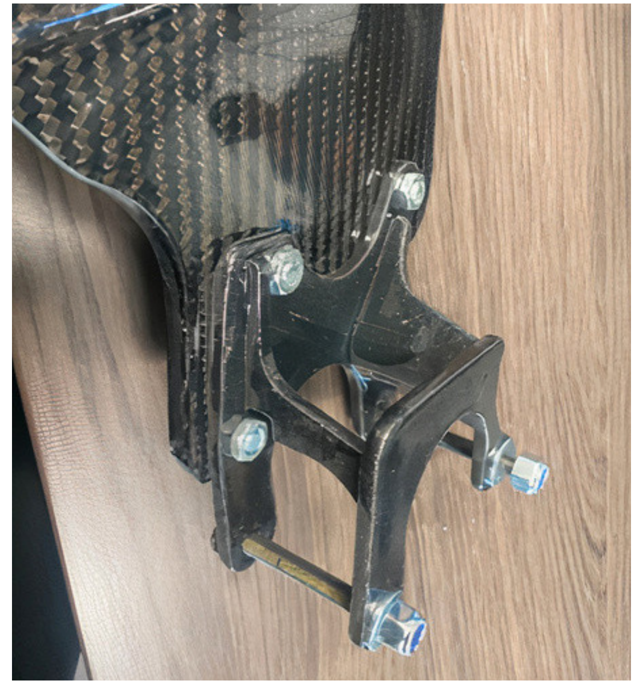


Figure 20, Add-on to the frame, not integrated

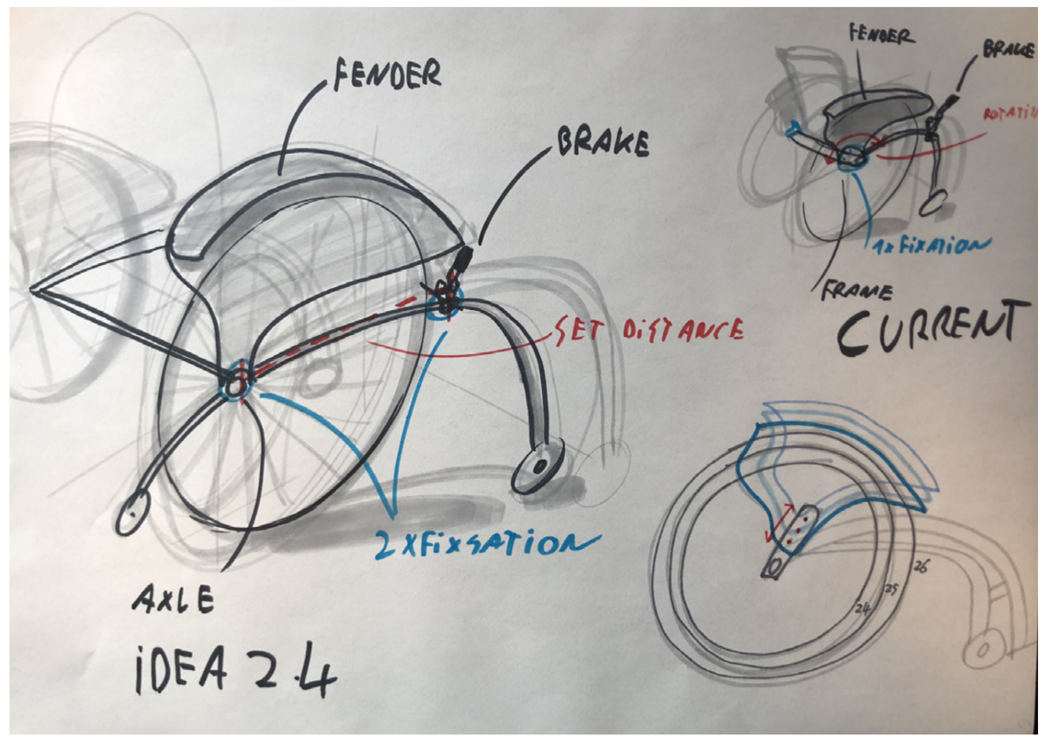
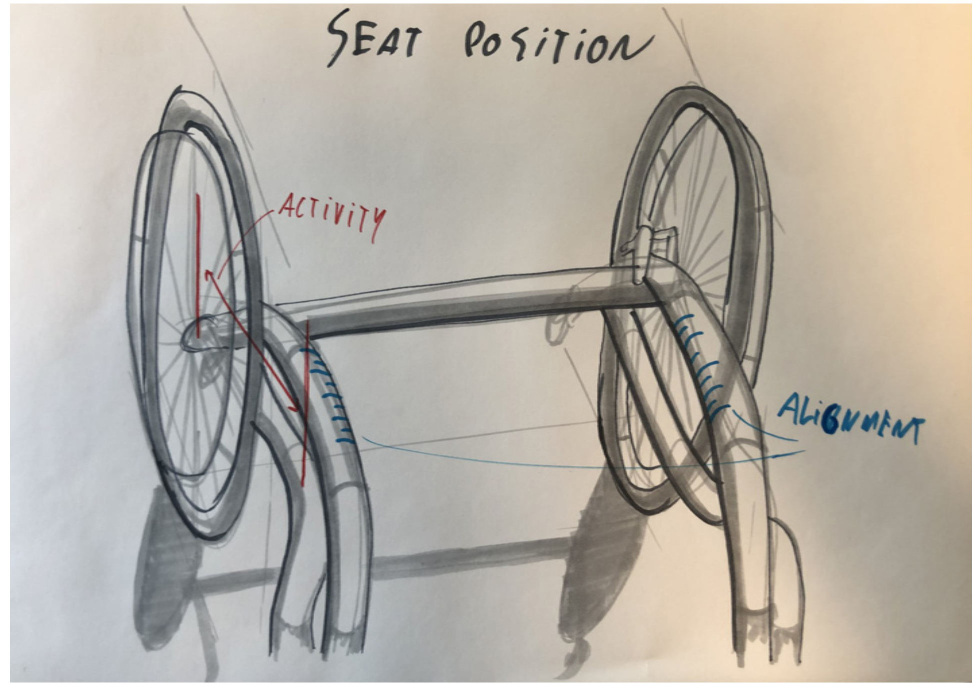


Figure 23, Fixation in two locations, instead of one.

Idea 4.1 Setting the seat position and height made straight straightforward.
The seat position and height can be set exactly to the user's needs (see Figure 26). At the moment, this is done by measuring manually with a tape measure if the seat is in the right position.
To make adjusting the position of the seat more easy, visual alignment indications could be used on the frame itself (as in Figure 25). As the position of the seat is crucial to the usage, adjusting the position should be as clear and accurate as possible. With indications every cm (or even mm) this can be achieved. Be noted is that the tube on which the seat is fixed is curved, so the height changes by adjusting the front and back position of the seat. To make sure the height is set precise, the seat height can be indicated by putting numbers at the holes on the seat brackets (as in Figure 24). These two interventions are even combinable with a standardized table, in which you could put in measurements of a person, and the specific position of the seat could be retrieved along with the corresponding holes to fixate the seat. No big design changes are done to the core of the wheelchair, it is more focused on interaction and use-cues. It also eliminates the need to measure the seat height and position manually, as it is now done.

Figure 24, Seat height bracket with indications

Figure 25, Seat activity indications on frame


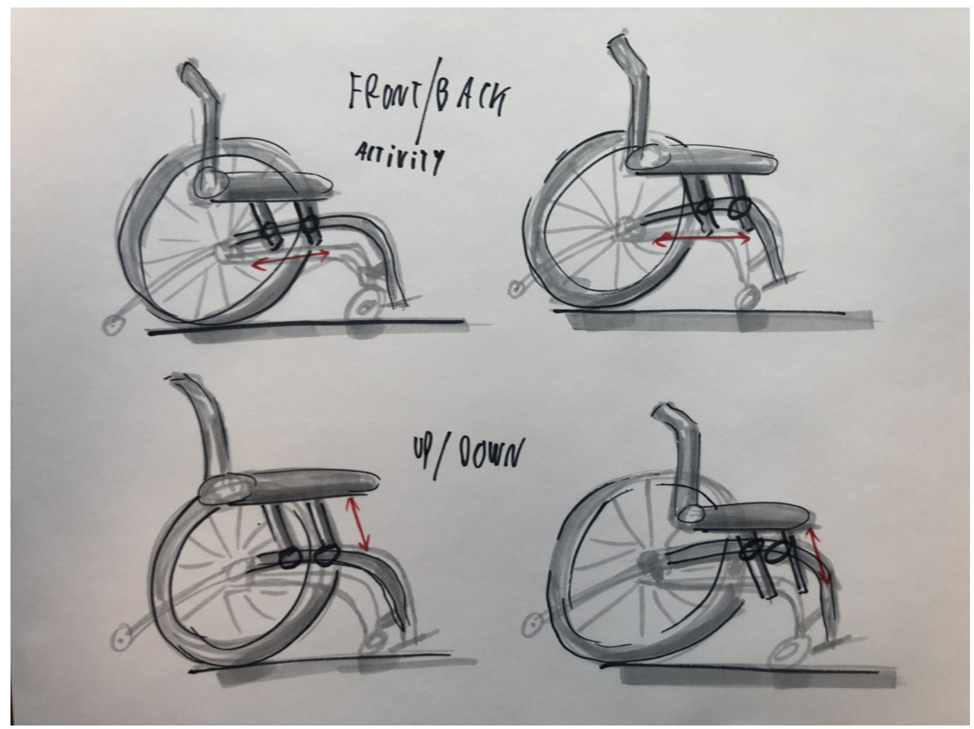


Figure 26, Overview of chair movement customisation

Figure 27, Brake directly to fender

Idea 5.3 Fixing the brake to the fender instead of the frame.
In the current situation, the brake is fixed to the frame with a clamp (see Figure 28). Now, the assembly worker has to manually align it in the right orientation and distance to the wheel.
Nevertheless, the distance from the axle to the brake is always known based on the wheel size.
So, the fender can be used to put the brake in the right position without the need for measuring or adjusting. Even more, the orientation (vertical) is automatically ensured because of the vertical fender (see Figure 27&29). This will decrease the assembly time, and ensure precise positioning, as the brake can only be in one fixed position.

Figure 28, Current situation:brake to frame

Figure 29, Brake vertically in line with fender.

4.2.4 Direction

To determine which idea to pursue, a deeper assessment needed to be done. This required a short detailing step to base the decision. Quantifying the possible assembly time gain, estimated costs, and the possibility of solving multiple other aspects of the wheelchair with the same idea for all ideas made it possible to assess the probable effectiveness.

Idea 2.4 Fix the fender to the frame in two positions.
The concept aims at using known positions (related to the axle) to fixate the fender in the right location. The potential time gain by using this solution to assemble the fender could be 37 minutes, which is 1/12th of the total assembly time. Due to the adjustment strip, it can be used with all 3 wheel sizes and all types of wheelchairs, as all have this type of fender.
-An estimation of costs would be roughly the same as the current situation, as the fender will not change shape that much, and the bracket will be transformed into the adjustment strip, both made from metal.
-The combinability is high as it could be combined with idea 5.3 (see Figure 29&30) and potentially more other ideas from the elaboration session in chapter 4.2.3.

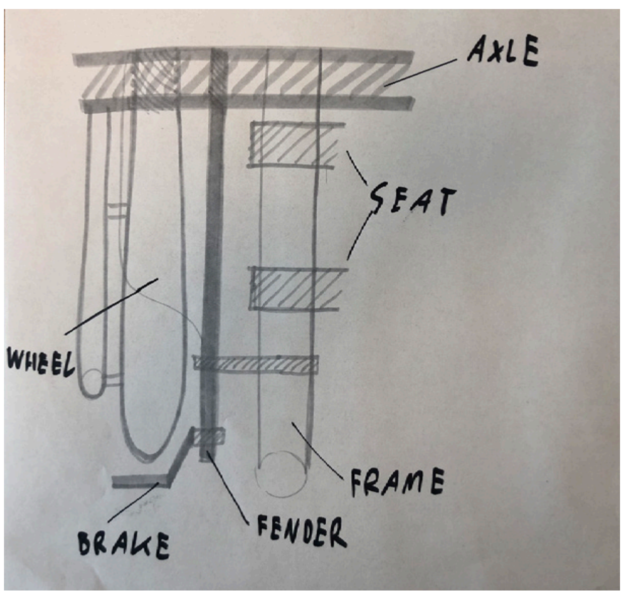


Figure 30, Brake to Fender to Frame fixation

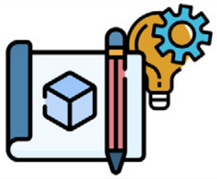
Idea 4.1 Setting the seat position and height made straight straightforward.
The concept is simple yet effective. As the activity (horizontal seat position) is known for each wheelchair order, the need for manual measuring is eliminated by engraving or painting the measurements on the frame itself. Combined with engraving hole numbers in the seat brackets, the right activity and height can be achieved without the need for measuring. This is possible because the relation between activity and height can be predetermined and the right position can be found by using the right holes and position.
This is beneficial for assembly, reseller technicians, ergo-therapists, and end-users themselves, as adjusting this measurement is made very easy.
-The potential time gain could be up to 18 minutes in assembly, and many more during use.
-The costs are relatively low, as the indications could be mechanically engraved before the frame is powder-coated.
-The concept would be even more effective if combined with a predetermined chart on which different activity, seat depth and seat height combinations could easily lead to a specific set of holes to use to fixate the seat in the perfect position.

Idea 5.3 Fixing the brake to the fender instead of the frame.
As already found in idea 2.4, Fixing the Fender to Axle and Brake, combining the idea of fixing the brake to the fender and the fender to the frame provides a stable and lean way of fixation. The need for adjusting and measuring is removed, and a more robust design is created.
The brake assembly itself will be trimmed down, as the current brake clamp can be disregarded, and the rotational characteristic is no longer needed.

To make an informed decision about which concept to continue the project with, an extensive discussion with the mentor at Pezy Group and the manager at O4 was needed. The balance between what would have the most positive influence on the production at O4 and where my skills and this project would be the most beneficial was one of the main choosing factors. Next to that, it was based on the project goals and also what provided enough room for iteration steps in the time set for this project. Idea 4.1 might not offer the needed complexity and would be relatively quick to solve. So if time needs to be effectively used, elaborating this idea may not bring the most value. The fact that the first and last concept concepts can be ideally combined, made us choose to further explore and elaborate on concept 2.4 Fixing the Fender to Axle and Brake with the goal of also integrating concept 5.3. Tackling this problem aligns with the role of Pezy Group within O4, of conceptual development to improve the product portfolio.

4.3 Recommendations

The analyses in Chapter 3 and the ideation in Chapter 4 yielded many insights. These insights are useful for O4 if translated into a roadmap that presents a clear path to follow to improve the production of their wheelchairs.
To compare the recommendations proposed with the chosen design direction, on the next pages, first the chosen direction is shown. After this, the 6 most important recommendations to O4 in the proposed execution order are shown. See Appendix 11.1&2 for a detailed description of all recommendations.

Chosen direction	Goal	Investment/Time/ Ease of implementation	Potential gain	Uncertainties
	Make fender sub-assembly quicker to instal Make fender sub-assembly fool proof Integrate brake assembly	-Time investment (development is needed) -Small change in way of working	13% of the total assembly time = 37 minutes -Less parts -Less room for error -One system fits all (no adaptations)	-Rigidity/strength -Wheel angle allowance

Step 1
Detail:
-axle fixation
-frame&brake fixation
-fender form

Step 2
Prototype new sub-assembly

Step 3
Test new sub-assembly
Quantify value added (time gain)

1.Electrical fastening	Goal	Investment/Time/ Ease of implementation	Potential gain	Uncertainties
	Make repeatable actions faster	-Direct implementation -Small investment in tools -Small change in way of working	12% of the total assembly time = 34 minutes -Improved ergonomics -Higher repeatability -Precise torque application	-Reachability of all fasteners -Switching between types of fastener bits

Step 1
Determine type of tool:
-Air powerd
-Accu powered
-Torque setting

Step 2
Standardise fastner sizes
Standardise fastner types

3.Activity & seatheight	Goal	Investment/Time/ Ease of implementation	Potential gain	Uncertainties
	Increase the ease of adjusting and thus assembly	-Quick implementation -Small intervention (Step 4: Large time investment. Long developing time)	4% of total the assembly time = 11 minutes -Less time spend by resellers, ergo-therapists and end users -Better use experience	-Applicability to all wheelchairs (Step 4: no guaranteed improvement)

Step 1
Develop a table that provides assembly positions according to needed activity & height

Step 2
Indicate activity & height visually on the frame (e.g. engraving)

Step 3
Test comprehensibility with stakeholders

Step 4: Eventuality
Develop a holistic activity&seatheight system

2.Order picking & order form	Goal	Investment/Time/ Ease of implementation	Potential gain	Uncertainties
	Decrease error sensititvity	-Time investment (analyses is needed) -Potential radical change in way of working	20% of total the assembly time = 55 minutes -Less errors (frustration?) -Effective way of working	-What is the exact root problem -Can it be improved & at wat costs

Step 1
Analyse order form
-Find common errors
-Rethink Paper→digital→paper conversion

Step 2
Review order picking method
(how, who, when, where)

Step 3
-Remove unnecesary steps
-Standardise order picking further
-Act upon findings from previous steps

4.Backrest foam tube	Goal	Investment/Time/ Ease of implementation	Potential Timegain	Uncertainties
	-Standardise a common part -No use of permanent fasteners	-Time investment (analyses is needed) -Uncertain	3% of total the assembly time = 8 minutes -Less custom parts -Increased recyclability (no glue)	-Can it be better than current solution -Investment vs. return is questionable -Preserving the form language of O4

Step 1
-Analyse the core of the need for the foam tube

Step 2
Ideate on ways to standardise and recyclability

Step 3
Implement new design

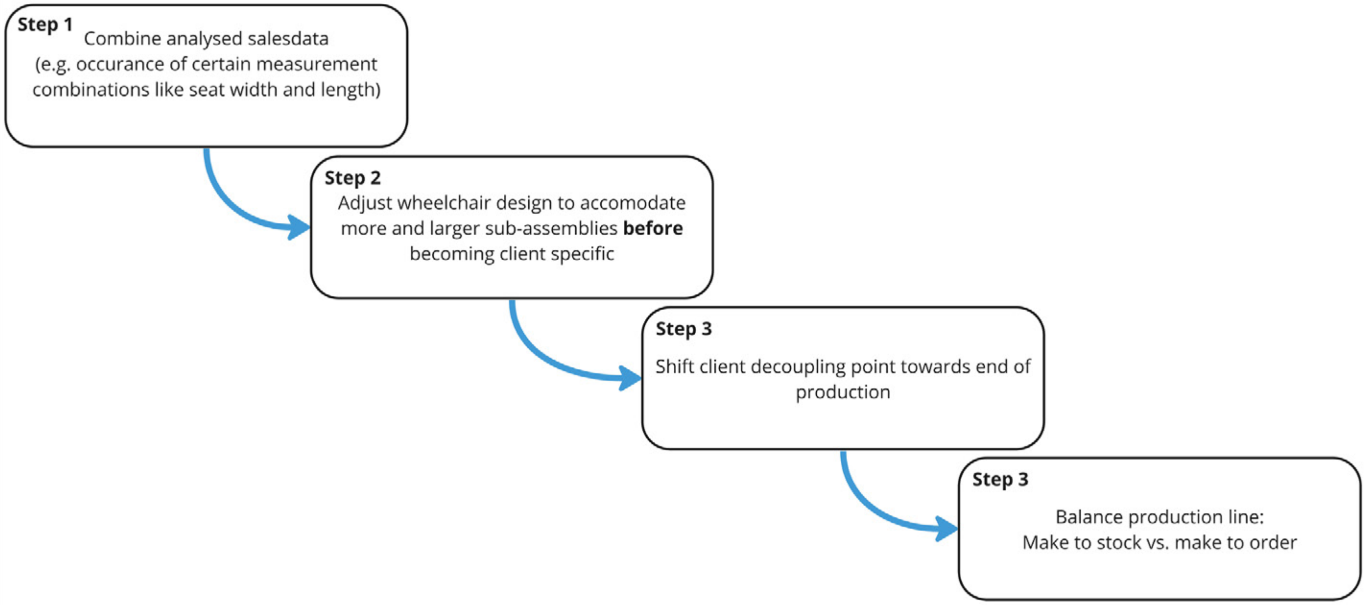
5.Anti-tip tube	Goal	Investment/Time/ Ease of implementation	Potential Timegain	Uncertainties
	-Stop ratteling during use -Improve scratch sensitivity -Improve reachability	-Time investment (analyses is needed)	No explicit timegain -Inceased product quality -Increased use experience	-Investment vs. return might be insignificant

Step 1
-Analyse the current anti-tip assembly
-Analyse reachability

Step 2
Ideate on ways to reach the goals

Step 3
Implement new design

6.Combining of salesdata	Goal	Investment/Time/ Ease of implementation	Potential gain	Uncertainties
	-Optimise warehouse stock -Flatten workload by pre-building sub-assemblies	-Indept data analysis (time) -Implementation requires design adjustments (long development time) -Specific production optimisation knowledge might be needed	-More even workload in production = effective production -Less warehouse space needed -Less locked liquidity in stockage	-Amount of redesign needed to accomodate the pre-assembly of sub-assemblies -Adaptation to radical change of production?



The chapter concludes with actionable recommendations for O4 and their corresponding potential gains, which means one part of the agreed-upon delivery is finished.
The program of requirements led to a basis to evaluate the ideas that were elaborated, and the chosen direction was adopted by all important parties. With the ideation phase of the project being concluded, the remainder of the project will focus on detailing the chosen design direction.

5. Detailing

This chapter will discuss the detailing of the chosen concept. The conclusions of the previous chapter lead to several aspects of the design that need attention. During the project, all aspects were addressed simultaneously, but in this chapter, they will be treated consecutively.
The concept can be divided into the following aspects.

- The axle fixation
- The frame and brake fixation
- The form of the fender

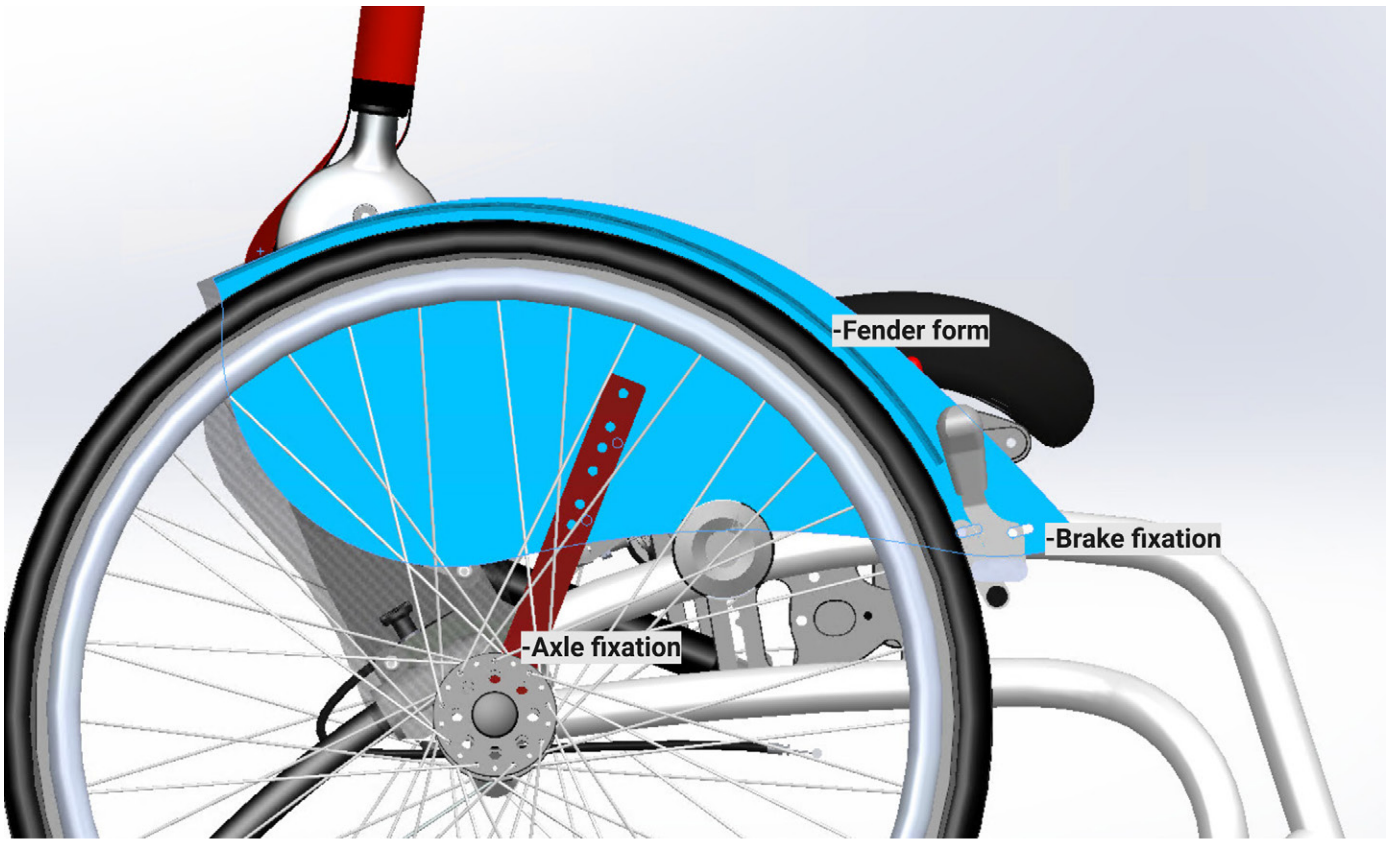


Figure 31, Concept overview with the three main aspects

5.1 Axle Fixation

The goal of fixing the fender to the axle is to have a standard reference point on which to base the position of the fender. As the distance from the axle to the wheel is always known (=the wheel size) the position of the fender can be determined.
Starting with the idea of using a strip with holes, several iterations were made using digital CAD models and wood prototypes.
Figure 33 shows the metal strip, which is added to the axle using the already-in-place bolt for the wheel. The metal used is RVS304L, which is the same type and thickness used for other strips on the wheelchair, to standardise materials as much as possible. As the strips used elsewhere are stressed under the same type of load as the fender strip, the material properties have the needed qualities (see Figure 34). This part is to be made at the same supplier as the similar strips used on the wheelchair.
The axle strip increases the total weight of the proposed assembly by 170 grams (compared to the old bracket), which is surmountable and insignificant to the total 18.5 kg of the wheelchair.
Notable is the allowance slot for the fixating of an electrical wheel (e-wheel, see Figure 36) to the wheelchair. This add-on can easily be integrated into the bracket instead of being welded on separately, as it currently happens. The torque applied on this e-wheel slot is countered by the fact that the fender itself is fixed to the frame and has a lot of torsion stiffness. Figure 35 shows the e-wheel slot and the way the torque is countered by the rest of the assembly. With this add-on, an extra welding step in production and a separate part is eliminated.

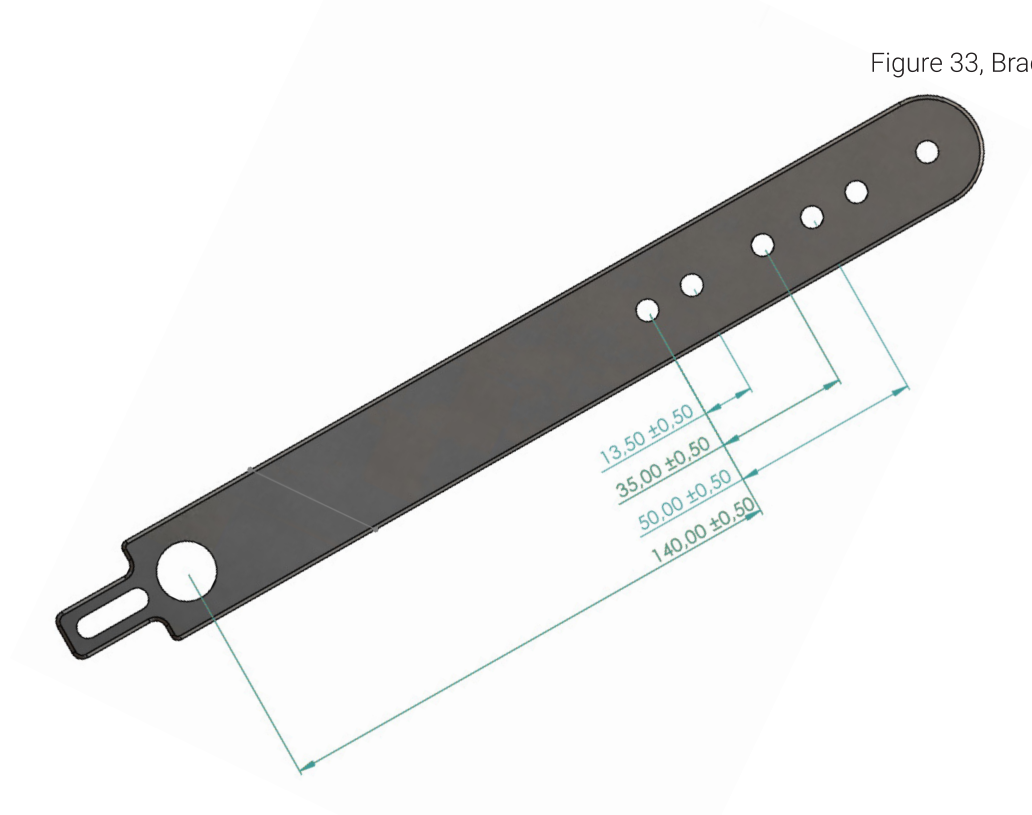


Figure 33, Bracket design

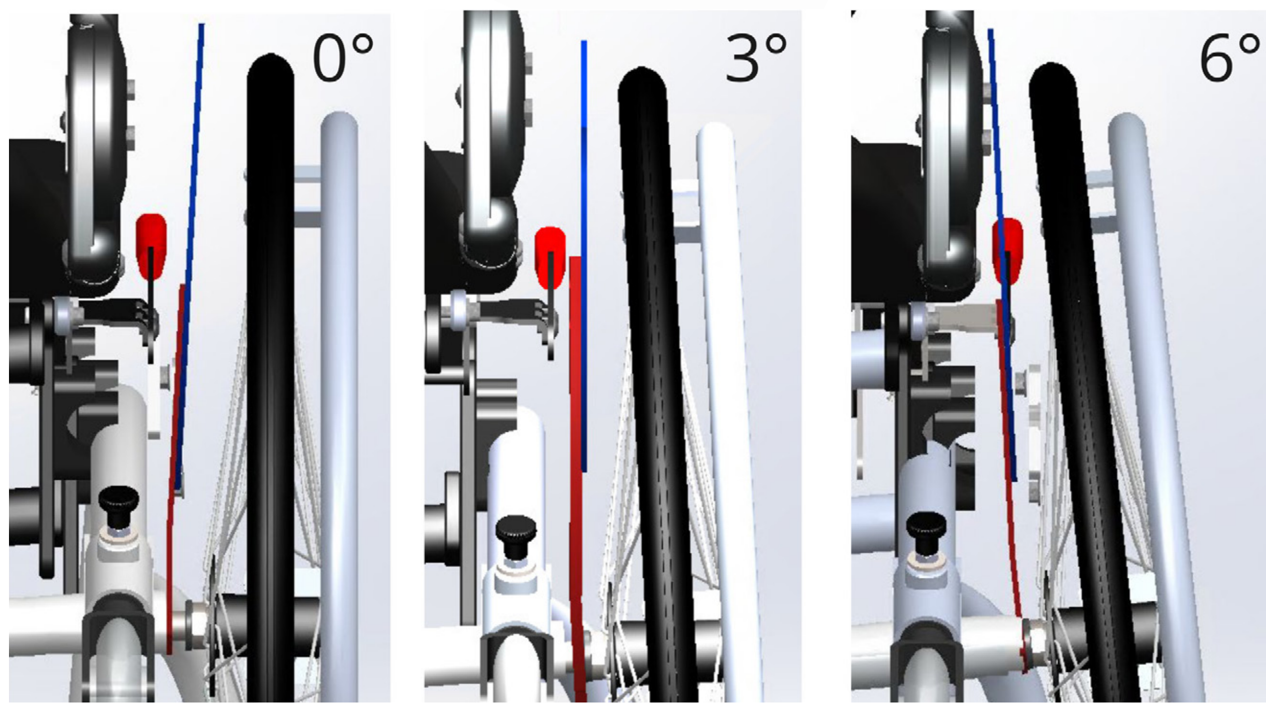


Figure 32, Camber (wheel) angles

The fender itself is fixed with two bolts to the strip to ensure no rotation is happening between the strip and the fender. Depending on the wheel size (24, 25 or 26 inches) the fender can be attached to the corresponding holes to ensure the wheel is always covered.
As the wheelchairs at O4 are sold with three different camber angles (0°, 3° and 6°) the bracket accounts for that by also having a bend in it of 3°. This is chosen because this angle works in combination with all 3 camber angles, and thus one type of strip is sufficient for all scenarios. Even more, the 3° variant is sold 80% of the time, and in that case, the fender is perfectly vertical, which is the same as the current fender. Figure 32 shows the angle in the bracket in all 3 camber scenarios.

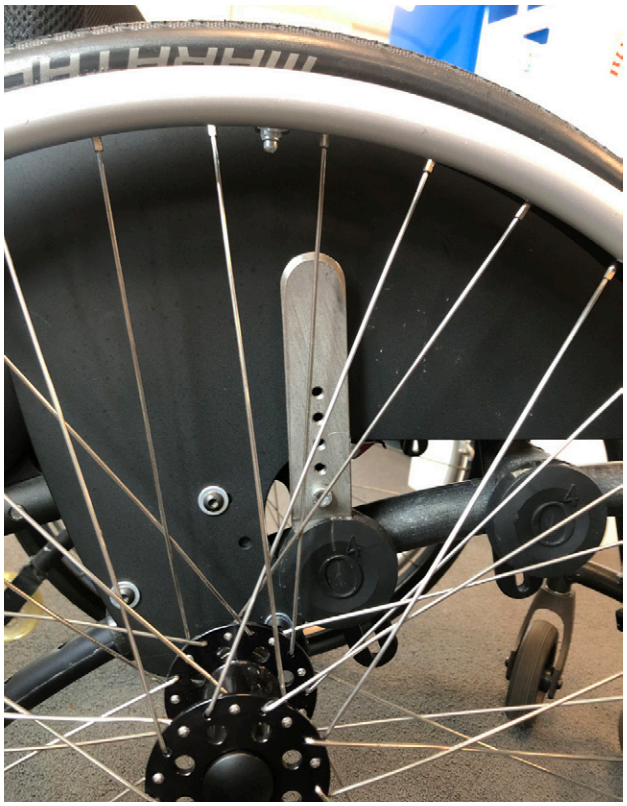


Figure 34, Current E-wheel fixation bracket

Figure 35, Current E-wheel fixation bracket

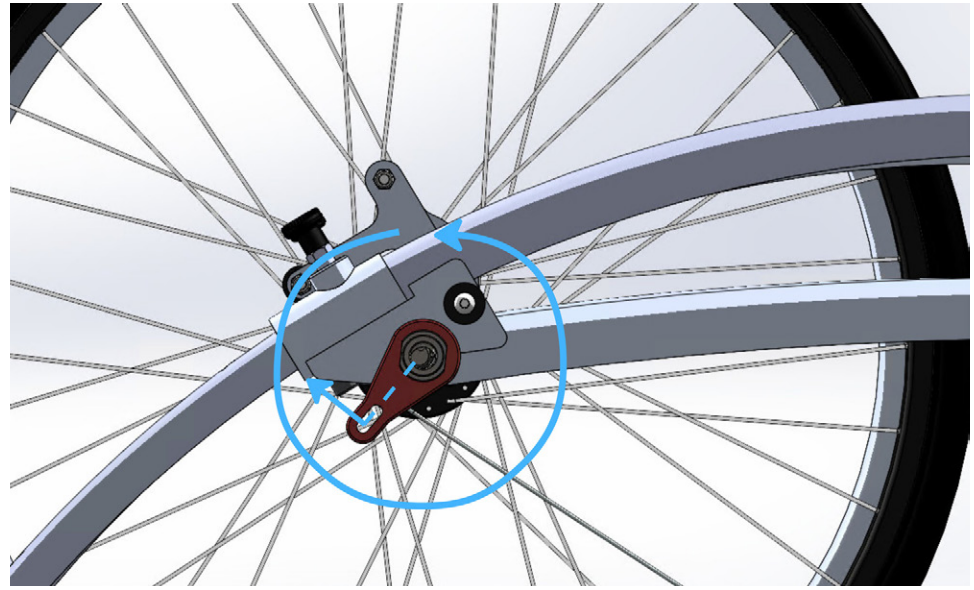


Figure 36, Common electric wheel on the frame

5.2 Frame & Brake Fixation

The second fixation point of the fender is to the frame. As shown in blue in the Figure to the right, this is achieved by welding an aluminium C-channel slot to the frame and sandwiching the fender between the brake and the C-channel.
The distance from the brake to the axle is always known (based on the wheel size), so the brake fixed to the fender is always in the right place.
To accommodate the three different wheel sizes, the horizontal c-channel is needed to guide the tip of the fender. The C-channel is horizontal, so the brake stays at the same height when changing between wheel sizes, so its reachability is always the same for the user.
The proposed assembly is shown in Figure 37&39. By using one of the two rotation points of the brake as the fixation bolt to the frame, the amount of fasteners and parts is minimised. The other rotation point of the brake is attached to only the fender.
As the brake must be slightly adjustable to accommodate different tyre thicknesses, two slots of 10mm in length are placed in the fender to allow for the needed adjustment. These slots are slightly angled to ensure that the distance of the brake to the tyre is perpendicularly adjusted (see Figure 38).
For an overview of all iterations of the frame and brake fixation, see appendix 11.7.

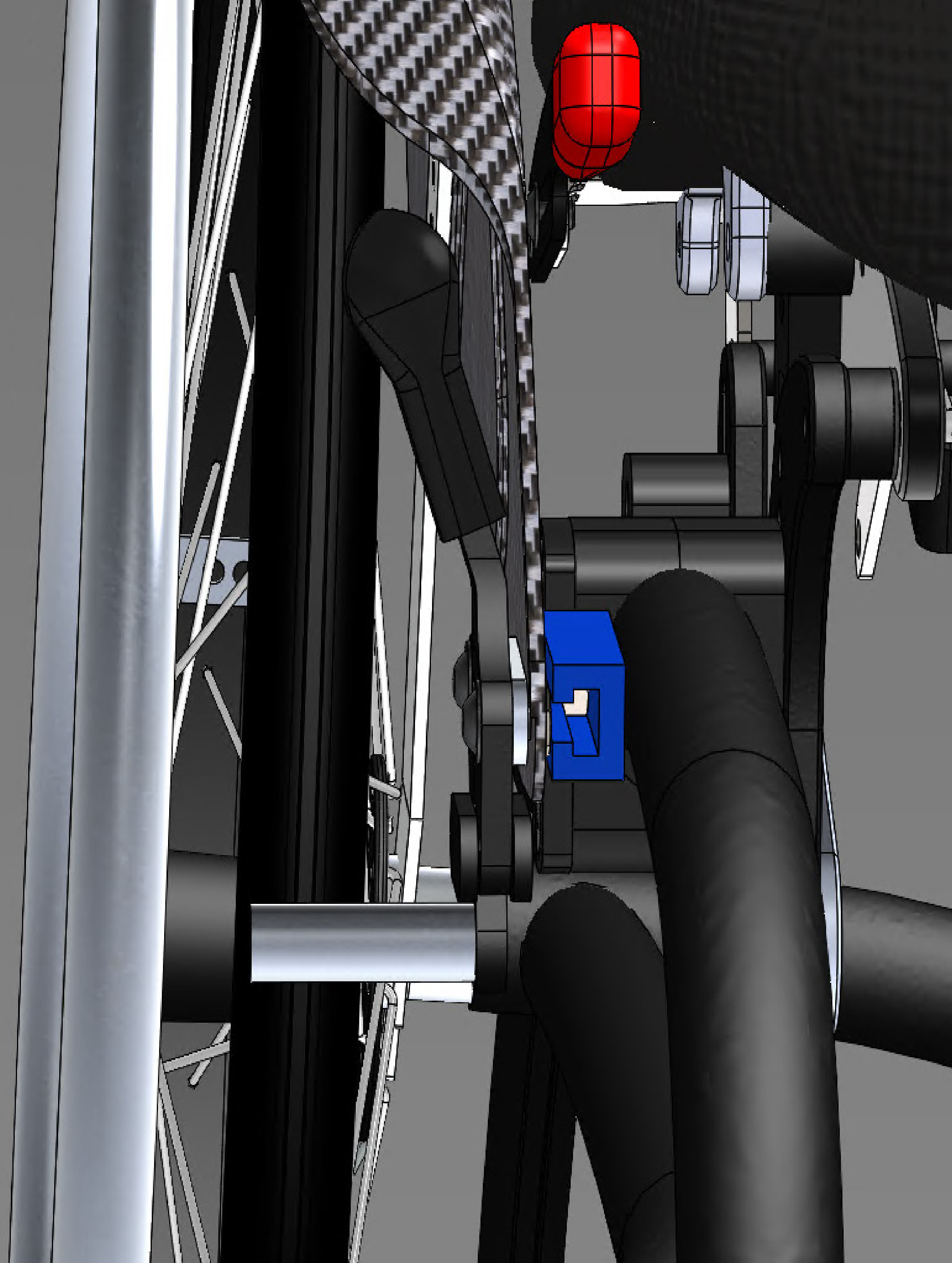
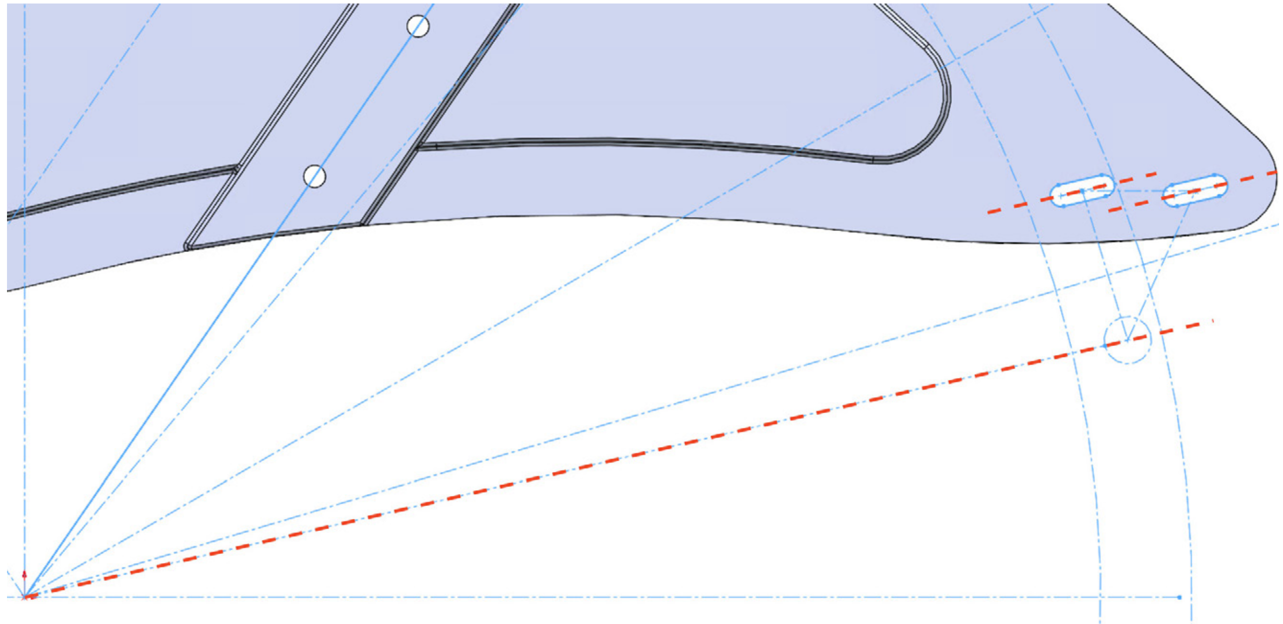


Figure 38, Parallel ajustment slots



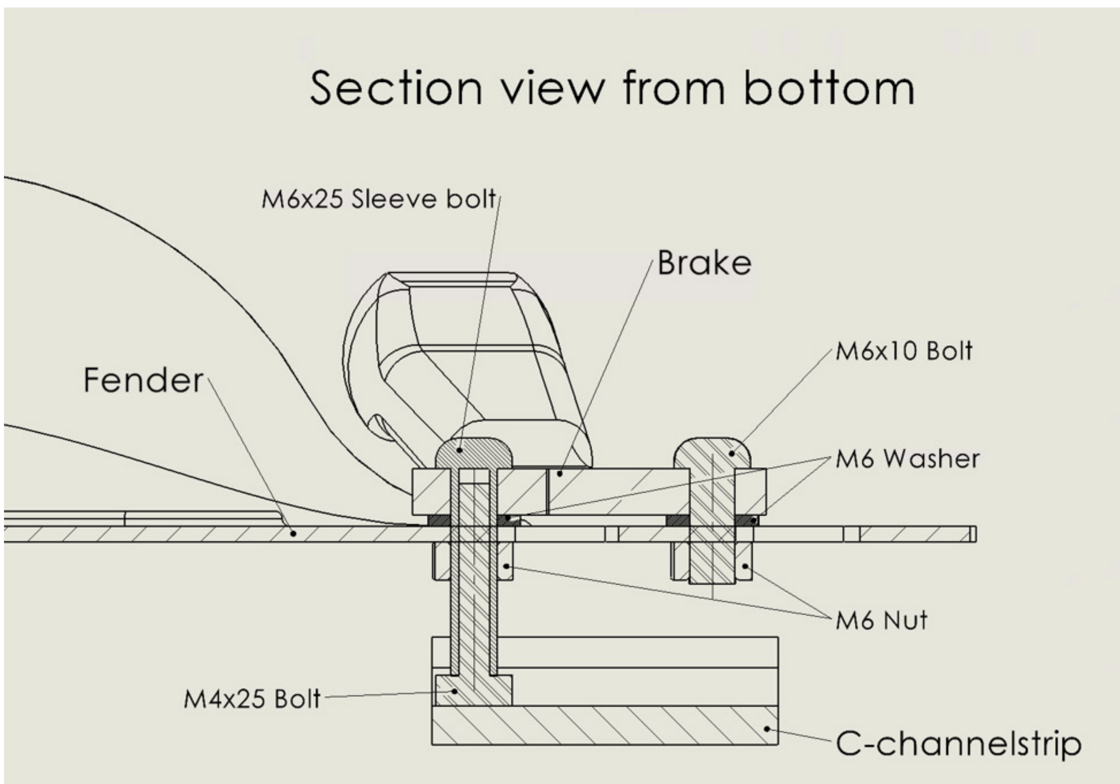


Figure 37, Bottom up section view of brake fixation

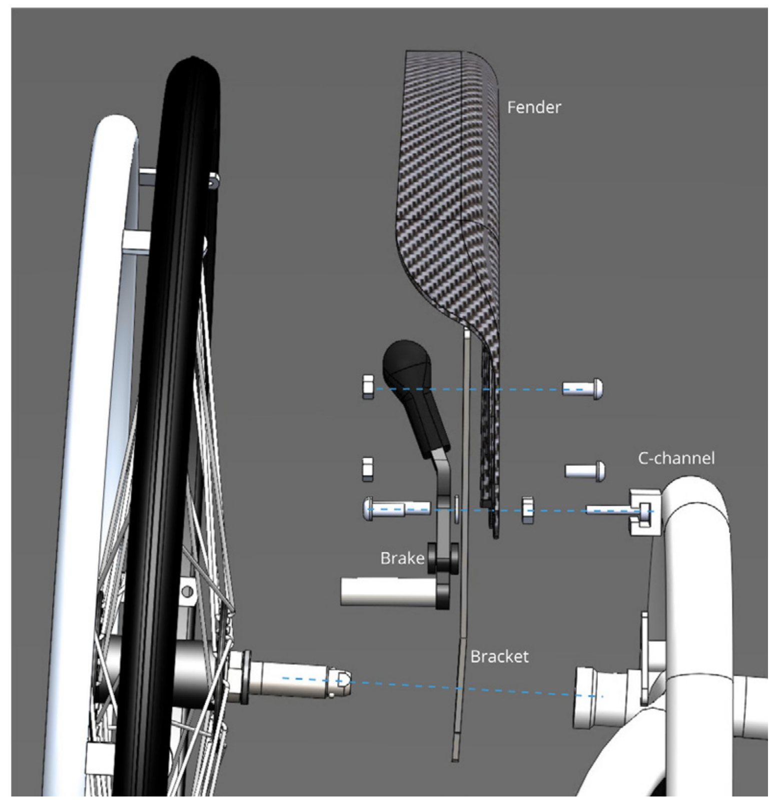


Figure 39, Exploded view of brake fixation assembly

5.3 Fender Form

By fixating the fender on two points, other than the current fender, the form can be reimagined.
The form of the fender is based on a set of requirements:

- Having enough wheel coverage to protect the user
- Allowing for the brake to be attached to the fender
- Fitting in the form language of the whole O4 wheelchair
- Minimising material usage (and thus weight and cost)

This led to a fender form seen in Figure 40. Note how, compared to the current fender, the new form sticks out past the wheel to accommodate the brake. Also, the bottom part of the current fender material can be disregarded.
Regarding aesthetics, the current fender was taken as a guide for curve radii and details. A detailed form study can be found in Appendix 11.8 and some examples are shown in Figure 41.
The same is true for the strength and stiffness properties of the fender as the material is kept the same (Thornell Mat VMA Carbon Fibre). The current fender was taken as the example, and the thickness of the material and embossed surfaces were used in roughly the same way (see Figure 42&43). By adding these embossed surfaces and ribs, the stiffness of the new fender was found to be comparable to or better than the current fender. This was tested by doing a relative compared FEM analysis of the current and the new fender and can be found in appendix 11.11. The new form is to be made the same way as the current fender, with a one-sided die not to increase costs more than necessary.
Finally, to make the brake reachable, the fender's 'roof' (the horizontal edge) makes way for the brake. As this part of the wheel is also not covered by the current fender, it is not necessary to have it covered.

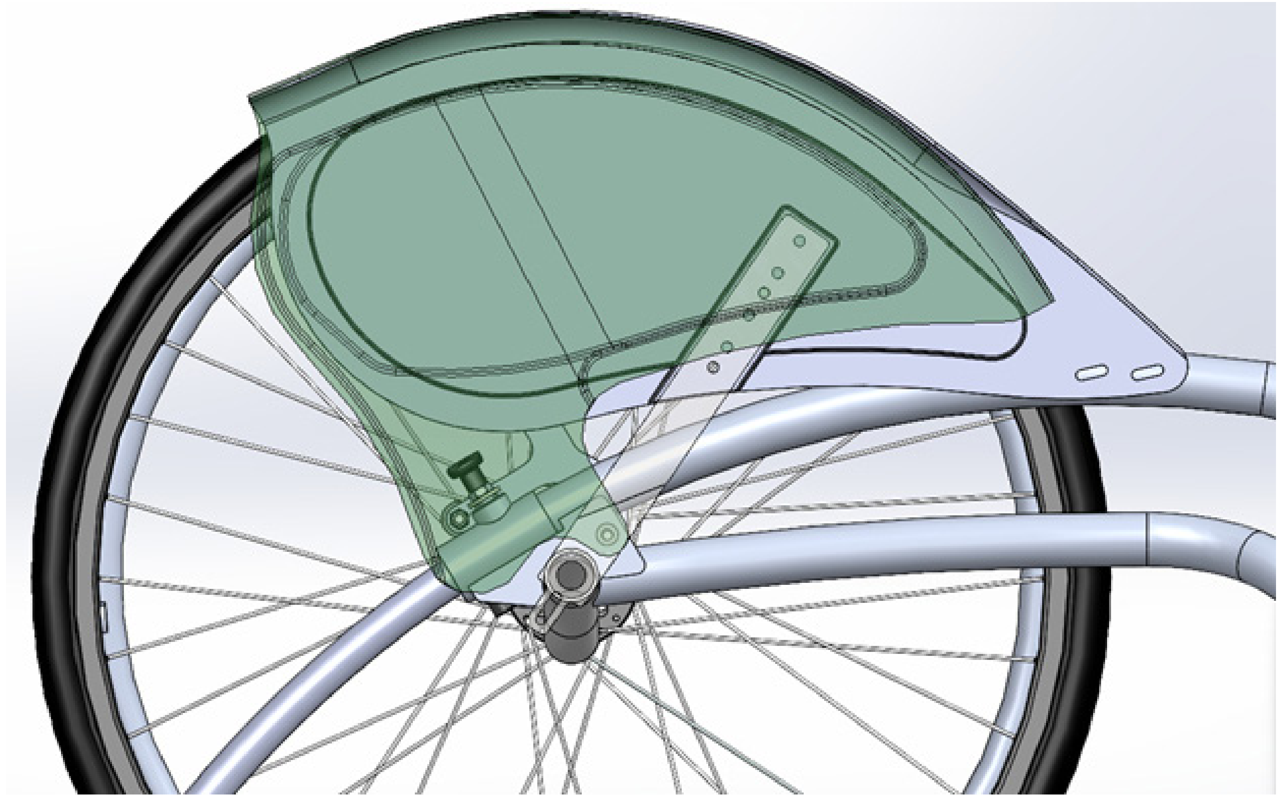


Figure 40, Old fender (green) and the new fender form (grey)

Figure 41, Small overview a of fender form study

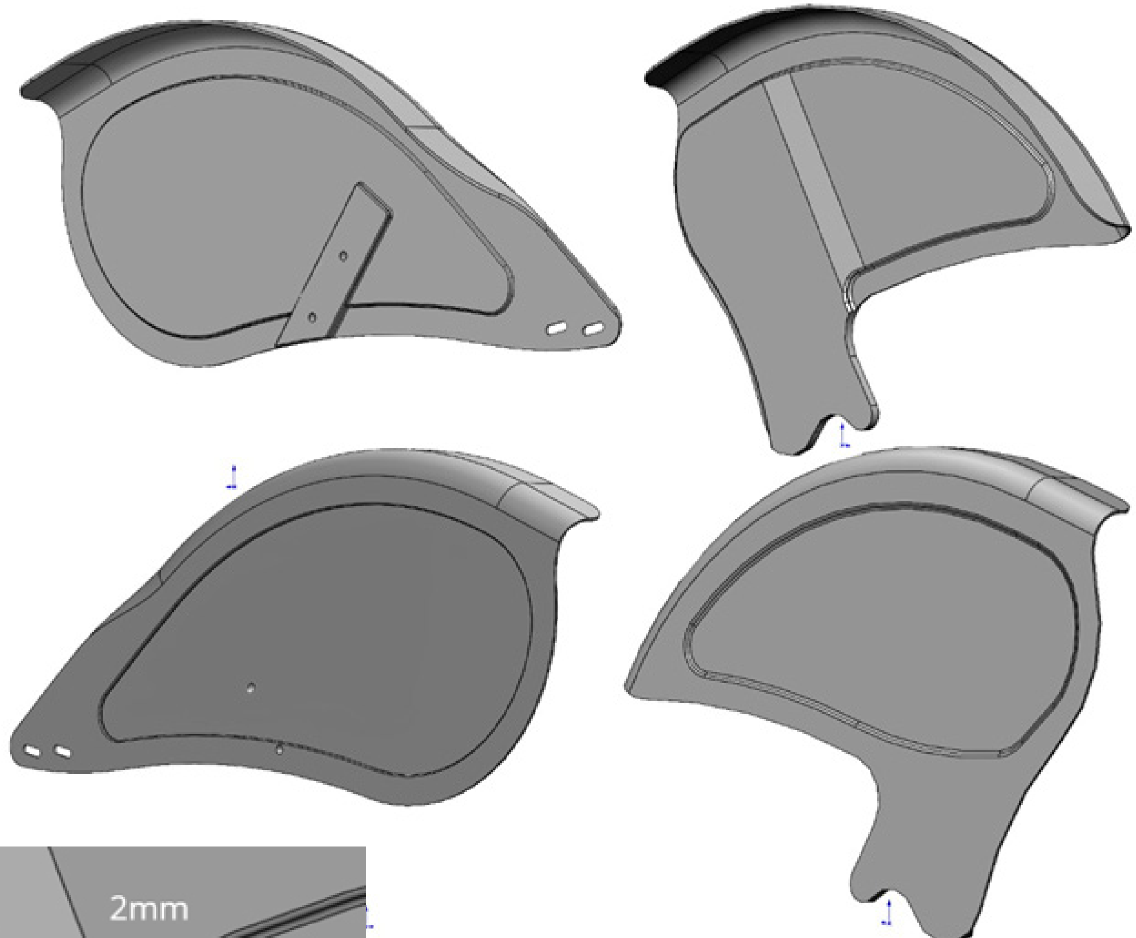
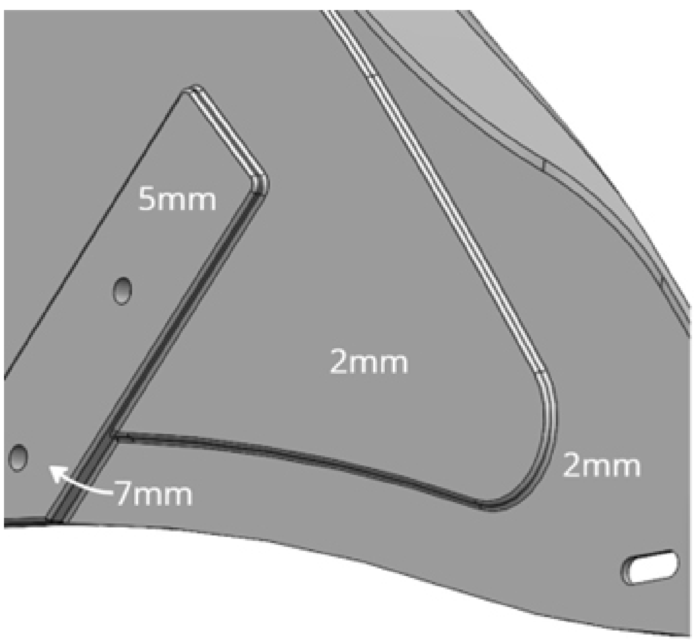
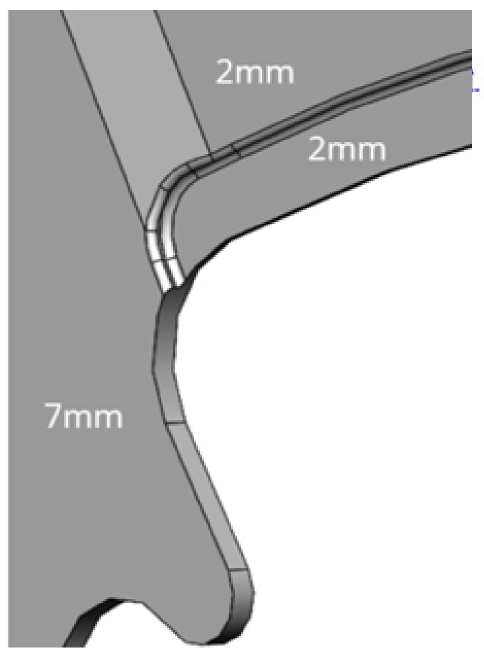


Figure 43, Design proposal for the new fender form (left), closely in line with the old form (right)

Figure 42, Thickness of new (left) and old (right) fender





5.4 Costs

A rough cost estimation of all the parts compared to the current fender is needed to asses (part of) the value of the new fender assembly. A detailed estimation can be found in Appendix 11.9 but the result compared with the current assembly is €24 cheaper. This is mainly due to the fact that the fender has less weight. Even more, the adjustment strip is comparable to the currently used bracket, and the number of bolts is roughly the same. The only difference C-channel slot which is 'extra' but as it is such a small part, and the dimensions are considered standard, this is a cheap product.
Also, some parts are exchanged for cheaper parts, such as the logo brackets (see Figure 44), as they are not visible because of the fender.
Comparing welding time, the fact that the old fixation bracket is not needed anymore, and the new design proposal requires welding on the c-channel, the total time is somewhat different, but as it is a matter of seconds, it does not have a big impact on costs.
The costs for assembly are discussed in the next chapter as they are directly related to assembly time.

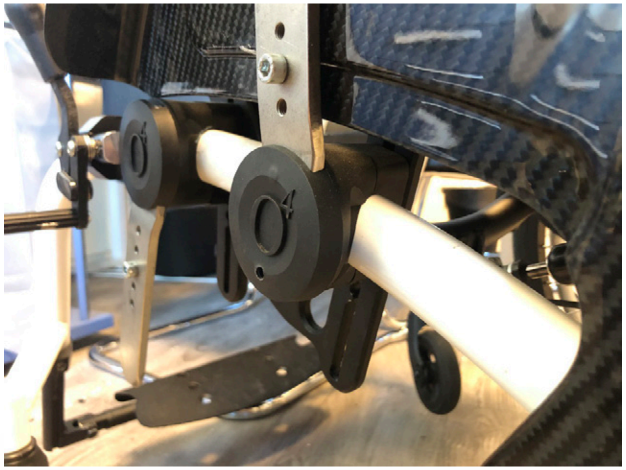


Figure 44, Tube clamp bracket with O4 logo.

Considering all detailing steps, the final design proposal can be established. The design is backed by a comparable cost price to the current fender assembly, and all aspects are elaborated at roughly the same level. This leaves us with a situation that can be discussed and validated.

6. Concept Validation

Finally, the concept is tested to evaluate if it accomplishes the intended goal. This test is performed with assembly workers in the O4 factory. To explain the validation, the design goal is stated again:

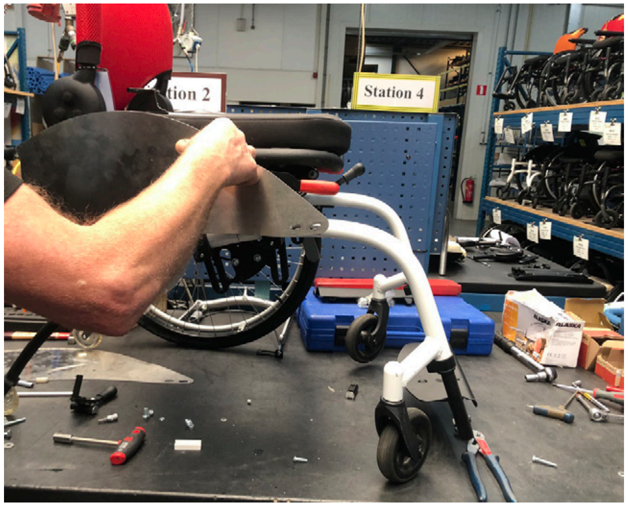
Redesign and prototype (parts of) the wheelchair of O4, to minimise the need for all fully custom parts and thus reduce the production- and assembly time, while still accommodating the needed customisation for the target user.

The test aims to quantify the new assembly time and compare it with the current assembly time of the fender and brake, which is 37 minutes.
As a sub-goal, it aims to optimise the assembly order, and/or find ways to make the assembly easier. By doing so, the 'user experience' of the assembly workers is also tested indirectly, as they can comment on how they experience assembling and suggest improvements.
The test also functions as a way to involve assembly workers in the new fender assembly and aid in the acceptance of a new design. This is important as they are direct stakeholders as well, and it is beneficial if they accept the change and provide their knowledge to optimise the design proposal further (Jhang, 2012).

6.1 Test Setup & Participants

The test is performed at the O4 factory with two different assembly workers. On a workbench, a wheelchair without a fender or brake is staged at the point in assembly where, usually, the fender would be the next step to put on. All necessary parts for the new fender assembly are put on the table, as is normal practice for the assembly workers to start each stage of assembly.

Figure 45, Testbuild of the new fender assembly



6.2 Method

First, the researcher builds and explains the fender assembly. The two assembly workers watch along and are asked to come up with clarifying questions, after which the researcher disassembles the assembly. This is to ensure a good understanding of the fender assembly before starting.
The first assembly worker is asked to put the assembly together once, while the time each step takes is recorded.
After the first time, the assembly worker is asked to review the order of assembly and improve on it if an opportunity is noted. This step is crucial as the way the researcher first assembled the fender influences the assembly worker, as he has one example.
By critically reviewing his own way, uninfluenced decisions can be made purely based on optimising the assembly.
The assembly worker then puts the assembly together for the second time and reviews it to optimise the assembly order.
This process of building and optimising is repeated until the assembly worker has no further optimisation ideas. At this point in the test, he is asked to perform 2 last assemblies, so to average the best times, and to accommodate for the assembly worker to surpass the initial steps of the learning curve of a new assembly way.
This exact process is repeated with the second assembly worker, leading to a sample size of at least four optimised runs.
The test is concluded by a discussion where the assembly workers can review the designed assembly, explain the experienced ease of installation and comment on it in general.

6.3 Results

The assembly was built 5 times in total. 3 times by the first assembly worker, and 2 times by the second.

The average time of both assembly workers was 16.27 minutes with a deviation of ±20 seconds between the builds (a record of the results can be found in Appendix 11.12).

In the review build with both assembly workers, 4 things came forward, which are built and shown in paragraph 6.5.
- The first was that opportunities were identified to reduce the number of parts used in the brake assembly.
- Secondly, the distance between the two brake fixation points was undefined so a bracket to set them at the right distance from each other was needed.
- The third remark was that the bolts used are sharp to the touch and different from the ones used in the rest of the wheelchairs.
- Lastly, the use of nuts on the axle strip could be eliminated by threading the axle bracket.

The design review and discussion after the assembly tests led to interesting remarks which are stated below:

- The order of assembly is logical and straightforward. Components go where you suspect them to go.
- By bolting the fender to the axle strip from the back, in some cases, the chair might be in the way.
-T he integration of the electric wheel fixation slot is

smart and makes an extra part unnecessary.
The c-channel slot limits the chair's front and back positioning range, but in practice, the chair will rarely be that much in the front.
- The adjustability range of 10mm of the brake was found to be sufficient, as the most common wheels at O4 were tried and fitted.
- The brake is ordered as a sub-assembly and would need to be broken down and adapted to work in the proposed design. It might be interesting to see if the brake could be made in-house exactly to how it is needed or if the sub-assembly that is bought from the external party could be changed.
- At the moment there are not many wheelchairs that change wheel size, so the c-channel slot could in theory also be just one hole in the frame, specific to the wheel size it is made for.
The welder noted that he was happy with the change from the complex and timely fixation bracket they use now to the simple C-channel slot.
- The form of the brake is carefully designed to be easy to operate with a small force for the user. Changing this to improve design looks (which was an idea) as shown in Figure 47, will likely compromise the ease of use.

6.4 Conclusion & Discussion

The new time of 16 minutes, compared to the old fender assembly time, has improved it by 44% and leads to a saving of ±€26 in man-hours (€46 to €20).
The test provided multiple small points of improvement that can easily be added to the design proposal.
The order of assembly was found to be straightforward and not much optimisable. The most important finding was to start by fixating the brake to the fender and then fixing the fender to the wheelchair.
Adjusting the brake is as easy (or difficult) as in the current situation, and could be a future point of improvement.
The test also sought acceptance finding, and while at first, the general attitude was mainly sceptic, after building the assembly a couple of times this slowly lessened.
It has to be noted, however, that the time it took to build the assembly will probably improve even more when the assembly workers really get used to it. Little tricks or optimising habits could form over time when they perform the same task over and over.
It also has to be determined if the use of the c-channel slot and its forthcoming aspects is desirable versus the benefits of having a wheel size-specific fender assembly. For this, further use case scenarios should be analysed.
Finally, the remark about the reachability of the axle strip bolts might be a little inconvenient, but not more than the current fender fixation method, where the same problem is prone. This is an area of opportunity to search for a way to overcome this inconvenience.

Figure 46, Assembly worker building the new fender assembly at O4

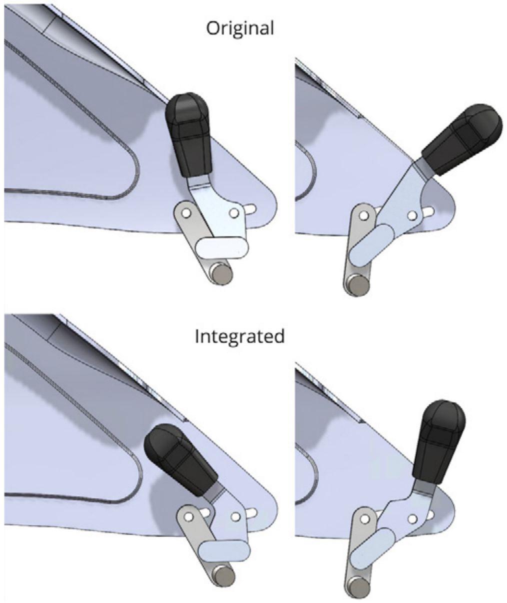


Figure 47, Integrated brake form idea

6.5 Final Iterations

Based on the test results, a couple of iterations were done to quickly improve the final design proposal.
- A bracket fixating the distance between the two hinge points of the brake was introduced (see Figure 48).
- With this bracket, the 4 washers that were present for distance keeping could be eliminated (see Figure 49&50).
- The type of bolts was changed to match the rest of the wheelchair and be easier on the touch. (see Figure 51).
- The axle strip was threaded, so the need for nuts was eliminated, making assembly quicker and reducing the part count (see Figure 52).

Figure 48, Distance fixation

Figure 49, Spacers/washers

Figure 51, Maching bolts

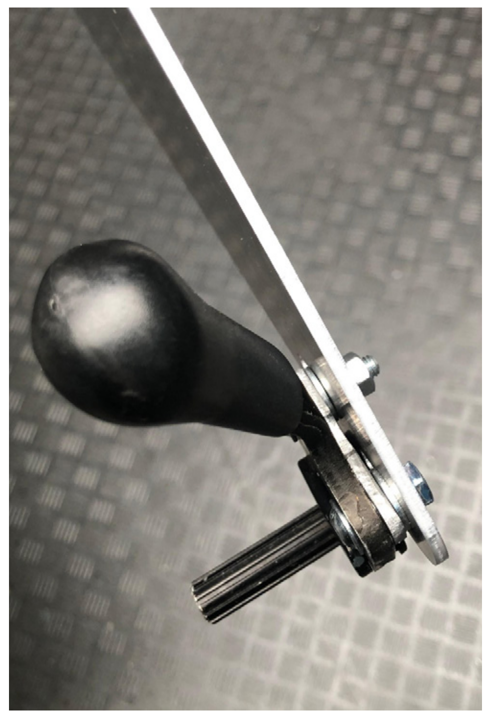


Figure 50, Less parts in the design

Figure 52, Threaded holes in the axle bracket

7. Conclusion

To conclude the project, the necessity to discuss the design goal stated at the beginning is evident.

Redesign and prototype (parts of) the wheelchair of O4, to **minimise** the need for all **fully custom parts** and thus r**educe the production- and assembly time**, while still **accommodating** the needed **customisation** for the target user.

The conflicting situation when working with customised wheelchairs, versus the assembly time being influenced by standardisation, is a struggle O4 faces head-on. Minimising production time benefits not only the cost of producing for O4 but also the cost and delivery time for their customers, ranging from resellers to actual end users.
The final concept, the new fender assembly, sought to accomplish this goal by fixating the fender based on the rear axle of the wheelchair. As this point is always known, the location of the wheel and brake can be determined. The need for manual alignment and adjusting is taken away from the assembly steps. Even more, the parts used, are applicable for all sold wheelchair configurations, and wheel sizes. This decreases the number of different parts in stock and lowers the chances of errors made during assembly. The new assembly also provides an assembly method that can be built independently of pre-knowledge or experience, thus making pre-knowledge in the company less necessary.
The design is kept as close as possible to the current parts and materials, to ensure similar reliability.
The table to the right compares the new proposed fender assembly with the old version. The most important differences are mentioned here.

The validation test provided an indication of the potential improvement the redesign could bring about. A new assembly time of 16 minutes, compared to 37. It also revealed that the order of assembly and the assembly overall is perceived as logical and straightforward, and some simple iterations were done.
This all adds to the desirability of the new fender assembly for O4 and its stakeholders (resellers, end-customers and aid-providing companies). They share the interest in low costs and fast lead times while keeping the unique quality of O4 adjustability untouched.
In addition to the main design proposal, a couple of actionable recommendations can positively impact production and even the products themselves, bringing value to O4 as a company.

Improvements	Old fender assembly	Proposed fender assembly
Time spend in assembly	37 minutes	16 minutes
Costs of parts & welding	±€30	±€23
Cost of fender	±€74	±€60
Error sensitivity	Medium	Low
Reusability with different wheelsizes	Low	High
Need for experience/prior knowledge in assembly	High	Medium
Sub-assembly wheight	640g	690g

8. Future development steps

If the design proposal would be taken further as a 'product', what would require more elaboration? As it would be beneficial for O4 to implement the design proposal, it is necessary to discuss the foreseen shortcomings for future reference and as a basis for further development of the design proposal. These recommendations focus only on the design proposal, as other recommendations have already been treated in Chapter 4.3.

8.1 Reliability and User Experience

The aspect of wear and tear is something only educated guesses can be made about, due to time constraints in this project. Extensive long-term testing would be necessary to judge this aspect properly. The redesign uses as much as possible the same type and dimensioned materials as the current wheelchair to not deviate as much from known working aspects in the current wheelchair design. To verify this method, duration tests specified at continuous load, impact or stress are needed. Theoretically, as shown with the FEM analyses in previous chapters, the new fender assembly should behave the same as the current, but this has to be verified in the physical world.
Secondly, the user's interaction with the new assembly requires attention. Tests that focus on daily use should be performed, to discover improvements regarding the interaction with the fender. Questions like: Where does filth accumulate? Are there user-harming points? Is the metal strip too cold to the touch? might need answering. This was not done due to the lack of time and access to daily users, as well as a lack of a suitable working prototype. Strict regulations apply to wheelchairs in general, so to have official tests done, a prototype to test with should also conform to these regulations (Medical Device Regulation, 2017).

8.2 Fender Form and Shape

The new proposed form of the fender is based on functional properties and somewhat on the form language of the O4 wheelchairs. It might be recommended to rethink the form language as this is a somewhat subjective aspect, as well as the endless possibilities to detail the exact form. Some tests have been done that focus on integrating the adjustment strip more into the whole design (see Appendix 11.10). Still, due to practical considerations (e.g., usability in all scenarios), it was chosen to go with the current form strip. This is a tradeoff between form and function and might be something O4 has more of an opinion about.
Secondly, the stiffness of the fender could be a point of further optimisation. Limited FEM analyses have been done to evaluate the material properties. It can be suspected that with the use of ribs, varying thickness, and other embossments, the fender might be optimised in terms of strength, weight, and needed material. As this specific part has high costs compared to the other parts in the assembly, trying to reduce them could have a big impact on total costs for O4 and optionally its clients.
Considering using a two-sided die for moulding the fender to make a more optimised intricate form, might outweigh the investment needed for the extra die.

8.3 Integration with Other Developments

Pezy Group is constantly improving on the O4 wheelchairs and parallel to this project multiple other projects were run, on other aspects to improve.
Due to the delineation of this project, these ongoing developments were not taken into account. They might however interfere with the proposed design.
If the design proposal is to be implemented, a feasibility study of the other developments is needed to discover the interference. On the other hand, the design proposal might provide opportunities to combine with other developments or might be simplifiable as constraints might change.
Of course, any project undergoing development will face these kinds of issues, but proper communication and project management are not to be taken lightly.

8.4 Reuse and Recycling

At the moment, O4 encounters often cases where a wheelchair gets sent back to them to be adjusted to the user's (changing) situation. The design proposal allows the necessary adjustments, better than the current fender assembly does. A step that still is underdeveloped is the end-of-life stage of the wheelchairs. It is recommended that the development of a reusing and recycling system is brought to life, as this might greatly benefit O4, in the sense of material reuse (costs) and corporate sustainability. Especially carbon fibre, from which the fenders are made, is known to be difficult to recycle, so reusing them might be a huge benefit, if only for the fact that it is costly but also very durable (Jhala, 2024).

8.5 Sunken Costs

A part that is not touched upon thoroughly, is the cost of, for example, a new die for the new fender form. As for the current fender, a die is also used; the costs could be regarded as similar, but an investment is required before the proposed fender form can be taken into manufacturing. Even more, as the current fender die has been used for just over 2 years, the payback period has not yet passed.
Even more, before the full deployment of the design proposal, some wheelchairs should be made with the new fender assembly and tested for longevity and extreme usage with real end users, as currently, it is only tested on assembly with assembly workers. The time and money needed for these tests and developments could be considerable, but not estimated in this report.

8.6 Brake Fixation Construction

As a designer, the construction of the brake fixation to the fender and frame gives the feeling of a 'mechanical engineering' solution. It fulfils its function, but the look & feel ánd elegance are discussable. Some ideation or optimisation of this part of the design proposal could improve the overall design, and integrate the sub-assembly more into the whole wheelchair design. As found in the validation test in Chapter 6, assembly technically, the ease of use could be improved, as well as the elegance of the solution.

Secondly, adjusting the brake exactly to the right tyre size is possible due to the 10mm slot in the fender. The ease of adjusting this is perceived as the same as the current way of brake fixation. This can, however, be improved in future research. Already existing solutions are in the area of linear adjustable brakes that work with a lead screw, but other solutions might be possible. As the exact location of the brake greatly depends on tyre pressure and the amount of force the user would want to apply, having the option to easily adjust this position is desirable.

9. Reflection

In this section I want to take a moment to reflect the project and I will end with a personal reflection. It is unlikely I will do a graduation project again in the future, but there are definitely points I can take with me from this experience.

9.1 Project Reflection

Looking back at the project, it can be said that it adds considerable value to O4 Wheelchairs. Specific recommendations and a tested design proposal that can be implemented or developed further.
Comparing the project to the typical design process (discover, define, develop, deliver), there could have been more emphasis on the develop phase. In this phase, the focus is on the assembly of the proposed design, but some elaboration and tests in the direction of other stakeholders, like the end user, might have added more value.
Even so, the topic of sustainability (which is important in the field of Industrial Design Engineering) is touched upon in some instances but was not a specific focus in developing the design proposal or the problem analysis phase. I have the feeling that, in terms of sustainability, O4 could make some major improvements, but a totally new study must be conducted to map out potential opportunities.
The importance to the broad field of IDE or the added value to this area is somewhat limited. The problem of having to standardise custom products and wheelchairs specifically is interesting, but the proposed solutions are quite specific to the wheelchairs of O4.
Finally, some time could have been spent on creating a functional prototype as well as a visual prototype. As these are now combined in one, it leads to the consequence of having to sacrifice some benefits of having eighter one separately.
With the project completed, one could ask if a full redesign of the complete wheelchair would be more effective in tackling the design goal of production optimisation, as then it can be built from scratch with that in mind. The proposed design and other recommendations are like plasters on a wound, instead of adding to a great design. On the other hand, this would be a huge investment of time and money, with no guaranteed benefits to all wheelchair requirements.

9.2 Personal Reflection

Regarding the flow of the project, which I effectively started 31 weeks ago, it feels like a long process with a lot of ups and downs. After a good start with analyses and getting to know the scope of the design goal, a big amount of time went into struggling with the next steps of ideating and coming to one concept. At the time of the mid-term, my motivation was very low due to mental problems and the feeling of making no progress in the project. After the mid-term, I still struggled but from the moment I started quick prototyping and testing I found enjoyment in the process of designing again. The feeling of making the 5th generation of the same mass-produced consumer good, or the lack of meaningfulness made way for my passion in the design process of fathoming the core of a problem and quickly testing and iterating on solutions. Writing everything down I had done so far, in the form of a mid-term report I should have made anyway, helped in move on to the next steps.
Running up to the green light, I worked hard on the design, which was both stressful and enjoyable. At the green light, I felt like I had a substantiated design and was content with the results.
Looking back at my graduation project, it has been a somewhat familiar process, as I know I often like the embodiment phase the most and always have a dip in motivation halfway through the project. A key learning was that I also enjoyed the analysis phase of this project, as I often find this phase not interesting and needlessly boresome. This was because I connected and worked intensely together with the stakeholders of the project. Even more, the project provided valuable experience about working in a big design agency firm, and made me feel the impact of working a “9 to 5 desk job”. My valuable conclusion about it is that working in such a situation is something I do not seek in my future career. I do however want to continue working with my passion for problem-solving, prototyping and practical design. Also, the great practice of optimising products and processes, which I got to experience in this projec, is something I do very much enjoy.

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11. Appendix

11.1 Assembly Analysis Report

RESEARCH REPORT LEAD TIME O4 FLOW ACTIVE WHEELCHAIR

SUMMARY

In this research report the lead time of an average wheelchair form O4 is performed. By means of recording the whole production process and timing each and every separate process step, an estimation is made. This estimation results in a total lead time of 5 hours and 17 minutes. Next to that, points prone to improvement within the entire process are identified, based on the potential to improve in the field of costs and standardisation. From this, eight potential points for improvement came forth. The most important one being the (long) duration of checking the order bill and picking all parts before the start of assembly.

1. INTRODUCTION

To create a clear and quantified image of the production of the wheelchairs at O4 Wheelchairs, it is decided to conduct a detailed investigation into the process steps and duration of the production, based on an 'average' wheelchair from the production line from O4 Wheelchairs. The reason for this investigation is the lack of clarity of production times because it is never established but guessed based on experience and gut feeling. By making the full production insightful, it will aid in making substantiated choices regarding production time, and thus for example costs, employee occupancy and stock management. Even more, it might be useful for getting a feeling for the context of the production of an O4 wheelchair and determining where potential time savings can be made within the production.

The central question is therefore: "What is the lead time of an 'average' wheelchair, and how is it structured?". A sub-question that is being answered is "Within what process steps lies a potential to improve (on costs, material and standardisation)?"

2. RESEARCH DESIGN AND IMPLEMENTATION

To answer the central question, a method of filming the whole production of one wheelchair is chosen. In this way, the employees can do their work uninterrupted, without the observing being of influence on the process. Because O4 Wheelchairs makes several types of wheelchairs, the Flow Active is chosen as the 'average wheelchair', as this type allows for a good estimation and comparison to the other types of wheelchairs.

Next, the shot footage is rewatched and all ±280 process steps are distilled plus their accompanying time duration. Subsequently, these separate actions were grouped based on forty-three wheelchair sub-parts. For example: 'Mounting the armrests' consists of three actions: 'Placing the cushion on the holder', 'tightening the screw to the holder' and 'Screwing the holder to the wheelchair.'

Next up, the wheelchair sub-parts are grouped into 16 main steps. This is divided based on the most zoomed-out main actions. The time duration of all process steps is taken +10% to compensate for coincidences and measure errors.

To answer the sub-question, there was active monitoring during the filming of the production and questions have been asked on, for example, what the reasoning is behind the setting up or carrying out of certain process steps. Afterwards, during the analysis of the video, there is looked again for notable actions in the process steps.

Based on experience and insight, all steps are judged on where potential gains could be made, without judging if it would actually be effective. This is done to identify as many opportunities as broad as possible.

3. RESULTS

The results of the analysis are described from broad to detailed.

The total lead time of the average wheelchair from order bill to packaged product is 5 hours and 17 minutes.

This consists of the welding of all parts: 1 hour and 25 minutes, and the assembly and quality control: 3 hours and 52 minutes. Added to this time is one week for the duration of the powder coating of the frame, which happens externally.

The distribution of the whole production is shown in Figure 1. What stands out is the step 'Orderbon checken' (checking of the order bill) before assembly takes almost a full hour and is out of proportion with other process steps. Figure 2 shows the dime distribution

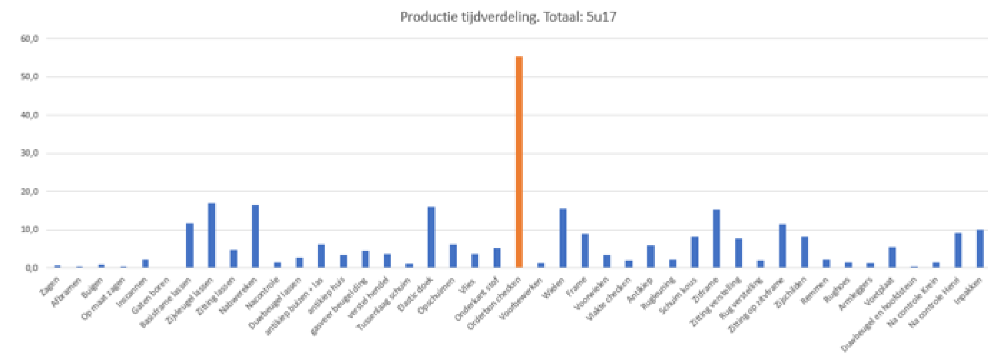

Figure 1, time distribution per production step

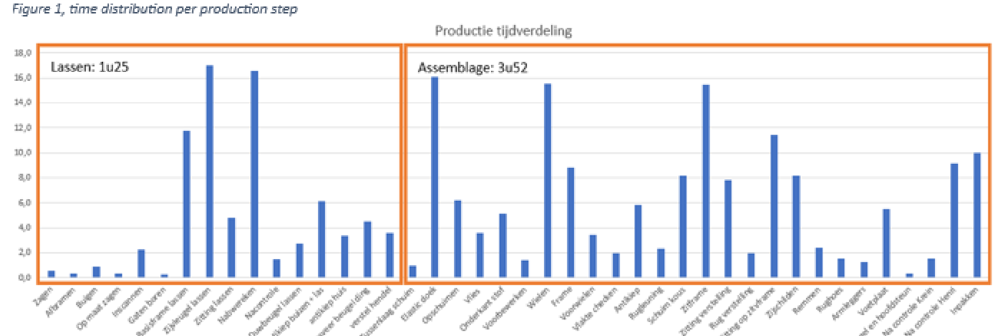

Figure 2, time distribution welding and assembly

from all process steps, with the steps for welding on the left, and the steps for assembly in the right box.

The welding can be separated into 6 main parts. What stands out is that post-processing takes almost a quarter of the total time (see Figure 4). Next to that the setting up of the pieces and adjusting the welding templates takes about 11% of the total welding time (see Figure 3).

	Sec	Min	%
INSTELLEN	503,5	8,39	11%
LASSEN	1474	24,57	32%

Figure 3, setting up time vs welding time.

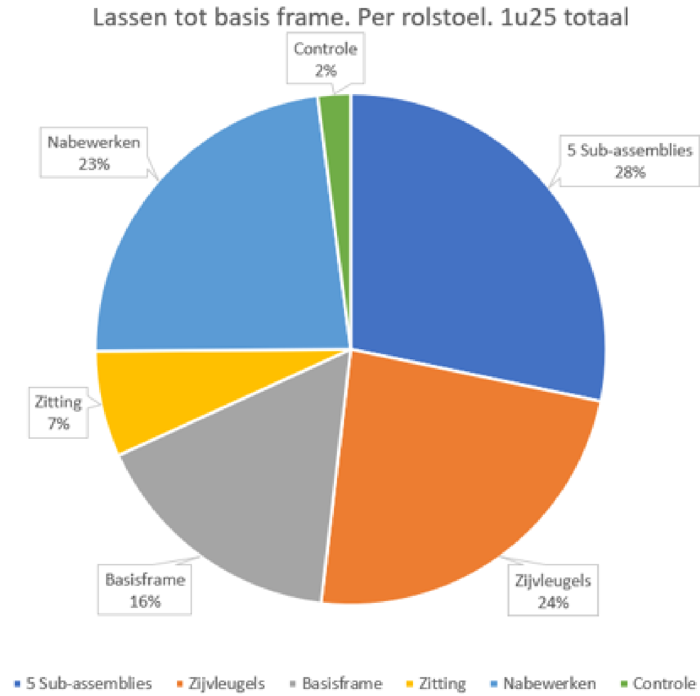

Figure 4, time distribution per main part of the welding

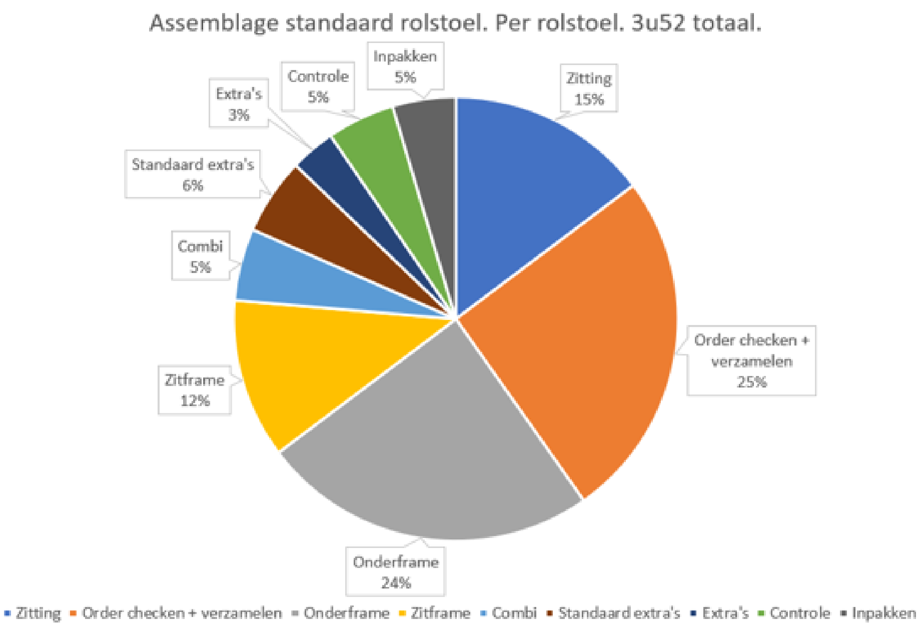

Figure 5, time distribution per main part of the assembly

The assembly steps can be placed in the categories: 'customisation, where customer-specific measurements are being adjusted, 'tightening' where the employee manually tightens bolts and screws, and 'quality checking' where quality and correctness checks are being done. What comes to the eye is that tightening takes almost 16% of the total assembly time (see Figure 6).

		Sec	Min	%
CUSTOMISATIE		671	11,18	5%
VAST SCHROEVEN		2012	33,53	16%
CHECKEN/CONTROLE		871	14,52	7%

Figure 6, customisation vs tightening vs quality checking.

Additionally, eight points stood out, where a potential gain could be made, in the area of assembly time, costs, material usage and standardisation.
-The position of the control lever in relation to the fender is different for every wheelchair and every fender is custom milled to fit.
-Attaching the fender to the frame is often different and requires several types of brackets. A lot of fenders are manually drilled.
-There is a lot of tightening which all happens manually.
-When setting the seat position (activity) and the height of the seat, the seat slides back down uncontrollably, and there is repeated manual measuring of the same distances to set the seat correctly.
-Brakes can twist in two places in the same plane, without it practically being necessary (see figure 10)
-The foam tube on the backrest, which you also push against, is custom-made per wheelchair, whereas it is almost always the same (see figure 11).
-The anti-tip tube at the back of the wheelchair rattles and scratches during use, so it is pre-scratched during assembly (see figure 9).
-Transferring the wishes of the customer into the system and on the order bill is error-prone manual labour. It goes from paper, to digital, to paper again.

Figure 9, the anti-tip prevention tubes, at the back of the wheelchair

Figure 11, Attachment of the brake. Note how the brake itself can rotate in the clamp, and the clamp can turn on the frame tube.

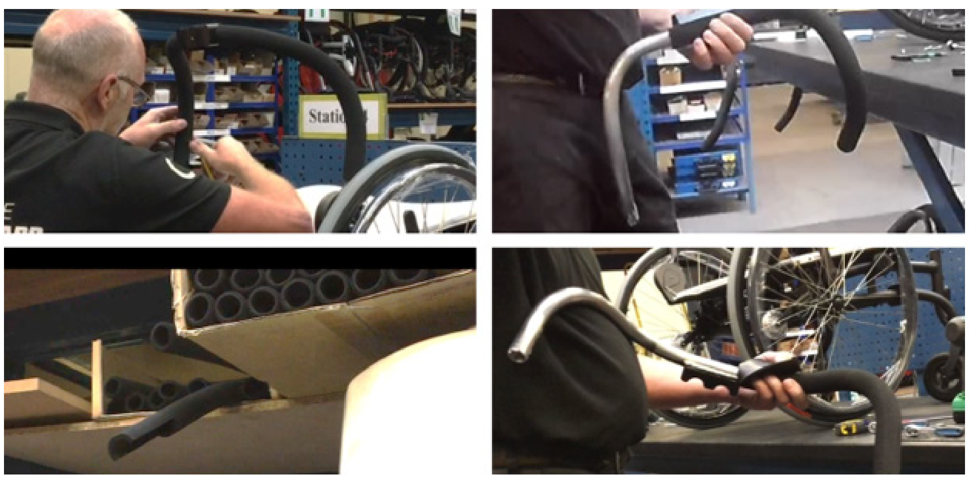

Figure 10, the foam tube that goes around the backrest, to soften it when sitting in or pushing the wheelchair

4. CONCLUSIOIN AND DISCUSSION

Thus, the total production time of the average wheelchair is 5 hours and 17 minutes. That would mean that theoretically 7.57 wheelchairs could be made per week in the current situation. Because the welded frames are powder coated externally, which takes a week, this time basically adds to the total time. However, as this is an external process, it is not directly influenceable.

Collecting all sub-assemblies and parts and checking the order bill took 55 minutes in the analysed case. Even after the official 'order picking' was already done. This is due to the errors often found in the order bill, perhaps the classification/management of warehouse stock and the specific content knowledge about wheelchair assembly. Many parts depend on each other, so are chosen based on each other. The question is whether this was an exception or whether in practice this process step always takes a long time.

The bulk of the time goes to the assembly of the wheelchair, as the wheelchair consists of a lot of parts and sub-assemblies.

Within the welding time, the post-processing of the welded parts takes relatively long, as multiple separate operations are just necessary for the frame. Further research will be needed to determine if this time can be shortened.

Next to that, the welding times have a slightly bigger margin of error, as these measurements are really frame-dependent, and only one frame is the basis for these measurements. This is generalised to be correct for all types of frames, however it results in a slightly bigger error margin.

To the total lead time calculation there is already 10% added to compensate for breaks, interruptions, and measure inaccuracies. In practice, this could be ineffective because there were moments where there was switching between wheelchairs, which resulted in a short startup and setup time before it was possible to continue on the 'current step' in assembly.

During the observation days, no one wheelchair was produced from A to Z. To compensate for this, next to the fact that all individual process steps are being recorded and measured, a couple of process steps are observed by multiple wheelchairs, and their average is taken. This is done while abiding the focus on the Flow Active wheelchair.

The eight points for improvement where gains may be made are all coming down to a lowering in total costs. Eighter through time gains, and thus fewer man-hours, as well as by using less materials.

Even so, the 4th point might add ease of use for the end user or the ergo therapist, if they use the option of adjustability.

Point 7 is about the design of the anti-pivot tube, rather influences the (perceived) quality of the wheelchair.

RECOMMENDATIONS

-It is absolutely necessary to look into the process step of checking the order bill and picking the sub-assemblies and parts. It seems unduly that this takes almost an hour, however, in the case that the measured instance was an exception and normally it happens in half the time, it instinctively feels longer than needed. Preventing errors in the order bill and during the gathering of the parts must be analysed on the process level, with a probable easy time gain as a result.
-It is also useful to look into the process of entering customer-specific wishes, as described in point 8 of the potential points of improvement. At the moment it seems like there are error-sensitive intermediate steps done, that are not essential. Improving this would bring about a systemic change that could be radical but also could yield a lot of gains.
-The eight potential points of improvement are a good start to rethink the design of the wheelchair on these points. It has to be reviewed during the elaboration of these improvements whether they are worth a redesign.
-For a really accurate estimation it is useful to analyse the production of more than one Flow Active wheelchair. In this way, one could take the average of each production step. This might be needed as every wheelchair is slightly different from others and thus its production time will differ.
-Only the Flow Active wheelchair is analysed. However, in practice, customers need a specific setup or adjustments, and precisely these 'not standard adjustments' take proportionally more time.
-For the analysis of the other types of wheelchairs, it is important to look into the differences between them and analyse those specifically. The Flow Mono and Flow Original will take less time than the Flow Active, and the Flow Relax most likely more, due to the complexity and extra parts.

11.2 Sales Data Analysis Report

SUMMARY

In this report, the sales data from O4 from 10-2022 until 10-2023 is being analysed. This data is tested on significance and turns out to roughly be comparable with the sales data from 2011 until 2023. The sales data is divided into 15 categories with accompanying offered options. Per categories, the percentage of each option is compared to the total sales is expressed.

1. INTRODUCTION

To create a quantified image for substantiating product technical choices, it is important to get insight into the sold wheelchairs of O4. Because each wheelchair is uniquely adapted to the wishes of the customer, all wheelchairs are different. Nonetheless, there will be various parts or configurations that are sold more often than others. To make this insightful, an analysis is done based on the sales data from O4. De reason for this analysis is a turbulent history in the field of wheelchair types at O4, and the potential value of this forthcoming knowledge for, for example, the focus on product improvements, the out-sourcing of sub-assemblies and detailed inventory management. Thus the central question states: “What is the distribution of the different sold wheelchair configurations”. Here, one can think about examples like: which wheel diameter is sold the most often, or which length and seat width combination can be ordered, but hardly ever is?

2. RESEARCH DESIGN AND IMPLEMENTATION

To answer the central question properly, the chosen data to analyse is that of all sold wheelchairs from 10-2022 until 10-2023. This specific window is chosen because, in 10-2022, O4 has renewed its product portfolio (a lot of old models and options are no longer offered), thus this interval being the most in line with the sales of the future. The sales data is saved in the ISAH system, where specific configurations of each wheelchair are separated and formulated into 3 product codes. To make this insightful and usable, an automatic separation is done based on the first two product codes, as they hold the main info. This separation is done per category that can be filled into the wishes of the customer. Next up, a distribution is made per category per option in said category and how often each specific option is sold compared to the total sales. For example: in the category wheel diameter, 3 sizes are being offered. Those are each expressed as a percentage of the total wheels being sold.

Because the sample size from 10-2022 contains just 163 sold wheelchairs, which is rather small, the sales data from 2011 until 2023 (2219 sold wheelchairs) is taken for the same analysis. Thereafter a paired t-test is done to determine if the average sales from 2011 are the same as the average sales from 10-2023. For the paired t-test, a quite high significance threshold is chosen (90% certainty) to compensate for the fact that between 2011 and 10-2023 a lot more different and other types of wheelchairs were being sold.

3. RESULTS

The results of the sales data analysis and the significance check are respectively described in this chapter.

Categorie	Aangeboden opties	% van totaal
Breedte	44	23%
	41,5	36%
	39	14%
	46,5	6%
	36,5	7%
Frame lengte	40	54%
	34	36%
	45	10%
Framevorm	U	36%
	V8	52%
	AB	10%
Camberhoek	3	68%
	0	28%
	6	4%
Type	Easy (Sway)	38%
	Flow (Olympic)	46%
	Mono (Easy)	14%
Diameter wiel	24	79%
	26	5%
	25	13%
Soort wiel	Standaard (D)	59%
	Alber E-motion (AM)	11%
	Alber E-fix (AF)	10%
Voorwiel	Soft Kunststof 5" (S5K)	75%
	Soft Kunststof 6" (S6K)	12%
	Frogleg Soft Kunststof 5" (F5K)	4%
Hoepel L=R	Aluminium blank anodiseert (A)	44%
	Gripversterker één (HG1)	2%
	Edelstaal rvs (ED)	9%
	Tetra Grip (TG)	3%
	Ergo-grip (EG)	8%
	0	31%
Band	Marathon plus evolution (M)	80%
	PU Massief (P)	7%
	Richtrun Rood (RR)	5%
Zitdiepte	45	33%
	42,5	20%
	40	17%
	47,5	15%
	50	6%
Soort zitting	Kontour Alu (KSA)	60%
	Wigverstelling Kontour alu (WKSA)	10%
	Vlak Alu (VSA)	20%
Rugscharnier	Standaard (R1)	66%
	Rug 2.5 cm naar voren (R1.5)	30%
	Basis maat R1 (E0)	4%
Rughoogte	R40	23%
	R45	40%
	R50	25%
	R35	3%
Rugvorm	Anatomisch strd. (ST)	67%
	Anatomisch vrouw (VR)	18%
	Recht (RE)	12%

Table 1, percentage sold options per category

Between October 2022 and October 2023, O4 sold 163 wheelchairs. The distribution of the options within each of the 15 categories is shown in Table 1.

What stands out is that within the categories that are based on ‘human measurements’, like width, seat depth and back height, the distribution is roughly nominal (see Figure 1).

Even so, in a lot of categories, there are one or two options that are sold together for more than 80% of the time and thus are mono-dominantly distributed. This is the case for frame length, -form, camber angle, tyre, type of seat, back hinge and back form (see Figure 2).

The results of the paired T-test are shown in Table 2, where the hypothesis “the average sales from 2011 are the same as the average sales from October 2022” is tested on significance. If one needs to be of 90% certainty that the hypothesis is correct, it shows that this cannot be done for 4 categories (in orange). For the last two categories shown, there is not enough data to perform a paired T-test so there are no results.

What stands out is that for 5 categories (in green) one can say with 99% certainty that the established hypothesis is true.

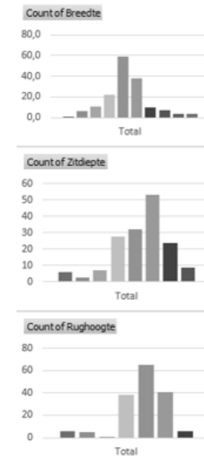

Figure 1, nominal distribution

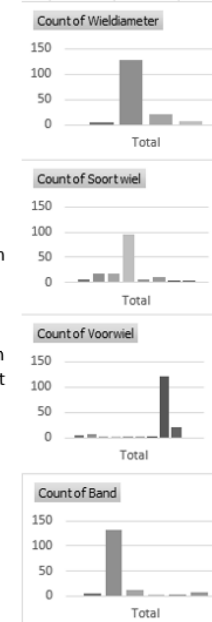

Figure 2, mono dominant distribution

H0= De gemiddelde verkoop vanaf 2011 is het zelfde als de gemiddelde verkoop vanaf oktober 2022		
α	0,05	90% zeker
Paired T-Test voor breedte	0,000205	
Paired T-Test voor frame lengte	0,649648	
Paired T-Test voor framevorm	0,002371	
Paired T-Test voor camberhoek	0,000000	
Paired T-Test voor type	0,025802	
Paired T-Test voor diameter wiel	0,138554	
Paired T-Test voor soort wiel	0,000269	
Paired T-Test voor hoepel	0,854891	
Paired T-Test voor voorwiel	0,027439	
Paired T-Test voor band	0,000038	
Paired T-Test voor zitdiepte	0,181871	
Paired T-Test voor soort zitting	0,019907	
Paired T-Test voor rugscharnier	-	
Paired T-Test voor rughoogte	-	

Table 2, the results of the significance of the established hypothesis per category

4. CONCLUSION AND DISCUSSION

One of the most important points from the analysis is that the options based on human measurements, are being sold following a nominal distribution. Next to that, there are a couple of options that are being offered but are rarely sold, so most wheelchairs have the same options.
This gives a clear image and a good foundation to base choices on. It is now easy to determine which parts in what quantity need to be kept in stock to always be able to assemble and deliver a certain percentage directly after the order.
Also when improving the design of the wheelchair, these results could be used to substantiate what options one must choose if it is chosen to use the 'Design for most' strategy (Mullen & Mace, 1998).

-Because the data from the ISAH database has a lot of mistakes and imperfections, some categories, like frame colour or back form, are somewhat manually selected from the list based on what data was expected to fall in that category. This lowers the accuracy a bit. Nonetheless, in most situations, the results are still valuable and they give a good indicative picture of the distribution of the sales quantities
-Not all analysed wheelchairs have data in all categories. This is compensated by using the total known data points as a reference instead of the total sold wheelchairs.
- The fact that the compared T-test is not positive in the category 'diameter wiel' (wheel diameter) and 'hoepel' (hoop), can be explained by the fact that between 2011 and October 2022 other types of wheelchairs were being sold that are no longer sold after 2023, so these data sets are actually not comparable.

5 RECOMMENDATIONS

-Investigate how combinations of measurements, like seat width and depth, are related. An example is that with a width of 44 cm, 55% of all sold wheelchairs have a depth of 45 cm, and just 3% of the cases have a depth of 50cm. This can give a lot more insights than the sole sales numbers from each separate category, and could also be a reason to make specific combinations in stock that are sold more regularly.
-One could make a good estimation based on the data on what the number of individual parts, like front-wheel or type of back hinge, should be in stock to be able to produce directly in different scenarios. For example: in a scenario where O4 wants to directly assemble 90% of all orders, they would need 104 type R1, and 38 type R1.5 back hinges in stock. Recommended is therefore to use the sales data for a better optimized inventory.

-The data can also be grouped per week or month, which makes it possible to do trend or peak analyses on sales pressure during the year.
-To make representations as accurate as possible, O4 should carefully gather and keep track of future data, combined with the data from October 2022. Despite the use of the data from the past 13 years could be used in the future

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Story, M. F., Mueller, J. L., & Mace, R. L. (1998). The universal design file: Designing for people of all ages and abilities.

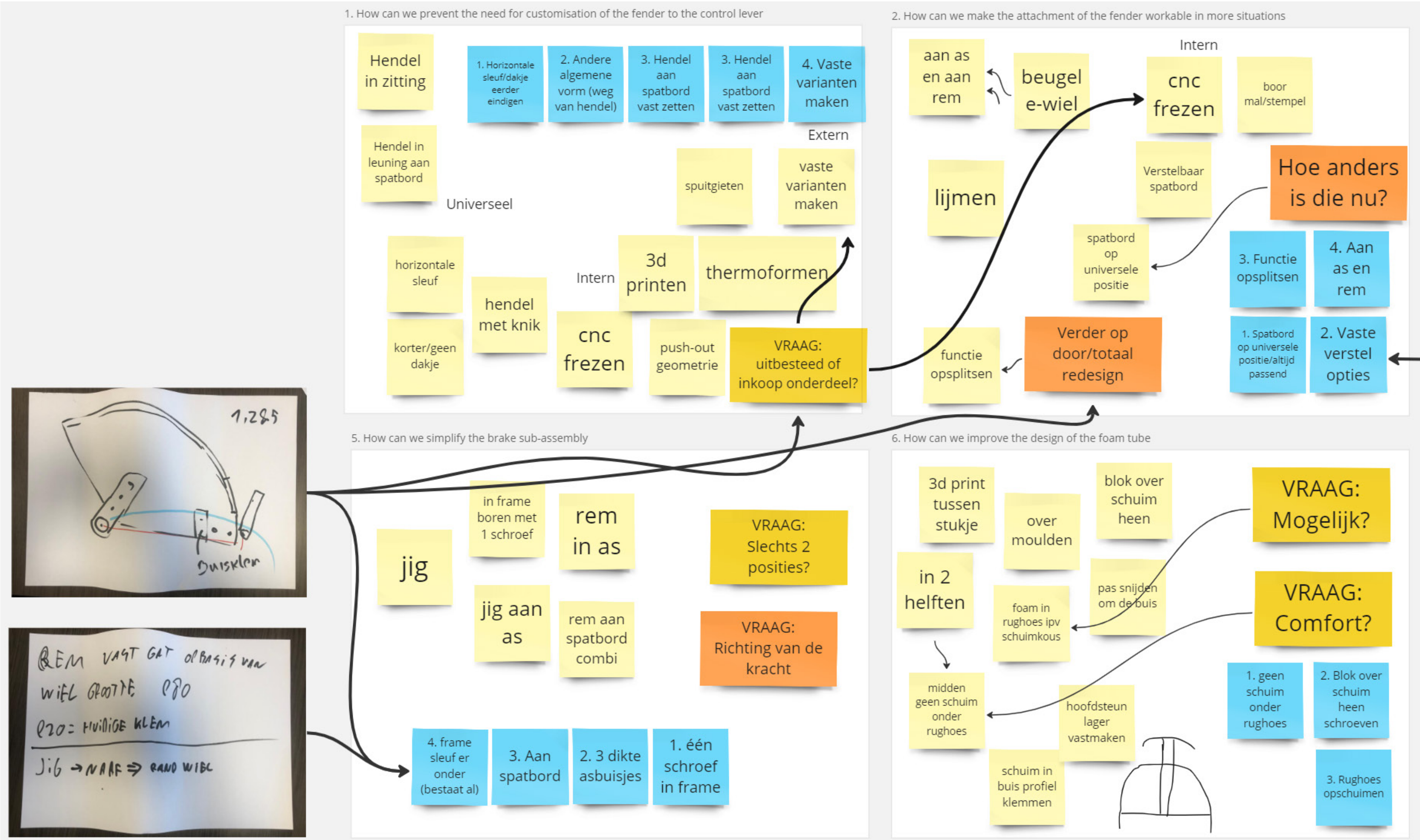
11.3 List of Requirements

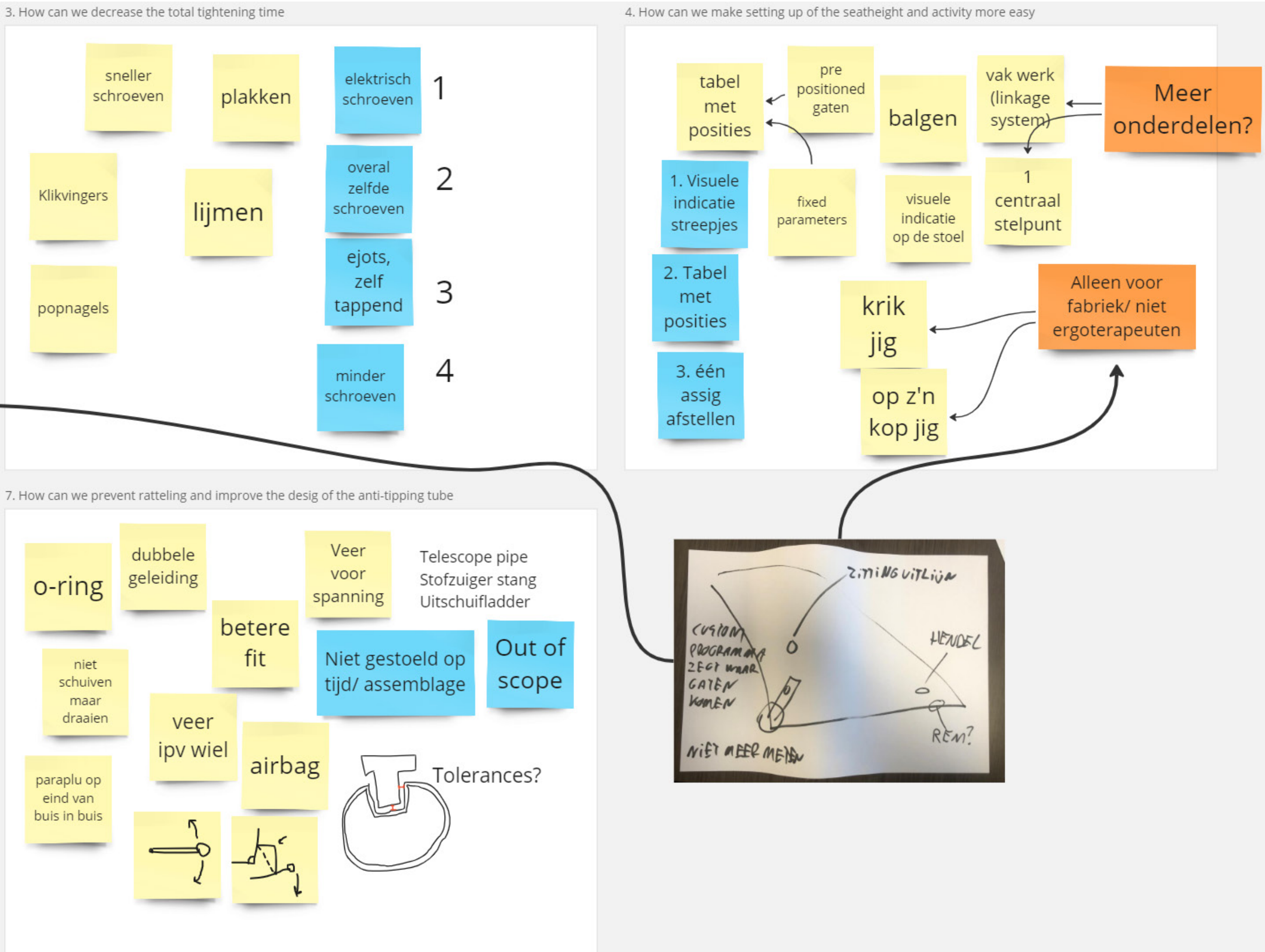
Main requirements
-The assembly time is less than the current situation
-As little as possible fasteners
-As little as possible permanent fasteners
-As little as possible parts
-As little as possible costs
-Allows for de-assemble/recycle as much as possible
-As nice looking & coherent as possible
-*Assembling should be as easy and intuitive as possible*
-*Same type of fasteners*
-*As lightweight as possible*
-*As reliable design as possible*
-*At least a lifecycle of 7 years. Wear and tear-resistant.*

Requirements concerning the fender
-Same protection against water (based on the range of hand travel=86°)
-Seat coverage from the side, in all positions.
-Not in the way of the user's hand
-Stiffness to carry a person (120 kg vertical load)
-Same or less amount of material
-Usable in all cases (3 wheel sizes, 3 camber angles)
-Look and feel should be in line with the design language of O4
-Workable with 3 wheel sizes (look & feel)
-Material is aluminium or carbon fibre
-Nice to the touch (for the hips)
-Same or better brake and lever reachability
Requirements concerning the brake assembly
-The effectiveness of the brake should at least be the same as the current situation
-The brake should have roughly the same placement
-The user should be able to access the brake with the same ease as the current situation
-At least 10mm adjustability allowance
-The brake should be at the same distance from the wheel in all 3 situations
-*Nice looking integration with the fender/chair*
-*No need for measuring/adjusting to wheel*

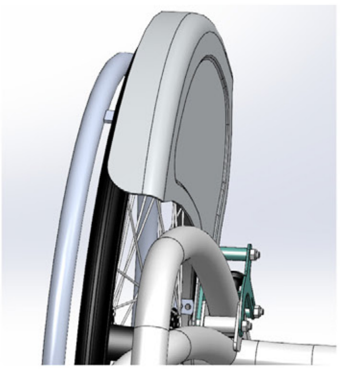
Requirements concerning the control lever
- The user should be able to access the control lever with the same ease as the current situation
- The control lever should have roughly the same placement
-The control lever should be able to withstand lean-on resistant stiffness (=800N vertical pressure)
-Same or longer length to accommodate the force that is needed to operate the lever
-Integratable on all 'standard' wheels

11.4 Results of the Brainstorm Session

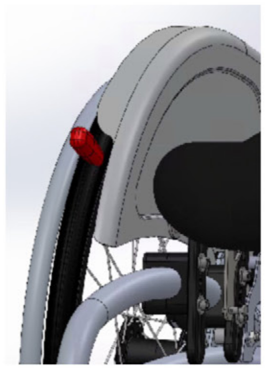



3. How can we decrease the total tightening time
sneller schroeven
plakken
elektrisch schroeven
1
Klikvingers
lijmen
overal zelfde schroeven
2
ejots, zelf tappend
3
popnagels
minder schroeven
4
4. How can we make setting up of the seatheight and activity more easy
tabel met posities
pre positioned gaten
balgen
vak werk (linkage system)
Meer onderdelen?
1. Visuele indicatie streepjes
fixed parameters
visuele indicatie op de stoel
1 centraal stelpunt
2. Tabel met posities
krik jig
Alleen voor fabriek/ niet ergoterapeuten
3. één assig afstellen
op z'n kop jig
7. How can we prevent ratteling and improve the desig of the anti-tipping tube
o-ring
dubbele geleiding
Veer voor spanning
Telescope pipe
Stofzuiger stang
Uitschuifladder
betere fit
Niet gestoeld op tijd/ assemblage
Out of scope
niet schuiven maar draaien
veer ipv wiel
airbag
paraplu op eind van buis in buis
Tolerances?
ZITTING UITLIJN
HENDEL
REM?

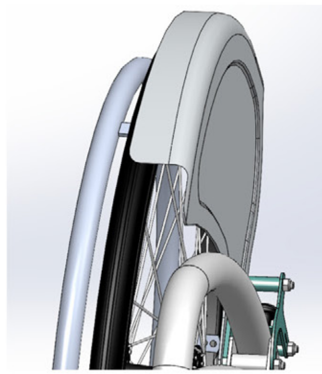
11.5 Elaborations of Most Promesing Ideas per Design Question



Current



Slightly gone



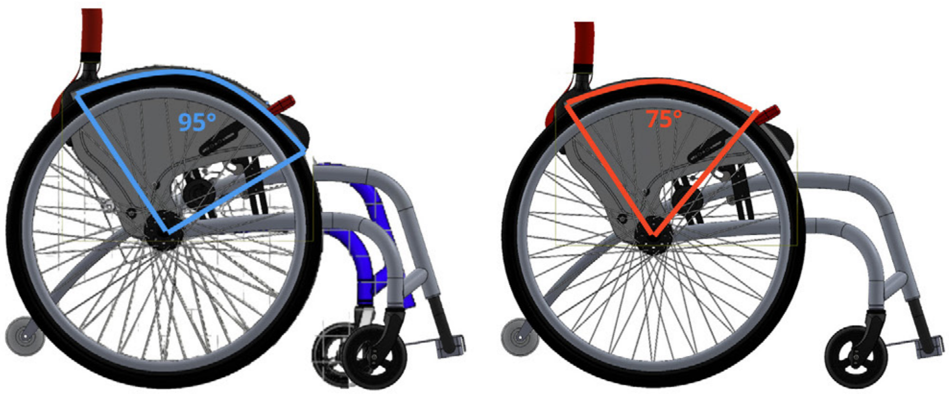
Totaly gone

Strengths

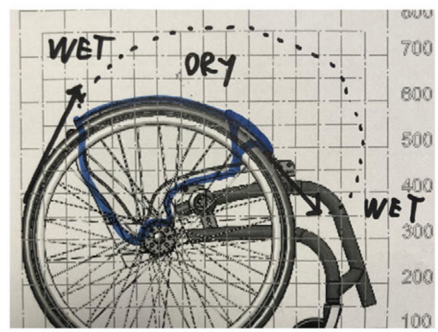
Works for all handle positions

Less material

1.1 Horizontale sleuf/dakje eerder eindigen



Fender coverage decrease

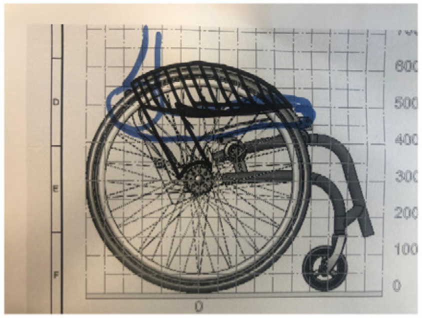


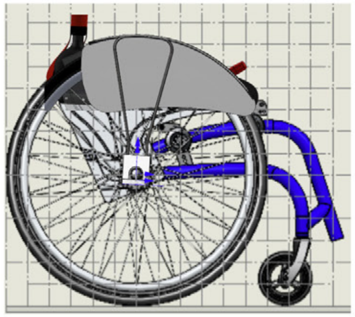
Weaknesses

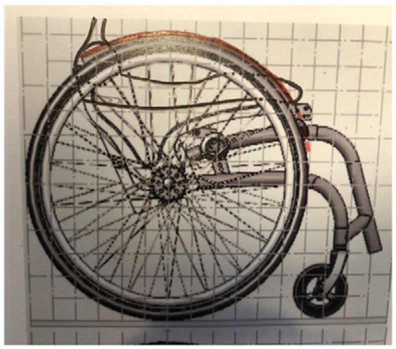
Less protection

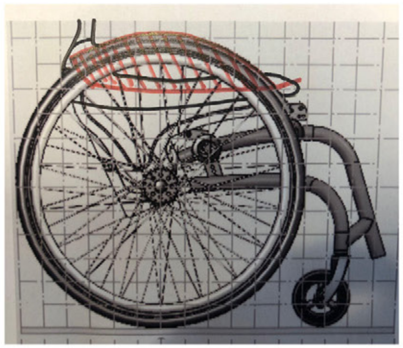
Not nescessary if no handle = 2 types of fenders

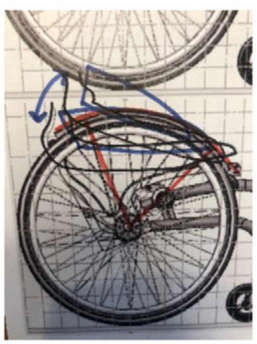
1.2 Andere algemene vorm (weg van hendel)

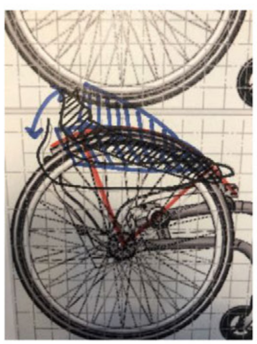


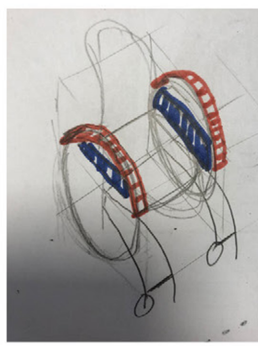












Blue fixed to chair

Red fixed to wheels

Strengths

- Less material
- Lean (only where needed)
- Less Weight
- Smaller = cheaper

Weaknesses

- Less protection
- Fixation adds extra parts?
- 2 parts per fender

1.3 Hendel aan spatbord vast zetten

Between fender and wheel

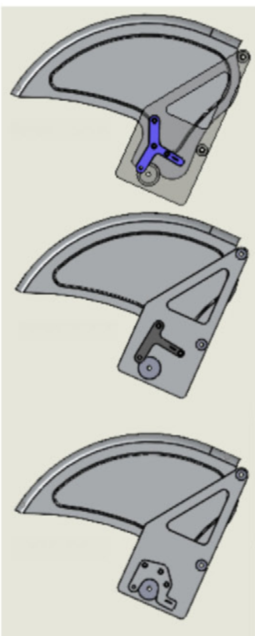
Strengths

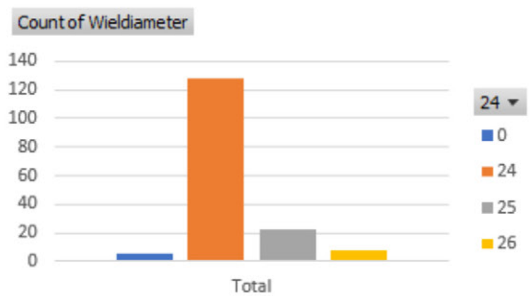
- Always same placement
- No adaptation to fender

Weaknesses

- Extra parts (brake cable etc)
- Indirect action to hinge
- Hard to fit with camber of 6-9?
- Not moving with chair movement

1.4 Vaste varianten maken





Strengths

Easy for tire size 80% same

Perfect design

Pick and go

Also alows for perfect montage in most situations (problem 2)

Weaknesses

More parts in stock

Lot of design work

Lots of lever positions thus lots of variants

2.1 Spatbord op universele positie/altijd passend

Strengths

- Easy assembly
- No customisation needed
- One type/way of connection to frame

Weaknesses

- Design look compromise
- Effectiveness of protection
- Extra (unused) material

2.2 Vaste verstel opties

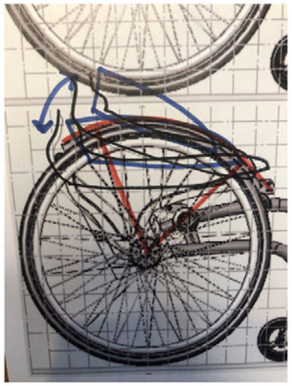
Strengths

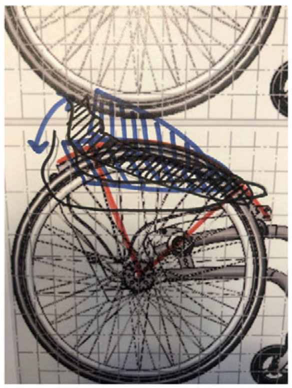
- No customisation needed
- Ease of adjustment
- Option to mark the holes

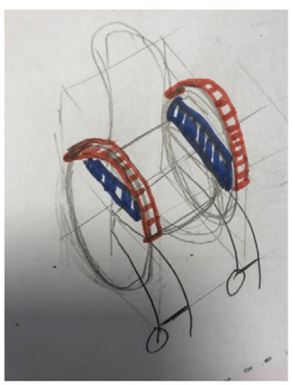
Weaknesses

- Aesthetics
- Lots of configurations
- Limiting options
- Overlapping holes/options?

2.3 Functie opsplitsen







Blue fixed to chair

Red fixed to wheels

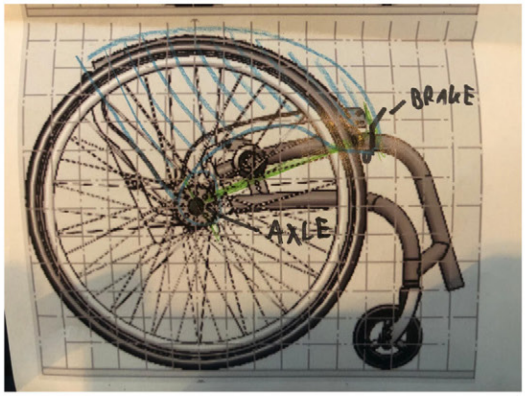
Strengths

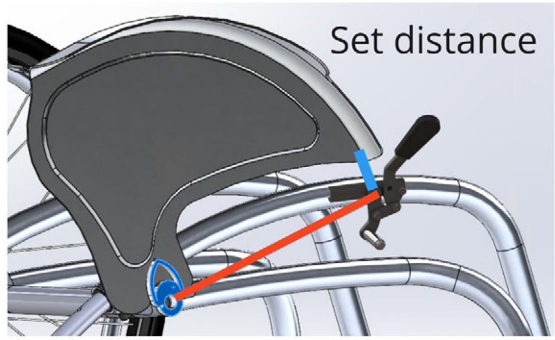
- both pieces can be made in optimal form
- lean
- always side support

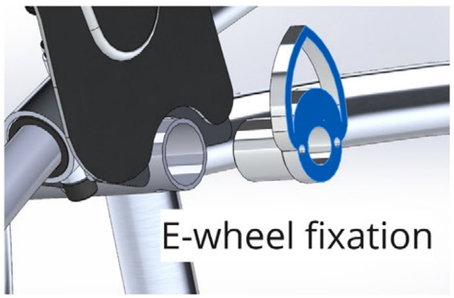
Weaknesses

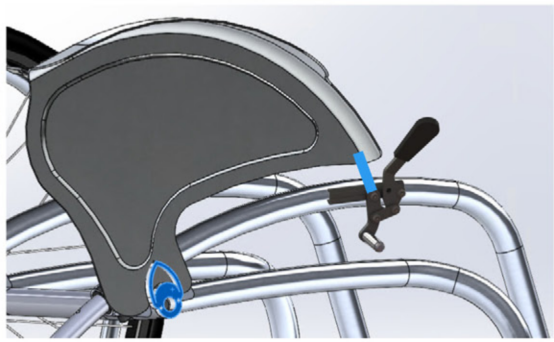
- more material needed
- more steps in montage
- strength problem?

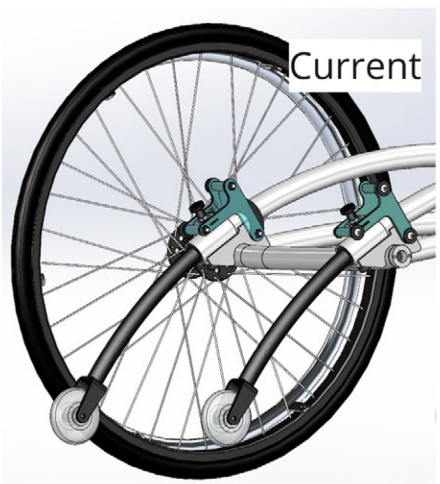
2.4 To axle & brake











Strengths

- Use e-wheel fixture
- Better torsion resistance
- Brake align jig
- Less parts

Weaknesses

- 3 sizes for wheels
- Brake strength

3.1 Electrisch schroeven

Strengths

- Torque control
- Time decrese
- Ergonomic improvement
- Repeatability

Weaknesses

- Acceptability
- Reachability issues → Space limitations

3.2 Overal zelfde schroeven

Fasteners	Count	Tool type
Bolt M8	2	Socket wrench
Imbus bolt M6X30	2	Allen key
Imbus bolt M6X55	2	Allen key
Imbus bolt M6X65	8	Allen key
Locknut M6	4	socket wrench
Imbus bolt M6X20	4	Allen key
Button head screw M6X20	4	Screwdriver
Sunken head bolt M8X35	4	Allen key

2 sizes

3 types

Strengths

- No switching of bits
- volume discount
- less think work

Weaknesses

- Less perfect fit
- sometimes overkill
- Space limitations

Integrated thread

Strengths

3.3 Zelf tappend/pre tapped

Less nuts

Quicker tightening

Weaknesses

wear & tear

need for pre-threading

strength issue?

3.4 Minder schroeven

Strengths

Less parts

Quicker instal

Welding

Snapfit

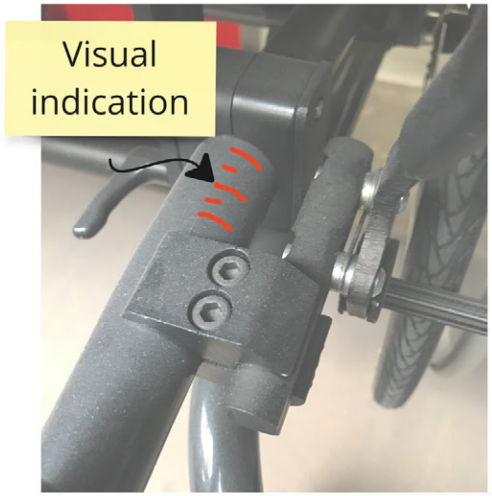
Weaknesses

Less recyclable

Less adjustability

Longer weld times

strength issue?



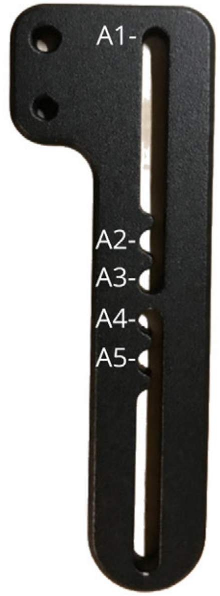
4.1 Visuele indicatie streepjes

Strengths

- Easy add on
- No need for measuring
- Left & Right align
- Also for brake

Weaknesses

- No limitless options
- Costs of engraving
- Permanent → Visible



Hight X & Activity Y = Hole A1 and B4

4.2 Tabel met posities

Strengths

Always right position

In combination with 4.1

Easy adjust

Advice

Weaknesses

Adjusting still hard

Engraving/ printing

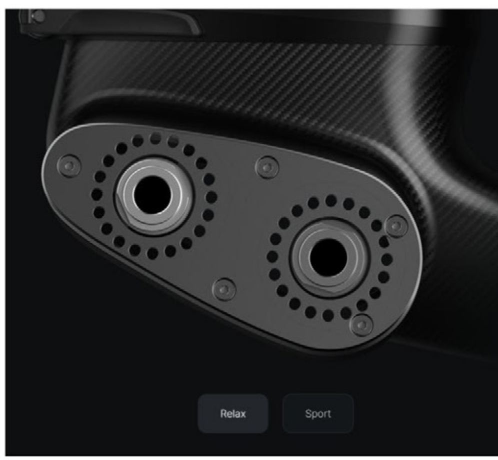
Strengths

4.3 een assig verstellen

Endless adjustment options

Perfect fit

Every day adjusting



Sport

Relax

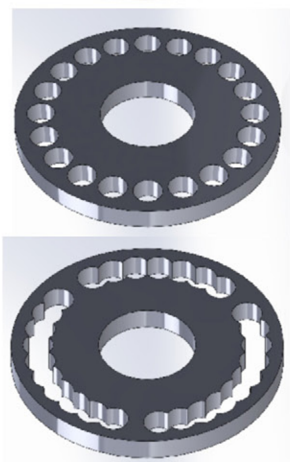
Weaknesses

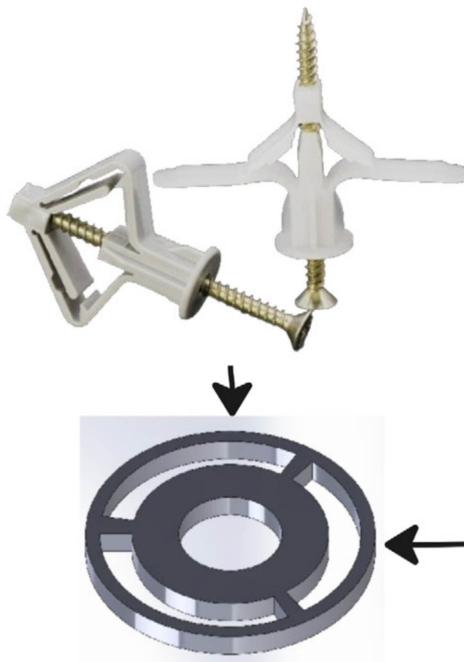
More parts

Not easier assembly

Weight

5.1 Rem in as van wiel





Strengths

- Regardless of tire pressure
- Never in the way
- limitless stop positions
- Already existing to build on

Weaknesses

- Strength
- Reachability

5.2 Drie dikte asbuisjes

3 diameters

Strengths

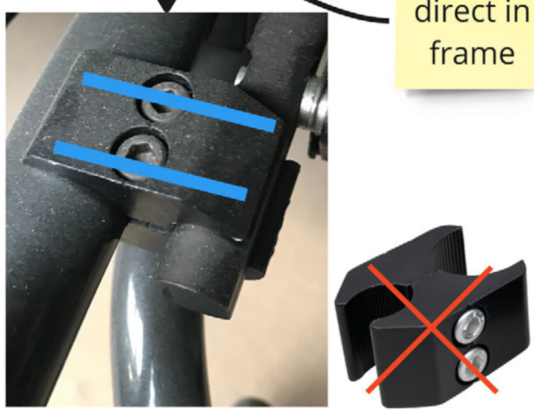
Same placement of frame

Same assembly, 1 different part

Less material

No extra tube

2 screws direct in frame



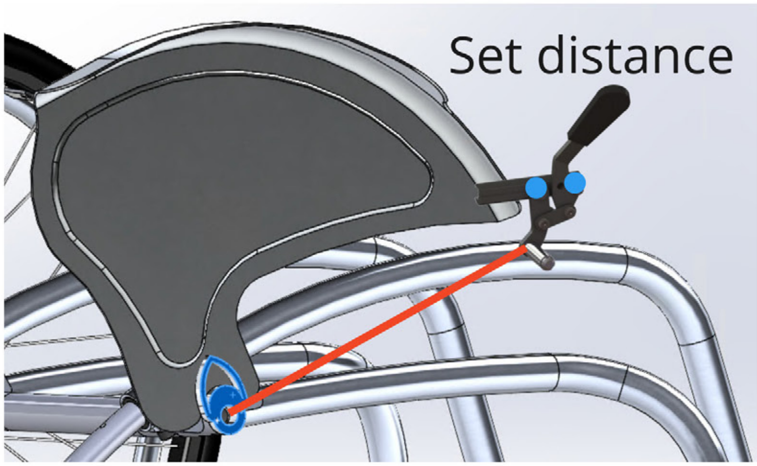
Weaknesses

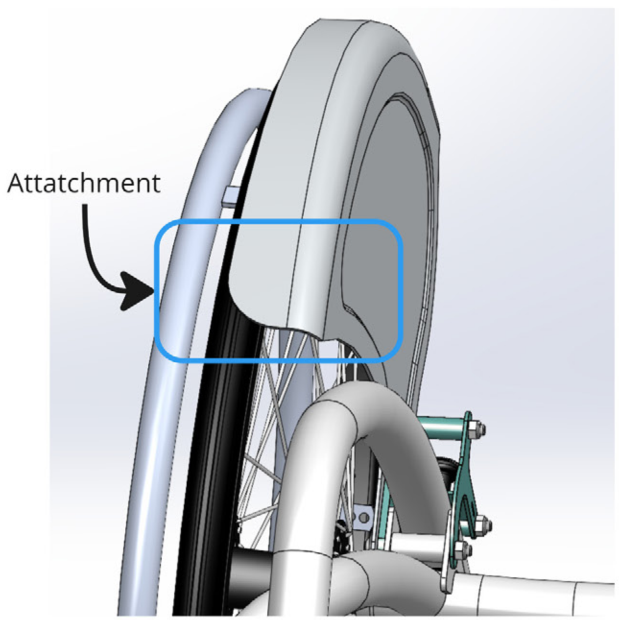
Clumsy look

No adjustability

Cilinder Ø5 cm

5.3 Aan spatbord





Between fender & wheel?

Between fender & seat?

Strengths

- Always good placement to wheel
- Less material
- Combination with 1.1 & 2.4

Weaknesses

- strength? torsion on fender
- Stickout to reach wheel
- Reachability

No extra tube

2 screws direct in frame

Strengths

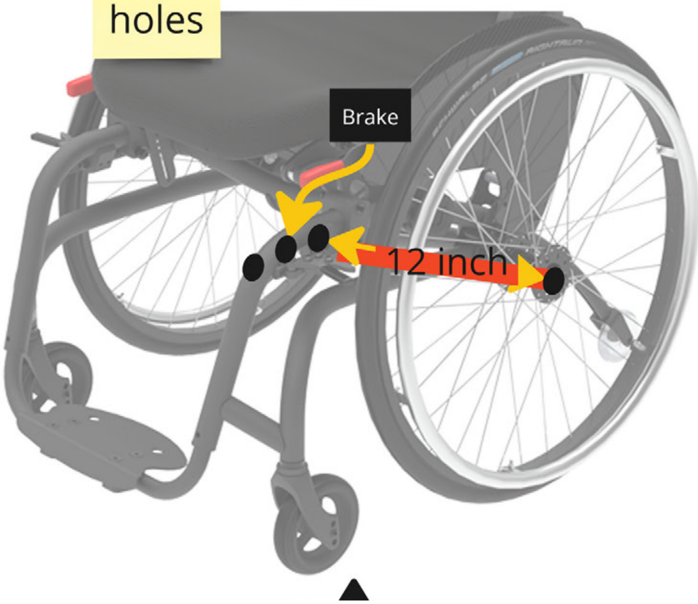
5.4&5.5 sleuf/set holes

Combination with 5.2

No unnececary torsion/turning

Easy placement

Set holes



Sliding position

Weaknesses

Need for welding

Extra material

Design look

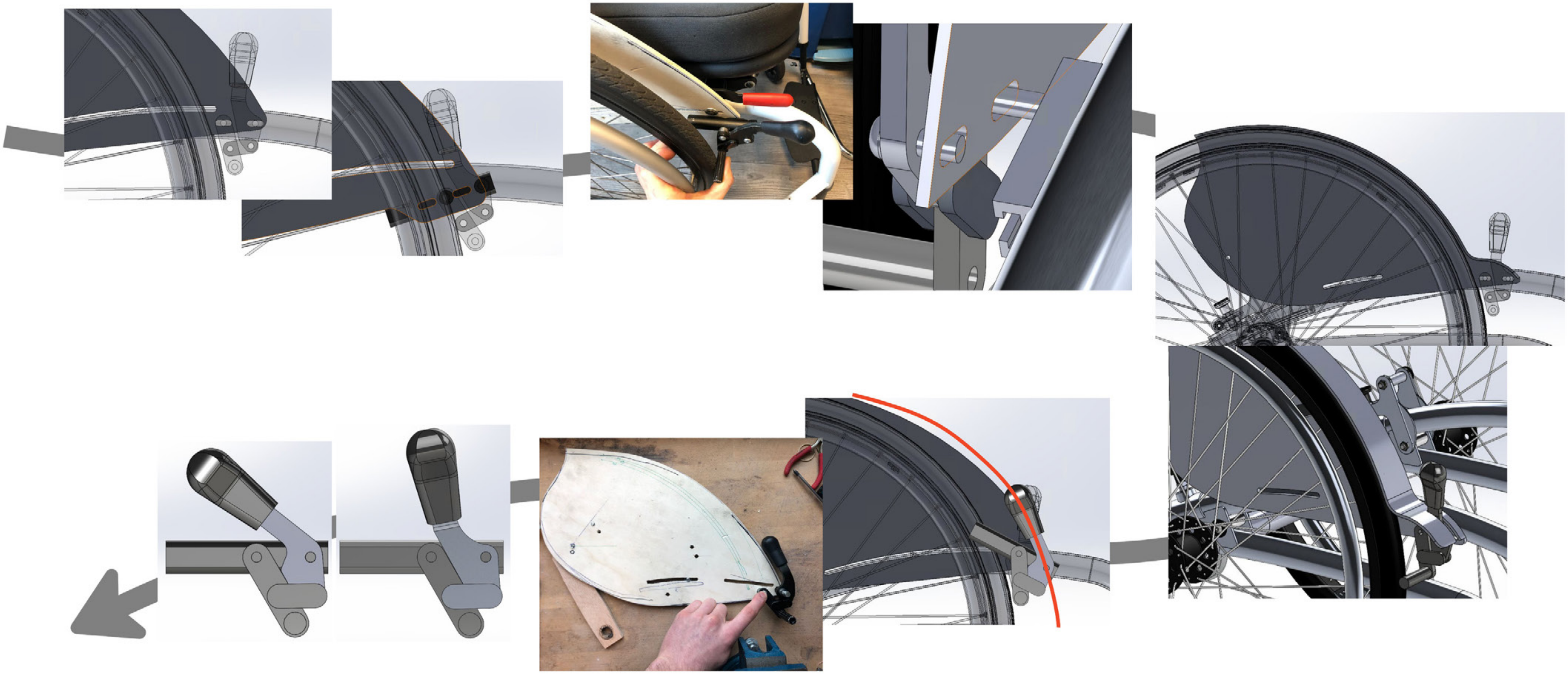
Holes in tube (rust/caps)

No adjusting

11.6 Assesment of all Promesing Ideas

Concepts	Viability	Desirability	Reliability	Requirements met	Combinable with other concepts	Result
Fender-control lever						
1.1 End fender before lever	++	+	-	+	+	4
1.2 Different form	+	+	+	+	-	3
1.3 Lever on fender	++	-	+	+	+	4
1.4 Fixed variants	-	-	++	+	-/+	1
Fender attachment						
2.1 Universal position	++	--	-	+/-	+/-	-1
2.2 Fixed adjust options	+	-	++	+	++	5
2.3 Seperate functions	-	+	-	+	+	1
2.4 To axle and brake	+	+	++	+	++	7
Tightening time						
3.1 Electric tightening	+/-	++	++	++	++	8
3.2 Same type screws	-	-	+	+	++	2
3.3 Pre tapped/ self tapping	-	-	-	-	+	-3
3.4 Less screws	-	-	+	-	-	-3
Seatheight & Activity						
4.1 Visual indicating position	++	-	++	+	++	6
4.2 Table with positions for variations	+	++	++	+/-	++	7
4.3 Single axis ajustment	--	+	+	-	-	-2
Brake assembly						
5.1 Brake in wheel axle	++	+	++	+	+	7
5.2 Different brake thicknesses	+	-	+	+	+	3
5.3 Brake on the fender	+	+/-	+	++	++	6
5.4 Set holes	+	+	++	+	++	7
5.5 Sliding slot	++	-	++	+	+	5

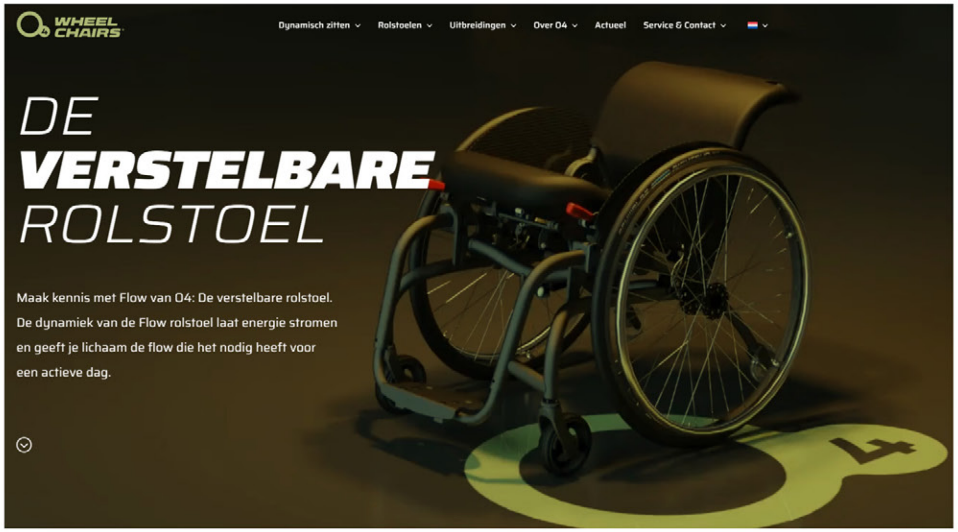
11.7 Frame & Brake Fixation Iterations



11.8 Form Study







WHEEL CHAIRS
Dynamisch zitten
Rolstoelen
Uitbreidingen
Over O4
Actueel
Service & Contact
DE
VERSTELBARE
ROLSTOEL
Maak kennis met Flow van O4: De verstelbare rolstoel. De dynamiek van de Flow rolstoel laat energie stromen en geeft je lichaam de flow die het nodig heeft voor een actieve dag.









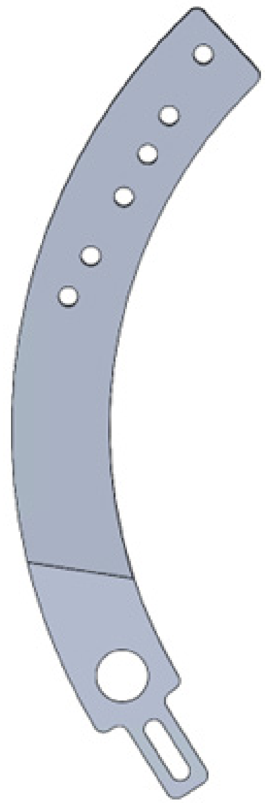

11.9 Costprice Estimation

Current fender assembly							
					Aantal		
	steun spartbord		€ 4,41		2		€ 8,82
	carbon zijschild		€ 74,90		2		€ 149,80
	klemblok	o4	€ 2,75		4		€ 11,00
	klemstuk rem 19/30mm		€ 3,56		2		€ 7,12
Grijpvooraad	Bouten				3		
	moeren				3		
	ringen				3		
Lassen	steun spatbord		€ 75,00	p/u	0,045		€ 3,38
					Total without fender		€ 30,32
						Totaal	€ 180,12

Concept proposal						
				Aantal		
Axle strip	vergelijkbaar met: armleuning strip	€ 3,32		2		€ 6,64
	nieuw carbon zijschild (72% gewicht)	€ 59,92		2		€ 119,84
	éenmalige investering nieuwe mal					
	klembok ter vervanging	€ 2,06		4		€ 8,24
C-Channel	vergelijkbaar met: antie kiep kraaglagerbus	€ 2,48		2		€ 4,96
	boekschroef	€ 0,21		2		€ 0,42
	boekschroefbus	€ 0,50		2		€ 1,00
Grijpvooraad	Bouten			3		
	moeren			2		
	ringen			4		
Lassen	C-channel	€ 75,00	p/u	0,01667		€ 1,25
				Total without fender		€ 22,51
					Totaal	€ 142,35
					marge 10%	€ 156,59

11.10 Curved Fender Bracket Option

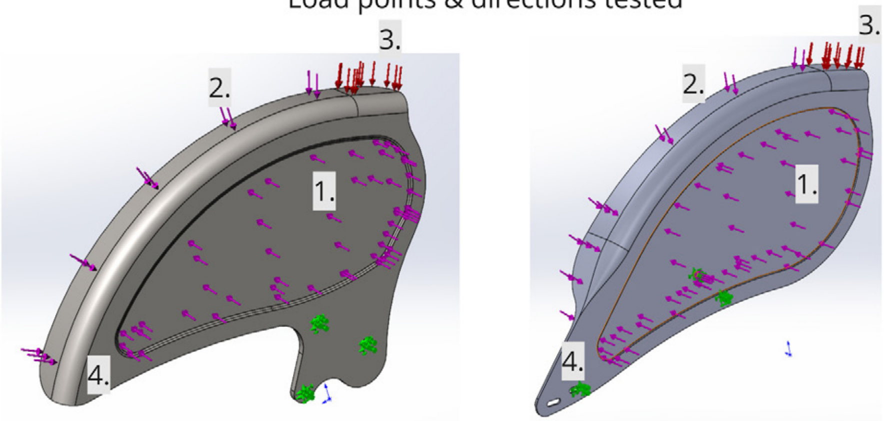
When exploring the form of the new fender and how to incorporate the bracket strip into it, a more integrated design was formed. Here, the recognisable and specific form language of organic forms and curves is also used in the bracket strip.
This idea is discarded, however, based on choosing a design that is usable in all situations and error-insensitive. Because of its camber angle, the curved bracket can not be used on both the left and right sides of the wheelchair. This would mean an extra part and the option to install the wrong bracket on the wrong side.



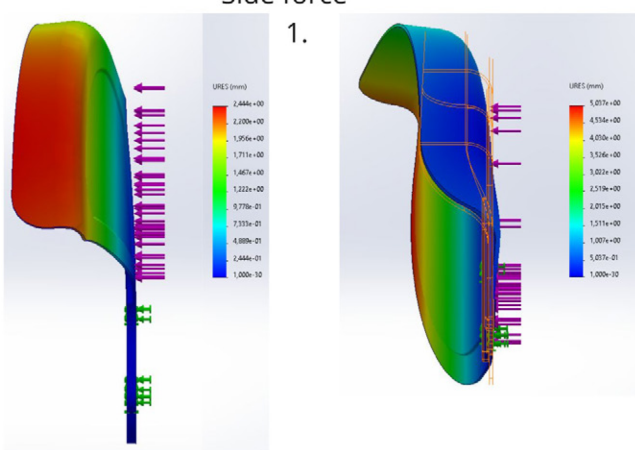
11.11 FEM Analysis New Fender Form

As shown in the figures below both fenders were compared to each other with the same relative loads in 4 situations. All tests came out to be in the same order of magnitude, with relative differences within the 0.X range. As this is a relative comparison and not representative of the real situation the numbers do not mean anything, except compared to each other. It can be concluded that the differences are there but not significantly different.

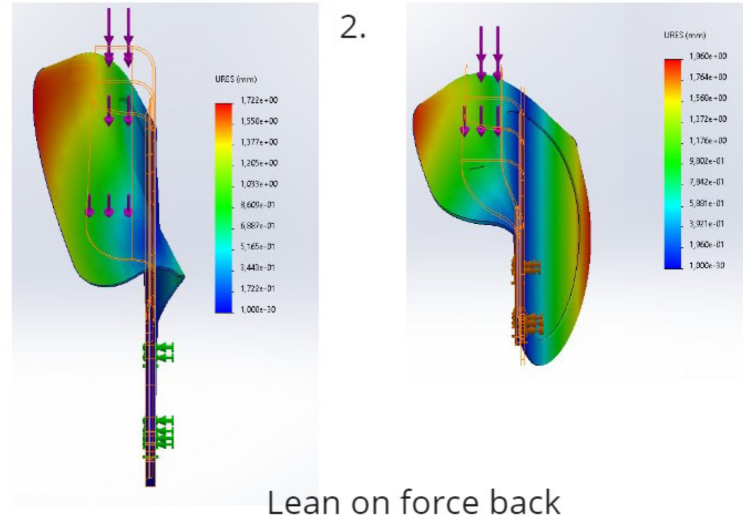
Load points & directions tested



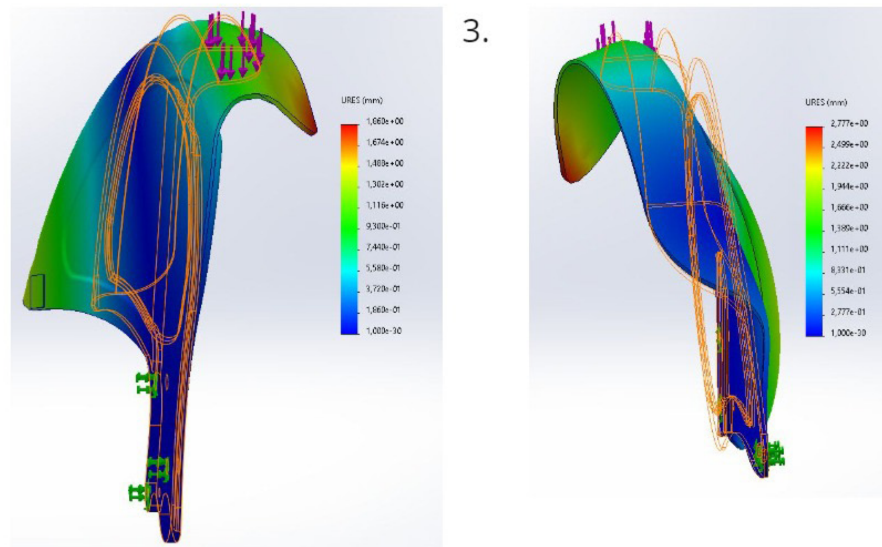
Side force



Lean on force

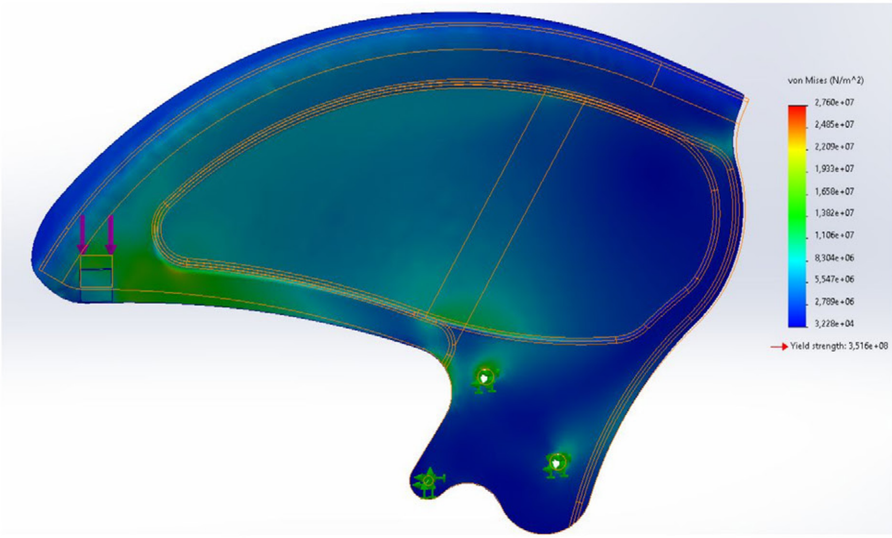


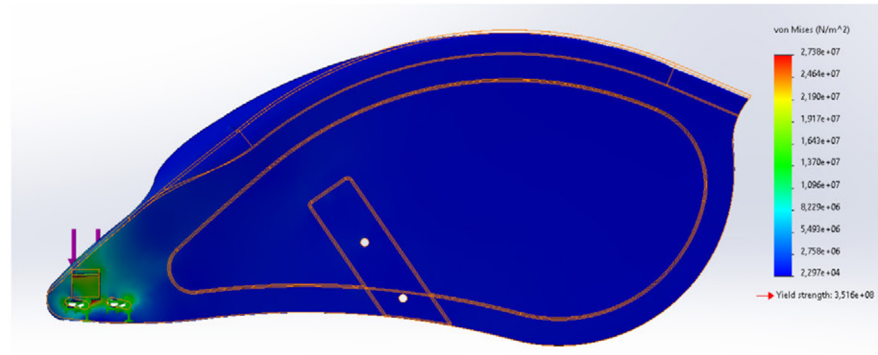
Lean on force back



Brake force

4.





11.12 Test Results

Remmen					Average	57,8	TEST 1	Test 2	Test 3	Test 4	Test 5
	Bus & ring om bout						7	6	7	5	10
	bout door rem						9	10	8	5	10
	vast zetten op fender						7	16	8	5	15
	Bus & ring om bout										
	bout door rem en fender						26	33	29	27	23
	vast zetten op fender						3	5	5	5	5
						Total	52	70	57	47	63
Zijschild					Average	81,0					
	in c-channel						6	4	5	4	6
	vast zetten						9	4	5	5	8
	bout in axle strip						11	11	15	16	14
	2e						11	9			
	Aandraaien						19	26	37	30	27
	wiel er op						8	6	7	7	8
	rem afstellen						7	9	6	8	6
	aandraaien						8	10	12	11	10
						Total	79	79	87	81	79
						Totaal	262	298	288	256	284
		real	rough								
Old	634	10,56667	37								
New	277,6	4,626667	16,20063								

Personal Project Brief – IDE Master Graduation Project

Name student Koen Ruijgrok **Student number** 4,666,453

PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT
Complete all fields, keep information clear, specific and concise

Project title Redesigning a custom wheelchair to shorten the production time and costs.

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 client in this project is O4 Wheelchairs, which is a venture from the design agency Pezy Group. O4 Wheelchairs is a company thatdevelops wheelchairs with the unique selling point of offering a wheelchair with the ability to adjust the seat and back pitch during the day for an egonomic and adaptable posture, suited to the tasks at hand. As there are many different users with different interests, this focus is on people who use their wheelchair daily in an active way. For example, people with a spinal cord injury or a type of muscular disease like ALS.
As all (target) users are different, each wheelchair needs to be custom-made for the specific dimensions of each customer as is needed in this context. This customisability that is needed for their wheelchair users, is impacting the production speed and costs in a negative way. If the wheelchair could be more standardized but still allow for customisation, a big step could be made, for both O4 as a company, their retail and assembly employees and the customers themselves, as it would shorten the production time and costs. There is some standardization as they offer adjustability, to the lengths that are needed to be custom, with increments of 2.5 cm. But this still means there are more than 80 configurations and as O4 sells between 100 and 200 wheelchairs a year it is too costly to have all configurations stored, besides them not being sold equally often.

➔ *space available for images / figures on next page*

image / figure 1 Line-up of the types of O4 wheelchairs. Adjustability in backrest and/or seat.

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)

The conflicting requirement of the wheelchairs being customized to all (target) users, and the need for more standardization (a less complicated and custom production process). The five main custom measurements - seat width, depth and height, backrest height, and the position of the rear axle - make it challenging to produce a less complicated and more standardized product.
An opportunity would be to find which combinations of measurements have the most potential to be standardized and see if those wheelchairs can be redesignd to have fewer parts, with the same customizability.
This would add value in the way of having fewer man-hours in assembling, and more standardized manufacturing steps and parts in the production process, wchich would benefit the costs for O4 and the customer, as well as the time to delivery.
Another (or combined) opportunity could be to investigate which parts and subassemblies of the wheelchair have the most influence on the assembly process to allow for more premade and standard sub-assemblies in stock that are usable for all wheelchairs, as well as the ability to schedule work more independently form wheelchair orders and the possibility to outsource some sub-assemblies.

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:

In this project, I will redesign and prototype (parts of) the wheelchair of O4, to minimise the need for all fully custom parts and thus reduce the production- and assembly time and costs, while still accommodating the needed customisation for the target user.

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)

I will start with a dive into the context (e.g. context-mapping, user interviews) to make myself familiar with the wants and needs of the target group and thus the wheelchairs. I would also do a market analysis on the customisation needed with this target group as well as make a list of requirements. Next, I would analyse the building and assembly process of an ordered wheelchair (e/g/ journeymapping, service blueprint, assembly deconstruction). This would give me a good basis to determine (with e.g. SWOT analysis) what parts or design aspects of the wheelchair to focus on, based on wat generates the most benefit, and try to standardize, simplify or make modular and usable in multiple scenarios. The next phase would be to do a lot of brainstorming and ideating on how to accomplish these redesigns. Selecting ideas (with weighted objectives or c-box), developing concepts, selecting again and building prototypes to evaluate and iterate on would be my preferred way to go.
I realise that the 100 days I have for this project is not enough to fully develop the redesigned wheelchair, the research and analysing phase could take long, so the aim is to deliver good validated concepts that O4 can continue to elaborate.

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 Nov 2023
Mid-term evaluation	17 jan 2024
Green light meeting	20 mrt 2024
Graduation ceremony	18 apr 2024

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	
Number of project days per week	

Comments:
I will interrupt my graduation with: 1 week for a sidejob in November, 2 weeks of Christmas holiday and 1 week holiday in Februari.

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 want to do this project as it gives me the opportunity to work at a large company, with experienced designers nearby that work for the same company. This is something I sometimes missed during my studies at the TU Delft. I would love to improve my proffesional communication skills, stakeholder management and prototyping skills. I like to build things, test it and iterate on it, in a quick and playful way, and I think that this project will alow for that. I want to work on my research skills, as I tend to not like it the most in a design project, but it is part of being a designer so that is a thing i want to improve want to accieve before graduating.

I hope to develop some skills in my personal ambition of generative design and strength/material optimisation. There are numerous tools out there that I like to discover and use and find out how they can be usefull in a design process. Furthermore, I want to use prototyping methods that are more durable and strenght-related like CNC milling, turning and welding, as I almost solely have used 'soft prototyping methods' like 3D printing.