

A blue wireframe model of a wheelchair frame is shown against a solid blue background. The frame consists of several interconnected tubes forming a structure for a seat and wheels.

A Convenient Wheelchair Frame For Spinal Cord Injured Users

July 2026 | Master thesis Integrated Product Design

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PEZY.

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Abstract

Most people with a spinal cord injury (SCI) depend on a manual wheelchair for independent daily mobility. Compared to the average wheelchair user, SCI wheelchair users are relatively young and active. For these users, good design of the wheelchair is critical.

A custom frame is made using the body dimensions of the user. This improves the user's posture and propulsion efficiency. Custom wheelchair frames are also very rigid which is beneficial for seating stability and the durability of the wheelchair. There are two types of custom frame constructions available but they require a trade-off between rigidity and transportability. Open frames are easier to transport, whereas Box frames provide higher rigidity. This thesis explores whether these advantages can be combined in a single frame design.

The goal was to design a custom active wheelchair frame for users with a spinal cord injury between the C6 and L2 segments. The frame had to combine the rigidity of the Box frame with improved transportability similar to the Open frame, while remaining feasible to manufacture using the available production methods of the wheelchair factory.

The analysis consisted of literature research, interviews. The analyses explored use scenarios, stakeholder interactions, market research, ergonomics, manufacturing methods, material selection and existing frame constructions were analysed through simulations in SolidWorks. The findings were translated into design requirements.

The proposed frame design replaces the conventional construction of the Box frame with a much more space efficient alternative which improves its transportability. The frame is titled

the 'Cross-Over' frame. It was designed to minimise the bending complexity of the components to make manufacturing more efficient which could lower the production cost.

The performance of the Cross-Over frame was evaluated using SolidWorks simulations and indicate a comparable stress performance to the Box frame. In addition, the frame is approximately 8.5% lighter than the reference Box frame and its shape is easier to transport by car, which was evaluated using a 1:1 PVC prototype.

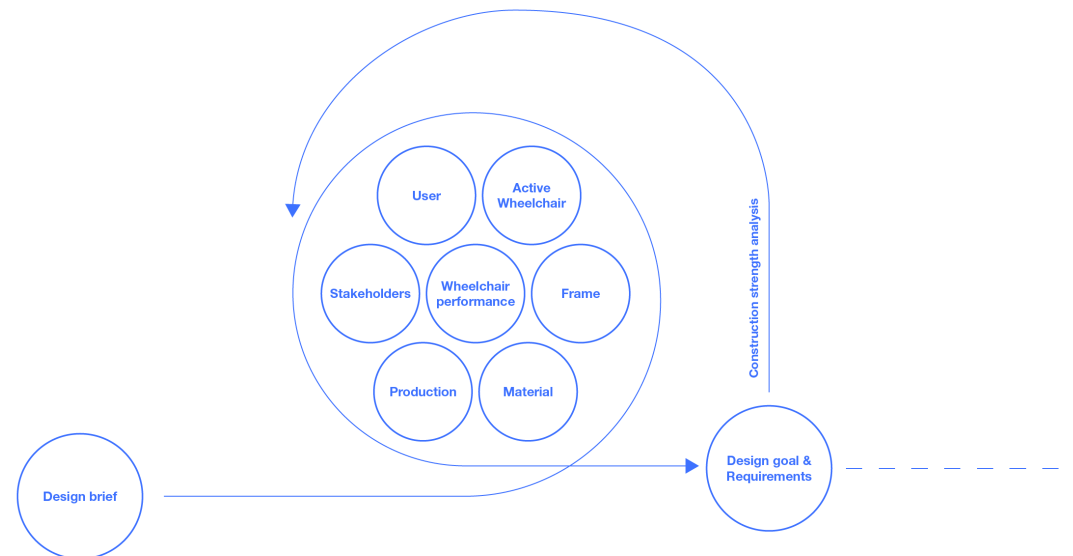
Although more physical testing is required to validate these findings, the results indicate that the new frame design improves transportability while maintaining the rigidity required for active daily use.

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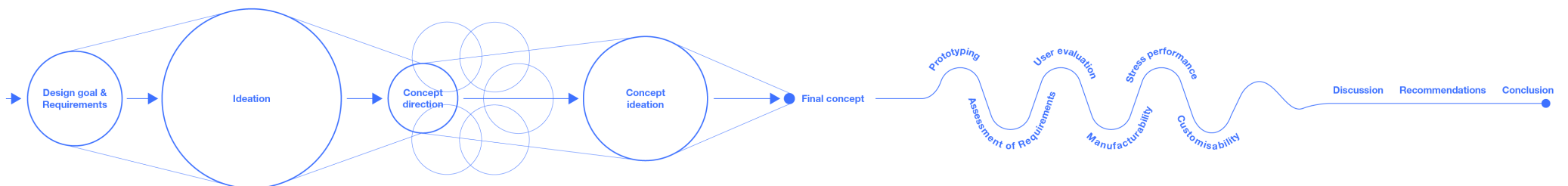
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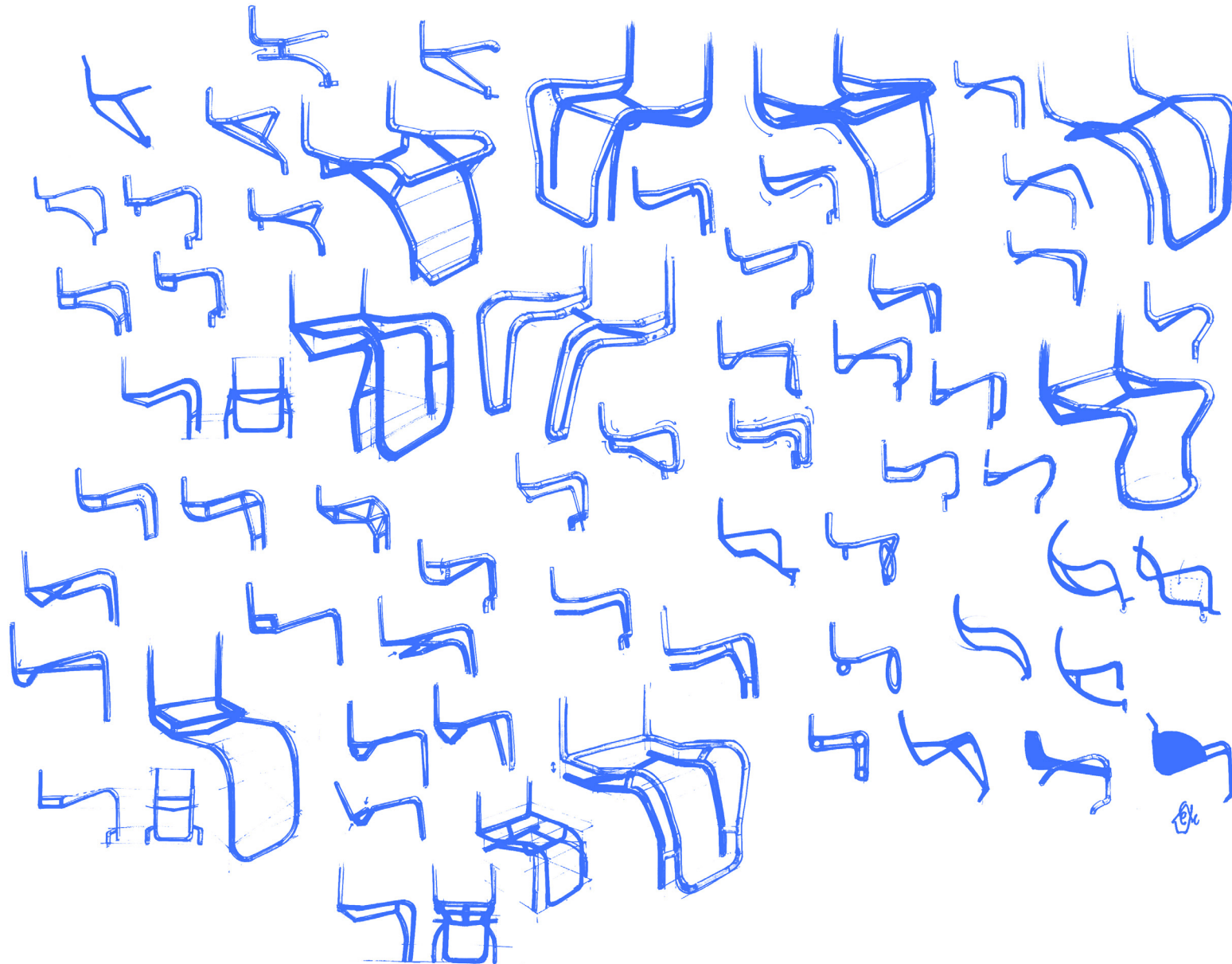
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Introduction

People with a spinal cord injury (SCI) rely on manual wheelchairs for independent daily mobility due to (near) complete loss of leg function. For these users, the design of the wheelchair is critical.

A custom-fitted (made-to-measure) frame enhances stability, durability and propulsion efficiency, allowing the user to comfortably use their wheelchair throughout the day, effectively replacing the user's legs (Van Breukelen, 2020). However, these frames can be difficult to transport which limits the users' autonomy and decreases their engagement in activities (Bayley et al., 2019; Kouzelis & Vlamis, 2022).

Opportunities to combine rigidity with transportability in the wheelchair frame would serve the interests of the user by improving their independent mobility and thereby sense of participation in society (Medola et al., 2014).

The assessment of the user and reimbursement of mobility aids distributed through local dealers (Meyra, Welzorg, etc.) are controlled by the WMO. For the WMO, low prices and standardised products (thus widely applicable solutions) are preferred. This was confirmed by RGK Wheelchairs in a preliminary interview about the differences between custom and standardised wheelchairs.

Custom wheelchairs are expensive and can take up to 5 months to build, so enabling faster production seems like a great opportunity for all stakeholders: Shortening the waiting time for the user and allowing the manufacturer to sell more wheelchairs in less time.

Standardisation of components could keep cost down and makes production easier for the manufacturer but poses a threat of lowered customisability of the wheelchair, negatively affecting users. The complexity of designing a wheelchair frame is finding the balance between good, fast and affordable design.

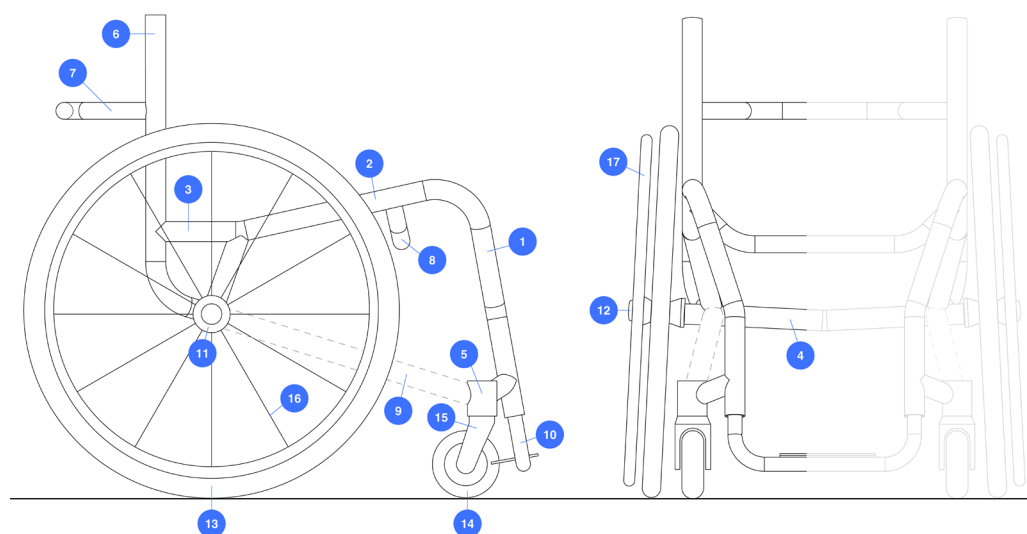
Assignment

This graduation project was commissioned by PEZY, a product engineering company with a manufacturing facility specialised in manual wheelchair frames. The goal of this project is to increase the accessibility of the wheelchair for spinal cord injured users, by designing a custom wheelchair frame that is both high-performance and independently transportable, without compromising on the manufacturing time and cost of the product to make it an attractive alternative for suppliers.

Wheelchair design vocabulary

Active wheelchair	A lightweight manual wheelchair designed for independent daily users with sufficient upper body strength to enable manual propulsion	ROM	Range of Motion
ADL	Activities of Daily Living	SCI	Spinal Cord Injury
Camber	Inward tilt of the rear wheels to increase manoeuvrability	Tetraplegia	Partial or complete loss of all four limbs and the torso. Also known as quadriplegia
COG	Centre of gravity of the user over the wheelchair. Affects stability and propulsion efficiency	Paraplegia	Partial or complete loss of motion in the lower body. Sometimes also affecting the torso
Frame	The structural component of the wheelchair that supports the user and holds all components together (Long, 2014). Also known as the chassis of the wheelchair	Pressure sores	Pressure induced skin and tissue damage. Also known as decubitus or pressure ulcers.
Interface	Contact surface between two components.	Wheelie	A controlled manoeuvre, where the user shifts their COG to lift the caster wheels from the ground.
Made-to-measure	Customisation method where a wheelchair frame is tailored to the measurements of the user (More et al., 2025).	Transfer	Movement where the user moves their body from one (seating) surface to another.
Propulsion	Moving the wheelchair, typically by pushing the hand rims (manual propulsion).	Hand bike	Manually powered cycling device that can be attached to the wheelchair, allowing for longer distance travel.

Components of an active wheelchair



- | | |
|----------------|--------------------------|
| 1 Front frame | 10 Footrest |
| 2 Seat frame | 11 Rear wheel axle |
| 3 Ergo seat | 12 Quick release pin |
| 4 Camber bar | 13 Rear wheel |
| 5 Caster house | 14 Caster or front wheel |
| 6 Backrest | 15 Caster fork |
| 7 Back brace | 16 Spokes |
| 8 Cross tube | 17 Push-/hand rims |
| 9 Cross bar | |

Figure 1. Components of an active (manual) wheelchair

Declaration of the use of AI and user data

Data sensitivity

This report will include research data about personal experiences of a sensitive group of people.

The personal identity of these individuals is not important to mention for the outcome of my research, which is why names and uniquely identifiable information of the interviewees are anonymised and redacted/blurred

Use of AI

ChatGPT was used to help estimate some data where there was no research data available. Throughout the report, for each of these incidences the use of AI was mentioned. No AI was used to generate text.

A. Analysis

A.1 Approach

The analysis phase is used to formulate the design goal and requirements that will be used in the synthesis phase. To achieve this, I researched a number of different factors that influence the design of an active manual wheelchair frame: the user, the differences between standardised and custom wheelchairs, stakeholders, wheelchair performance, frame construction, production capabilities and materials. Each research area starts with a small set of goals. These goals helped me to focus on finding the right information, rather than branching out further than necessary. The goals for all seven topics are laid out on the next page.

Ultimately these fields of research helped me to compose a list of requirements and specify my design goal. With this design goal in mind, I also performed a construction strength analysis to gain more insight into the stress distributions on the existing frame types. Combined with my design goal, these insights will form the theoretical foundation for the following phase of synthesis.

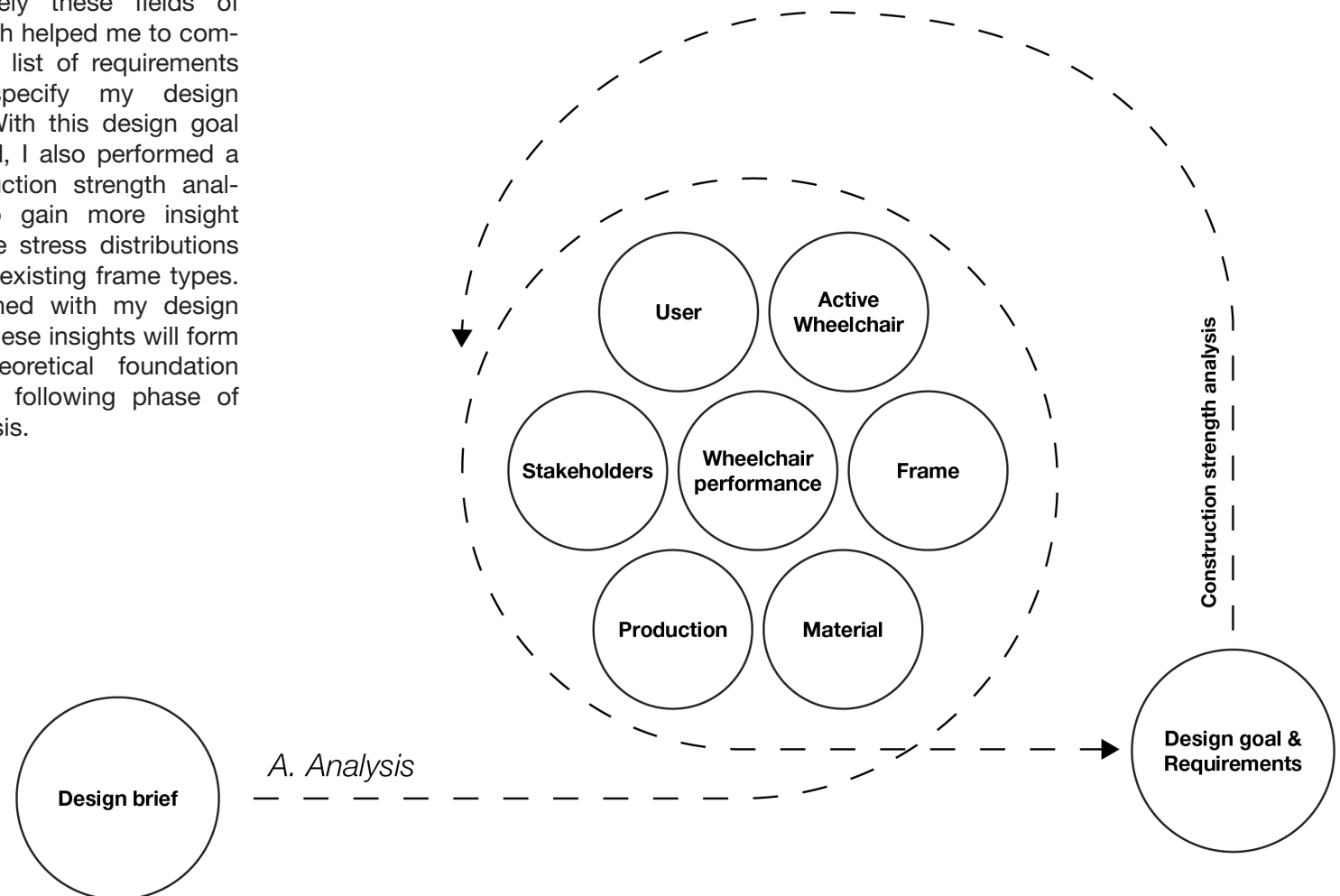


Figure 2. Illustration of the approach for the analysis phase

Analysis | Approach

Goals | User analysis

- **Gaining insight in the physical capabilities & limitations of the user**
- **Specifying user requirements**

Goals | Wheelchair performance analysis

- **Identifying performance goals and -conditions**
- **Specifying design parameters regarding ergonomics**

Goals | Production analysis

- **Creating an overview of the capabilities of the factory**
- **Specifying limitations to ensure feasibility of the design**

Goals | Active wheelchair analysis

- **Mapping the differences between active frame types**
- **Indicating which types of wheelchair users should use a custom frame**

Goals | Frame analysis

- **Understanding the limitations and benefits of different frame types.**
- **Specifying frame dimensions based on market averages.**
- **Specifying the scope of components to design.**
- **Identifying limitations of the design from out-of-scope components.**

Goals | Material analysis

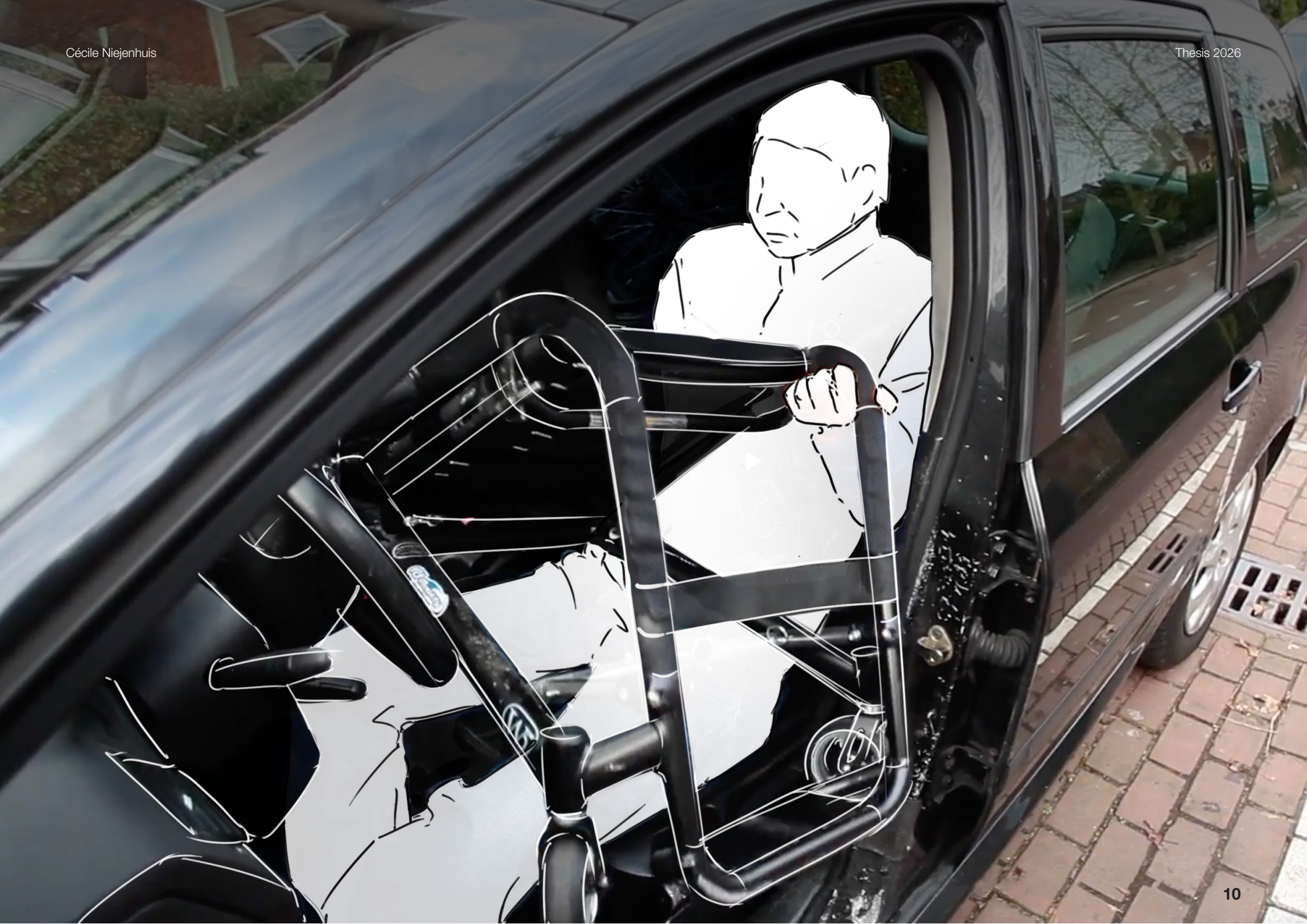
- **Gaining insight in the properties of different materials and their application in a frame**
- **Analysing the strength-to-weight ratio of different materials**

Goals | Stakeholder analysis

- **Understanding the impact of stakeholder groups on the product.**
- **Gaining insight in current stakeholder interactions.**

Goal | Construction strength analysis

- **Compare different frame constructions to gain insights into the stress distributions in the frame**



A.2 User

Goals | User analysis

- Gaining insight in the physical capabilities & limitations of the user
- Specifying user requirements

In the Netherlands, an estimated 12,000–15,000 people live with a spinal cord injury (SCI) (De Hoogstraat Revalidatie, 2023; Tepper et al., 2024). With nearly 80% of this group using a manual wheelchair as their primary means of mobility (De Groot et al., 2010), SCI patients form one of the largest groups of permanent manual wheelchair users in the Netherlands.



Figure 3. Spinal cord injured wheelchair user

The average age of injury for spinal cord injured people in the Netherlands is 43 (Post et al., 2020). This is relatively young, in comparison to other wheelchair user groups such as CVA patients (Appendix a.1) with an average age of injury of 73 (Harten Vaatcijfers, 2023).

Because of this young age, SCI patients use the wheelchair in a more active way than other wheelchair users would as they are generally more fit.

To specify my target group and learn more about their requirements, I interviewed several users (Table 1) and analysed several ADL use scenarios with emphasis on SCI (Table 2).

Injury height	Cervical (n = 3) Thoracic (n = 4) Lumbar (n = 1)
Age	20-29 (n = 2) 30-39 (n = 3) 50-59 (n = 1) 60-69 (n = 2)
Gender	Male (n = 6) Female (n = 2)

Table 1. Interviewees

What?	Why?	Who?
Interviews with spinal cord injured wheelchair users	<ul style="list-style-type: none"> • User experiences and touchpoints • Understanding the unique requirements of the user • Indicate performance factors • Insight in the good features of existing products • Insight in parts that can be improved 	<ul style="list-style-type: none"> • Spinal cord injured wheelchair users (n = 8) (Table 2)
Interviews with wheelchair experts and dealers	<ul style="list-style-type: none"> • Understanding the demographic: what makes SCI wheelchair users different from other users • Design choices specific for SCI users 	<ul style="list-style-type: none"> • Sunrise Mobility • RD Mobility • Wolturnus • Permobil • Wheelchair skills team
Experience forums & knowledge platforms	<ul style="list-style-type: none"> • User experiences and touchpoints • Comparing experiences of different injury heights • Insight in the system of wheelchair provision 	<ul style="list-style-type: none"> • Dwarslaesie Organisatie Nederland • CheckJeZit • WheelchairSkillsTeam • Permobil blog
YouTube & Instagram	<ul style="list-style-type: none"> • Learning about the experiences of young SCI users 	<ul style="list-style-type: none"> • Anonymous wheelchair users sharing their experiences (n = ±20)

Table 2. User research methods

A.2.1 Target user

Gaining insight in the physical capabilities & limitations of the user

The main symptoms associated with spinal cord injuries can be divided into three categories: motor symptoms, sensory symptoms, and autonomic symptoms. The experienced symptoms depend on the height of the injury and by severity (complete or incomplete). Complete SCI affects all nerves in the spinal cord at the level of injury. This usually means permanent loss of all abilities below the injury, including paralysis. Incomplete SCI affects only part of the nerves in the spinal cord which can result in paralysis, but sometimes without loss of sensory response in the affected body parts (Cleveland Clinic, 2026).

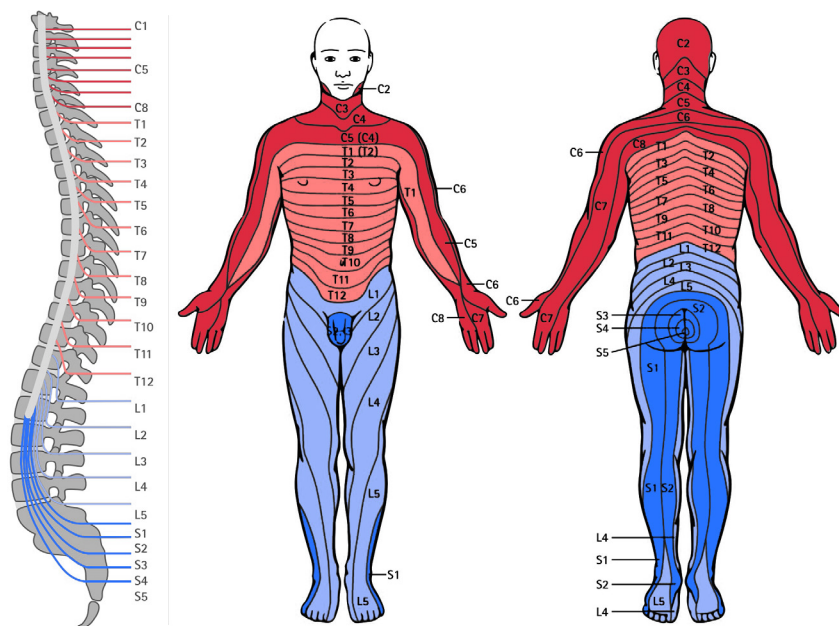


Figure 4. Segments of the spine and affected parts of the body in case of injury

The types of SCI are categorised by location (cervical, thoracic, lumbar or sacral). The exact location of the injury is indicated by letter-number combinations for each segment (Figure 4).

There are two categories of spinal cord injuries: quadriplegics, who experience symptoms in all four limbs, and paraplegics, who only experience symptoms in their lower body and legs.

Quadriplegia (Tetraplegia) <i>Injury in cervical segments</i>	Paraplegia <i>Injury in thoracic, lumbar or sacral segments</i>
C1 to C5: Complete paralysis of all muscles required for manual wheelchair propulsion	
C6 to C8: Varying levels of paralysis in arms and hands, but sufficient for manual wheelchair propulsion. Likely have limitations with fine motor skills.	
	T1 to T6: Hips, legs, abdominal and chest muscles are paralysed.
	T7 to T12: Hips, legs and abdominal muscles are paralysed, but chest muscles are not affected.
	L1 to L2: Hips and leg muscles are paralysed, but chest and abdominal muscles are not affected.
	L3 to S5: Incomplete paraplegia becomes more common further down. Can usually walk with or without braces or a walker.

Table 3. Spinal cord injury height and affected parts of the body (Cleveland Clinic 2025b, 2025c). Scope highlighted in blue

Table 3 shows the injury heights of these categories, split into sections of segments that cause similar symptoms (Cleveland Clinic 2025b, 2025c). To manually propel a wheelchair, the user needs to have sufficient upper body strength and mobility. Through interviews

with both users and wheelchair experts and with the help of user stories from Dwarslaesie Organisatie Nederland, I narrowed the scope of my target group to spinal cord injuries between the C6 and L2 segments.

A.2.2 ADL use scenarios

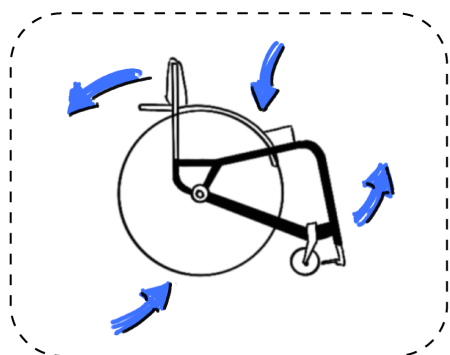
Specifying user requirements

The use scenarios that are described in this chapter are normal ADL activities derived from the research methods mentioned earlier. (Figure 5)

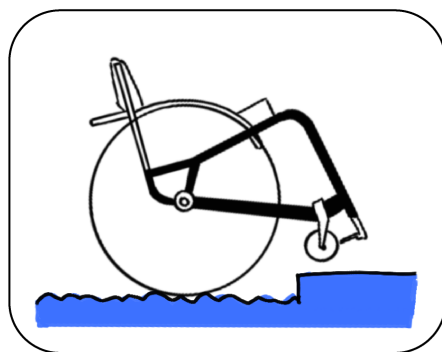
First, I will briefly analyse the interactions between the user and the wheelchair. These use scenarios explain the skills that wheelchair users have to learn and the difficulties they might experience in day to day use.

Next, I will delve into the scenarios that show touch-points of mobility. The concept of mobility is split into three distances: short distance (walking), medium distance (biking) and long distance travel, where the wheelchair is transported by train or car.

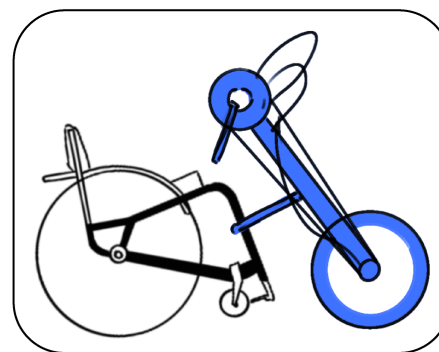
For some of these scenarios, more than one use technique is possible. In this analysis, I chose to only describe the techniques that highlight the most common use scenarios. These visualise the basic wheelchair skills and desired independence of spinal cord injured wheelchair users the best.



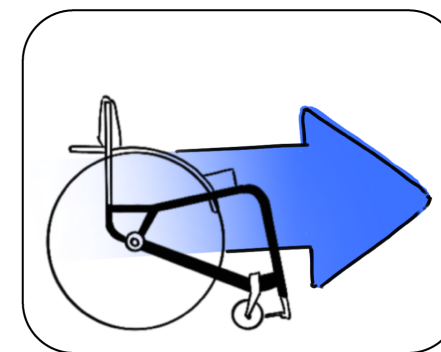
ADL interactions
With the wheelchair



Short distance travel
Walking distance



Medium distance travel
Biking distance



Long distance travel

Figure 5. ADL Use scenarios

Analysis | User

Interactions with the wheelchair**Transferring**

Being able to get in and out of the wheelchair without help from an assistant is one of the most important skills for a manual wheelchair user to have. This manoeuvre is called 'transferring'.

The user in [Figure 6](#) places their right hand on the frame for balance and their left hand on the seat to transfer in to. The seat frame must allow space to place the hands during transferring, and the construction should be strong enough to support increased local weight-bearing.



Figure 6. Transferring

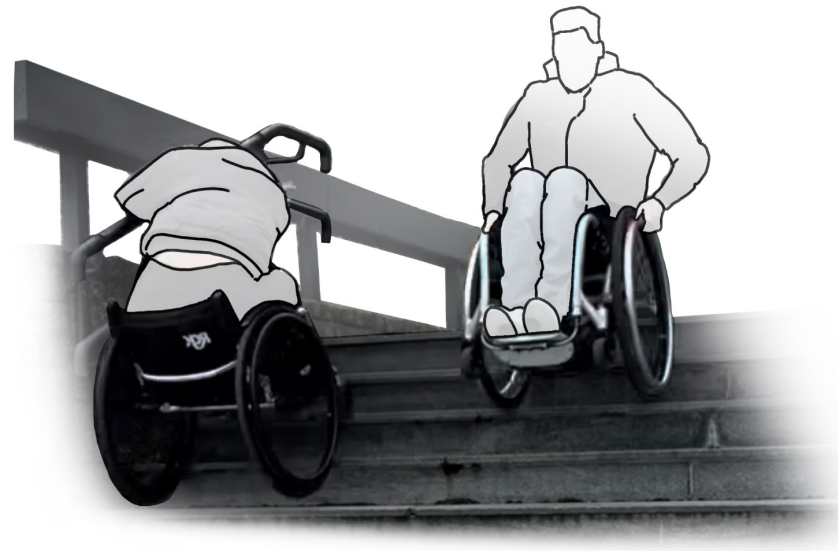


Figure 8. Ascending & descending stairs in a wheelchair

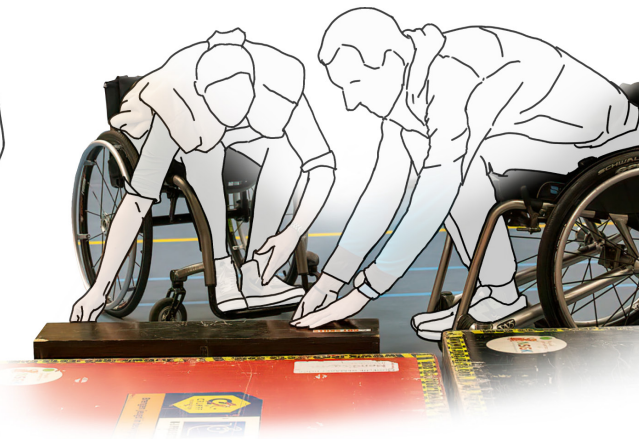


Figure 7. Reaching the ground



Figure 9. Ascending & descending escalators in a wheelchair

Wheelchair skills

A custom wheelchair increases the independence of the use by providing enough stability to confidently perform wheelchair skills. These skills include general mobility around the wheelchair like reaching the ground ([Figure 7](#)), but also more advanced skills like wheelies.

A wheelie is a manoeuvre where the user lifts the caster wheels from the ground by moving backwards in their seat. The skill to perform a balanced wheelie allows the user to independently ascend and descend curbs, stairs and escalators ([Figure 8, 9](#)), which helps to participate in society.

Analysis | User

Indoor (& personal) use

The wheelchair is used as an extension of the body and goes anywhere the user goes. To use the wheelchair in indoor environments (e.g. at home, at work, in a supermarket etc.), it should be designed with respect to the dimensions of the user's environment. Important user specific dimensions include table- and kitchen counter height (Figure 10) and the width of doorways. Additionally, the user could request unique customisations to the wheelchair to help with ADL activities like walking a dog or being able to have a child sit on their lap.



Figure 10. Indoor use

Mobility**Short distance travel**

Manual propulsion of the wheelchair, or walking, as some wheelchair users call it, is the most tiring way to move in a wheelchair and therefore mainly used for short distances. The propulsion efficiency is dependent on several factors: the size of the wheelchair, the rigidity of the frame and the posture of the user.

A large and heavy wheelchair can be difficult to manoeuvre through urban areas where quick turning and repeated stopping are required. The rigidity of the frame impacts the vibration that the user feels while rolling over rougher terrains (Figure 11), but it also minimises flexing of the frame which improves propulsion efficiency. (Van Breukelen, 2020)



Figure 11. Walking over cobblestones

Analysis | User

Medium distance travel

A hand bike (Figure 12) or a motorised power device attached to the front of the frame allows the user to travel for longer distances and exercise their upper body. A hand bike lifts the caster wheels from the ground to minimise rolling friction. Many hand bike systems require the leg frame

of the wheelchair to be constructed with cylindrical tubes for attachment of the bike to the frame. Interviews with wheelchair manufacturers pointed out that open frame constructions are prone to warp over time due to the pulling force on the frame.

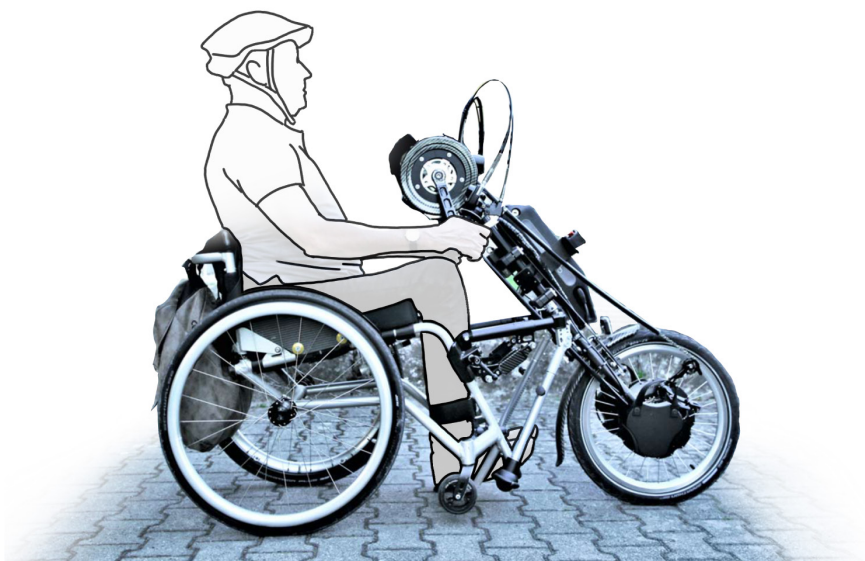


Figure 12. Hand biking

Long distance travel

To transport a wheelchair frame by car, the wheels and cushioning are removed from the frame and then the bare frame is lifted over the driver seat (Figure 13). This manoeuvre is only recommended to use with open frame wheelchairs because the slim design fits more easily in the car.

The standard solution for public transport is to ask for a service assistant. Due to consistent problems with understaffing and improper training, this service is too often inadequate: the assistants will be too late, wait at the wrong doors or not arrive at all (Dirksen, 2022). Wheelchair users with enough wheelchair skills, will often take matters into their own hands by individually getting on and off the train. To do this, the user transfers from the wheelchair on to the floor of the train (Figure 14).



Figure 13. Independent transportation of the wheelchair by car

From here, they will lift the entire wheelchair in the train and transfer back into the wheelchair using the hinges of the train doors. To get off the train, the user will either

perform the same technique again, or they will jump out of the train in wheelie position. This method can cause the frame to break upon impact.



Figure 14. Independent transportation of the (open frame) wheelchair by train

Conclusion | User

In this chapter I have analysed the symptoms of different types of SCI and narrowed the target group to only include spinal cord injuries between the C6 and L2 segments. Injuries between these segments generally allow for sufficient upper body strength to propel a manual wheelchair.

The analysis of ADL use scenarios led to the design criteria on the right, and were translated into requirements which are listed in Appendix [d.1](#).

Design criteria from use scenarios

Interactions with the wheelchair

Transferring

- The frame should support increased local load bearing on the bend of the seat frame.
- The seat frame must allow space to place the hands during transferring.

Indoor (and personal) use

- Wheelchair frame should be narrow enough to manoeuvre through built environments.
- Wheelchair frame should be designed with the dimensions of the users' home in consideration.
- Wheelchair frame design should allow for unique customisations.

Wheelchair skills

- Wheelchair shouldn't tip over when shifting the COG forwards to reach the ground
- Wheelchair frame shouldn't obstruct reach of the user when bowing down to grab something
- The width of the seat should be very precisely fitted to allow the user to lean forwards without losing contact with the wheelchair.
- The wheelchair frame should be built to withstand increased impact on the wheelchair as the user goes down the stairs in wheelie position

Mobility

Short distance travel

- Frame should ideally absorb some of the vibrations when riding over rough terrain to improve propulsion efficiency

Medium distance travel

- Frame should be compatible with existing hand bike attachment systems

Long distance travel (transport)

- Frame should fit over the driver seat
- Complete weight of the wheelchair should be portable with one hand
- A foldable backrest increases transportation convenience
- The wheelchair frame should be light enough to lift it over the user with the wheels attached.
- The frame should withstand the impact from jumping out of the train.

Analysis | Active wheelchair

A.3 Active wheelchair

Goals | Active wheelchair analysis

- Mapping the differences between active frame types
- Indicating which types of wheelchair users should use a custom frame

As of 2025, there are about 250.000 wheelchair users in the Netherlands (Radar, 2025). Only 10% uses an active manual wheelchair (Figure 15). An active wheelchair user is defined as someone who depends on their manual wheelchair to participate in daily activities and for at least 4 hours a day (Budai et al., 2018).

Within the category of active wheelchairs, there is a distinction between standardised wheelchairs, which are constructed with pre-fab components, and custom wheelchairs, which are designed for an individual user.

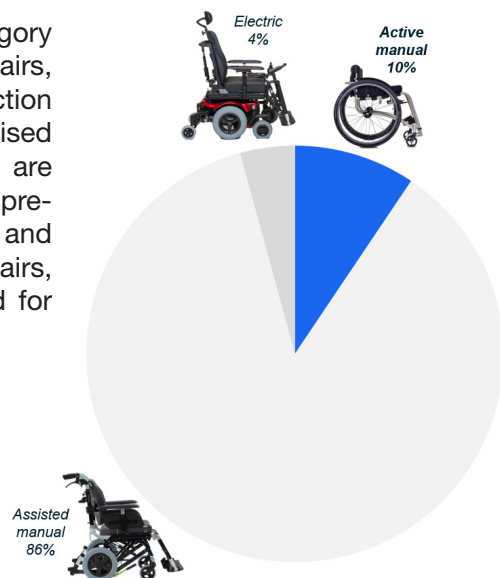


Figure 15. Types of wheelchairs used in the Netherlands

A.3.1 Standardised and custom frames

Mapping the differences between active frame types

Standardised frames

A standardised frame (Figure 16) is modular and can be tailored to some extent, but will almost never perfectly fit the user. Standardised frames are mass-produced, making them affordable and therefore the preferred solution for suppliers.

Most standardised frames are non-welded and can therefore be adjusted over time. The number of modular components varies per brand, but will generally include seat width, seat depth, backrest height and axle position. Adjustable settings are well liked by suppliers, as this allows for the frame to be re-fit to a new user. Adjustability is useful for new wheelchair users to find out what their preferred settings are, but after a few weeks or months

the user is used to their settings and will no longer need to adjust them. After this period, the user will only experience downsides to this adjustability, as it makes the frame heavier, less rigid and larger than necessary.

A frame that is too large for the user causes poor positioning, which can lead to the development of pressure sores, orthopaedic deformities in the spine and pain (Ventura & Bendix, 2020).

Standard active wheelchair
Model: Quicky Nitrum

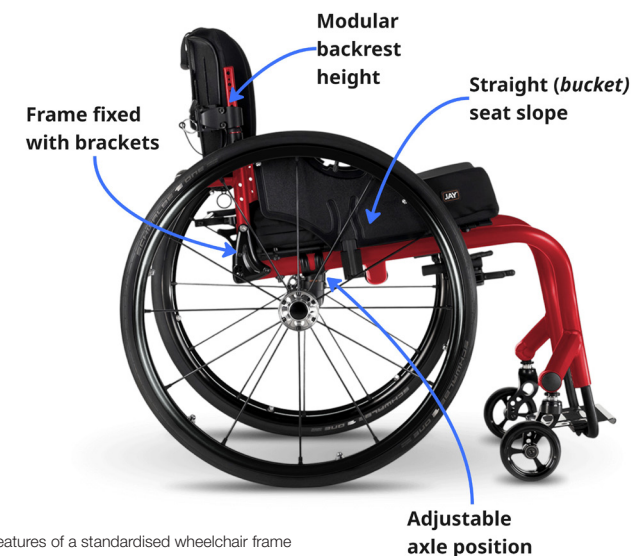


Figure 16. Features of a standardised wheelchair frame

A.3.2 Who should use a custom frame?

Indicating which types of wheelchair users should use a custom frame

Custom frames

A custom frame (Figure 17) is always completely unique. Using the user’s body, a made-to-measure frame is designed, which can be modified to support irregular body shapes to realise a perfect fit. This allows for good stability and comfortable use of the wheelchair, which are important features for confident use of wheelchair skills such as wheelies to manoeuvre over curbs.

A well-fitted manual wheelchair is of great importance to maximise the users’ quality of life, allowing for better participation in daily activities and improved independence (Budai et al., 2018). Custom wheelchair design also increases the users’ sense of ownership (More et al., 2025).

Not all of the active wheelchair users in Figure 15 meet the requirements for a custom wheelchair prescription.

This is illustrated in the graph in Figure 18. In this figure, the disability types that would theoretically benefit from the optimised design of a custom frame are indicated in blue. These disability types include permanent injuries such as spinal cord injuries, amputations and EDS, which affects the skin and joints of the user.

The residual disability types (MS, chronic fatigue and HSP) are disabilities that progress too quickly and unpredictably to truly benefit from a made-to-measure wheelchair. Appendix a.1 shows the estimated number of users for each wheelchair type.

While this shows that 70% of all active manual wheelchair users could benefit from a custom frame, many are still using standard frames, due to their modular sizing and low pricing compared to custom frames.

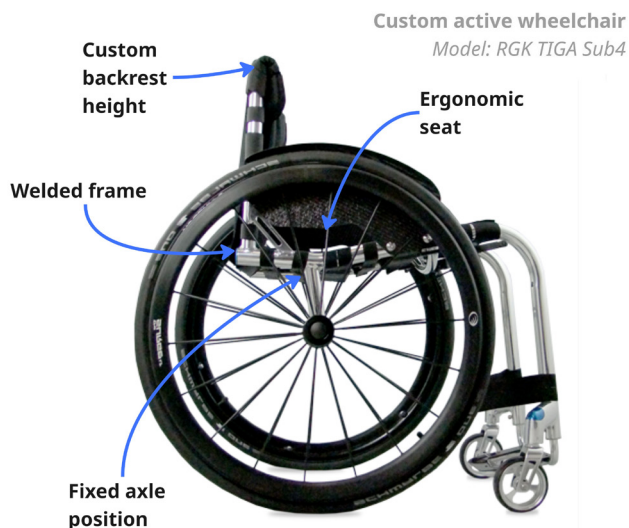


Figure 17. Features of a custom wheelchair frame

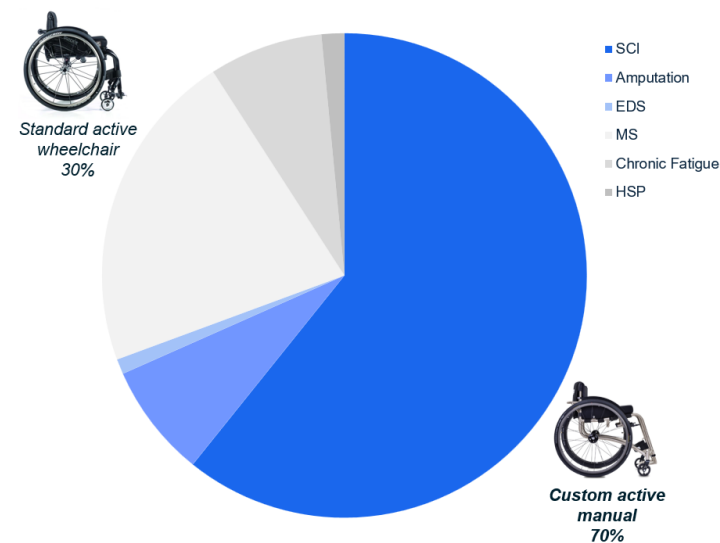


Figure 18. Permanent active wheelchair users in the Netherlands

Analysis | Active wheelchair

Conclusion | Active wheelchair

In [Table 4](#), the differences between the standardised and custom frame are compared. Custom frames enable a made-to-measure fit that allows for better stability and comfort in the wheelchair, which allow the user to be more independent (Budai et al., 2018).

A standardised frame is adjustable, but this adds weight and size which makes it more likely to develop secondary health problems (Ventura & Bendix, 2020). Due to mass production, standardised frames are more affordable, making it a preferred frame by suppliers even though more users would benefit from a custom frame.

	Standardised wheelchair frame	Custom wheelchair frame
Sizing	Standardized sizing. Frame is built with standard components in 2 cm steps.	Built to user measurements
Customisation	Limited customisation possible	Frame can be customised to accommodate specific needs
Rigidity	Non-welded frame	Rigid welded frame
Weight (relative)	Heavier (due to non-welded components)	Lightweight
Pelvic containment	Bucket seat	Ergonomic seat
Rear wheel axle	Adjustable axle position (reduced rigidity)	Fixed axle position (reduced weight & more rigid)
Longevity	Less durable materials & components wear out over time. (designed to last for 5-7 years)	Durable materials. (designed to last for 7-10 years)
Pricing	Starts at ±€3000	Starts at ±€6000

Table 4. Differences between a custom- and a standardised wheelchair frame

A.4 Stakeholders

Goals | Stakeholder analysis

- **Understanding the impact of stakeholder groups on the product.**
- **Gaining insight in current stakeholder interactions.**

In this chapter, I analyse the influence of different stakeholders on the provision of a wheelchair. By mapping relationships between the stakeholders, I will gain insight in the way the system affects decision-making and understand the impact this has on the quality of the product to the user.

The selection of stakeholders is derived from the interviews I did with users and experts, as well as desk research and literature review. Appendix a.2 shows the interests and influence of the individual stakeholders.

A.4.1 Stakeholder groups

Understanding the impact of stakeholder groups on the product

In [Figure 19](#), the stakeholders are grouped in categories that share the same priority regarding their influence on the provision of the best wheelchair for the user. *The user is not included in one of the groups below.*

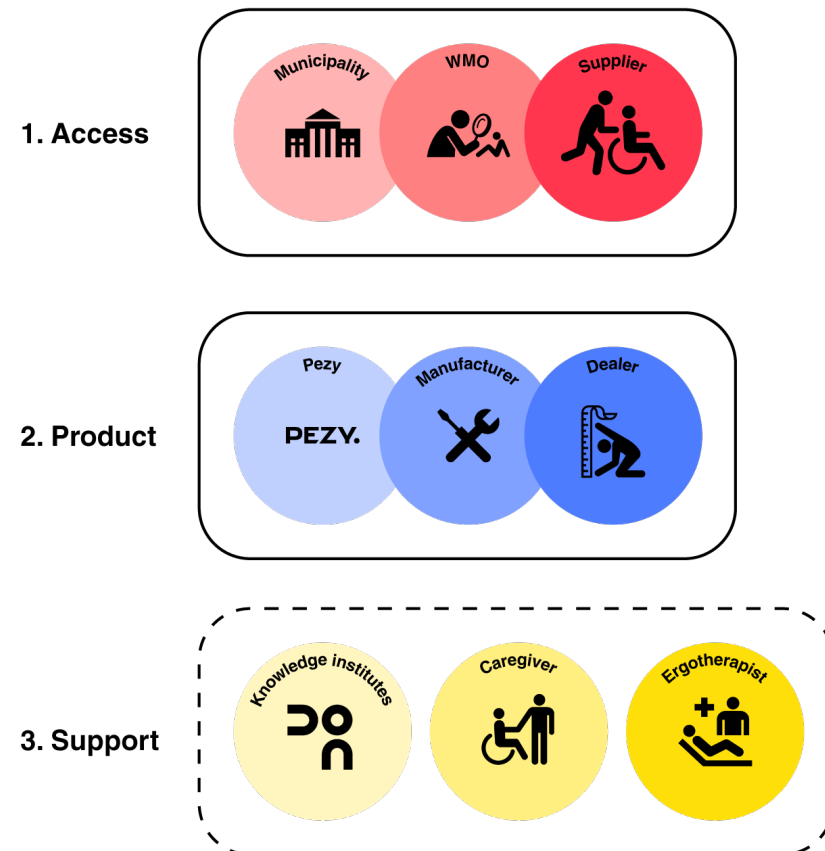


Figure 19. Stakeholder groups

Analysis | Stakeholders



1. Access to the product

The first group (Figure 19) is composed of the stakeholders that work on the provision of the wheelchair. Their interest is to make sure that the user has access to the product. Active wheelchairs can't be purchased directly from the dealer by the user, but are provided by the municipality (Figure 20).

To acquire a wheelchair, the patient has to contact the municipality. The municipality oversees the total budget for aid reimbursement. They are not concerned with the individual user, but rather with maintaining equal access to the right medical aid for all users.

The Wet Maatschappelijke Ondersteuning (WMO) is a separate department of the municipality which assesses the requirements of the user. The WMO consultant will discuss the assistive requirements of the user.

If the patient is able to convince the consultant of their need for the custom wheelchair, the WMO will recommend the required budget to the municipality. The WMO allocates the budget to a supplier (Welzorg, Medipoint, Kersten etc.). The supplier will re-assess the user's needs and prescribes the wheelchair. They will first try to fit the user with a standardised wheelchair frame, which is the most affordable. In some cases the cost of the prescribed wheelchair differs from the budget allocated by the WMO. The remainder of the budget stays with the supplier. This system can make it attractive for suppliers to prescribe more standardised wheelchairs even when a custom wheelchair would be more suitable.



2. Product

Once permission is granted, a wheelchair dealer will measure the user and compile the users' body dimensions and personal requirements into a data sheet for the manufacturer that can be used to construct the wheelchair.

The design of the wheelchair, which contains specifications, limitations and certifications, is the responsibility of PEZY. PEZY also decides on the possibilities

for customisation. The direct influence on the product quality lies with the manufacturer, who builds the final, custom wheelchair. It is their responsibility to maintain proper production quality, control the materials used and evaluate the quality of the wheelchair before delivery. A more complete overview of the phases that follow the provision process can be found in appendix a.4.



3. Information & Support

The last group are the stakeholders that provide information and support to the user. The ergo therapist and the caregiver share the interest to get the user the best care possible and support them to advocate for it. The ergo therapist has a more direct role in this, as they are a respected party and bring verified arguments about the users' requirements. Knowledge institutes such as 'Dwarslaesie Organisatie Nederland' and 'CheckJeZit' can help to inform the user about the possibilities of the wheelchair provision and to learn from the experiences of other wheelchair users.

Analysis | Stakeholders

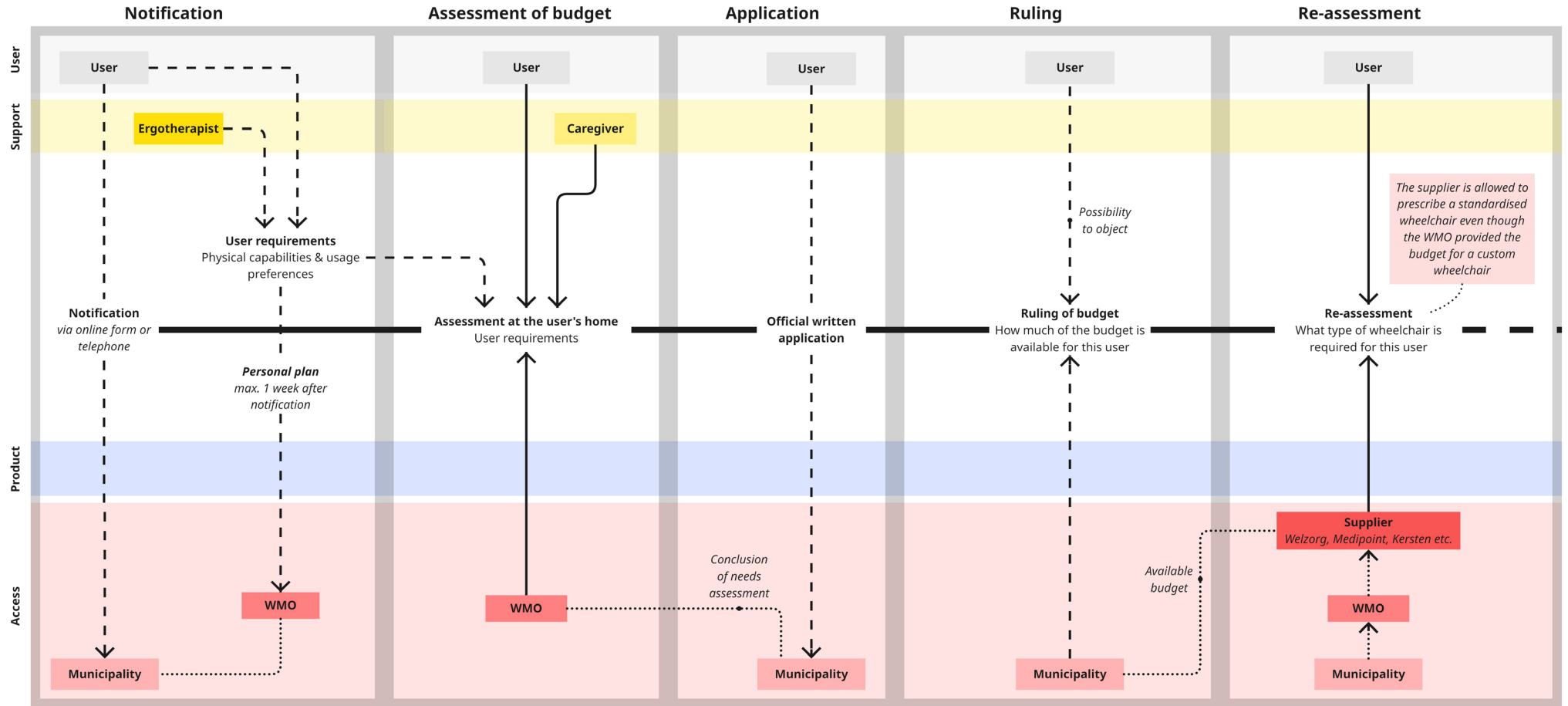
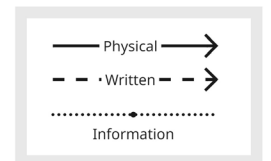


Figure 20. System map of the wheelchair provision process | Full system map including the later phases (fitting, drawing, production & delivery) can be found in appendix X



A.4.2 Stakeholder interactions

Gaining insight in current stakeholder interactions

Figure 21 shows the stakeholders in a matrix with *influence* plotted vertically and *interest* in the horizontal direction. The arrows depict the most important lines of influence for each stakeholder. In this graph, the groups that were introduced in chapter A.4.1 are indicated in the same colours as before. Ideally, all stakeholders would be in the top right corner, indicating peak interest in combination with the influence needed to realise the best product for the user.

In this corner we find the dealer as the most involved stakeholder. The dealer has direct contact with the user, and it is their goal to meet the requirements of their client the best they can. Also high on the influence scale is the manufacturer who has a good reputation to keep up, to keep collaborating with the dealer. Their interest is a little lower as they don't have a direct relationship with the user.

The design of the product is the influence of PEZY, who have limited interest towards the individual user as they wish to serve a large group of users at once. The municipality and WMO are both placed in the top-left corner of the matrix. Both stakeholders have a lot of influence in the decision-making process.

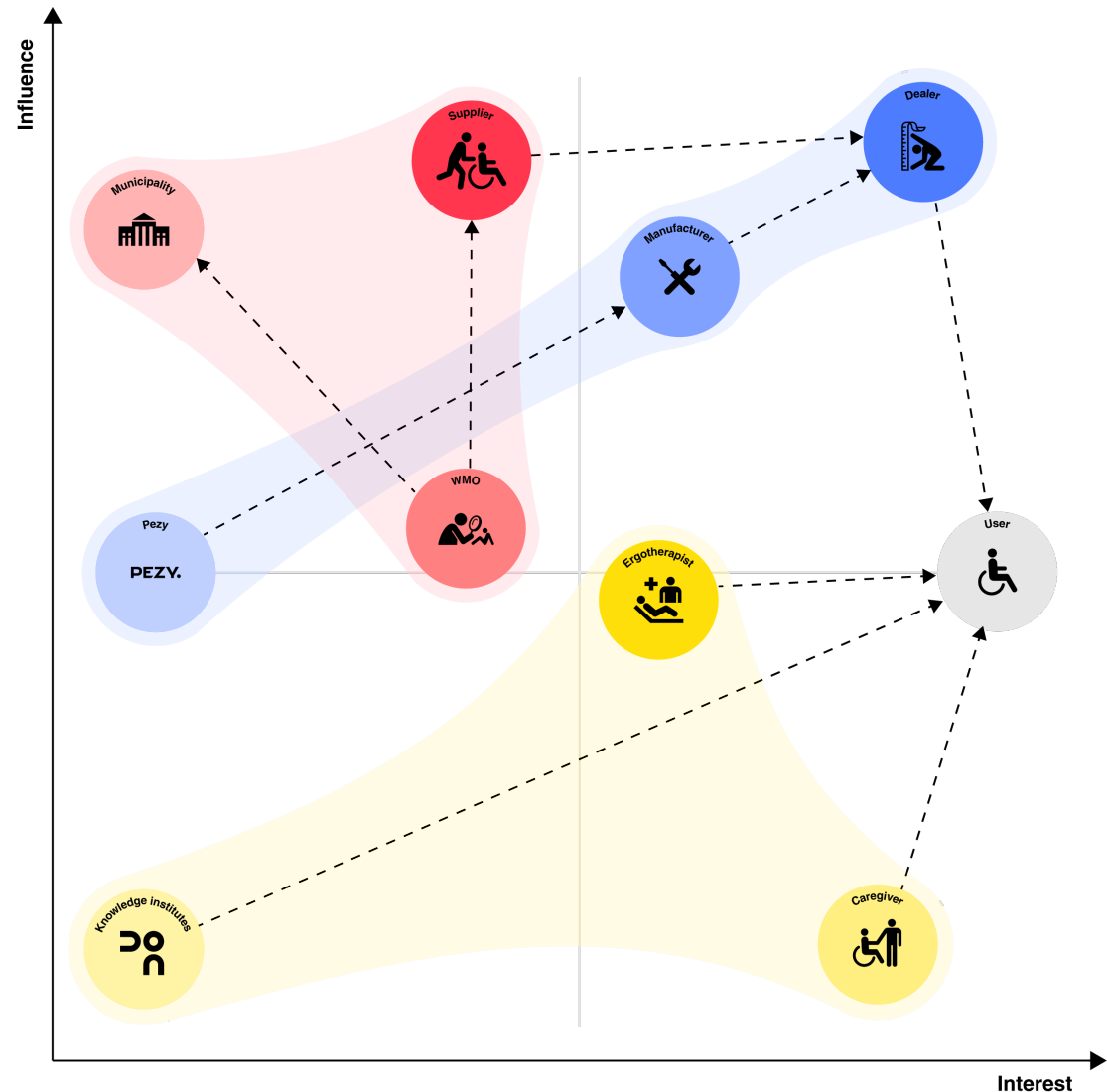


Figure 21. Stakeholder map: Influence vs Interest matrix. The stakeholder groups are indicated in the same colours as in Figure 16.

Analysis | Stakeholders

The WMO operates in a more user centred way, as they assess the individual needs of the user. The supplier has more influence than the WMO as they are responsible for the prescription of the product to the user.

The stakeholders of the information and support group are all situated in the lower half of the matrix. The ergo therapist and caregiver both have high interest, but with respected expertise, the ergo therapist has more influence in the provision of the wheelchair. Knowledge institutions are mainly there to provide information and share experiences, which doesn't require personal interest nor influence from their end.

The most influential stakeholder group for the user is the access group (red) in the top left corner. This creates a conflict of interest: The user wants a custom frame that precisely fits their requirements and lifestyle, yet the suppliers prefer standardised frames for their adjustability and affordable pricing. As explained in the previous chapter, adjustability is not a desirable feature for most active wheelchair users. An opportunity that would bring these stakeholders closer together is to offer a custom frame at a more attractive price point. The price of a custom wheelchair frame is mostly dependent on the manufacturing efficiency and the materials that are used.

Conclusion | Stakeholders

The stakeholders can be categorised in three priority groups: access (*to the product*), product and support. The matrix shows that the individual stakeholders act in different quarters of the matrix, even though they share the same interest. There is an imbalanced price-quality relation between the stakeholders that provide access to the wheelchair, and the user. The user requires a custom frame, but the current system of provision favours affordable one-fits-all solutions. The price of a custom wheelchair frame is mostly dependent on the manufacturing efficiency and the materials that are used.

Analysis | Wheelchair performance

A.5 Wheelchair performance

Goals | Wheelchair performance analysis

- Identifying performance goals and -conditions
- Specifying design parameters regarding ergonomics

Wheelchair ergonomics play an important role in the stability, comfort and propulsion efficiency of the user. This chapter summarises the most important ergonomic constraints that influence the design of the frame according to literature.

The ADL performance of an active wheelchair is measured by the user's agility, stability and reach (Van Breukelen, 2020).

- *Agility* is important for manoeuvrability and allows for quick movements.
- *Stability* is important to prevent tipping of the wheelchair and support the user's spine.
- *Reach* allows for independence, for example picking something from the ground or bending forwards.

These performance goals are dependent on a set of three performance conditions: rolling friction, propulsion efficiency and balance.

Figure 22 shows the relationship between each performance condition and -goal. Using both literature and interviews, I have concluded that there are four design parameters that influence the performance conditions of the wheelchair: seating support (& posture), rigidity, weight and size.

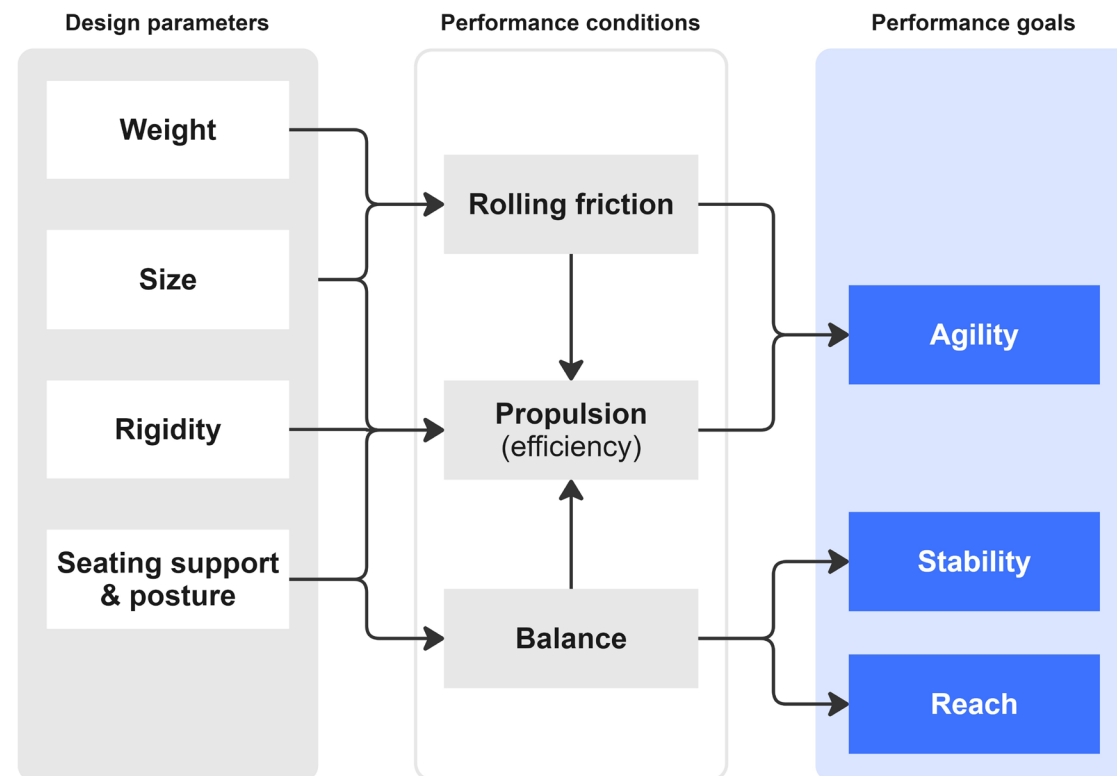


Figure 22. Performance conditions & goals influenced by design parameters. Inspired by Van Breukelen (2020)

A.5.1 Ergonomics

Seating posture

The spine is curved in 4 places: the cervical curve, the thoracic curve, the lumbar curve, and the sacral curve (Hines & Mayfield Clinic, 2018). Together these form a natural S-shape. The bones of the sacrum are fused together and form the pelvis. (Figure 23)

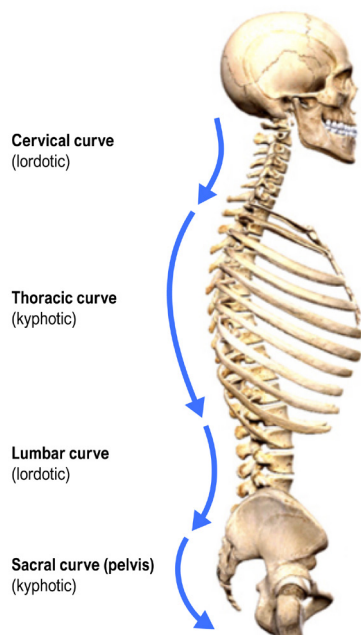


Figure 23. Curvature of the spine

Figure 24 shows the spinal posture of the user in different seat types. The shape of the seat of the wheelchair has a large effect on the positioning and rotation of the pelvis, which determines the position of the spine and thereby the position of the head. Spinal cord injured wheelchair users have no or very limited control over their abdominal muscles and legs. Improper lumbar support in the seat can cause the user to slouch, which makes the spinal curvature kyphotic. (Figure 24, left).

A kyphotic spinal curvature decreases the stability of the user and can cause neck strain due to the extension of the neck required to look up (Van Breukelen, 2020).

SCI patients spend an average of 9.2 hrs per day in their wheelchair, which is more than twice as long as the average active wheelchair user (Budai et al., 2018). To help the user maintain proper posture in the wheelchair, the seat frame is often slanted (Figure 24, middle).

The slope in the seat tilts the user backwards to prevent slouching, but at the same time this tilting rotates the pelvis forward. This forces the lumbar area of the spine into a kyphotic curve. The most ergonomic wheelchair seating solution is the ergo seat (Figure 24, right).

This seating is built to match the length of the pelvis of the user before the frame tubes bend upwards to support the legs and keep the user contained (Permobil & Mullis, 2021a). Ergonomic seating is only possible with custom body measurements and is therefore only used in custom frames.

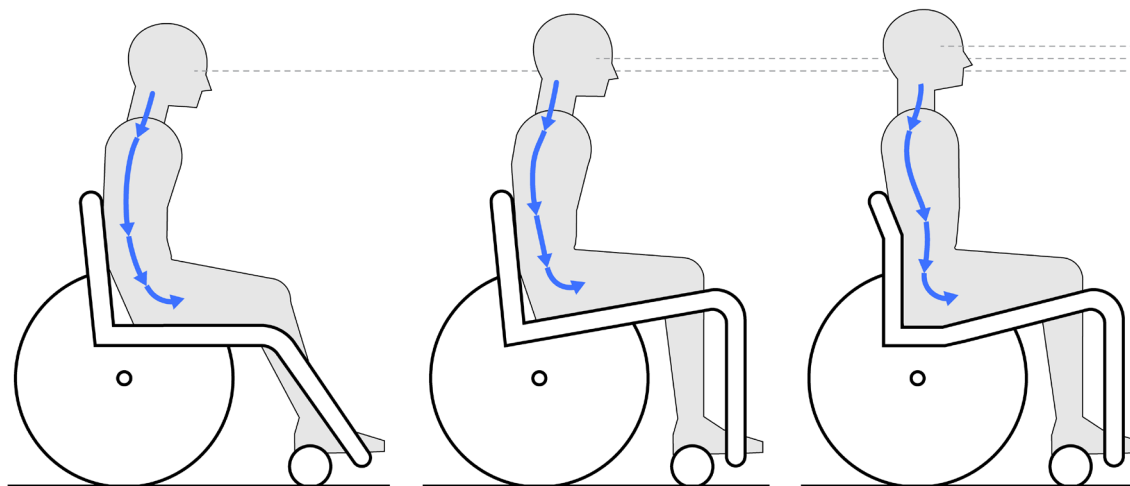


Figure 24. Posture of the spine in *flat* seat (left), *bucket* seat (middle) and *ergo* seat (right)

Analysis | Wheelchair performance

Rear wheel placement

The position of the rear wheels relative to the users' centre of gravity (COG) influences stability and propulsion. Rearward position of the wheels increases stability as it places the COG in front of the wheel axle. (Figure 25) At the same time this reduces the push angle of the user, which makes manual propulsion less optimal.

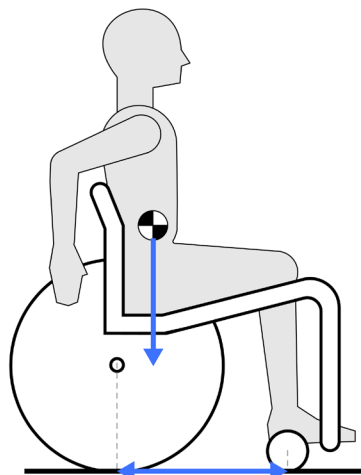


Figure 25. COG in front of the rear wheel axle

A more forward position of the rear wheels (Figure 26) improves propulsion and shoulder range of motion (ROM) of the user (Medola et al., 2014). The anterior-posterior placement of the wheels also affects the total wheelchair length, which impacts manoeuvrability (International Organization for Standardization, 2008).

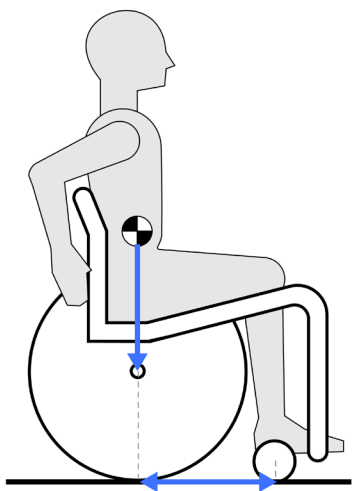


Figure 26. COG exactly above the rear wheel axle

Backrest

A low backrest (<200 mm) allows for the best ROM in the shoulder, resulting in a lower push frequency (Yang et al., 2012). However, the posterior stability is limited (Figure 27). For users with impaired trunk control, a high backrest (>400 mm) is more suitable (Figure 28). A higher backrest provides greater support, but limits shoulder extension which makes manual propulsion of the wheelchair more difficult (Medola et al., 2014).

The backrest shouldn't extend higher than 20 mm below the scapulae inferior angle (the lowest point of the shoulder blade that protrudes outwards when moving the arm) (Cherubini & Melchiorri, 2012).

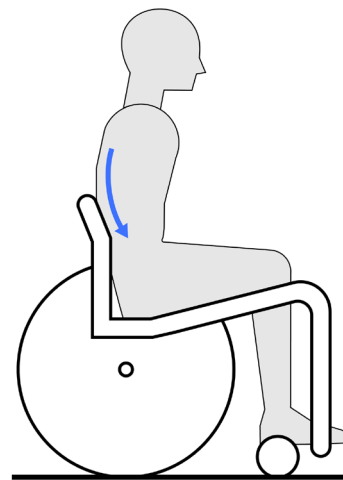


Figure 27. Backrest too low

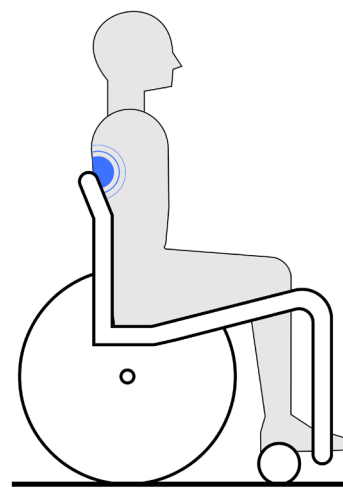


Figure 28. Backrest too high

Conclusion | Ergonomics

The research shows that ergonomic constraints are often a balance between the users' requirements and the most optimal seating. Therefore, it is difficult to specify exact design requirements.

Proper pelvic positioning and spinal support are essential to maintain stability and prevent harmful postures, while also improving propulsion (Van Breukelen, 2020; Budai et al., 2018). The position of the rear wheels determines the balance and stability of the user, while also impacting the propulsion efficiency (Medola et al., 2014). The backrest shouldn't extend higher than 20mm below the shoulder blades to allow for shoulder ROM combined with good postural support (Cherubini & Melchiorri, 2012).

A.5.2 Design parameters



Design parameter 1 | Seating support & posture

Why?

Stability

Spinal Cord Injured wheelchair users often have impaired abdominal muscles which limits their ability to independently support their lumbar posture. Stability in the seat supports the trunk of the user to prevent harmful postures which could lead to secondary injuries (e.g. pressure sores or strain)

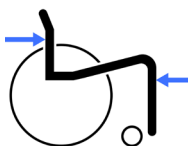
Propulsion ergonomics

Proper postural support allows the user to sit upright without slouching. Sitting upright ensures that the shoulders are in the most optimal position for manual propulsion.

How?

Made-to-measure frame

A frame that is designed for a specific user allows for the most optimal support of the posture, because it is designed to accommodate for unique measurements of the user's body. This ensures that the seat instantly prevents slouching and other poor postures, without the user having to fix their posture themselves.



Design parameter 2 | Rigidity

Why?

Stability

A rigid frame minimised deformation of the frame during ADL use. Reduced flexing improves the user's control and balance in the wheelchair.

Propulsion efficiency

When the frame is able to flex/deform during propulsion, part of the user's input energy is lost.

Durability

Repeated flexing increases the stress on the welded joints of the frame. A rigid frame is able to distribute the loads more evenly: reducing these stress concentrations and making the frame last longer.

How?

Crossbar construction

A crossbar connects the casters to the rear wheel axle reducing flexing in the frame and giving it more stiffness.

Welded frame

A fully welded frame minimises the chance of components loosening over time due to poor tolerances of the material. Welding fixes these components in a more rigid and durable construction.

Fixed geometry

Avoiding adjustable frame angles and folding mechanisms increases the rigidity of the frame by reducing the number of non-welded components.

Analysis | Wheelchair performance

Design parameter 3 | **Weight**

Why?

Propulsion efficiency

A lightweight frame makes for a lightweight wheelchair. A lighter wheelchair requires less force to accelerate, turn or brake, which minimises fatigue and strain. Additionally, a lightweight wheelchair has less rolling friction, which makes propulsion even more efficient (Van Breukelen, 2020).

Transportation

Users frequently lift their wheelchair into a car or train. Minimising the weight of the frame can make these activities easier and reduce fatigue.

How?

Made-to-measure frame

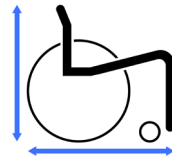
A frame that is custom designed for an individual user eliminates unnecessary material.

Welded frame

Limiting components that are adjustable in size will reduce the total number of components in the frame. A welded frame only includes the components that are required for the user it is designed for.

Use of material

Optimising the thickness of the tubes in the construction may reduce weight in places where thinner tubes can be used to achieve the required strength.

Design parameter 4 | **Size**

Why?

Manoeuvrability

A small wheelchair is easier to manoeuvre through narrow environments than a large wheelchair. This improves the agility of the user.

Transportation

A wheelchair that is designed for transportability minimises the space used underneath the frame, to allow for more convenient lifting and rotating of the frame in the confined space of a car. Ideally this can be done by reducing the outside dimensions of the frame, rather than designing the frame with folding components, because these also reduce its rigidity.

How?

Made-to-measure frame

A custom designed frame doesn't have oversized components, but is made to provide only the space that is required for a specific user. This results in a frame that has the smallest possible footprint.

Analysis | Frame

A.6 Frame

Goals | Frame analysis

- **Understanding the limitations and benefits of different frame types.**
- **Specifying frame dimensions based on market averages.**
- **Specifying the scope of components to design.**
- **Identifying limitations of the design from out-of-scope components.**

<i>What</i>	<i>Why</i>	<i>Who</i>
Interviews with wheelchair experts and dealers	<ul style="list-style-type: none"> • Understanding the unique requirements of the customer • Indicate performance factors • General insights: How are users measured, how is the WMO budget decided, what do they recommend, what is the most important distinguishing feature of their product compared to that of other wheelchair dealers? 	<ul style="list-style-type: none"> • Sunrise Mobility (RGK & Quickie) • RD Mobility (Wolturnus)
Rehacare & Veine Dagen	<ul style="list-style-type: none"> • Talking to experts about performance indicators • Talking to users about their experiences • Insight in new innovations and focus areas 	<ul style="list-style-type: none"> • Wolturnus • RGK • Permobil • Wheelchair skills team
Supplier websites	<ul style="list-style-type: none"> • Creating an overview of the competing products on the markets and indicating the different specifications • Learning about wheelchair ergonomics 	<ul style="list-style-type: none"> • RGK • Wolturnus • TNS • Permobil
Prescription forms from different dealers	<ul style="list-style-type: none"> • Collecting and comparing the different ranges of body measurements (and their respective translations to wheelchair components) to calculate an average set of measurements that aligns best with the target user group • List of requirements 	<ul style="list-style-type: none"> • RGK • Wolturnus • TNS

Table 5. Market research methods

All manual wheelchairs are designed with two large rear wheels, which are required for manual propulsion and two smaller front wheels (casters) for balance. The distinguishing factor between the different frames on the market is the frame (Figure 29). In the Netherlands, there are only 4 dealers of custom wheelchair frames: RGK, Wolturnus, TNS and the PEZY wheelchairs. I will gain insights about the different frames that these dealers offer using the research methods in Table 5. With this information I will create an overview of the specifications and decide on the scope of components to design.



Figure 29. Wheelchair with the frame highlighted in blue

Analysis | Frame

A.6.1 Market

Understanding the differences between types of frames

Specifying frame dimensions based on market averages

To compare different wheelchair frames, I created an overview of all ADL frames I could find on the Dutch market.

Figure 30 shows the compared frames, ordered by frame type and clustered by brand. In the table in appendix a.3, I have listed the technical specifications and sizing ranges that the compared brands offer. Using insights from manufacturers and dealers, I have composed a list of advantages and disadvantages of each frame type (Table 6) with respect to the design parameters in chapter A.5.2.




	Advantages	Disadvantages
Open frame 	Lightweight Less construction material is required to produce this frame compared to the Box- and Folding frames Transportable Can be lifted over driver seat for transport Minimal design The Open frame is designed with a slim frame, which is preferred by many users according to dealers	Limited rigidity Frame is more prone to flexing than the Box frame. Repetitive flexing of the frame can cause fatigue cracks in the construction, reducing the frame's longevity. Propulsion efficiency Reduced frame rigidity also decreases the propulsion efficiency as part of the user's input energy is lost to the flexing of the frame, rather than rotation of the wheels. Less compatible with assistive devices The limited rigidity of the frame makes it less suitable for use with hand bikes or motorised devices that mount to the front of the frame. These attachments apply upward and forward forces which can lead to fatigue cracks and deformation of the frame.
Box frame 	High rigidity The crossbar construction allows for a more rigid frame Propulsion efficiency The rigidity of the frame minimises flexing of the frame, which means that it requires less effort to use the wheelchair Durable The frame is better suited to withstand increased load and repeated impacts on the frame. Compatible with assistive devices The increased frame strength reduces the risk of deformation to the frame due to upwards and forwards pulling of devices like hand bikes and motorised wheels.	Difficult to transport The addition of the crossbar to the frame increases its overall size, making it harder to transport Weight The construction requires more material, which increases the total weight of the frame Bulky appearance The construction of the Box frame is generally considered less attractive to users than the slimmer Open frame design.
Folding frame 	Transportability The frame is designed like an open frame with hinges in along the front frame, allowing it to fold to a compact, travel friendly size.	Hinges The hinges used to create the folding mechanism can loosen over time. This will impact the rigidity and durability of the frame.

Table 6. Advantages and disadvantages of the three custom ADL frame types

Analysis | Frame



Figure 30. The compared frames which are available in the Netherlands

Analysis | Frame

These wheelchair frames all show a trade-off between rigidity and transportability, with the box frame in the top-left corner of the matrix in [Figure 31](#): A very strong construction that allows for a lot of postural stability with very limited frame flexibility, making it ideal for riding longer distances and everyday use. The open frame is less rigid but has increased portability due to the slimmer frame design.

Even lower on the rigidity scale is the folding frame. Based on the open frame, the folding frame has hinges in the leg frame, allowing it to be folded to a compact package. This serves as a nice solution for people who travel often, but according to wheelchair dealers, this frame isn't recommended for intensive ADL use as the hinges are prone to loosen over time, making the construction less rigid.

I believe a wheelchair frame for spinal cord injured users should be transportable, allowing for individual mobility, but not in a way that limits its rigidity. The matrix shows the market gap for this opportunity: rigidity at the level of the box frame with open frame transportability.

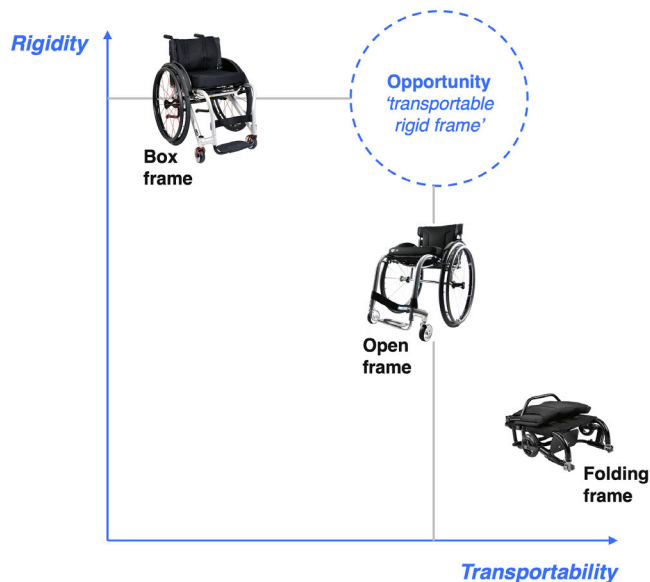


Figure 31. Matrix of the different custom active wheelchair types compared on rigidity vs. transportability

A.6.2 Frame components

Specifying the scope of components to design

The frame is the structural component of the wheelchair that supports the user and holds all components together (Long, 2014). In this chapter, I have deconstructed the classic design of the box-frame into separate parts, to specify the function and significance of each component with respect to the overall frame construction.

The classic design of an active wheelchair frame is built with the components in [Figure 33](#). Not all components are equally important for the performance of the wheelchair, and some can be designed more freely than others, as can be seen in [Figure 32](#), where I outlined the silhouettes of frame designs of different manufacturers.

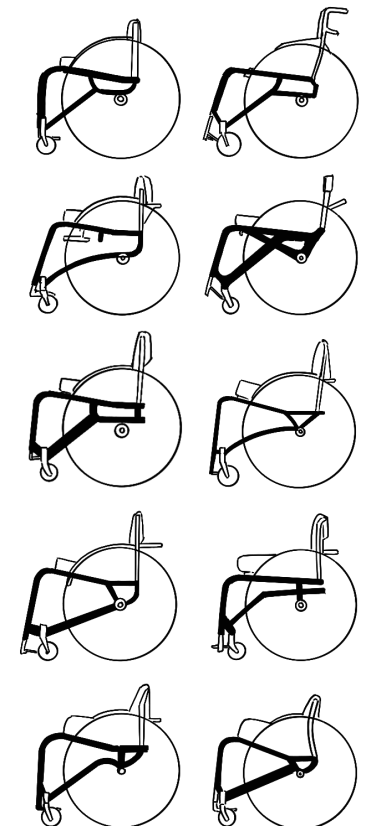


Figure 32. Different but similar Box frames (silhouettes from RGK, Panthera, Woltturnus, Quickie and TNS)

Analysis | Frame

The product breakdown in Figure 33 shows the interfacing relationship between the different components of the wheelchair frame. The hierarchy of importance between the components is derived from market interviews and by analysing a variety of frame designs by different manufacturers (Figure 30 & 32).

The blue components are the most *essential* components, which define the shape of the construction. This translates to the

ergonomic performance of the wheelchair, which is dependent on the backrest and seating construction, and the camber of the wheels. In the frames that are currently on the market, the leg support and seating construction are always integrated into a single tube shape, rather than two separate components that are welded in a later stage.

The grey components are *secondary* frame components: these can be a part of the frame but aren't always

included as separate components. These components include custom ergonomic features, such as a back brace, but also components that are often left out or integrated in other parts of the frame. Such integrations could make the frame easier to manufacture. Examples of this are the connection to the seating and the caster house.

The white components, are *related* components which are not a part of the fixed frame, yet because of their

interface with the frame, they do play a role in the layout of the frame.

The caster for example, is not a fixed component of the frame, but it's placement has a direct impact on the frame. The related components are not visualised in the exploded view.

When designing a wheelchair frame, it is important to make sure that these features are not overlooked, as this could lead to a non-viable product.

Conclusion | frame components

This analysis focusses on the frame as the structural component of the wheelchair (Long, 2014). The product breakdown in Figure 33 helped me to prioritise the importance of individual components and categorise them in three tiers: essential-, secondary- and related components. This allowed me to determine which components allow for design freedom and which are essential. The essential components are the camber bar, seating construction and the backrest. The secondary components can be designed more freely to make the frame more efficient to manufacture.

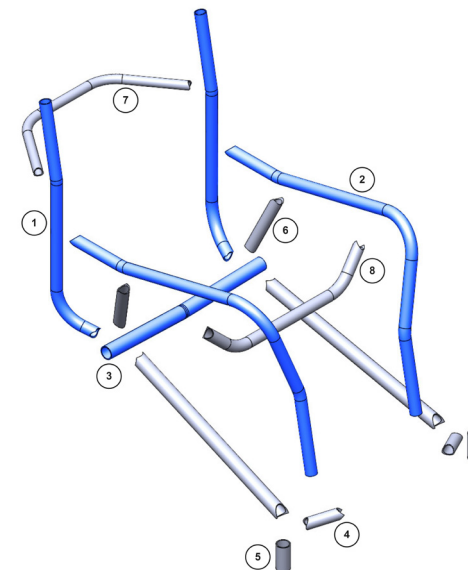
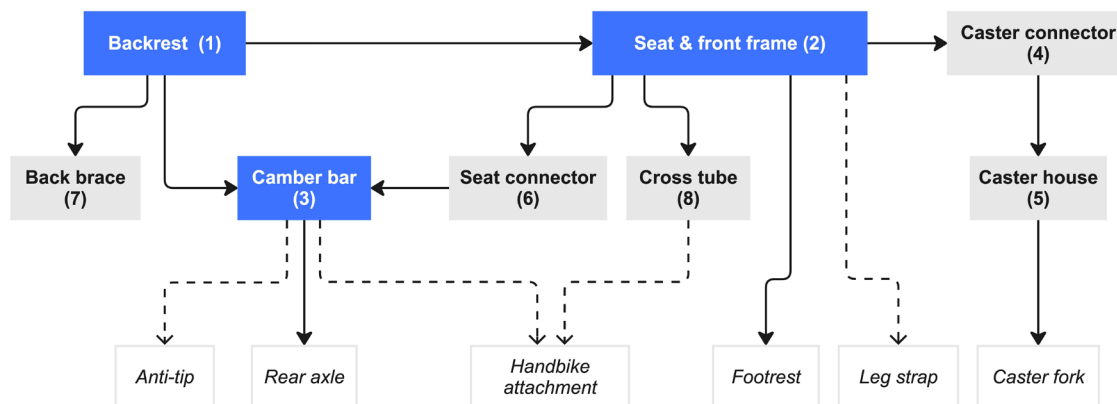


Figure 33. Product breakdown of the Box frame (on the right and in Figure 32) | blue: essential components; grey: secondary components; white: related components

Analysis | Production

A.7 Production

Goals | Production analysis

- **Creating an overview of the capabilities of the factory**
- **Specifying limitations to ensure feasibility of the design**

The design of the frame is commissioned by PEZY. One of their requirements is that the wheelchair can be manufactured in their factory. Ideally this would even be possible using the machines and skills that they currently have. I have visited the factory to analyse the in-house production capabilities and to identify technical constraints. With these insights, I hope to ensure a manufacturable concept. Figure 35 shows a simplified overview of the production steps. Due to scheduling difficulties with the factory, I was only able to gain insights in the process of tube bending.

Tube bending

The tubes are bent with a 3-axis freeform bending machine. The machine works by pushing a tube through a fixed bending head that rotates in 3 dimensions: influencing bending radius, bending angle and bend direction (Figure 34).

The bending radius of a tube is at least 3 times the diameter of the tube (Guo et al., 2018). The machine extrudes a tube in ± 20 seconds, depending on the length of the tube which can be up to 4800 mm.

The machine can extrude tube diameters of 10, 16, 19, 22, 25 and 30 mm. The wall thickness is always 2mm.

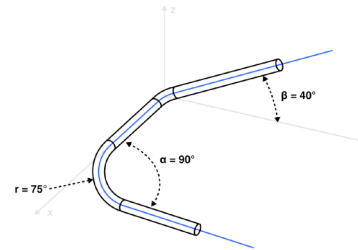


Figure 34. Bending radius (r), bending angle (α) and bending direction (β) for a tube with a diameter of $\varnothing 25$ mm

The factory has experience with bending aluminium (5086 and 7020), titanium, stainless steel and Cr-Mo steel.

The machine is quite accurate with a standard deviation of only ± 0.3 mm and calibrated at least once a year. The machine can automatically calculate the deviation using a scan of the bent tube. (Figure 38)

During regular production days, the team bends in shifts, to minimise the preparation time. It takes ± 30 minutes to swap the bending head (Figure 36) of the machine for a different tube dimension.



Figure 35. Production steps

Tube bending workflow

1. The tube is placed in the machine and extracted.
2. The tube is sprayed with white paint to allow for better depth recognition of the scanner which is used to analyse the master tube for bending errors.
3. The scanning program places the master tube scan over the original master model file and calculates the deviation. If the deviation stays below 2% the part is regarded as successful. If the deviation is larger than 2%, the program will calculate a new program that over- or undershoots the bending angles to extrude the right shape.
4. The machine extrudes the corrected tube, and the tube is checked again for deviations. If the frame component needs to be reproduced, the same program can be used to produce more tubes.

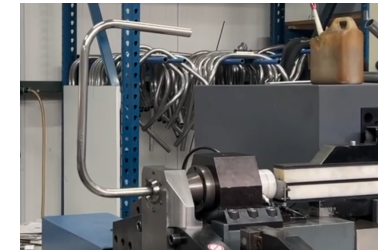


Figure 36. Extrusion of a footrest tube



Figure 37. White paint



Figure 38. Scanning the tube

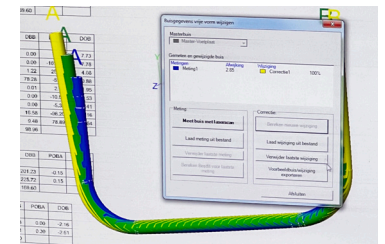


Figure 39. The deviation of the bent tube. The green tube shows the master model, the blue tube is the scanned extrusion and the yellow is the correction calculated by the program.

Analysis | Production

Observations

Something I observed while the tubes were bent is that the more complicated the shape was (e.g. more steep angles or tubes that need to be bent in 3 directions), the higher the deviation tended to be.

For simple shapes such as the footrest in the [Figure 39](#), the deviation was always very low, and the correction calculated by the machine gave a good extrusion at the first (re-)try. A more complicated frame component like the seat-leg frame ([Figure 40](#)) caused more difficulties. The deviation with this type of shape is difficult to correct, due to the many factors that influence the outcome of the extrusion ([Figure 36](#)).

Due to the three-dimensional shape of the tube, it is difficult to scan the tube correctly. Therefore it is uncertain whether this deviation is an error in the bending machine or due to the out-dated scanning

hardware that is used. It may be advisable to design a frame with limited curvature to minimise deviation. Designing the tubes to be bent in a two dimensional plane reduces the number of factors that influence the outcome.

Normally, the factory builds wheelchairs that have a few standard frame components that always have the same bends but are cut to different lengths. To save time scanning each newly bent component, moulds are used that are the exact shape of the master component ([Figure 41](#)). These moulds also have markings to make it easier to cut the tube to the right size.

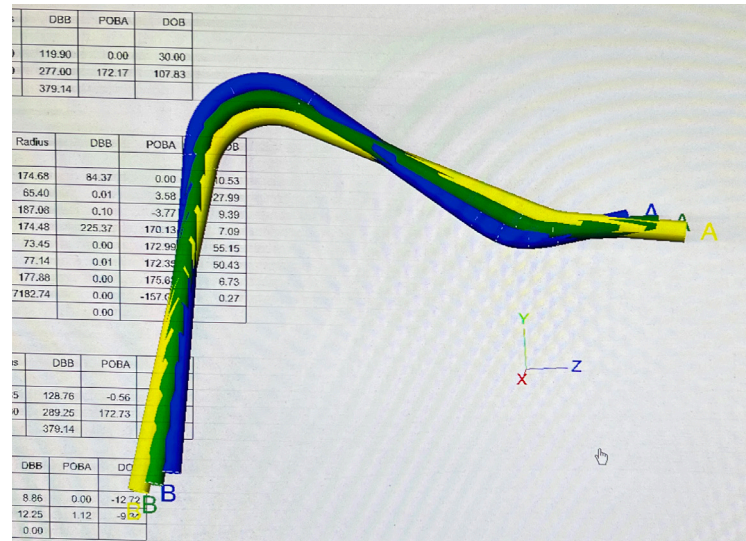


Figure 40. The deviation result of a seat-leg frame

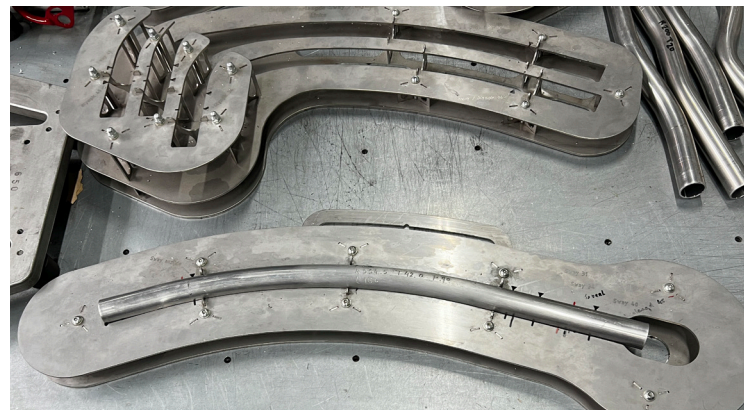


Figure 41. Standardised moulds to check for deviation and size.

Conclusion | Production

To save time: design the frame using mostly the same diameter tubing to save time preparing the machine. The minimum bending radius is three times the diameter of the tube. It may be advisable to limit the maximum angle of bending to minimise deviation. Deviation is only measured if the machine bends a new angle. A component that uses consistent bending angles with custom straight parts in between is therefore more time efficient.

A.8 Material

Goals | Material analysis

- **Gaining insight in the properties of different materials and their application in a frame**
- **Analysing the strength-to-weight ratio of different materials**

Generally, wheelchair frames are constructed with metal tubes that are welded in the desired shape. To decide which materials are suitable, I have compared different alloys that are used by competing brands. Appendix a.5 includes a full overview of the material properties of the materials described below. Table 7 shows a simplified overview.

	Young's (elastic) Modulus	Yield Strength	Density	Price (relative)
Aluminium AA5086	68 GPa	110 MPa	2700 kg/m ³	±1%
Aluminium AA7020	70 GPa	310 MPa	2900 kg/m ³	9,50%
Titanium Grade 9	110 GPa	550 MPa	4500 kg/m ³	37%
4130 Cr-Mo Steel	190 GPa	980 MPa	7800 kg/m ³	2,40%

Table 7. Material properties of various alloys that are commonly used for wheelchair frame construction

A.8.1 Material properties

Gaining insight in the properties of different materials and their application in a frame

Aluminium

A widely used material is aluminium, due to its ideal strength to weight ratio and good welding capabilities (Liu et al., 2010). PEZY's wheelchair frames are built with Aluminium AA5086, a strong alloy that doesn't require additional treatment after welding.

This alloy is relatively flexible, which prevents a sudden break when forces are surpassing the yield strength. Instead, it will start to show cracks, which will lower the performance of the material over time. In comparison to other commonly used materials, the rigidity of this alloy is lower.

A common alternative to this alloy is Aluminium AA7020, which is used by both RGK and Wolturnus. AA7020 is much more rigid but loses a lot of its

strength during the welding process (welding fatigue). To retain its original strength, the alloy requires a precipitation hardening treatment (Kumar & Namboodhiri, 2011). During this treatment the material is heated which causes the molecules to go back into their original formation: regaining its strength.

Titanium

Titanium has increased shock and vibration absorption due to its high strength-to-weight-ratio compared to aluminium (Medola et al., 2014). This allows for construction with thinner tube diameters than aluminium. According to the manufacturers it is more difficult to weld than aluminium. Compared to aluminium and steel, titanium is a very expensive material, which would result in an expensive construction.

Cr-Mo steel

This material is very strong but also heavy and has a strength-to-weight ratio lower than titanium and aluminium AA7020. Its high tensile strength allows it to be used in smaller diameter tubes than aluminium and titanium which makes it possible to design a relatively lightweight frame, despite the high density of the material (Table 7). The downside of Cr-Mo steel is its bending performance. The high elasticity makes the bent tube spring back and warp more than aluminium, which makes it less suitable for the design of a highly customisable frame where angles might be unique for each build.

A.8.2 Deflection performance

Analysing the strength-to-weight ratio of different materials

In the construction of a wheelchair frame, the two most important parameters to choose a material are its strength (deflection) and the weight of the material (density). To get a better understanding of the strength-to-weight performance, I calculated the mass of a one meter long tube for each of the materials, in each combination of diameter that the machine can bend. To calculate the deflection, I used the formulas in Appendix a.6.

The results of each of these calculations can be found in appendix a.7 and were used to make a graph that shows the relation between mass and deflection (Figure 42). The most suitable materials are situated in the bottom left corner of the graph: indicating low weight, combined with minimal deflection.

Because this graph only accounts for yield strength and density, the two aluminium alloys perform very similarly. Both alloys perform well with tube diameters of 22, 25 and 30mm. Thinner aluminium tubes show an almost exponential growth in deflection which makes diameters of 19 and 16mm less suitable to use for components that have a long unsupported tube to which load is applied directly, such as the seating and front frame. Titanium performs better than aluminium, but this effect is most visible in the 19mm tubes. This graph shows that Cr-Mo steel deflects the least, which allows for constructions of even thinner tubes.

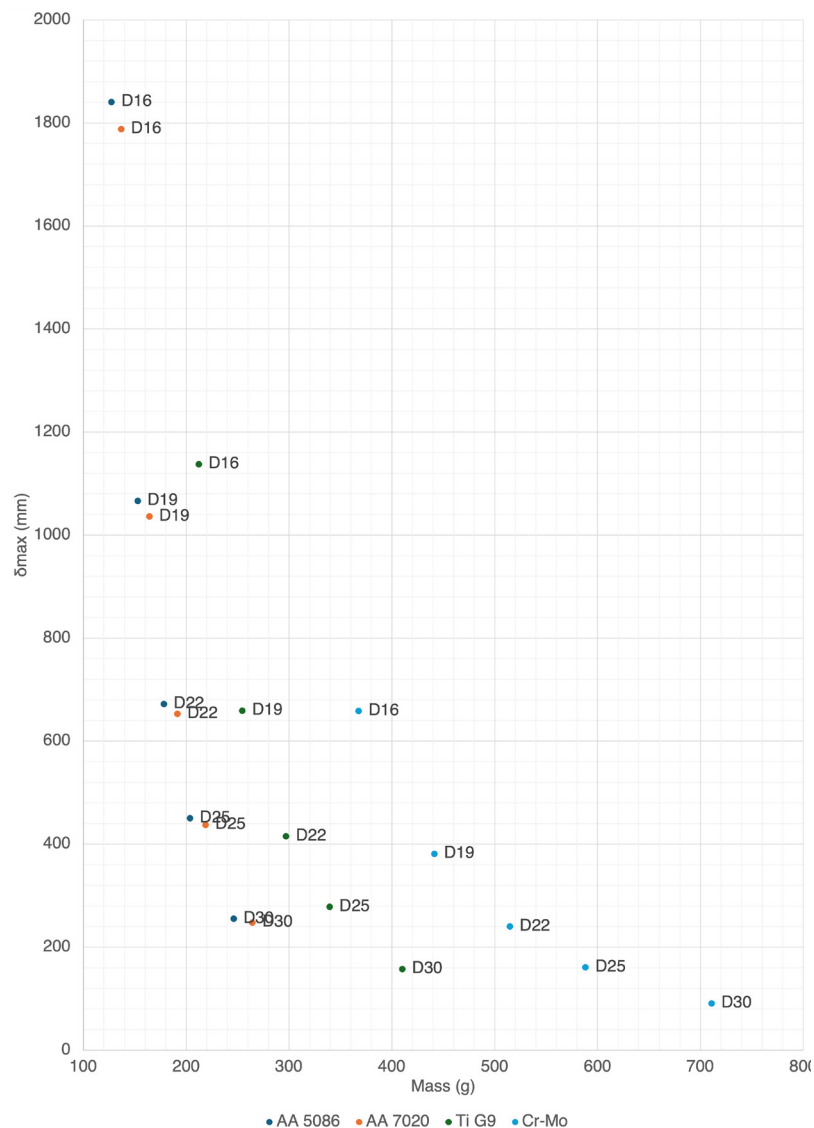


Figure 42. Mass vs. deflection of the different metal alloys

Conclusion | Material

Aluminium offers the best balance of weight, strength, cost, and manufacturability. Titanium has a better deflection performance, but a much higher cost price. Cr-Mo steel is the strongest alloy, but the significantly higher weight than the other materials, makes it less attractive.

Aluminium AA7020 is the most suitable for the design of a frame that is lightweight, strong and also affordable to produce. Although aluminium AA5086 is more affordable, its low yield stress makes it difficult to design the frame in a more transportable way than the Box frame without sacrificing too much rigidity.

Analysis | Construction strength

A.9 Construction strength

Goals | Construction strength analysis

→ Compare different frame constructions to gain insights into the stress distributions in the frame

One of the most important performance factors of construction strength is the design of the frame. Frame construction directly impacts the rigidity of the frame and thereby the durability.

Market research has shown that the most used designs are Open frames and Box frames (Figure 43). Open frames are easier to transport because of the slim frame design, yet most manufacturers prefer the Box frame design, arguing that it will last longer and suits more active use.

A recurring insight from interviews with manufacturers and wheelchair users is the difference in rigidity between these two types of frames. Even though this seems a logical observation, it raises the question: *How substantial does the construction have to be to support the user in every use scenario?*

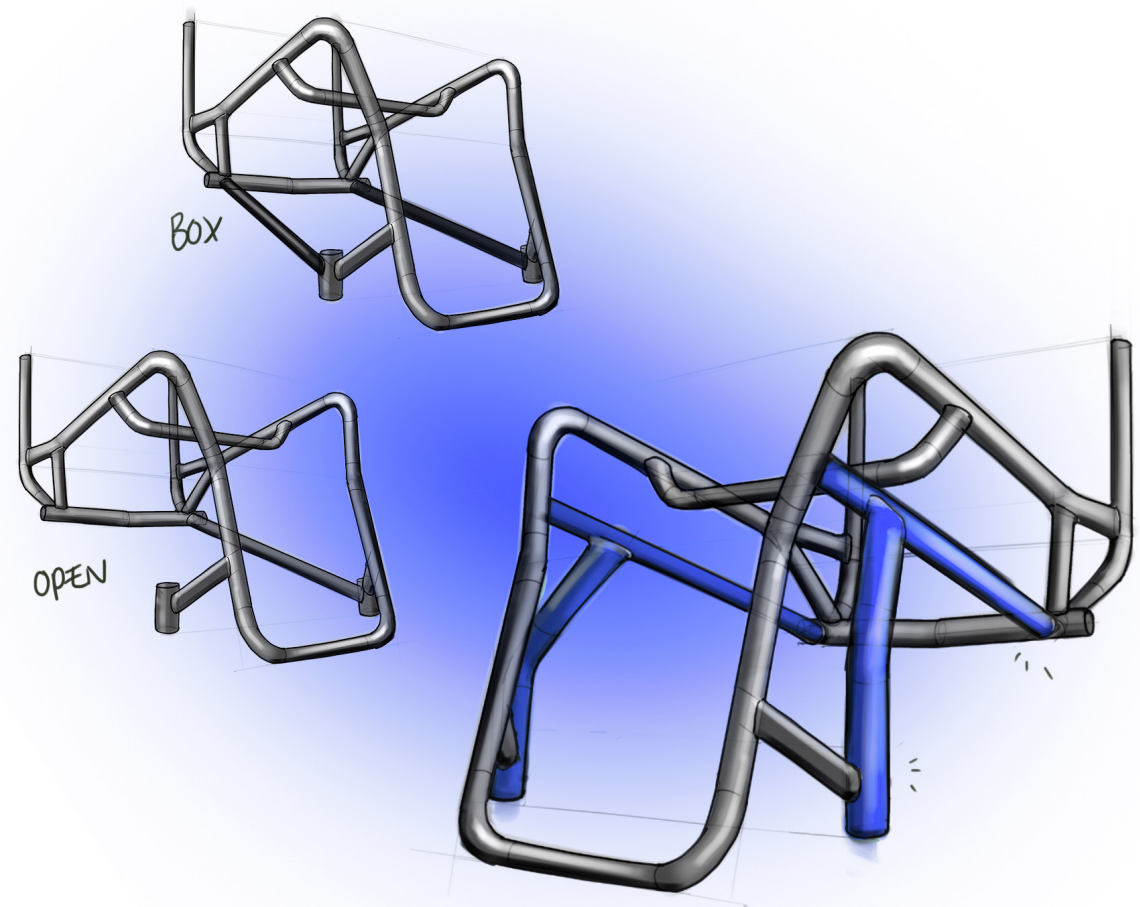


Figure 43. Open frame, Box frame and a conceptual frame

Analysis | Construction strength

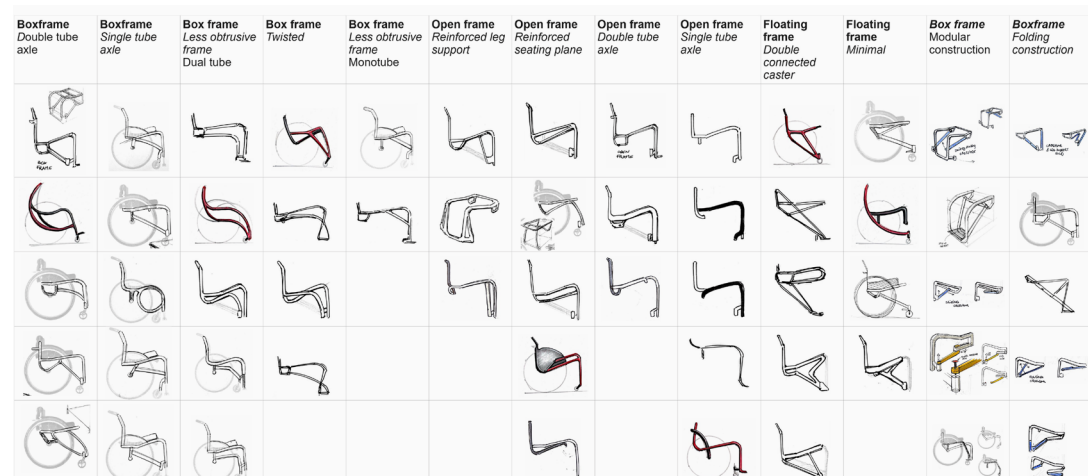


Figure 44. Broad frame ideation

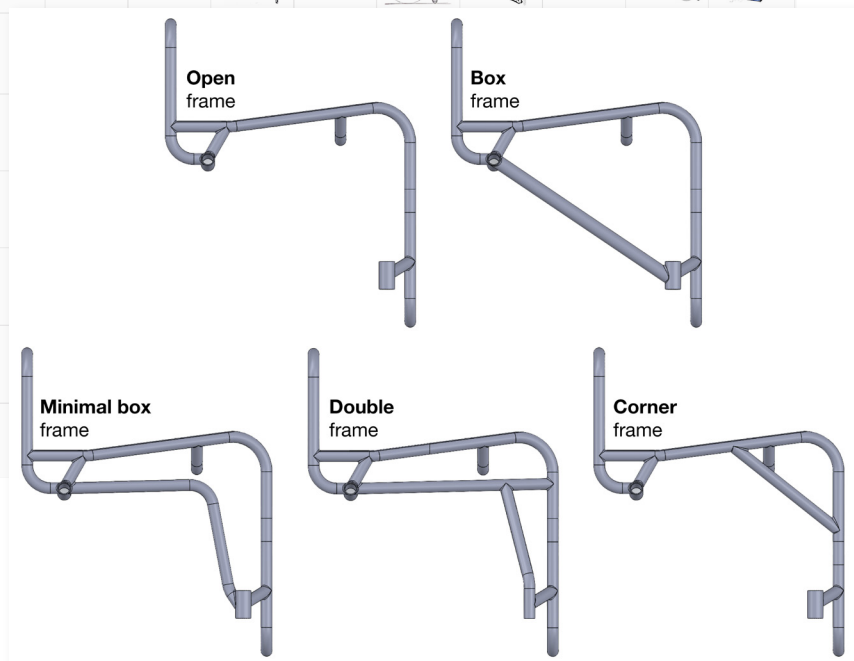


Figure 45. The five frame construction designs modelled for finite element analysis (FEA) simulation in SolidWorks

A.9.1 Frame construction

Inspired by the designs of existing rigid wheelchairs, I sketched a broad range of frame variations that could potentially increase the transportability of the frame (Figure 44). Based on this range of sketches, I modelled three simple designs to compare in SolidWorks (Figure 45). The Open frame was used as a reference to construct the alternative frames. This made sure that the proportions were consistent throughout the compared designs. I used the Open frame instead of the Box frame, for it was easier to manipulate the Open frame design.

To analyse the differences in construction strength, I simulated the five designs in SolidWorks using the same settings. Two of the designs were based on the existing Open and Box frame, the other three were new variations. For the Minimal box frame

design the diagonal crossbar of the Box frame was swapped for a thinner tube that follows the shape of the outer seat frame. The Double frame is similar, but splits this tube into two smaller tubes. In this design, the tube is connected to the outer frame. In the third variation, the crossbar is placed much higher on the frame, which saves the most space underneath the frame. This variation would also use less material.

To gain insight in the strength of these types of constructions, I analysed two common use scenarios:

- 1. Sitting** in the wheelchair with both the rear wheels and casters (front wheels) in contact with the ground.
- 2. Wheelie:** balancing the wheelchair. In this position the casters are lifted from the ground and the rear wheels are touching the ground.

A.9.2 Simulations in SolidWorks

Scenario 1 | User sitting in the wheelchair

The person sitting on the chair makes direct contact with the seating plane and the footrest (Figure 46). The distribution of bodyweight is approximately 80% on the seat and backrest and the remaining 20% on the footrest (Shen et al., 1999).

In this scenario, both the rear wheels and the casters (front wheels) are in contact with the ground (Figure 47). To minimize the complexity of the CAD model, only the forces on the frame were simulated. The forces on the wheels were simulated with a hinge constraint on the rear wheel and a roller/slider constraint on the casterhouse (Figure 48).



Figure 46. Scenario 1: Sitting in the wheelchair, both rear wheels and castor wheels touching the ground.

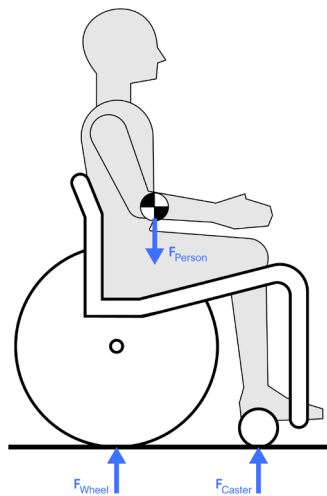


Figure 47. FBD of user sitting in the wheelchair

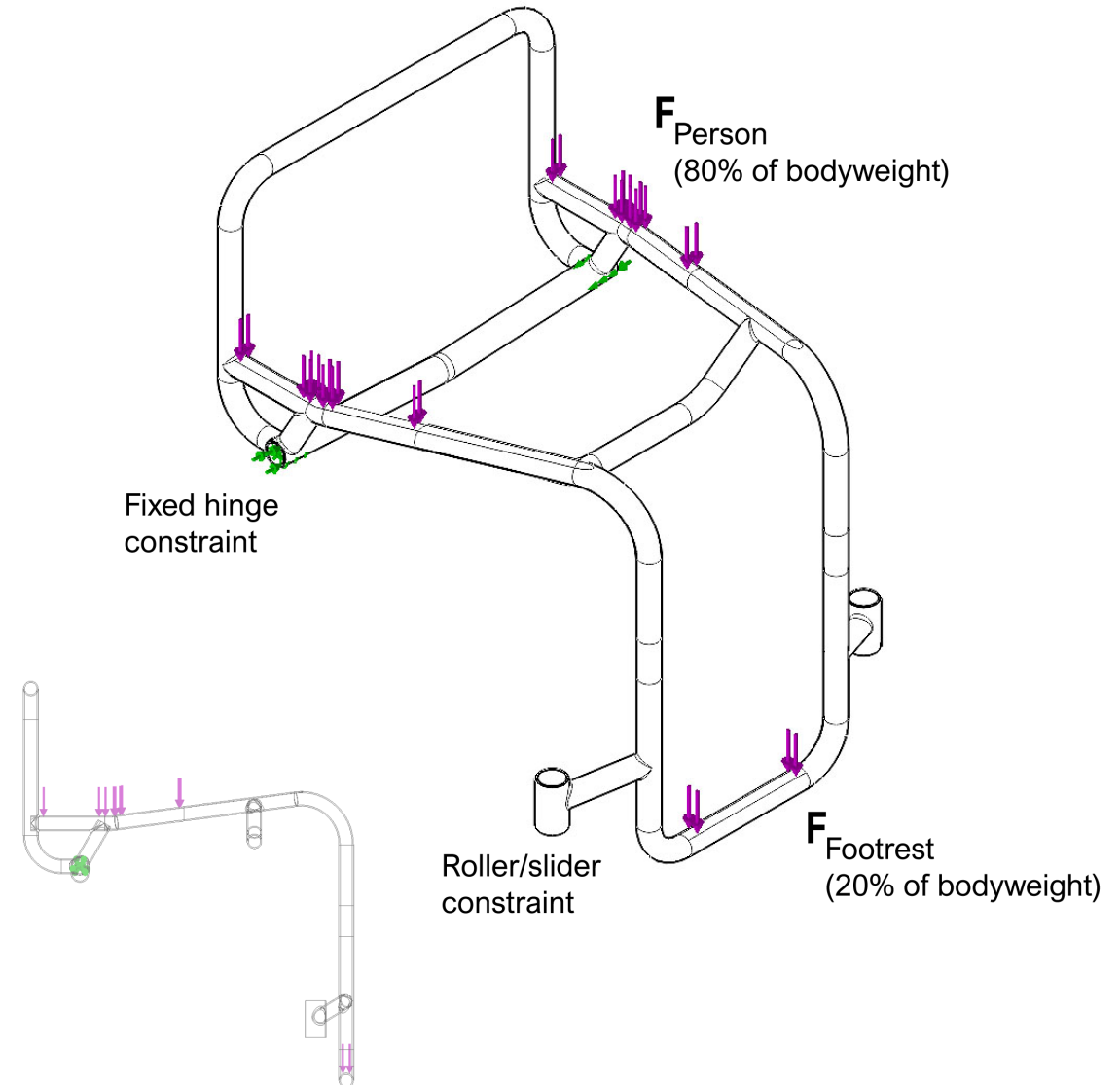


Figure 48. Forces and constraints of scenario 1 in SolidWorks model shown on Open frame construction

Analysis | Construction strength

Results | Scenario 1

Simulation 1A | 120 kg

In this simulation, the stress is visualised for a user load of 120 kg, in line with the average specifications of active rigid wheelchair frames on the market. Although the stress is very low in all five frame designs, a little reaction can be seen in the seating frame of both the Open frame and the Corner frame designs (Figure 49).

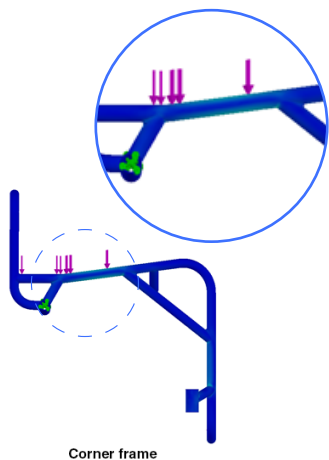


Figure 49. The Corner frame in simulation 1A with a distributed load of 120 kg (Fperson: 960N (80%), Ffootrest: 240N (20%))

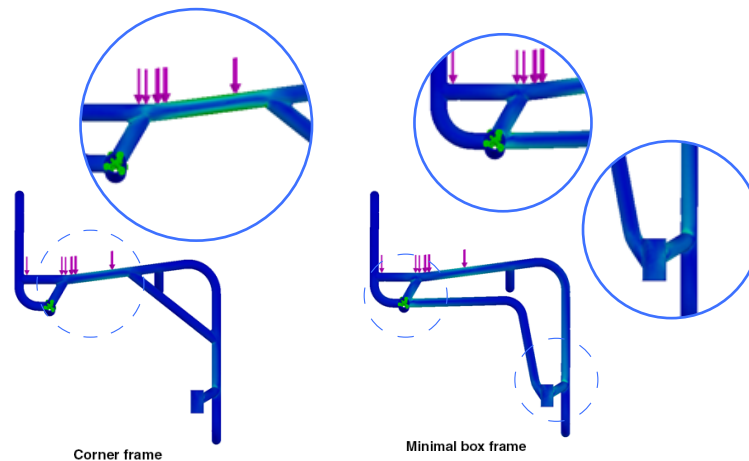


Figure 50. The Corner- and Minimal box frames in simulation 1B with a distributed load of 240 kg (Fperson: 1920N (80%), Ffootrest: 480N (20%))

Simulation 1B | 240 kg

Most products are designed to withstand Double the maximum specified load for safety purposes. This factor of safety accounts for material fatigue and extreme scenarios. Therefore, in this simulation the stress is visualised for a user load of 240 kg.

Again, all five wheelchair frames would be more than suited to carry this weight, yet the weak spots in the Open and Corner frames that were also visible in simulation 1A, are more extreme. All five designs also show increased stress near the casters, with more visible discolorations in the Open, Corner and Minimal Box frames (Figure 50).

The results of all five frames in each simulation are visible in Appendix X

Simulation 1C | 480 kg

To get a better understanding of the most critical parts of the construction, I ran the simulation again, this time with a quadruple load of 480 kg. This showed more extreme results: both the Open and Corner frame surpass the yield strength in the seat frame under this load (Figure 51).

The Box and Minimal Box frames appear to experience stress in similar areas, showing hot spots near the seat frame, between the caster and the leg frame and at the first part of the cross bar. Interestingly, the Double frame reacts very differently. The stress in the seat frame appears to be stretched more evenly across the entire seat to leg frame and there also seems to be less stress around the casters.

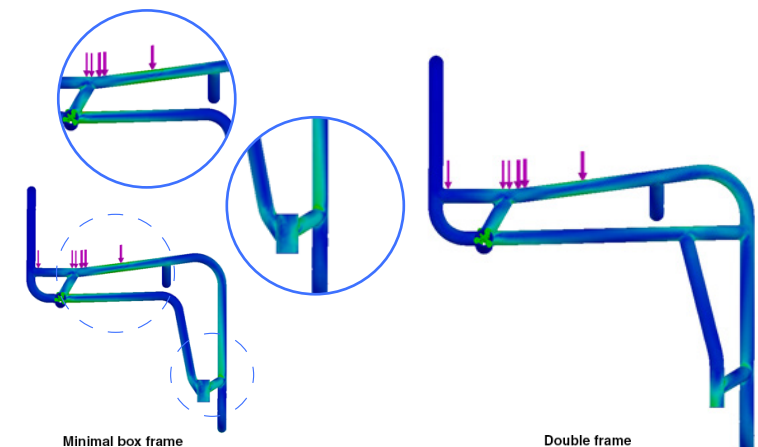


Figure 51. The Minimal box- and Double frames in simulation 1C with a distributed load of 480 kg (Fperson: 3840N (80%), Ffootrest: 960N (20%))

Scenario 2 | Wheelie: User balancing the wheelchair on the rear wheels

During a wheelie manoeuvre the user shifts their COG to lift the caster wheels from the ground (Figure 52). To simulate the tilt of the wheelchair during a wheelie I asked ChatGPT to estimate the rotation angle. This led me to use 15° .

The person sitting on the chair makes direct contact with the seating plane and the footrest, but the weight is distributed more on the seat than in scenario 1. I was unable to find a source for the exact weight distribution, so I estimated that the seat would contain 95% of the weight and the remaining 5% would rest on the footrest for balance.

In this scenario, only the rear wheels are in contact with the ground (Figure 53). Again, only the forces on the frame were simulated in SolidWorks. The forces on the wheels were simulated with a fixed constraint on the rear wheel instead of a hinge constraint to account for the hands of the user that hold the wheel firmly in place (Figure 54).



Figure 52. Scenario 2: User performs a static wheelie: balancing the wheelchair without moving.

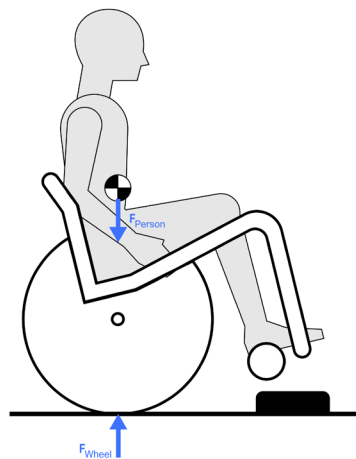


Figure 53. FBD of user balancing the wheelchair when tilted by 15°

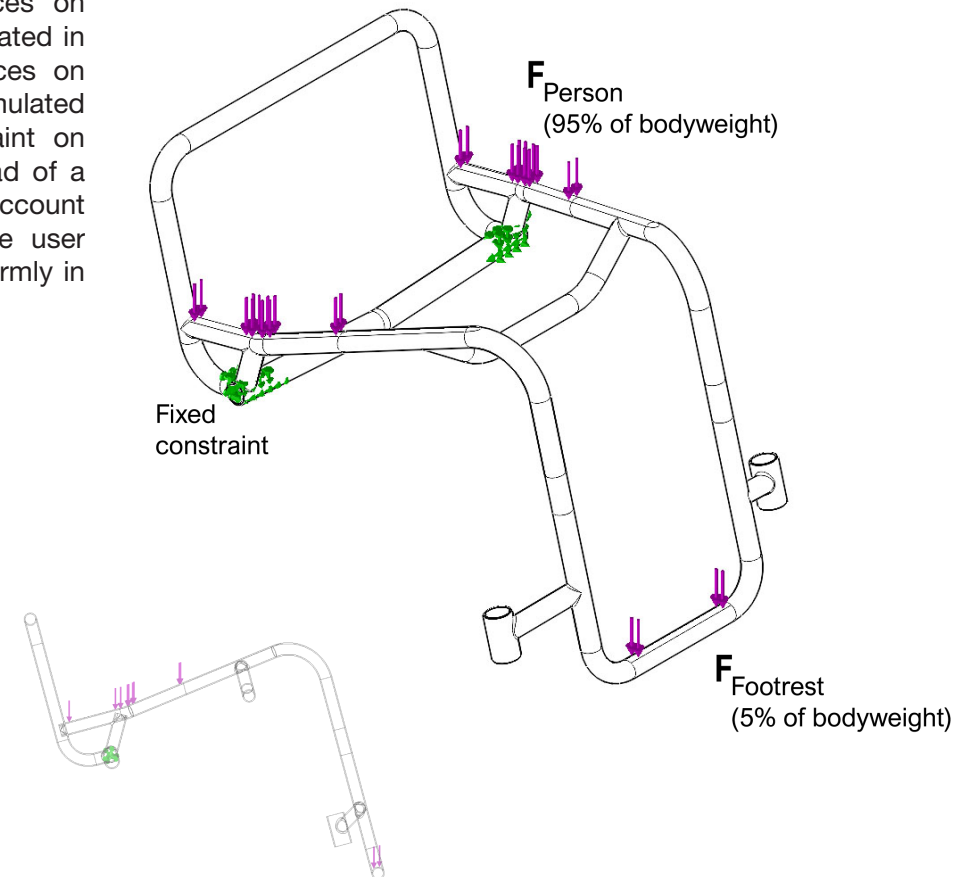


Figure 54. Forces and constraints of scenario 2 in SolidWorks model shown on Open frame construction

Results | Scenario 2

Simulation 2A | 120 kg

The first thing that stands out in this simulation compared to scenario 1 is the increased stress at the weld junction above the axle where it meets the seat frame. This is most visible in the Open- and Corner frames (Figure 55).

Simulation 2B | 240 kg

With a doubled load of 240 kg, the stress shows much more visibly. In the Open- and Corner frame designs, this simulation even shows spots that reach the yield stress. The other three frames all respond similarly to this load. When zooming in as far as possible, Minimal box- and Double frame appear to show small red dots at the interface between the seat frame and the wheel axle. Whether this is a result of the mesh settings or the construction is uncertain. (Figure 56).

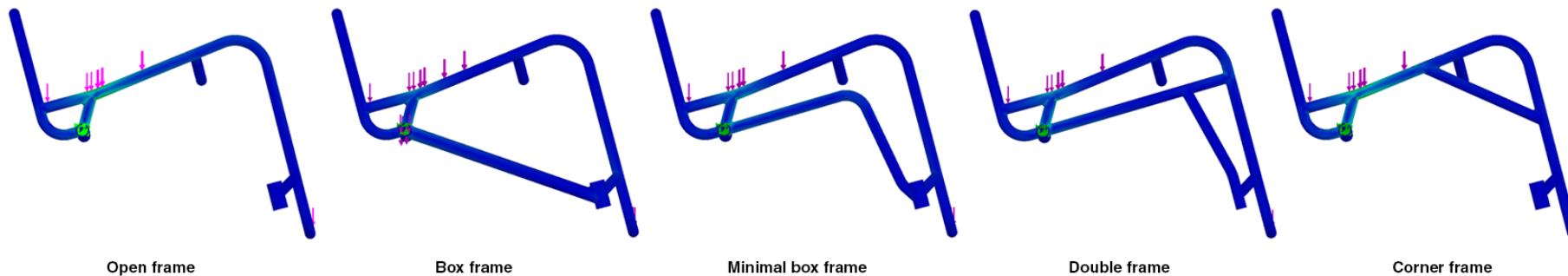


Figure 55. Simulation 2A with a distributed load of 120 kg (Fperson: 1140N (95%), Ffootrest: 60N (5%))

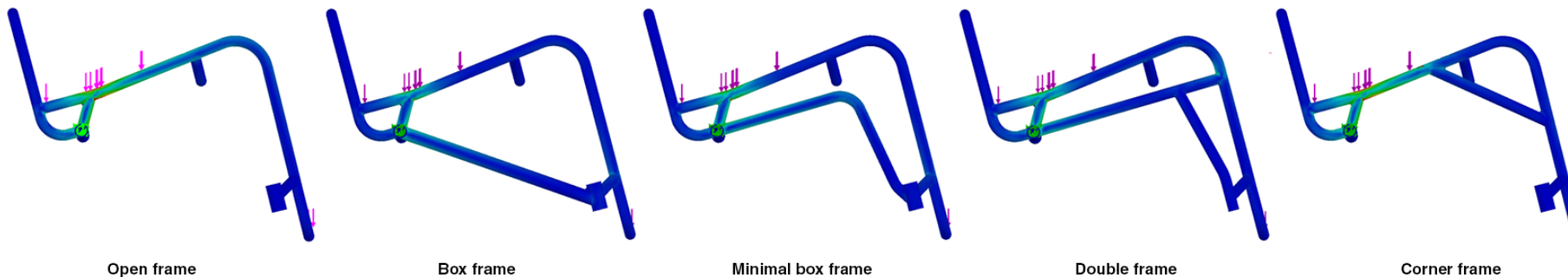


Figure 56. Simulation 2B with a distributed load of 240 kg (Fperson: 2280N (95%), Ffootrest: 120N (5%))

Analysis | Construction strength

Conclusion | Construction strength

The goal of this construction analysis was to determine if and how the strength of a rigid wheelchair frame could be maintained when the frame is designed in a more minimal way. The traditional Box frame is generally regarded as more rigid and durable than the more transportable Open frame.

To learn about the construction of the Open frame and the Box frame, I simulated both frames in SolidWorks and modelled three new designs based on the Box

frame to simulate the performance of different design decisions: The Corner frame, Minimal box frame and Double frame.

The five frames were simulated in two static scenarios: sitting and performing a wheelie. The simulations show that a more structural frame construction has a significant influence on stress distribution and overall rigidity. In both scenarios, the Open- and Corner frames showed the highest peak stresses, especially

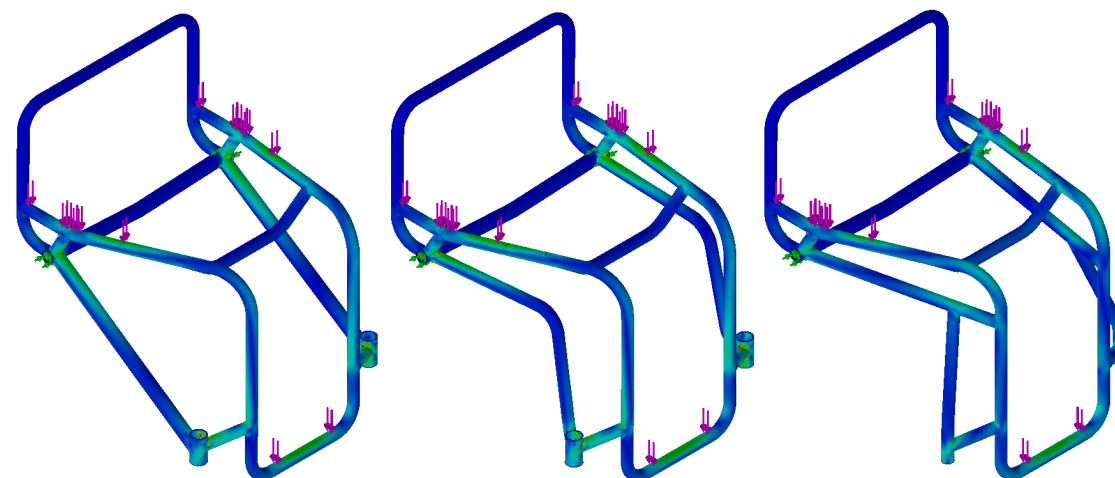


Figure 58. Simulation 1C showing the stress distribution on the Box frame (left), Minimal box frame (middle) and Double frame (right)

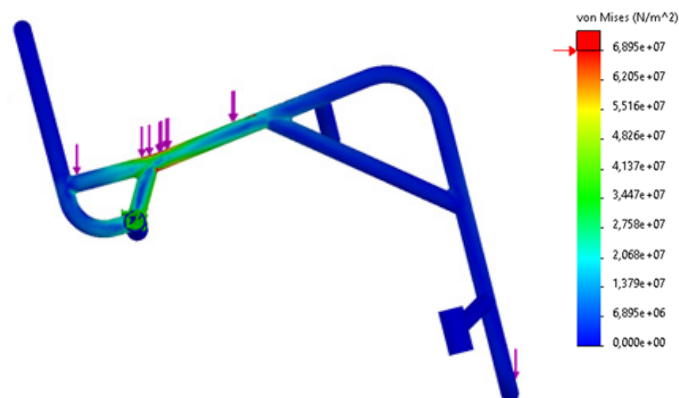


Figure 57. Corner frame in Scenario 2B showing increased stress on the rear side of the seat frame.

around the seat frame, axle junction and caster area (Figure 57).

The designs with more structural support show significantly better results (Figure 58). The Minimal box frame performs very similarly to the Box frame. In all scenarios, the Double frame performed the best.

In the Double frame design, the structure under the seat is connected to the front frame, which creates a more even distribution throughout the entire frame and thereby minimizes peak stress.

These simulations are simplified static representations of real-world use scenarios and should therefore not be

interpreted as exact predictions of durability. However, they provide valuable insight into the way stress distributions change with different design decisions and indicate that it is possible to design a frame that is similar in rigidity to the Box frame with improved transportability.

Analysis

A.10 Conclusion | Analysis

In the analysis phase, I investigated the user, the stakeholders and the various technical aspects that influence the design of an active manual wheelchair frame.

The target group was defined as SCI users with an injury between the C6 and L2 segments, where sufficient upper body strength allows for manual propulsion. The user analysis showed that independence is the most important requirement for active wheelchair users. This depends on efficient manual propulsion, good stability and the ability to independently transport the wheelchair.

The stakeholder analysis showed that there is a conflict between the interests of the user and those of the suppliers who are responsible for the provision of

the wheelchair. While many users would benefit from a custom wheelchair, suppliers often prefer standardised solutions because they are more affordable.

The wheelchair performance analysis identified four design parameters that determine the performance of an active wheelchair: seating support, rigidity, weight and size. Comparing the existing frame constructions showed that there is a trade-off between transportability and rigidity. Open frames are lightweight and transportable but lack rigidity and Box frames provide high rigidity and durability but are difficult to transport.

Observations in the wheelchair factory during the production analysis identified opportunities to optimise the bending efficiency of the frame by reducing number of complex bends to

limit deviation. This could bring down production time, which could lower the cost of the frame.

The comparison of material properties and pricing showed that aluminium AA7020 is the most suitable material to design a frame that combines a good strength-to-weight ratio with relatively affordable pricing.

The construction strength analysis indicated that there is an opportunity to combine the rigidity of the Box frame with the transportability of the Open frame and gives insights into where the stress concentrates in the frame.

In the next phase, these analyses will be translated into a set of design requirements and a design goal that form the basis for the concept ideation.

B. Synthesis

B.1 Problem definition

Active spinal cord injured wheelchair users require a wheelchair frame that supports their body during intensive ADL use. The wheelchair should be made-to-measure as well as comfortable, to allow for confidence during wheelchair skills and independent mobility as well as to prevent secondary injuries such as muscle strains and/or decubitus. Current

ADL frames force users to choose between rigidity and transportability. Box frames provide stability and durability, but they are difficult to transport independently due to their large and heavy construction (Figure 59). Open frames are much easier to transport (Figure 60), but lack rigidity, which decreases propulsion efficiency and the longevity of the frame.

This creates a conflict between ergonomic postural support and independence to go anywhere the user wants.

A second conflict is based around the provision of the wheelchair. Although custom wheelchairs offer better seating support and last longer, they are more expensive and therefore less attractive to suppliers within the current system of wheelchair provision. As a result, users have to settle for a standardised wheelchair that either limits stability or reduces independence.

Design Goal

The goal of this project is to design a custom active manual wheelchair frame for users with a spinal cord injury between the C6 and L2 segments. The frame should combine the rigidity of the Box frame with a shape that allows for improved transportability allowing the user to be more independent. The construction should be feasible to manufacture at the PEZY wheelchair factory, using the already available skills and machinery. The material of the frame needs to have a good strength-to-weight ratio. Production should be optimised to balance made-to-measure customisability with efficient tooling. This combination will allow for an affordable frame that is attractive to suppliers, and brings value to the user.



Figure 59. Transportability of the Box frame by car

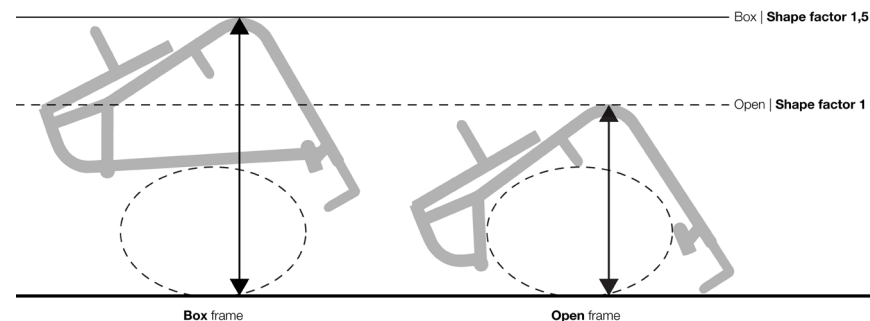


Figure 60. Manoeuvring space comparison of the Open frame and the Box frame when lifting it over the user. | Shape factor indicates the factor of increased space occupied by the frame relative to the body (ellipses)

Synthesis | Requirements

B.2 Requirements

The list of requirements is based on the research outcomes of the previous chapter, as well as additional insights from interviews with users and manufacturers. The full list of requirements has 57 requirements, [Table 8](#) shows a small selection of these.

To prioritise the criteria, I used the MoSCoW method by Dai Clegg (1994). This method distinguishes four levels:

- **(M) Must have**
The design cannot function without meeting these requirements.
- **(S) Should have**
Important but can be added/improved at a later time.
- **(C) Could have**
Desirable but not necessary for the main purpose of the design.
- **(W) Won't have**
Least critical. Priority must be re-assessed at after this project.

This selection includes only the criteria that will help me to make decisions about the synthesis process of this project. The residual criteria are related to the ones listed here and requirements that refer to small sub-components of the frame.

Ultimately, the goal is to meet all requirements that are prioritised as 'Must have'. If the time frame allows it, I hope to meet as many of the 'Should have' requirements as possible. The final design will be evaluated in a user test and validated by the manufacturer. The conclusion of this assessment will be added to [Appendix d.1](#) in written format.

Requirement	Description	MoSCoW	Additional notes	ID
Made-to-measure	Frame is custom designed and manufactured for use by a named individual occupant. (made-to-measure)	M	<i>Measurements can be customised up to 0.5cm increments within a range specified in Appendix X (C. Functionality)</i>	A1.2
Transportability	User can transport the wheelchair independently by car	M	<i>Over the driver seat of the car. Preferably without having to adjust the seat placement in the car.</i>	B1.6
	Transport weight of the frame can be lifted by the wheelchair user is below 6 kg	M	<i>Average transport weight is 4-8 kg (no wheels/cushioning)</i>	C1.1.2
Stability	Seating frame allows for proper postural support	M	<i>Ergo seat and rigid frame that minimises the transference of vibrations from the wheelchair into the body</i>	C2.2.5
Aesthetics	The design is recognisable / indistinguishable from similar products	M		A2.2
Rigidity	Wheelchair can transport a max load of 120 kg	M	<i>RGK HiLite XTR: 115 kg Woltumus W5: 150 kg Simulation was performed with vertical loads on the seat and footrest</i>	C1.1.3
Stress performance	The frame has a better or similar stress distribution as the reference Box frame design	M		D3.3
Feasibility	Tubes can be bent using in-house bending machine	M	<i>Max. tube length: 4800 mm Max. bending radius: 3 x tube Ø Diameters: 10mm, 16mm, 19mm, 22mm, 25mm, 30mm</i>	D2.1
Complexity	The frame can be manufactured faster than the current frame types	M	<i>Time to assemble (build) the wheelchair below 5.5 hrs</i>	D1.3
Estimated cost	Pricing is lower than current custom wheelchair prices: below €6000	S	<i>Allows for increased interest of wheelchair suppliers; Prices range between €6000 and €8000</i>	A4.1

Table 8. Selection of the most relevant requirements in Appendix X | MoSCoW method of prioritisation. (The Moscow Method: A Comprehensive Guide To Prioritization in Project Management, 2023) | ID's of these requirements are consistent with the ID in the full list of requirements in Appendix X

Synthesis | Approach

B.3 Approach

The approach used in the synthesis phase of this project is similar to the Double Diamond method (Design Council, 2004).

The first diamond (Figure 61) starts with the design goal that followed the analysis phase. In the diverging phase, the goal is to generate a wide variety of ideas by sketching. These ideas aren't yet complete concepts, but scattered partial solutions. In the converging phase, these partial solutions and ideas are clustered into focus areas: concept directions. The datum method (Van Boeijen, 2020) is used to select the most viable direction.

The second diamond (Figure 62) is used to develop the chosen direction into a final concept. In a second round of ideation, I will diverge to develop different concepts within this direction. The final concept is chosen using SolidWorks simulations and weighted objectives.

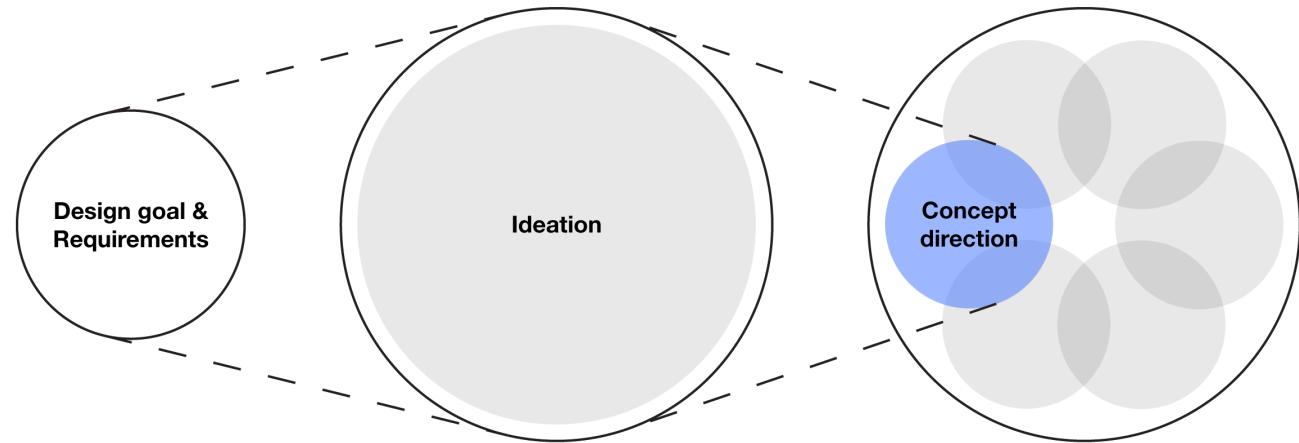


Figure 61. The first diamond

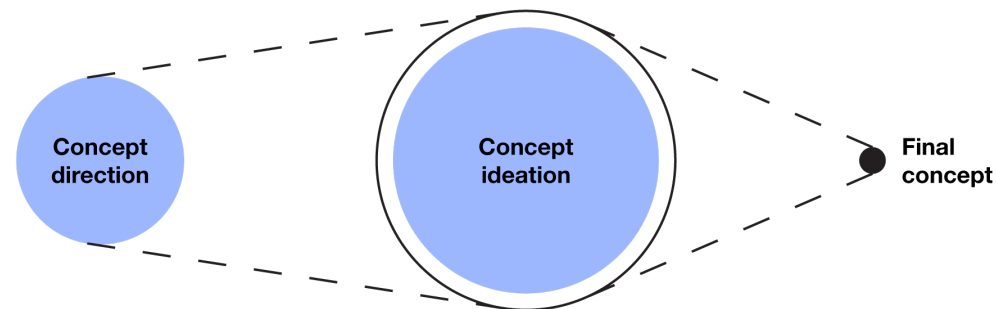
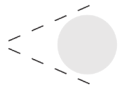


Figure 62. The second diamond

Synthesis | Ideation

B.4 Ideation



Diverging

Ideating to choose a concept direction

Using the insights I gained from the various analyses, I started sketching. The goal was to come up with three to six concept directions that each try to solve one or more of the problems of *transportability, weight, rigidity* and *durability*. I tried to also include the insights about manufacturability by sketching frames that require less material or that could potentially be manufactured more efficiently.

During the process of sketching, I asked myself questions to start my ideation flow (Figure 63). Examples of these types of questions are:

"How can I design a frame that is lightweight?"

"How can I design a frame that is stronger than the Box frame?"

"How can I design a frame with as little tubes as possible?"

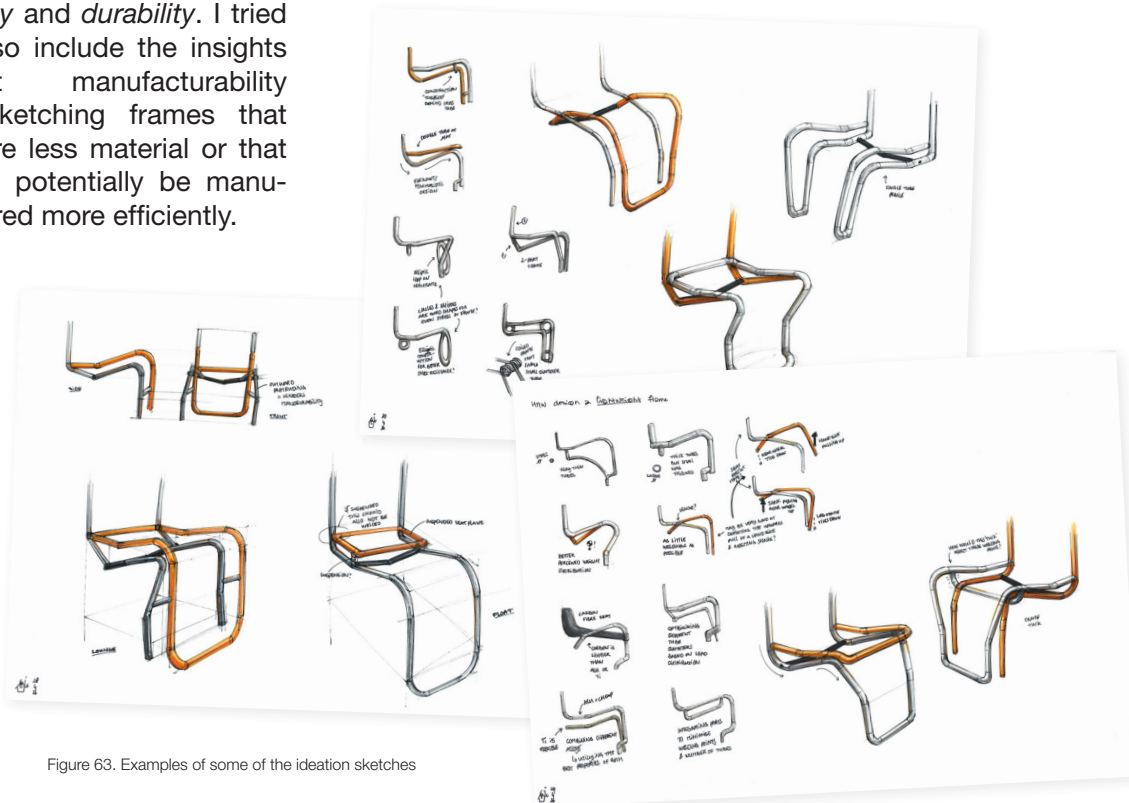


Figure 63. Examples of some of the ideation sketches



B.4.1 Concept Directions

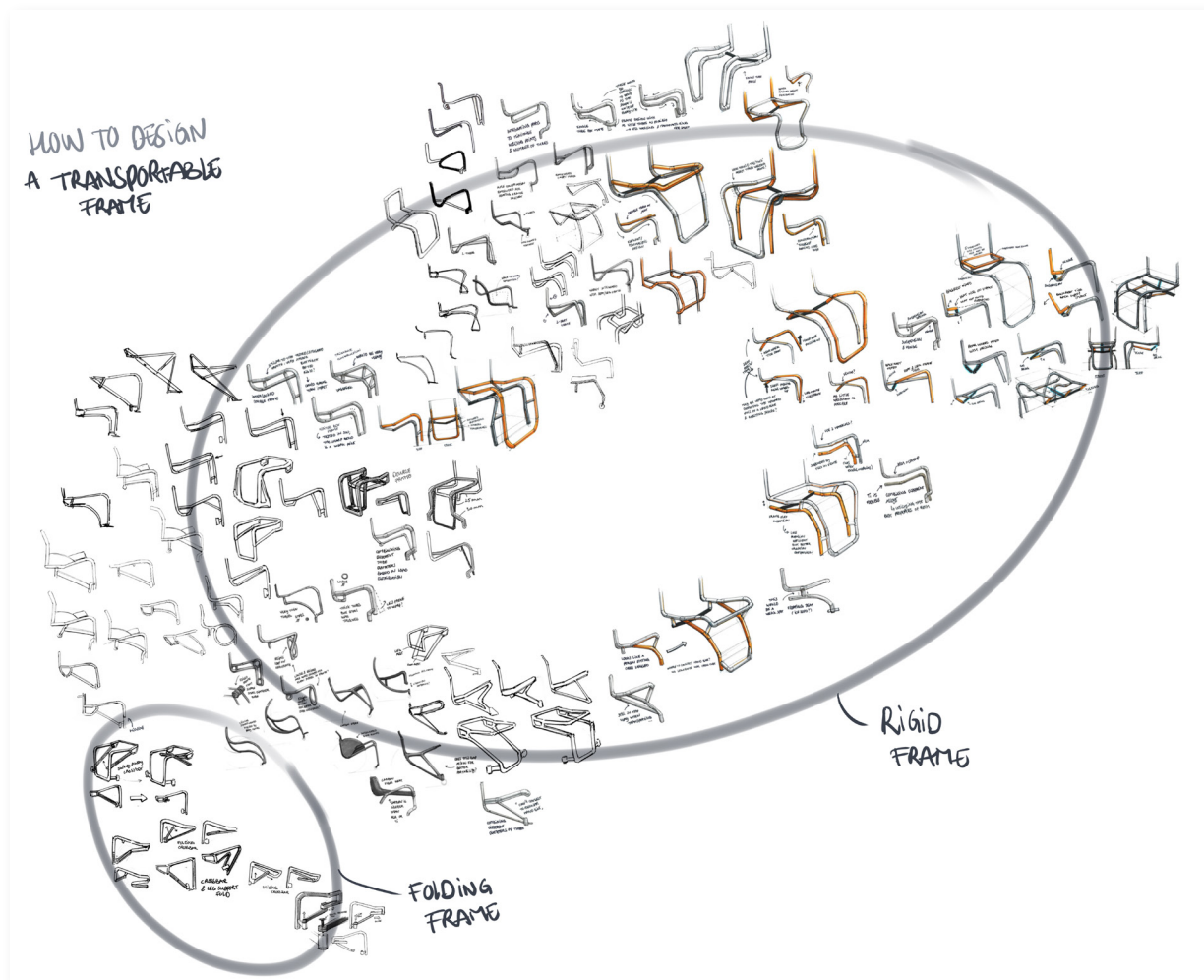


Figure 64. Clustering 1 | Rigid and folding frame sketches



Figure 65. Ideation flow with 4 areas of interest within the cluster of rigid frames

Digitally, I brought all of my sketches into a single file. I clustered the sketches in two ways with the goal to distinguish at least three concept directions.

The first clustering (Figure 64) is by frame type: rigid frames which are welded into a fixed position and folding frames, which can be compacted for improved transportability. The *Folding frame* is the first concept direction.

Using this cluster of rigid frames, I visualised my ideation 'flow' (Figure 65). Within this flow I identified four areas of interest:

- Minimal frame (shape)
- Simplification (manufacturability)
- Weight (transportability)
- Durability (shock absorption)

Synthesis | Ideation

Within the ideation flow streams, I did a second level of clustering (Figure 66). I identified five other concept directions:

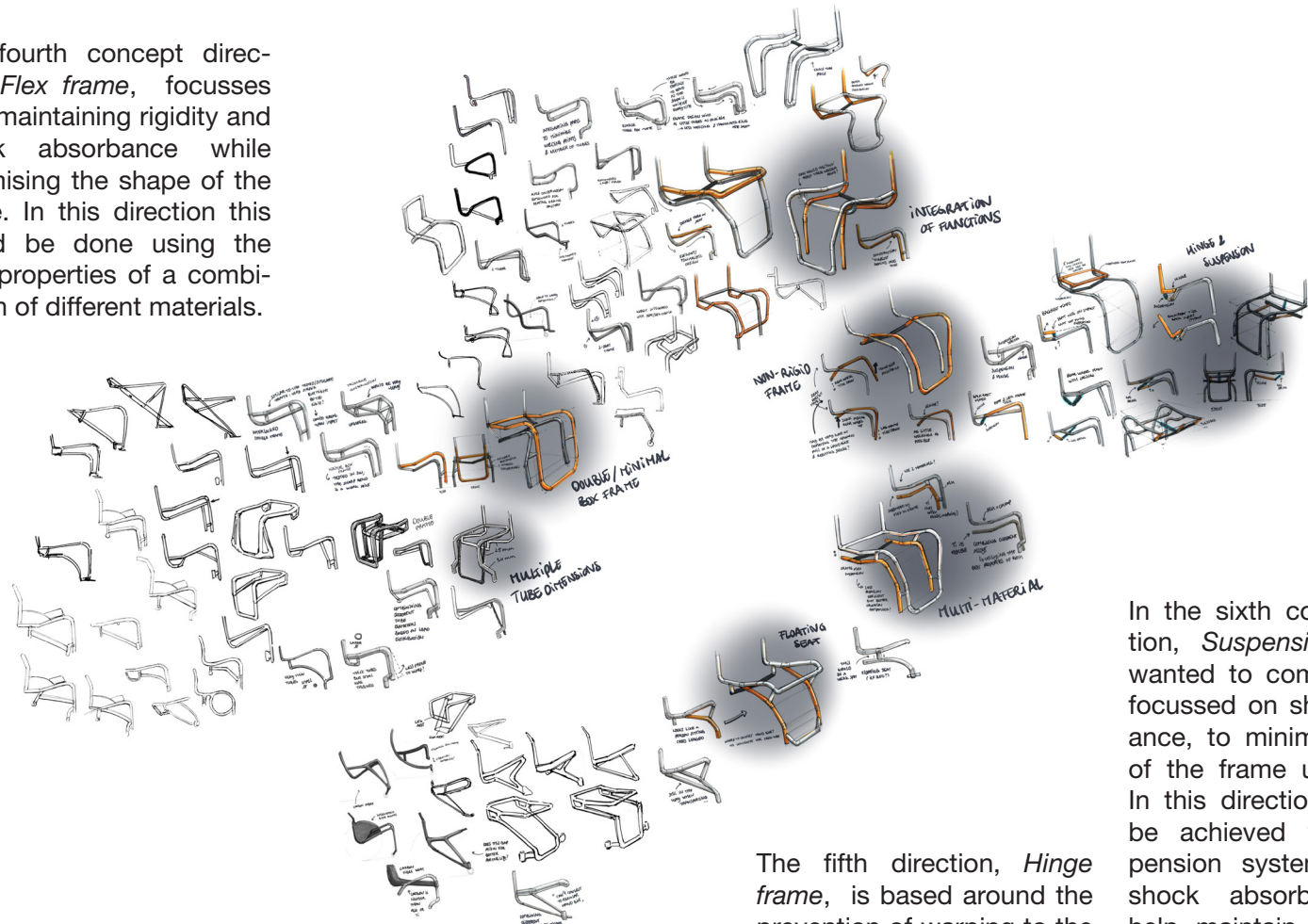
The second direction is a *Minimal frame*, which is a combination of the ideas in the upper half of the figure.

The main focus of this direction is minimisation of the shape to increase transportability. Ways to achieve this could include the use of multiple tube dimensions to save weight and integration of functions to save space and simplify the frame for manufacturing at the same time.

The other directions are more conceptual and each focus on a specific area of improvement, while also improving the transportability of the frame in terms of shape.

The third direction is a *Float frame*, which focusses on weight (material) reduction.

The fourth concept direction, *Flex frame*, focusses on maintaining rigidity and shock absorbance while minimising the shape of the frame. In this direction this would be done using the best properties of a combination of different materials.



The fifth direction, *Hinge frame*, is based around the prevention of warping to the frame by designing a range of motion in to the frame itself using a hinge system.

In the sixth concept direction, *Suspension frame*, I wanted to compare is also focussed on shock absorbance, to minimise cracking of the frame upon impact. In this direction this would be achieved with a suspension system. Improved shock absorbance could help maintain the required strength in a more minimal frame design, without adding rigidifying tubes.

Figure 66. Clustering 2 | Ideation flow clustered into different concept directions

Synthesis | Ideation

Direction 1 | **Folding frame**

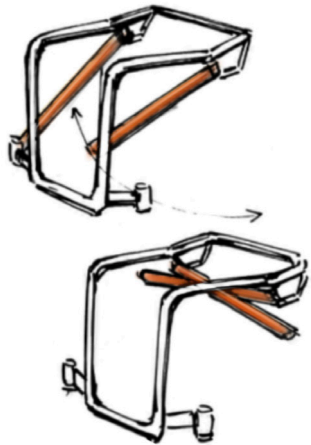


Figure 69. Folding frame

Folding frame

Folding or compactible components allow for better transportability. Folding can be realised with hinges or with parts that can be removed in order for the frame to be compacted.

Threats / unknowns

- How to maintain rigidity?
- What if components are not placed/folded the right way?
- How to prevent parts from loosening?

Direction 2 | **Minimal frame**

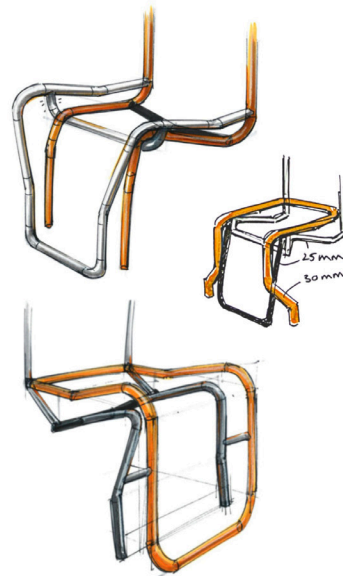


Figure 67. Minimal frame

Minimal frame

More transportable shape that leaves empty space to be lifted over the driver seat. Potentially, weight could be minimised by combining different tube diameters.

Integrating different components could allow for more efficient manufacturing. (less tube bending complexity)

Threats / unknowns

- Rigidity must remain similar to the Box frame



Figure 70. Sketch models 'Minimal Box frame' | Metal wire and tape



Figure 68. Sketch model 'Minimal Box frame' | Paper straw, wooden skewers and Vivak

Direction 3 | **Float frame**



Figure 71. Float frame

Figure 72. Sketch model 'float frame' | Paper straw, wooden skewers and Vivak

Float frame

Unique and lightweight design with floating seat frame. More transportable shape that leaves empty space to be lifted over the driver seat.

Threats / unknowns

- Floating seat may compromise stability
- How will this design deflect shocks?

Synthesis | Ideation

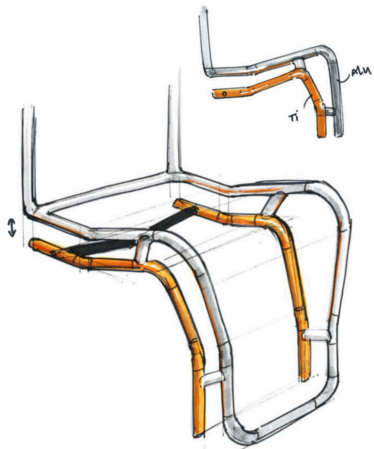
Direction 4 | **Flex frame**

Figure 74. Flex frame

Flex frame

Using the elastic properties of titanium to dampen vibrations but constructing the main body of the frame from aluminium to save on cost.

Threats / unknowns

- Can these materials be welded together?

Direction 5 | **Hinge frame**

Figure 75. Hinge frame

Hinge frame

Frame made out of two parts connected with a hinge. This construction allows for built in movement of the frame, rather than stretching/bending the frame when the load surpasses the yield strength of the material.

Threats / unknowns

- How to maintain rigidity?
- May compromise the stability of the user
- Requires additional components to 'anchor' the natural position.



Figure 76. Sketch model 'hinge frame' | Paper straw, wooden skewers and Vivak.

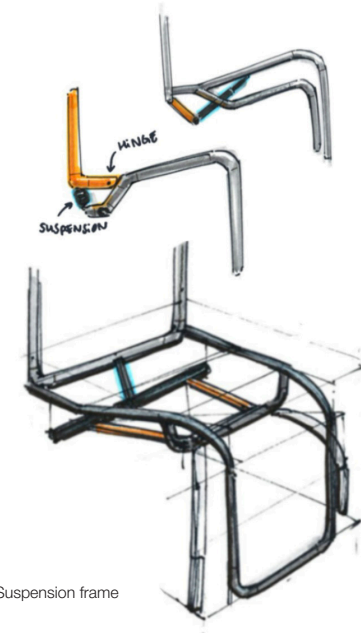
Direction 6 | **Suspension frame**

Figure 73. Suspension frame

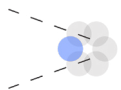
Suspension frame

Improved shock absorption which could elongate the lifespan of the frame.

Threats / unknowns

- A suspension system adds weight
- Could be expensive
- Does everyone require such a system?

B.4.2 Selection | Direction



Converging

Selecting the most viable concept direction

To decide which of these concept directions is the most likely to meet my list of requirements, I used the shortened list of requirements (Table 8, page 49).

The concept directions that will be compared are still in a very conceptual phase. Therefore, I chose to simplify the descriptions of these requirements to the

list of criteria (Table 9). To assess the criteria, I used the datum method (Van Boeijen et al., 2020). Each direction is compared to the Box frame on whether

it would perform similar (S), better (+) or worse (-). To calculate the final scores, I multiplied the sum of each value by 0, 1 or -1 points.

The assessment of the criteria was based on assumptions regarding everything that I learned in the analysis phase of this project and the ideation sketches.

Criterion	Description	Box	Folding	Minimal	Float	Flex	Hinge	Suspension	
Made-to-measure	Design allows for custom measurements		-	S	-	S	-	-	
Transportability	The shape allows for easier transport by car		+	+	+	+	+	+	
Stability	Stability and ergonomic support that can be expected from design		-	S	-	-	-	-	
Aesthetics	How attractive, novel and/or recognisable is the design		+	S	+	+	+	+	
Rigidity	How rigid is the design / Will it be able to transport 120 kg?		-	S	-	-	-	-	
Stress performance	How well does the design resist loads and shocks on the frame		-	S	-	+	+	+	
Feasibility	Can it be manufactured using in-house skills/tools		-	S	S	-	-	-	
Complexity	How difficult/time consuming is it to manufacture		-	+	+	-	-	-	
Estimated cost	Rough estimate based on material amount and type		-	S	+	-	-	-	
		0 pt	S	0	7	1	1	0	0
		+ 1 pts	+	2	2	4	3	3	3
		- 1 pts	-	7	0	4	5	6	6
		Score	-5	3	0	-2	-3	-3	

Table 9. Datum method | (Van Boeijen et al., 2020)

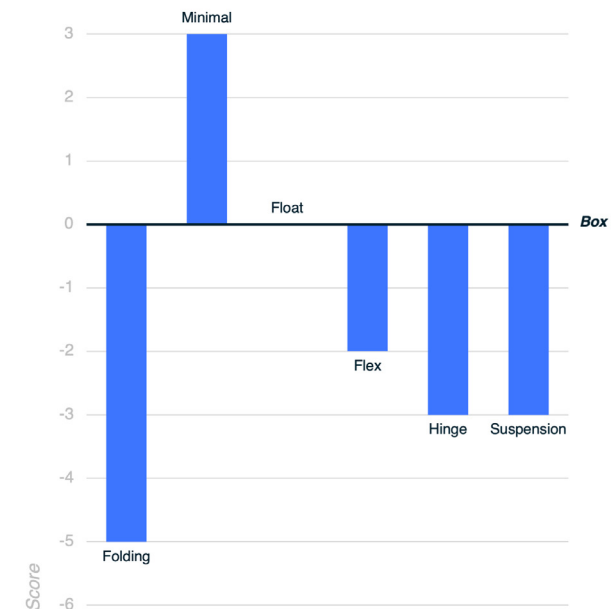


Figure 77. Graph of the final scores | The Box frame model was used as the datum and therefore visualised as the X-axis

Synthesis | Conceptualisation

In this process, I sketched incremental changes to concepts, for example in the concept direction on the right of [Figure 80](#) where I explored a connection between the front of the frame and the cross tube, but also stand-alone concepts that have less relation to the others ([Figure 81](#)).

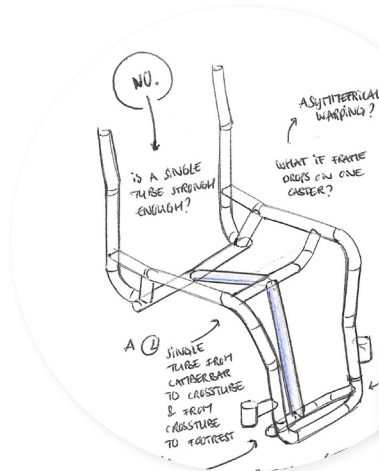


Figure 80. Incremental changes between different variations: some parts stay the same, others are different.

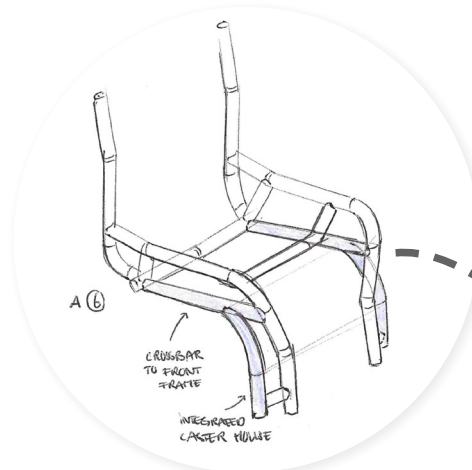


Figure 81. Example of a sketched concept variation where the rear axle is connected to the front of the frame

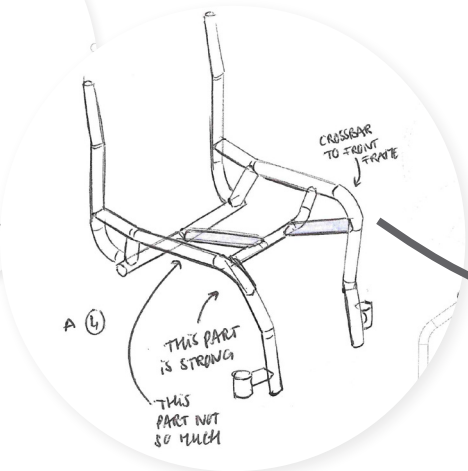


Figure 82. SolidWorks model copied from the sketch in Figure 78

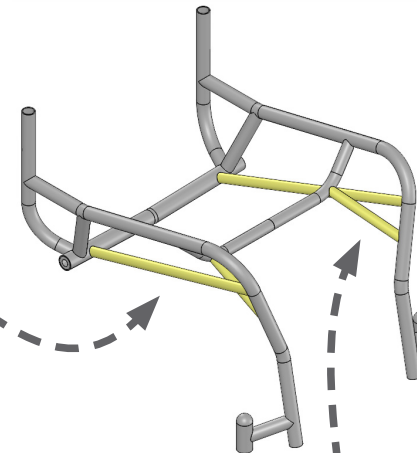
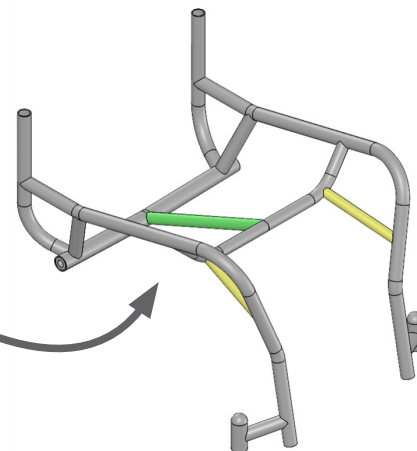


Figure 83. SolidWorks model derived from the sketch in Figure 79 with influences of the model in Figure 80



Once I had drawn most of the variations I could think of, I translated the sketches into SolidWorks ([Figure 82](#)). In SolidWorks, I ran stress simulations on the frame to see which changes had the most impact on the strength-to-weight ratio of the frame.

To find the most ideal construction, I combined features from different sketches and later also from different SolidWorks models ([Figure 83](#)). Aside from the overall shape of the construction, I also tested some concepts with different combinations of tube diameters to find the best balance.

[Figure 84](#) on the next page, shows the evolution of the different iterations and how they relate to one another. In total, I designed 21 different concept variations.

Synthesis | Conceptualisation

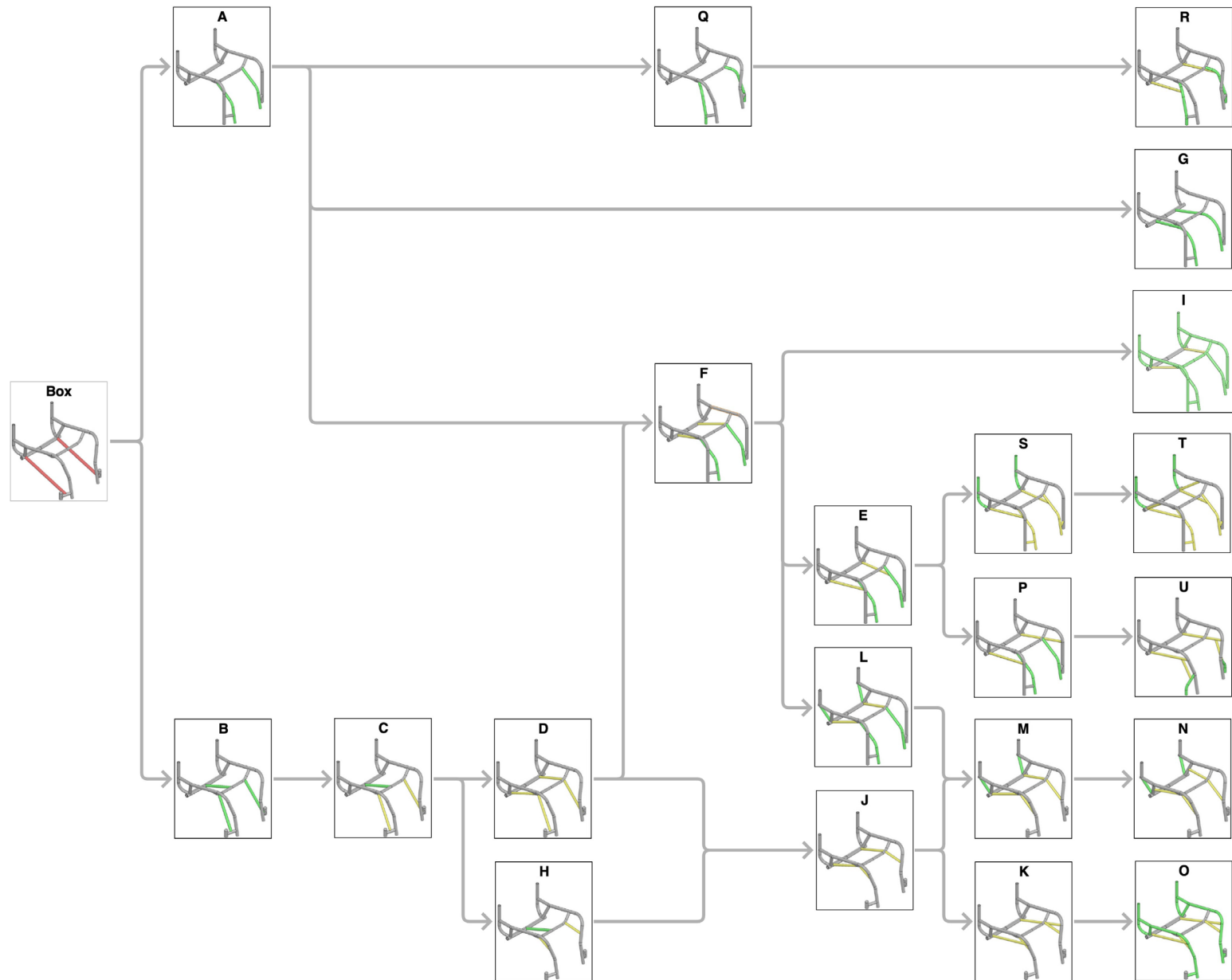
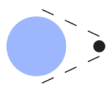


Figure 84. Evolution of the 21 different concept iterations

B.5.2 Selection | Concept



Converging
Selecting the final concept

To select the most promising concepts, I started by only comparing the weight and stress performance of the 21 different variations. These two criteria show the balance between transportability and the strength of the frame.

The concepts that performed the best in this comparison will be rated using a more in depth list of criteria.

B.5.2.1 Strength-to-weight ratio

The 21 concept variations were compared to the Box frame (Figure 85) based on:

1. **Weight reduction**
Relative to the classic Box frame design
2. **Stress performance**
Stress distribution in the model

In all of the models, The upper part of the backrest and the footrest were removed, for these are the same for all concepts. The models were all simulated with the same load*, placed only on the seat.

To compare the stress performances of each concept, I scored the stress distribution on a scale from 0 to 4. In this scale, a high rating means that there is a good

distribution where the forces are evenly spread along the tubes. To better assess the stress distribution, I also looked at the peak stress graph of each concept. An example of this is shown in Figures 86 and Figure 87.

Appendix b.1 shows the stress performances of all of the 21 concept variations.

The graph in Figure 89, on the next page, shows the results of the stress simulations plotted against the weight reduction. Based on these results, I will compare the six concepts that performed the best: K, O, F, I, L and S. Table 7 shows the weight of these concepts compared to the Box frame.

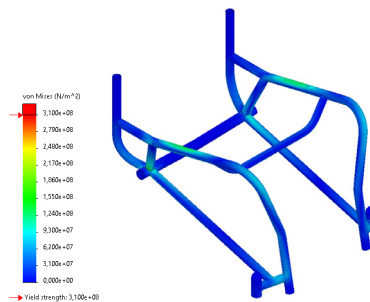


Figure 85. Stress distribution in the reference Box frame

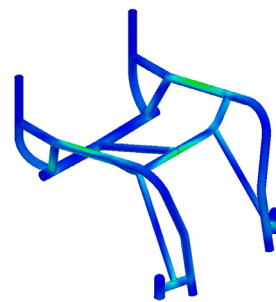


Figure 86. Stress distribution in concept C using the scale in Figure 83

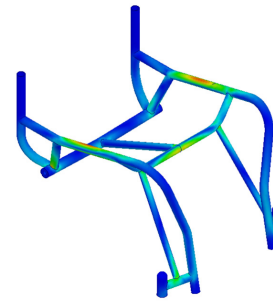


Figure 87. Peak stress in concept C showing poor distribution (red areas) | The scale in figure 83 is not applicable here)

	Mass (g)	Weight reduction (g)	Weight reduction (%)
Box	2157		
K	2046	-111	5%
O	1989	-168	3%
F	2150	-7	-8%
I	2001	-156	7%
L	2110	-47	-5%
S	2097	-60	1%

Table 10. Mass of the 6 best performing designs compared to the Box frame

* 8 times the maximum load of 120kg. This was the highest load that didn't surpass the yield strength in the Open frame model. I used the highest load to visualise more extreme results which made it easier to rate the performance of the concepts.

Synthesis | Conceptualisation

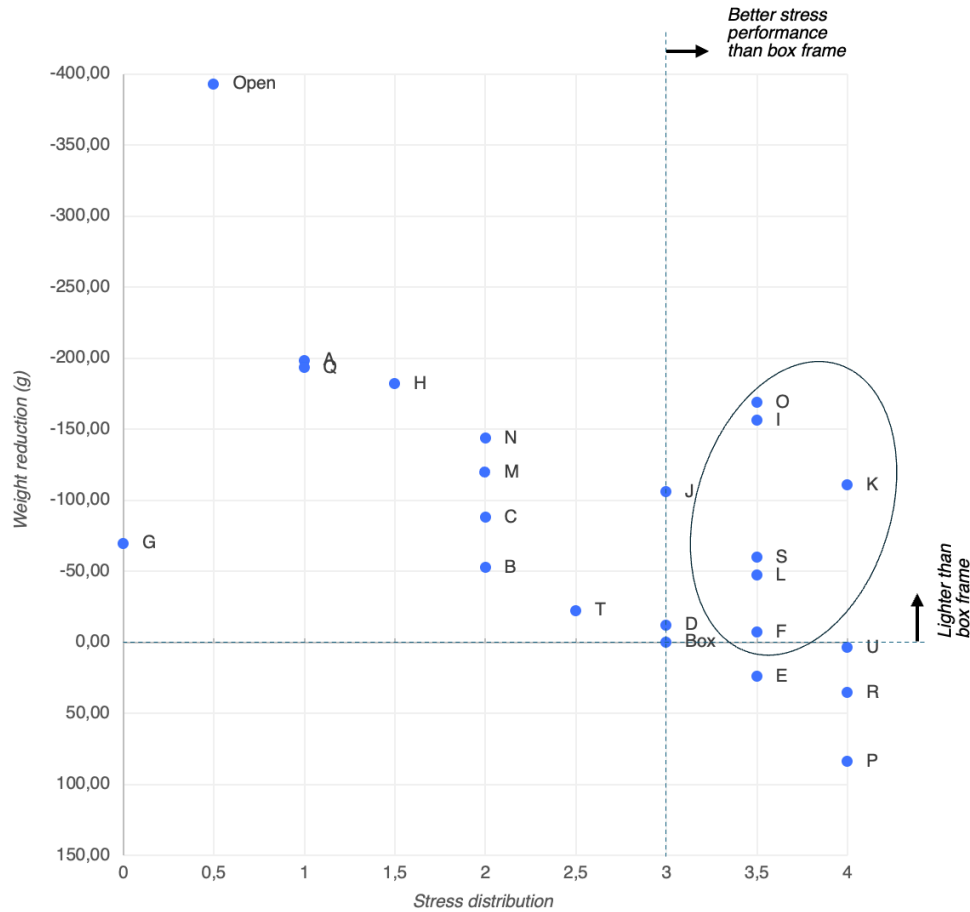


Figure 88. Results of the simulations and weight evaluations for each concept.

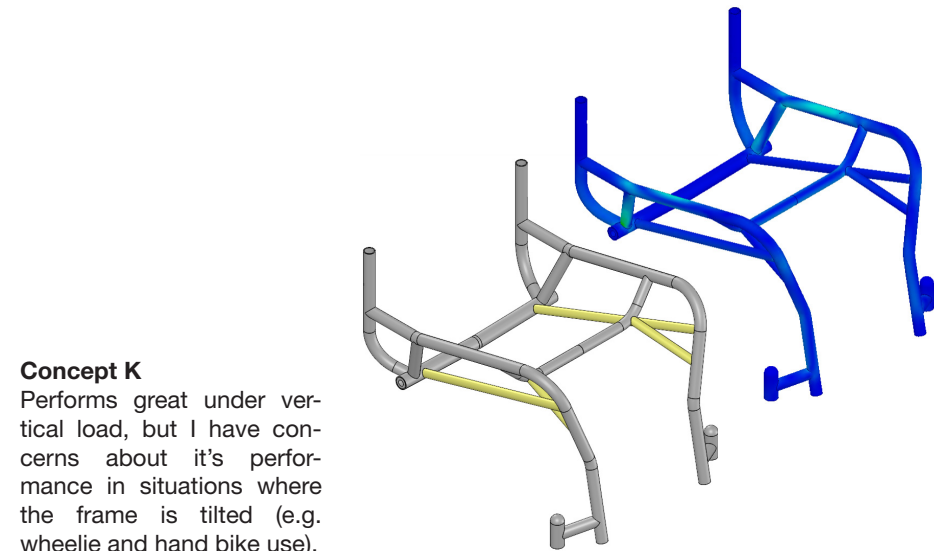


Figure 89. Concept K

Concept K
 Performs great under vertical load, but I have concerns about its performance in situations where the frame is tilted (e.g. wheelie and hand bike use).

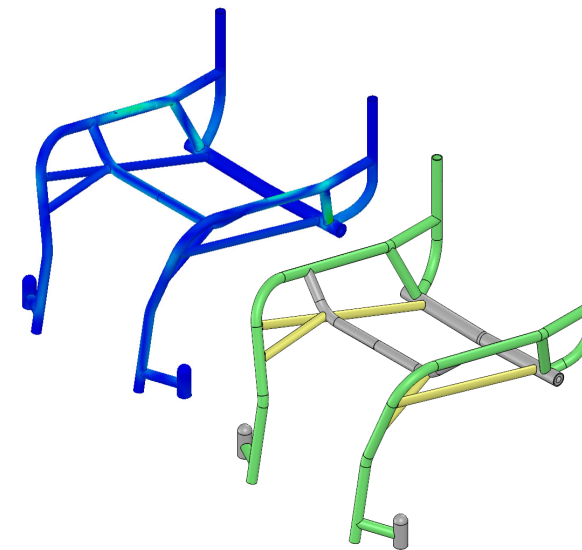


Figure 90. Concept O

Concept O
 Similar design as Concept K, but the thinner tubing of the main frame saves weight. My concerns about the performance of this concept during wheelies and hand bike use remain. The shape of both concept K and O would allow for the most improved transportation experience.

Synthesis | Conceptualisation

Concept F

This concept uses the cross tube under the seat as part of the rigidifying structure. Two additional tubes are used to connect the cross tube to the camber bar. None of the tubes are bent in three directions, making it less prone to bending deviations. The frame is mostly constructed with 25mm tubes which make it rigid, but also heavy.

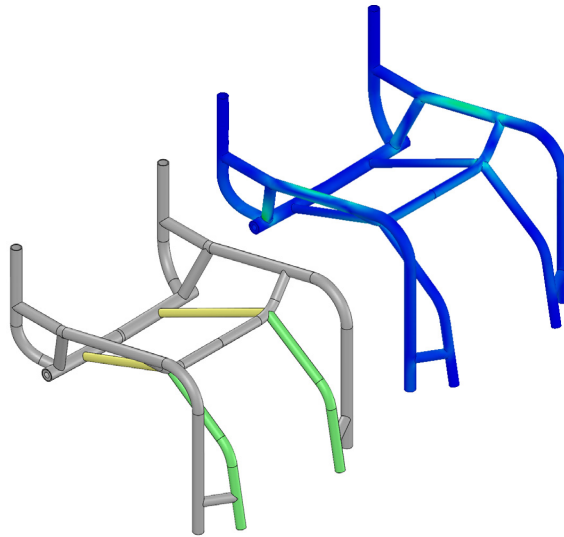


Figure 91. Concept F

Concept L

The backrest of concept L is connected to the camber bar using straight tubes. Although this would limit the bending time, it adds time for cutting & welding, so a reduction in production time wouldn't be certain.

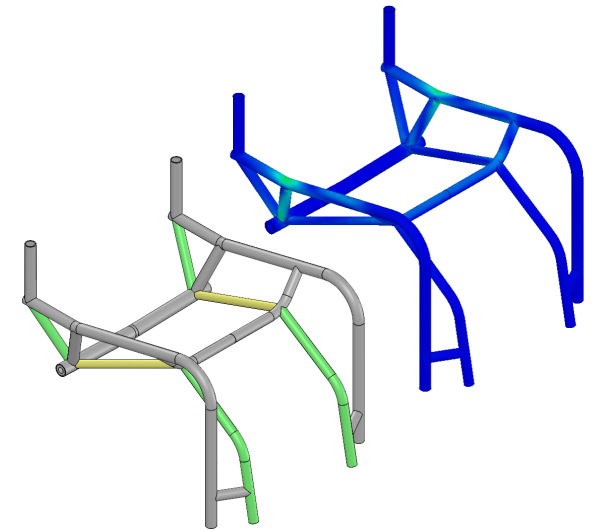


Figure 93. Concept L

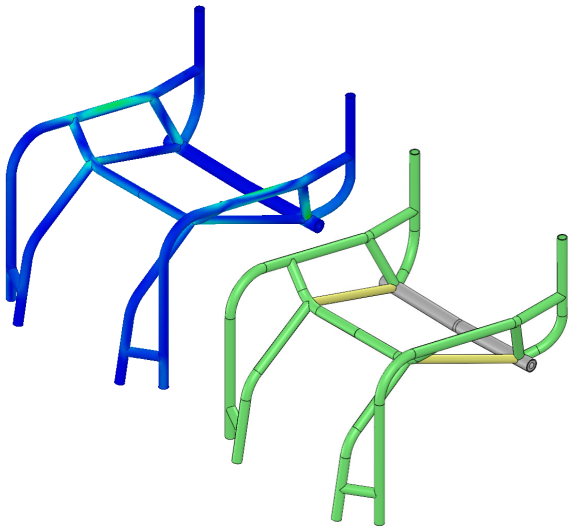


Figure 92. Concept I

Concept I

The frame is constructed nearly the same as concept F, but uses 22mm tubes for the seating, casters and backrest. Due to the slim tubes, this design is much lighter than concept F. Additionally, this variation may be easier to customise for made-to-measure production as the tubes under the seat connect to the junction where the backrest and seat connector tube already connect to the camber bar.

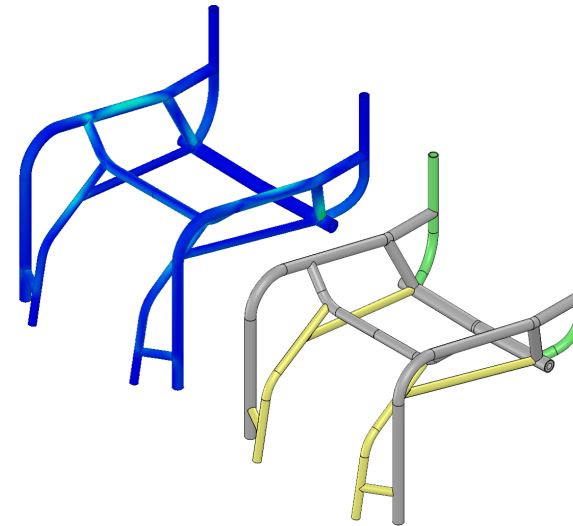


Figure 94. Concept S

Concept S

This concept features a 19mm front frame tubes. To maintain a rigid structure, the seat frame is constructed from 25mm tube. I am uncertain whether it is feasible to fit a footrest into the 19mm front frame tube as this would require very thin tubing.

B.5.2.2 Weighted objectives

To rate the final selection of concepts, I revised my set of criteria to allow for a more objective rating (Table 11). In this rating, I left out the criteria for made-to-measure, stability and rigidity. Because these concept variations were all designed with the dimensions of the Box frame, they will ideally all be customisable. To assess this more objectively, the final design will be evaluated with the wheelchair factory.

To evaluate the six concepts consistently, I composed a scoring rubric (Table 12). Each criterium is assigned a weight, based on the priority it has to the design and how well I am able to assess the concepts. I based the rating for the criteria within *complexity (bending diameters, 2D bends, 3D bends, cuts/welds)* on the relative performance among the concepts. (Appendix b.2)

Stability and rigidity are difficult to quantify based on a SolidWorks model. To evaluate stability, testing is required where the user can ride in the wheelchair. To assess rigidity, the frame would have to endure a ‘double drum’ test, where the durability of the frame is tested over a prolonged period of time. In Appendix b.2, I explain my reasoning for each criterium that is used in this rating of concepts.

	Weight	Criterium	Box frame	K	O	L	—	└	o
Design 40%	0,15	Transportability	1	5	5	5	5	5	3
	0,15	Weight	1	3	5	1	5	1	3
	0,10	Aesthetics	1	3	5	5	5	1	3
Performance 20%	0,20	Stress distribution	3	5	3	3	3	3	5
	0,10	Feasibility	5	3	3	5	5	5	1
Manufacturability 40%	0,25	Complexity							
	0,05	Bending diameters	3	3	5	3	5	3	1
	0,05	2D bends	5	5	5	1	1	3	1
	0,10	3D bends	3	3	3	5	5	5	5
	0,05	Cuts / Welds	5	1	1	3	3	1	3
	0,05	Estimated cost	5	3	3	3	3	3	3
Total			2,7	3,7	3,9	3,5	4,2	3,1	3,2

Table 11. Weighted objective method

Criterion	Description	1	3	5
Transportability	The shape allows for easier transport by car	Similar to Box frame	A little better but not very convincing	Shape to Open frame
Weight	How much does the design weight (estimate)	<50 grams lighter	50-150 grams lighter	>150 grams lighter
Aesthetics	How attractive is the design	Not attractive	Boring, but not ugly	Interesting/attractive
Stress distribution	Distribution of stress throughout the frame	Stress located at welds	Some areas are affected more than others	Even distribution
Feasibility	Can it be manufactured using in-house skills/tools	Requires training and/or new machinery (high investment)	Skills/tools not yet available but compatible with existing machines (small investment)	All skills/tools available. (no investment)
Complexity	How difficult/time consuming is it to manufacture	More than Box frame	Similar to Box frame	Less than Box frame
Estimated cost	Rough estimate based on material amount	More than Box frame	Similar to Box frame	Less than Box frame

Table 12. Descriptions of criteria and scoring rubric for weighted objective method

Synthesis | Conceptualisation

Results

The graph in [Figure 96](#) shows that *Concept I* scores the best overall.

Concept O also performs well according to the criteria, but as stated before: I am uncertain about the performance of this design outside of the SolidWorks simulation.

Concept S performs really well in the simulations, but the thin tube at the front of the frame would require a very thin tube for the footrest, which makes it a less feasible option.

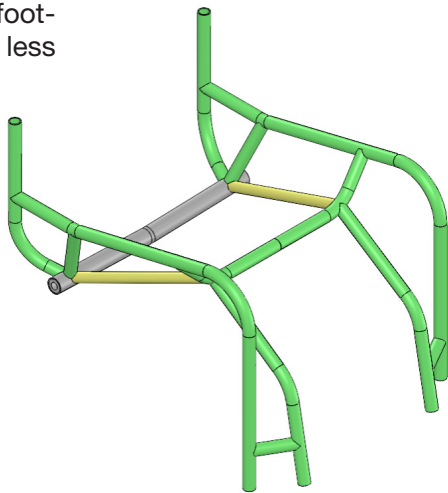


Figure 95. The winning concept: Concept I

All in all I chose to continue with *Concept I* ([Figure 95](#)), for it performs well enough to compete with the Box frame design, features the best manufacturing specifications and its design is aesthetically pleasing.

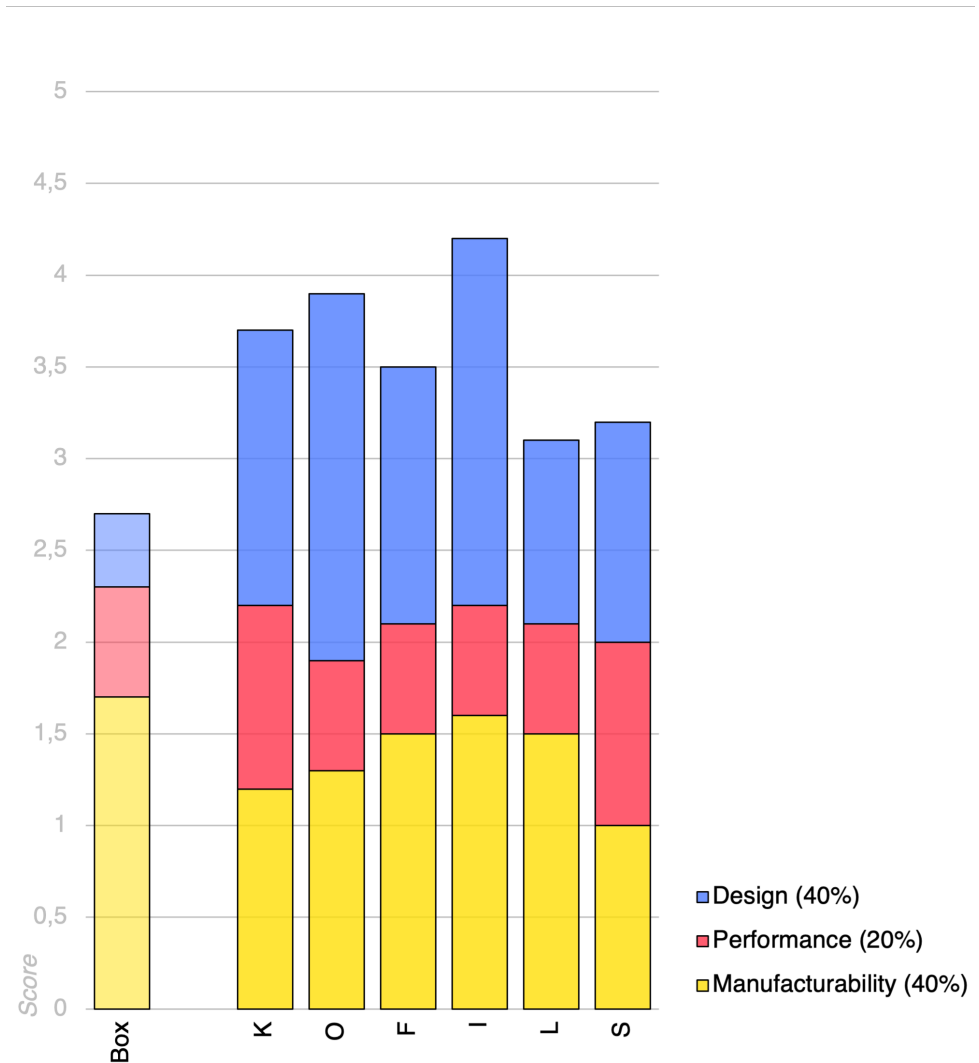


Figure 96. Results of the weighted objective rating

C. Final Design

The Cross-Over frame

- Transportable shape
- 8.5% Lighter construction
- Easier to manufacture
- Similar stress performance*
- Elegant slim tube design



* Compared to the Box frame

Final Design | Cross-Over



Figure 97. Integration of the Cross-Over frame with upholstery and wheels. The backrest is visualised with hinges, which is a desirable feature among wheelchair users who transport the wheelchair often.

Final Design | Design

C.1 Design



Figure 98. The Cross-Over frame

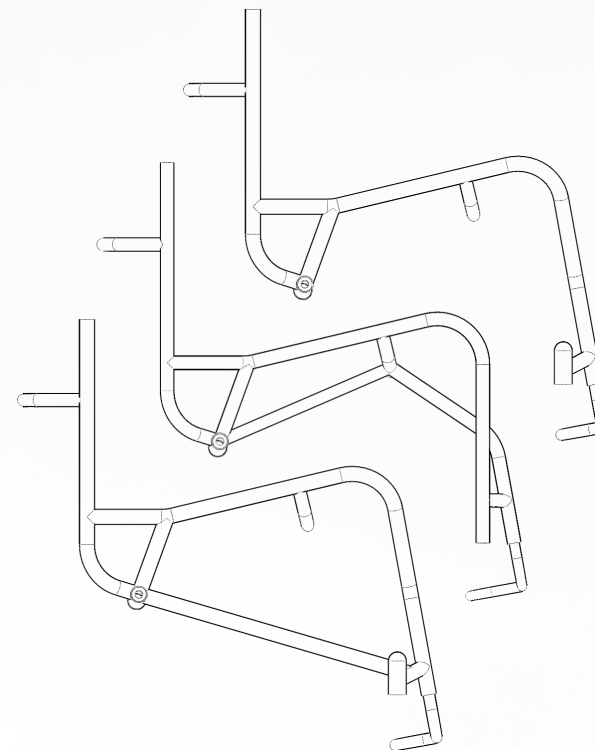


Figure 99. Side-to-side profiles of the Box frame (bottom), Open frame (top) and Cross-Over frame, displaying the increase of empty space underneath the frame.

The most visible improvement of the final design in relation to the existing frames on the market is its slim shape with a twist in the side-profile of the frame, earning it the name 'Cross-Over' frame. This design allows for a great improvement of (trans-)portability (Figure 99) as well as improved production efficiency compared to the Box frame.

To realise this design, without compromising the rigidity of the frame, I used the already existing cross tube under the seat, as an integral part of the construction.

Rather than constructing the front frame as a continuous shape that flows out of the seat, this design features two separate tubes that connect to the cross tube.

Final Design | Design

Additionally, I added two thin tubes that connect the cross tube to the camber bar (Figure 101).

Of course, the seat needs to be attached to the frame of the body. This design solves this in an elegant way, by

integrating the seat frame and caster house into one single component: the seat-to-caster tube. From the side, this creates a unique twist in the frame design, which makes it stand out instantly (Figure 100).

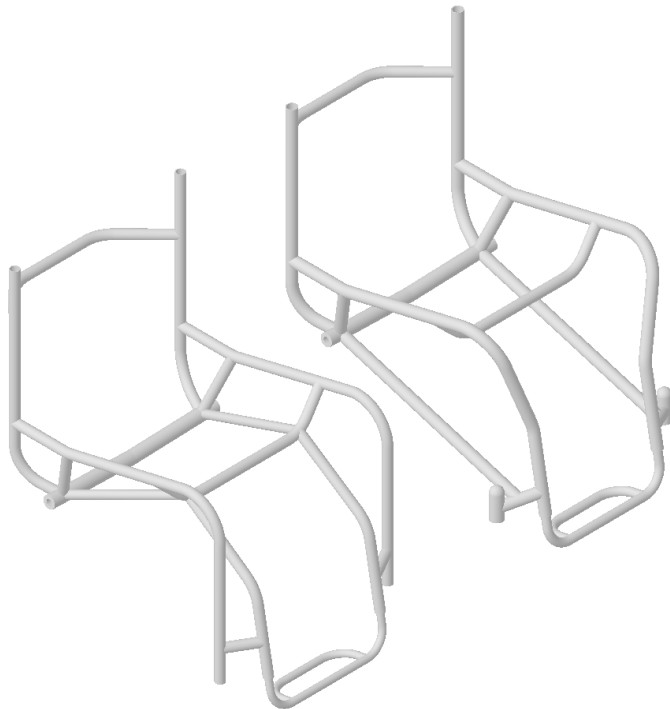


Figure 100. Side-to-side of the Cross-Over frame (left) and the Box frame (right)



Figure 101. Side profile of the Cross-Over frame design with indications of design features

Final Design | Transportability

C.2 Transportability

In [Figure 103](#), the transportability of the Cross-Over frame is compared to the Open and Box frames. The space occupied by the frame is visualised around an ellipsis that simulates the space occupied by the user. The total space of the frame around the user is indicated with a shape factor. This factor is 1 for the Open frame. The Box frame uses 1,5 times the space of the Open frame (shape factor 1,5). The Cross-Over frame has a shape factor of 1,2. This means that the frame uses significantly less space than the Box frame, but still uses more than the Open frame.

This is also visualised in [Figure 104](#), where the frame is placed in the context of a car. Ideally the driver seat doesn't have to be adjusted to lift the frame inside. With a design similar to the Box frame, this is almost always necessary because the frame occupies too much space. The empty space underneath the Cross-Over frame allows the user to rotate the frame around their body ([Figure 105](#)). This way the COG of the frame is held closer to the body, which is preferable regarding ergonomics.

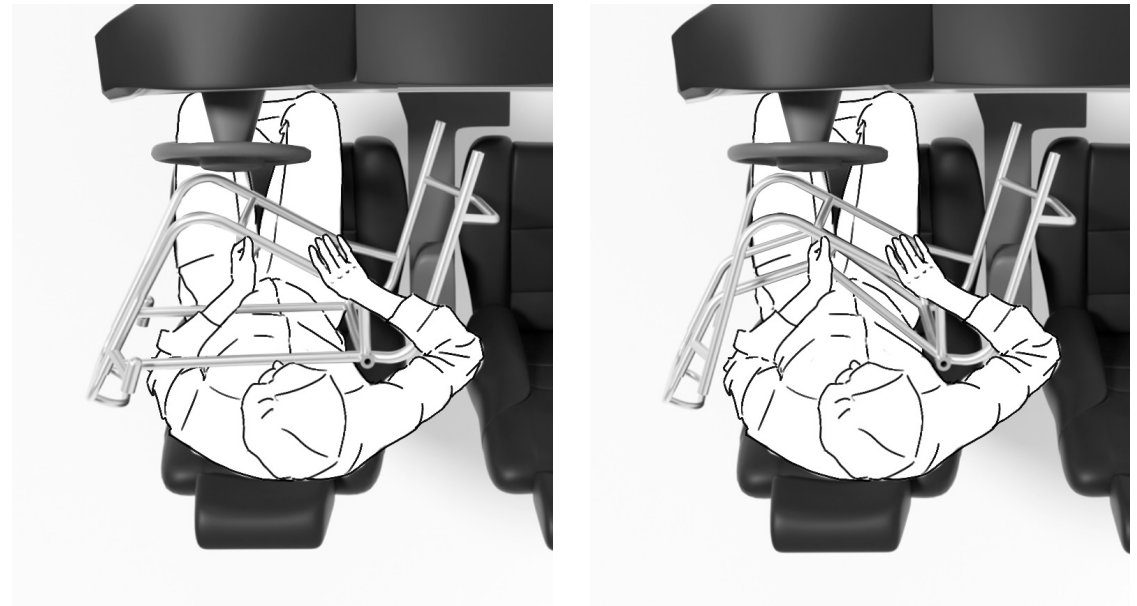


Figure 103. Occupied space of the Box frame (left) compared to the Cross-Over frame (right)

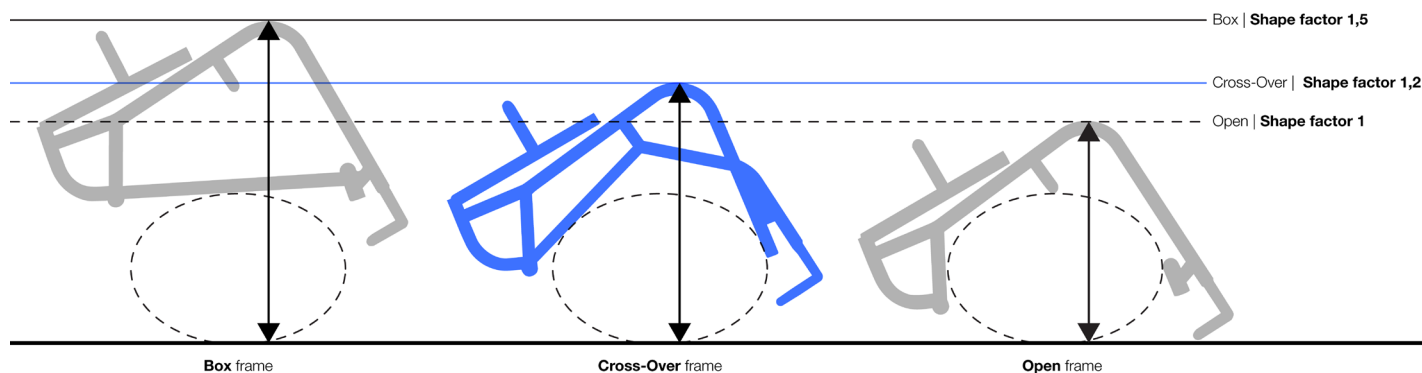


Figure 102. Manoeuvring space comparison of the Cross-Over frame compared to the Open frame and the Box frame when lifting it over the user.

Figure 104. On the right page | Lifting the Cross-Over frame (prototype) in a car.



Final Design | Transportability

Weight reduction

The new frame is not only more transportable than the Box frame due to its space efficiency, but it also weighs less. The Cross-Over frame is over 230 grams lighter than the Box frame (Table 13). This is an 8,5% reduction of the bare frame weight.

The market overview in Appendix a.3 shows that the difference between the average total weight of the wheelchair and the average transport weight of the wheelchair is 2,5 kg. This difference is calculated by removing the rear wheels and cushioning (Table 14).

In the context of the entire wheelchair (Figure 105), the relative weight reduction is smaller. The estimated transport weight (Figure 106) of the Cross-Over frame is 4,5% lower than the Box frame (Table 15).



Figure 105. The Cross-Over wheelchair (Total weight)



Figure 106. The transportable part of the Cross-Over wheelchair (Transport weight)

	Box frame	Cross-Over frame	Difference
Mass*	2720 g	2487 g	-233 g
Total length of tubes*	681 cm	635 cm	46 cm
Bending diameters	4	3	-1
2D bent tubes	7	11	4
3D bent tubes	2	0	-2
Straight tubes	6	6	0
Cuts/welds	22	22	0

Table 13. Technical specifications of the Cross-Over frame compared to the Box frame | Values were rounded to the nearest integers. * Calculated using the same dimensions and material specifications

	Combined weight	Weight	Component	Additional notes
Transport weight (without frame)	2,5 kg	± 1 kg	Casters	Includes the caster fork, bearing and fasteners
		± 0,5 kg	Upholstery	Fabric that stays fixed to the frame
		± 1 kg	Accessories	Brakes, backrest hinges, clothing guards, fasteners etc.
Removable for transportation	2,5 kg	± 2 kg	Rear wheels	Includes axles, hand rims, tires, spokes etc.
		± 0,5 kg	Cushioning	Removable seat pad

Table 14. Transport weight estimation based on wheelchairs sold by RGK and Woltumus

	Box frame	Cross-Over frame	Difference (%)
Transport weight without the frame	2500 g	2500 g	
Mass of the frame	2720 g	2487 g	- 8,6%
Total transport weight	5220 g	4987 g	- 4,5%
Removable for transportation	2500 g	2500 g	
Total weight	7720 g	7487 g	-3,0%

Table 15. Estimated weight reduction in context of the complete wheelchair

Final Design | Manufacturability

C.3 Manufacturability

The re-envisioned design of the front frame and caster components allowed for another valuable improvement of the design: simplified shapes to bend. The new architecture of the frame features only 2D bent tubes. This means that the tubes are shaped along a single plane (Figure 107). The benefit of only using 2D bent tubes is a potential decrease of bending deviation, which saves time and thus cost.

The Cross-Over frame features $\text{Ø}22\text{mm}$ tubes in the majority of the frame construction (Figure 108).

Smaller tube diameters allowed me to create a frame that weighs less and feels more breathable compared to the robust and industrial appearance of the Box frame.

The camber bar is almost always bent at an angle of three degrees, for this is the industry standard for ADL wheelchairs. This means that this component can be produced in batches and cut to size later.

Effectively this means that the production of a custom frame only requires 2 tube diameters to be bent and therefore a single extrusion head change. Limiting the number of bending diameters saves time changing the extruder of the machine, which takes 30 minutes per change.

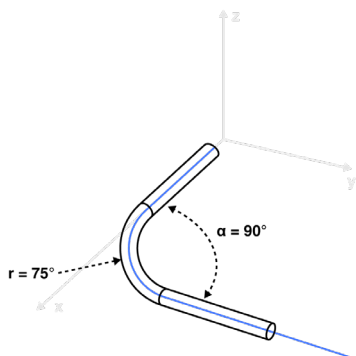


Figure 107. 2D bending angles

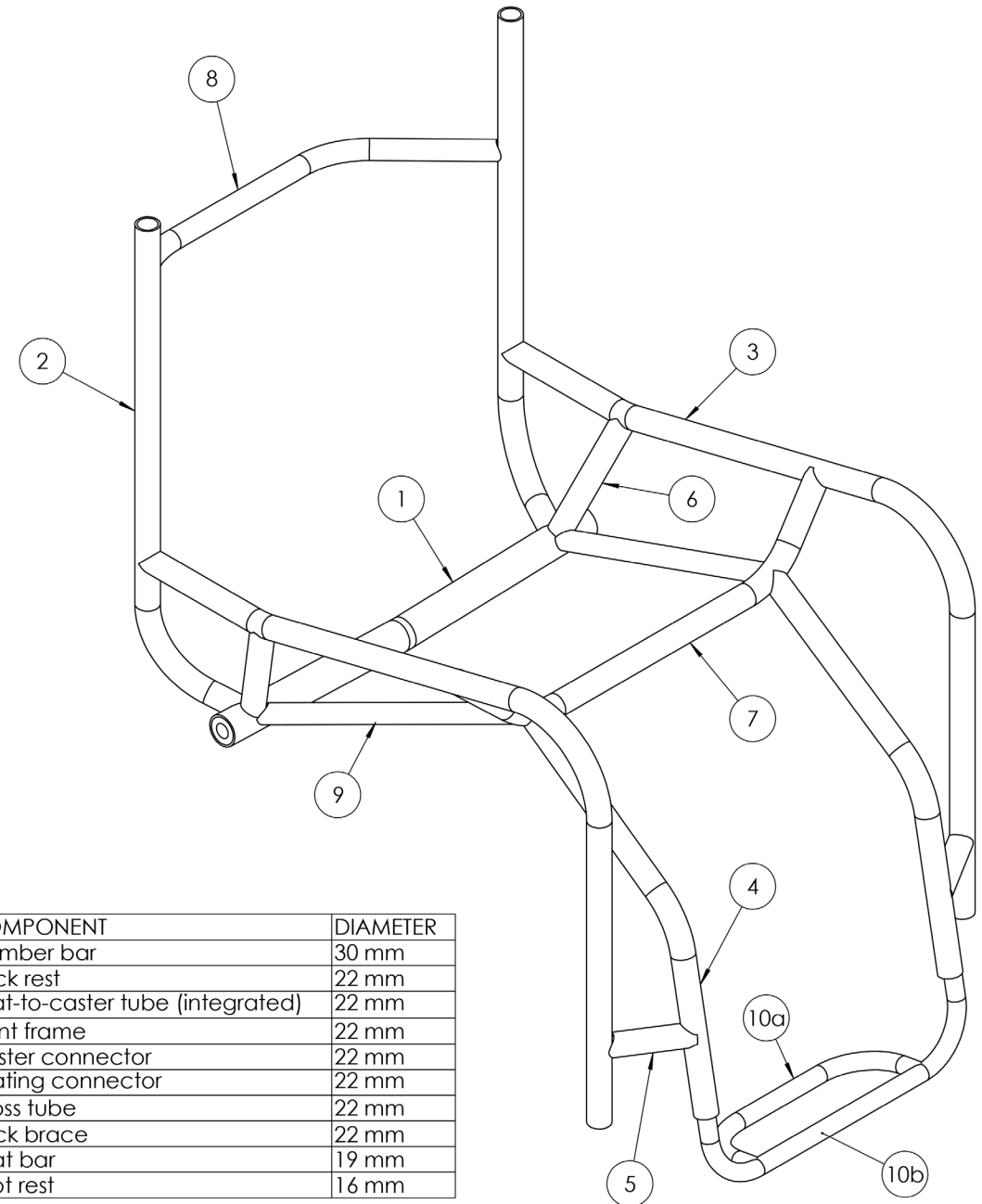


Figure 108. Indication of where components and tube diameters are placed in the Cross-Over frame

Final Design | Manufacturability

Figure 110 shows all of the components flat on a wall. The Cross-Over frame features only 3 bending diameters; one less than the Box frame design (Figure 110). The diameter of the camber bar remains unchanged from the Box frame, for a diameter of 30mm is required for compatibility with industry standard rear wheels and -axle components.

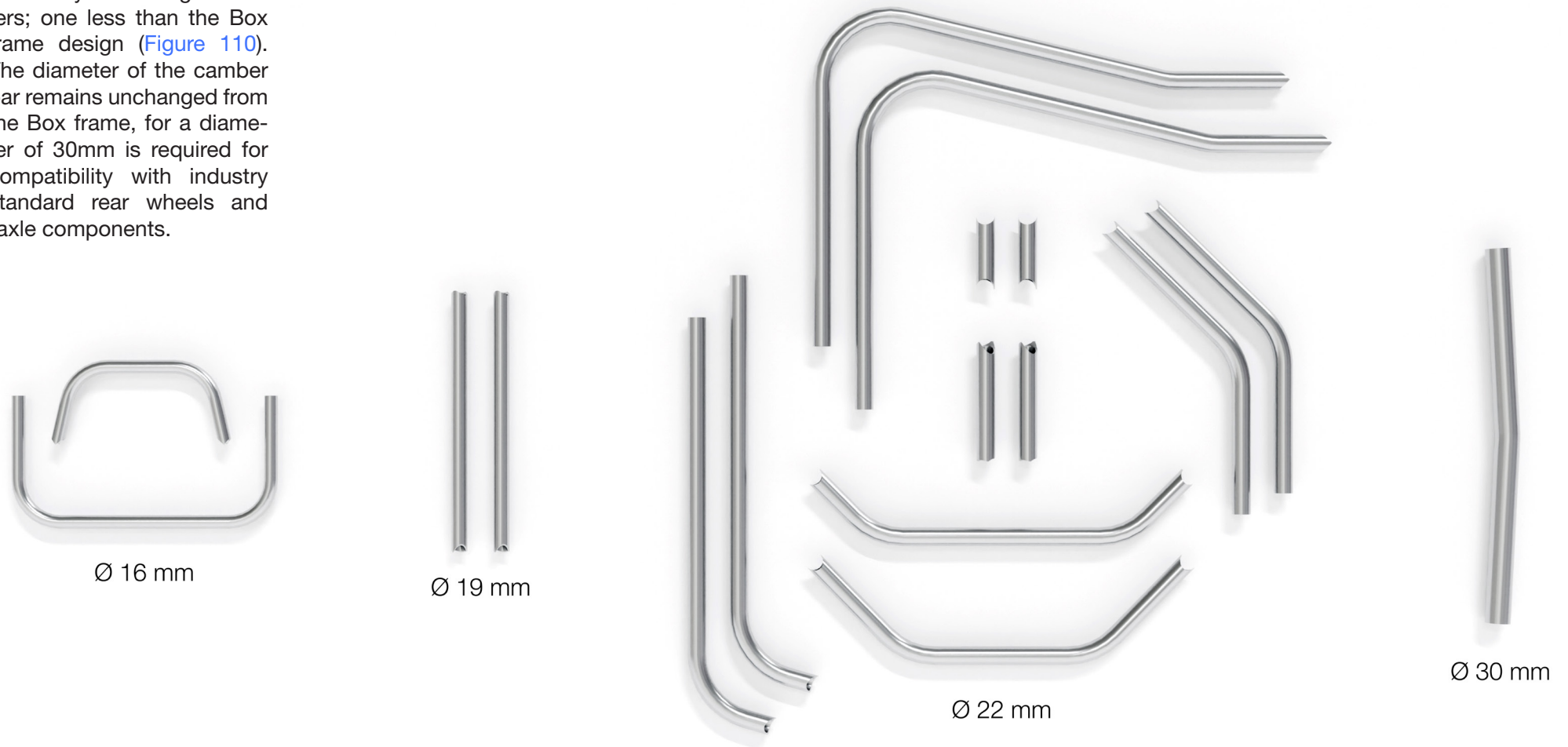
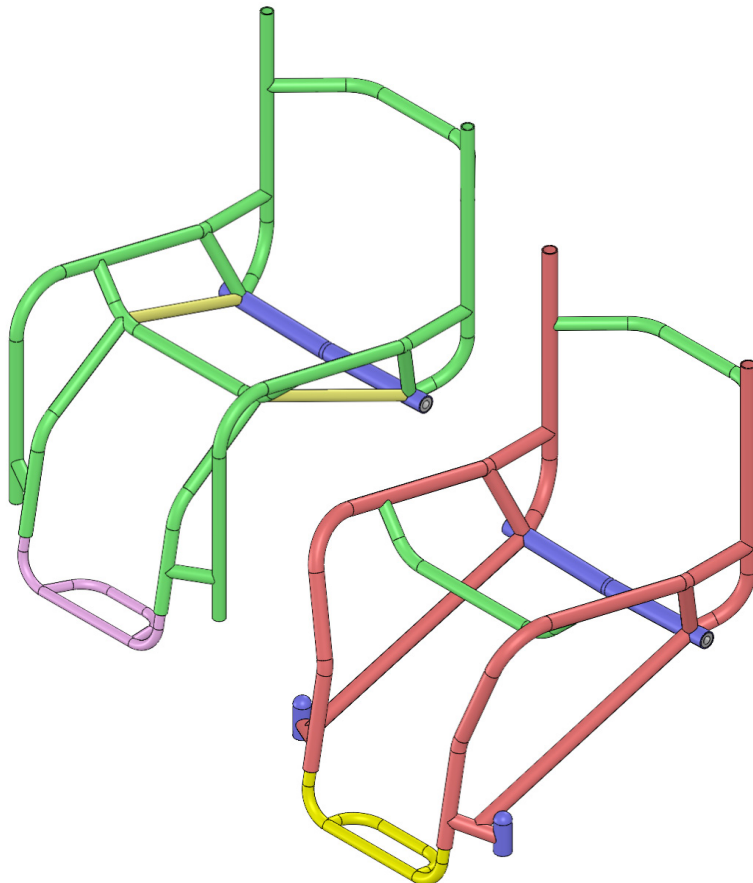


Figure 109. Layout of all components of the Cross-Over frame, sorted by tube diameter

Final Design | Specifications

The colours in the models indicate the diameter of the tube that is used:

- Ø 30 mm
- Ø 25 mm
- Ø 22 mm
- Ø 19 mm
- Ø 16 mm



Material

The thin tubes of the material require the material to be as rigid as possible. To achieve this, I chose to use the AA7020 aluminium alloy, which has a very high yield strength. This alloy is one of the most popular materials among competitors due to its strength-to-weight ratio and relatively affordable pricing.

A downside to this material is that it requires a precipitation hardening treatment after welding, to restore its original properties. This treatment is expensive and increases production complexity. If the factory were to scale their production, I recommend purchasing a precipitation oven to keep outsourcing costs low.

Cost price estimation

The AA7020 alloy is priced at €28 per meter. This price is roughly the same for all available diameters. If the frame were to be produced in larger batches, the cost is expected to be fixed at a lower price point. This does not influence the relative price compared to the production of a Box frame for the material is the same.

The estimated price to manufacture the Cross-Over frame is ±€70 lower than the Box frame (Table 16). This difference is partly due to the minimised bending complexity and by the time that is saved preparing the machine for the extrusion of a different tube diameter.

		Box frame		Cross-Over	
€ 28	AA7020 €/m	6,50 m	€ 185	6,15 m	€ 175
€ 90	Tube bending €/hr	± 3,6	€ 320	± 2,9	€ 260
€ 90	Welding €/hr	± 2	€ 180	± 2	€ 180
€ 90	Post-processing €/hr	± 2,5	€ 225	± 2,5	€ 225
€380	Precipitation hardening treatment		€380		€380
Rounded estimate of production price		± € 1290		± € 1220	

Table 16. Production price estimation of the Cross-Over frame compared to the Box frame | Values were rounded.

Figure 110. The tube dimensions used for the frame components of the Cross-Over frame (left) and for the Box frame (right)

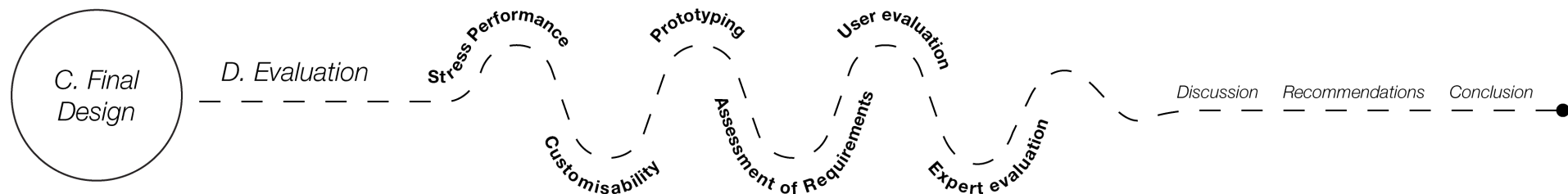


D. Evaluation

D.1 Approach

The evaluation phase assesses whether the final design meets the design goal and the requirements that were defined during the analysis phase. To test the transportability of the shape of the final design, I built a 1:1 prototype out of PVC and validated this with a spinal cord injured wheelchair user. To evaluate the stress performance of the Cross-Over frame I used SolidWorks simulations to

compare it to a reference Box. In addition to the structural evaluation, I assessed the final design with respect to weight, transportability, manufacturability and customisability. Together, these evaluations determine to what extent the Cross-Over frame actually balances rigidity and transportability and identify aspects that require further validation through physical testing.



Evaluation | Prototyping

D.2 Prototyping

To build the 1:1 prototype, I used 19mm PVC. The frame design has many bends that need to be symmetrical for the frame to come together in the right proportions. Additionally, I needed to find a way to join the pieces together. Rather than trying to bend all of these curves by hand, I opted to 3D print the bends and joints (Figure 111, 1-3).

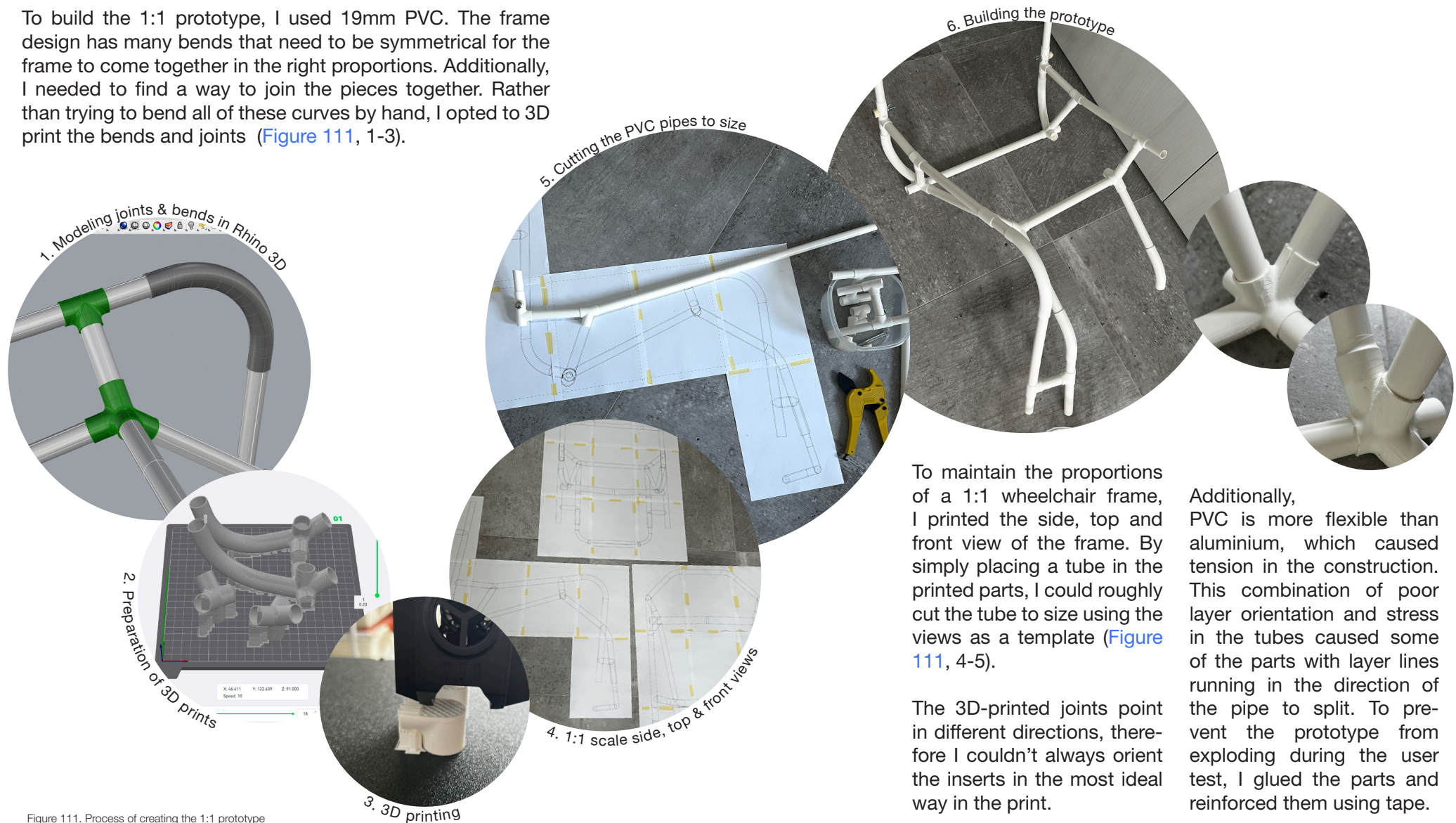


Figure 111. Process of creating the 1:1 prototype

To maintain the proportions of a 1:1 wheelchair frame, I printed the side, top and front view of the frame. By simply placing a tube in the printed parts, I could roughly cut the tube to size using the views as a template (Figure 111, 4-5).

The 3D-printed joints point in different directions, therefore I couldn't always orient the inserts in the most ideal way in the print.

Additionally, PVC is more flexible than aluminium, which caused tension in the construction. This combination of poor layer orientation and stress in the tubes caused some of the parts with layer lines running in the direction of the pipe to split. To prevent the prototype from exploding during the user test, I glued the parts and reinforced them using tape.

Evaluation | User

D.3 User evaluation

Does it fit in the car?

To test this, I lifted the frame into a KIA Picanto without moving the seat backwards.

I started by folding the backrest down (Figure 112) and lifted the frame on the cross tube (Figure 113). The cross tube is a very balanced place to hold the frame as it is a central point with the weight of the backrest on one side and the casters on the other. This allows for a more controlled manoeuvre when rotating the frame between the steering wheel and yourself. (Figure 114) The flat folding backrest allows for the frame to be placed with the (dirty) casters facing away from the passenger seat (Figure 115). For me this was the first time to lift a wheelchair frame into a car, so it took a few tries to get the manoeuvre right. Although this car is very small, I was able to lift the frame over myself quite easily.



Figure 112. Folding down the backrest



Figure 113. Lifting the frame by picking it up on the cross tube



Figure 114. Rotating the frame between myself and the steering wheel

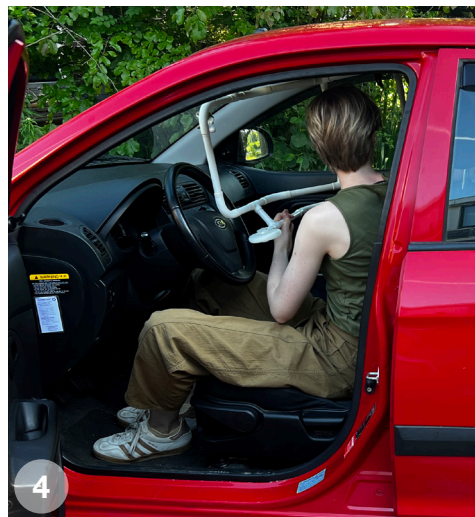


Figure 115. Placing the frame on the passenger seat

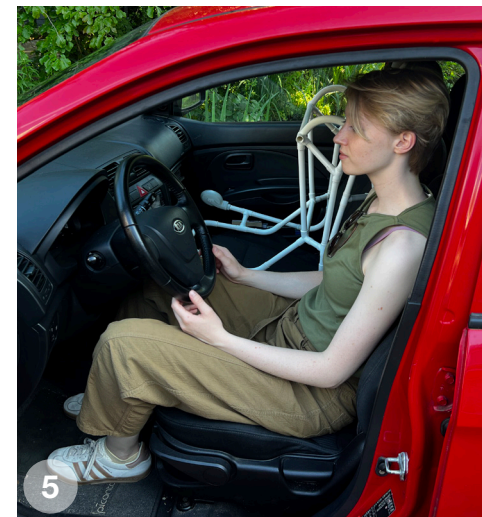


Figure 116. Ready to start driving!

Evaluation | User

To test the transportability performance of the frame for someone with a spinal cord injury I asked one of the previously interviewed wheelchair users to lift the frame over the driver seat of their car.

The car that is used is larger than a regular car. The ceiling is a bit higher and the car is wider. To minimise the effect of this extra space we didn't move the driver seat backwards.

This way the space is still limited and the user has to rotate the frame around their body to place it on the passenger seat.

The prototype I built has a folding backrest to make transportation easier. The user informed me that it should also be possible to transport the frame with the backrest extended as if it were fixed. [Figures 117 - 120](#) show the user lifting the frame over the driver seat with the backrest extended.

In this van the ceiling is a bit higher than it would be in a regular car. This made it quite easy for the user to lift the frame over the driver seat with the backrest extended. In a smaller car I would recommend a folding backrest.

[Figures 121 - 123](#) show the user lifting the frame in the car with the backrest folded down. This compacted shape allows the user to keep the frame closer to their body while lifting it over the driver seat.

When the user places the frame on the passenger seat, they place their hand on the doorframe for stability. The user prefers to lift the frame while holding on to the cross tube because this is the most balanced point to easily grab onto.

While placing the frame on the passenger seat, the user makes sure to place it with the casters facing away from the seat, to minimise traces of dirt on the upholstery off the car.

Taking the frame out of the car follows the same procedure in reverse. ([Figures 124 - 127](#))

All in all, the user was positively surprised with my prototype. He showed me that the frame the frame was easy to lift and manoeuvre around in the car. Based on the prototype and a short presentation with renders of the final concept he believes that the design of the frame could be able to accommodate the needs of a spinal cord injured user.

Transport of the Cross-Over frame with a fixed backrest



Figure 117. User lifts the frame with the casters still resting on the ground to detach the rear wheels (rear wheels were not prototyped)



Figure 118. With the backrest extended, the user has to lift the frame higher



Figure 119. Rotating the frame behind the steering wheel. The casters are pointing towards the open doorframe. Since the fixed backrest extends the frame further, this isn't advisable to do in cars where space is limited.



Figure 120. The user places the frame on the passenger seat with the dirty casters facing the seat.
Note: in the picture the backrest is slightly tilted upwards because the prototype doesn't have a fixed backrest.

Evaluation | User

Placing the Cross-Over frame with a folding backrest in the car

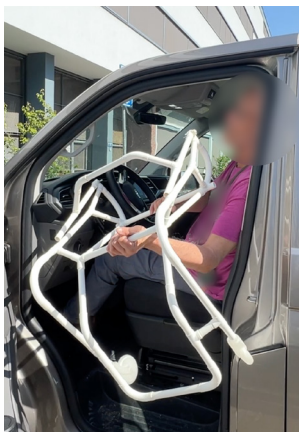


Figure 121. Lifting the frame by picking it up on the cross tube. *Rear wheels and seat cushion would already be removed.*



Figure 122. Rotating the frame behind the steering wheel. The casters are pointing towards the open doorframe



Figure 123. Placing the frame on the passenger seat with the dirty casters away from the seat. The user places their hand on the doorframe for stability.

Limitations | user evaluation

- *The prototype weighs only 1055 grams which is factor 2,5 lighter than the frame would be in reality.*
- *The tubes of the prototype are slightly thinner (19mm instead of 22mm)*
- *The casters of an actual wheelchair would be much heavier, which influences the center of gravity of the frame when rotating it around the body.*
- *The footrest is prototyped as a single U curve. In reality it would also have a tube that protrudes inwards to create a surface for the feet to rest on.*
- *The prototype doesn't have upholstery. upholstery could make the backrest fold less flat. Upholstery would also add some weight.*
- *The van that was used in this evaluation is larger than a regular car.*
- *Although I tested whether I could lift the frame over the driver seat of a small car, the results may be different than when spinal cord injured wheelchair users perform the same manoeuvre due to the differences in abdominal muscle.*
- *The body shape of the person lifting the wheelchair is another important factor. People with larger bodies may experience more difficulty during this manoeuvre.*

Lifting the Cross-Over frame with a folding backrest out of the car



Figure 124. User lifts the frame from the passenger seat



Figure 125. User rotates the frame for easier access to the cross tube



Figure 126. User rotates the frame with the casters pointing outside



Figure 127. User places the casters on the ground and can now attach the rear wheels and cushioning (*not prototyped*)

Evaluation | Assessment of requirements

D.4 Assessment of requirements

All requirements that are prioritised as ‘Must have’ should be met in this design. The final design will be evaluated in a user test and validated by the manufacturer. The assessment of the complete list of requirements is placed in Appendix d.1.

In this assessment, I have highlighted all requirements that are met in green, the requirements that are not yet met and those that require more testing are highlighted with yellow. None of the requirements are regarded unfeasible.

Requirement	Description	Assessment	MoSCoW	Additional notes	ID
Made-to-measure	Frame is custom designed and manufactured for use by a named individual occupant. (made-to-measure)	The improved manufacturability of the frame makes it easier to bend custom tubes for individual users	M	Measurements can be customised up to 0.5cm increments within a range specified in Appendix X (C. Functionality)	A1.2
Transportability	User can transport the wheelchair independently by car	The frame is designed for improved transportability, by minimising the space used underneath the frame and reducing the overall weight of the frame. This allows for the frame to be lifted over the driver seat.	M	The shape was tested for transportability (D2). Weight was not included in this test but is likely to have an impact.	B1.6
	Transport weight of the frame can be lifted by the wheelchair user is below 6 kg	Improved. The frame is 233 grams lighter than the box frame, which can be lifted by the user.	M	Average transport weight is 4-8 kg (no wheels/cushioning)	C1.1.2
Stability	Seating frame allows for proper postural support	The frame uses the same ergonomic seating construction as similar frames on the market. The final design of the frame was validated with a spinal cord injured user, but was not yet tested with the user in the seat.	M	Ergo seat and rigid frame that minimises the transference of vibrations from the wheelchair into the body	C2.2.5
Aesthetics	The design is recognisable / indistinguishable from similar products	The design is recognisable and unique by crossing the caster over the front frame of the wheelchair.	M		A2.2
Rigidity	Wheelchair can transport a max load of 120 kg	The stress performance simulations in SolidWorks show that the frame is able to support at least 8 times the maximum load of 120kg with a performance similar to the box frame	M	RGK HiLite XTR: 115 kg Woltumus W5: 150 kg Simulation was performed with vertical loads on the seat and footrest	C1.1.3
Stress performance	The frame has a better or similar stress distribution as the reference Box frame design	The stress distribution is similar under the conditions tested in the report	M		D3.3
Feasibility	Tubes can be bent using in-house bending machine	The frame is constructed using the available diameters. None of the tubes extend beyond 4800mm and radii are larger than 3 x tube Ø	M	Max. tube length: 4800 mm Max. bending radius: 3 x tube Ø Diameters: 10mm, 16mm, 19mm, 22mm, 25mm, 30mm	D2.1
Complexity	The frame can be manufactured faster than the current frame types	The frame is constructed using only 2D bent tubes. These tubes are expected to be bent with minimal deviations. This reduces manufacturing time, compared to the box frame. Additionally, this design only requires the extrusion head of the machine to be swapped once. Which saves 30 minutes.	M	Time to assemble (build) the wheelchair below 5.5 hrs	D1.3
Estimated cost	Pricing is lower than current custom wheelchair prices: below €6000	Expected due to the improved manufacturability of the frame. This could save time, which would lower production costs.	S	Allows for increased interest of wheelchair suppliers; Prices range between €6000 and €8000	A4.1

Table 17. Assessment of a selection of the most relevant requirements in Appendix X

Evaluation | Feasibility

D.5 Feasibility

D.5.1 Manufacturability

To validate my arguments regarding the improvements of manufacturability for the new frame, I revisited the PEZY wheelchair factory.

The team is very optimistic about the feasibility of the design. They believe the frame is designed efficiently and are even willing and able to produce a prototype using the technical drawing of the design (Appendix c.5).

Angle measurements

The 2D bent components allow for a faster method of deviation checking by using an angle measuring tool (Figure 128), rather than scanning the components which takes more time. Analog measuring tools are less convenient to be used for 3D bent shapes, so this improves the process. The factory suggested that this frame could therefore also be produced with a less advanced machine or even

by hand, because the simplified bends can be compared checked for deviation more easily.

Welding feasibility

While designing the frame, I tried to strategically place the components to make it feasible to weld. This was confirmed by the factory, who agreed that the way the parts come together is fairly easy to build. The frame

can be fixed on the rear wheel axle and casterhouse (Figure 129). The welding isn't necessarily faster or easier than with a conventional Box frame, but will take about the same time.

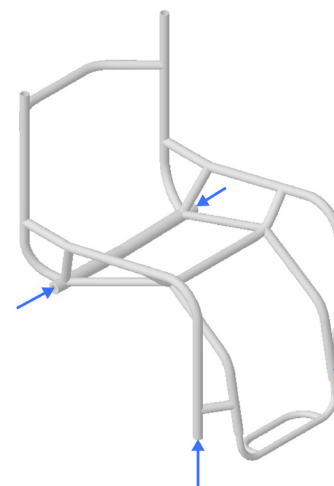


Figure 129. Cross-Over frame with arrows indicating the places where the frame would be fixated during the welding process.

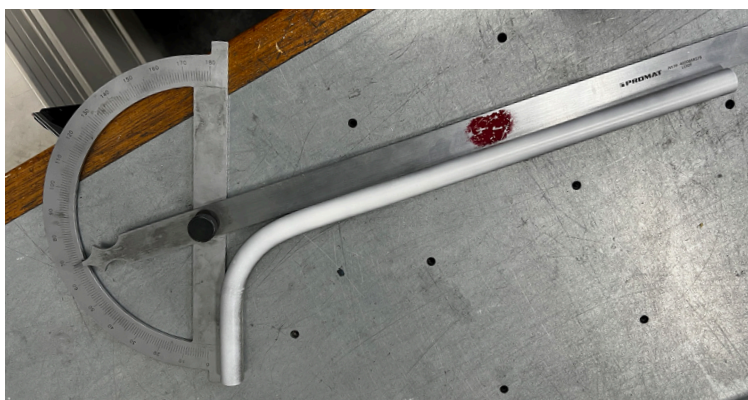


Figure 128. Measuring the angles of the backrest tube

Bending efficiency

To validate my claims about the improved bending efficiency of the frame, the factory made the effort to prototype some of the frame tubes. I wanted to compare the efficiency of both simple and more complex shapes.

We started by bending the tubes for the backrest (Figure 128), which is a fairly simple shape with only one bend. The first extrusion had a deviation just a little over the 2% benchmark. This deviation was easily corrected by the machine, which automatically calculated a new program. This program successfully extruded the tube with a deviation below 2%. Because the factory worker doesn't have to manually override the program when bending simple shapes, this process is very quick and took ± 10 minutes.

Evaluation | Feasibility

To compare this process with a more complex tube, we bent the seat-to-caster tube. Similar to the backrest, we started by bending the 'master model'. This extrusion showed much more deviation (Figure 132), similar to the extrusion of the seat-leg tube in Figure 40 (page 37). The machine bent the angles too far which made it difficult to instantly see which angles required correction.

Because this frame is designed with only 2D bent tubes, it was easier to consistently scan each extrusion of the tube. The factory worker mentioned that the automatically corrected

program generated by the scanning software often doesn't give good results for shapes with higher complexity and tends to overshoot the correction. The result of this generated correction was indeed overcorrected (Figure 133).

The limited number of bending parameters that influence the shape of the 2D bent tube made it possible for the factory worker to more efficiently overwrite the program of the bending machine. This way, the tube was successfully bent in two more tries (Figure 134). Figure 135 on the right page shows the four extruded tubes in order of extrusion.



Figure 130. Extrusion of the seat-to-caster tube



Figure 131. Scanning the seat-to-caster tube | Tube coated in white paint for easier scanner recognition

In total, the bending process of this component took nearly 45 minutes. The factory worker ensured me that even though the parameters of custom frame components will always require some do-overs,

there is a learning curve to understanding the way the machine extrudes a certain tube design. This concerns the types of bending angles that cause problems in the extrusion. I estimated that, with more experience, the

production time could be reduced to about 20 minutes. To conclude: simple shapes can be bent in approximately 10 minutes. The most complex component is the seat-to-caster frame which is estimated to take twice as much time. Compared to the time to bend a Box frame, efficient bending reduces ± 40 minutes, which is approximately 20% faster (Appendix c.4).

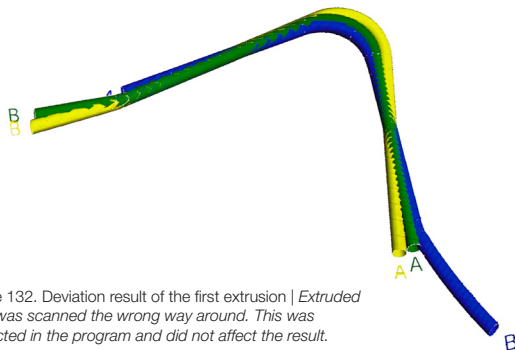


Figure 132. Deviation result of the first extrusion | Extruded tube was scanned the wrong way around. This was corrected in the program and did not affect the result.

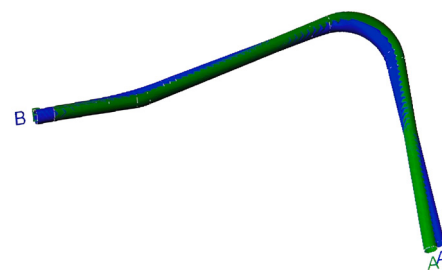


Figure 133. Deviation result of the second extrusion (corrected program generated by the machine)

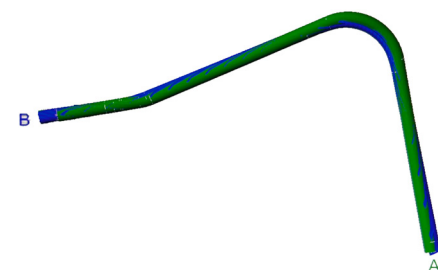
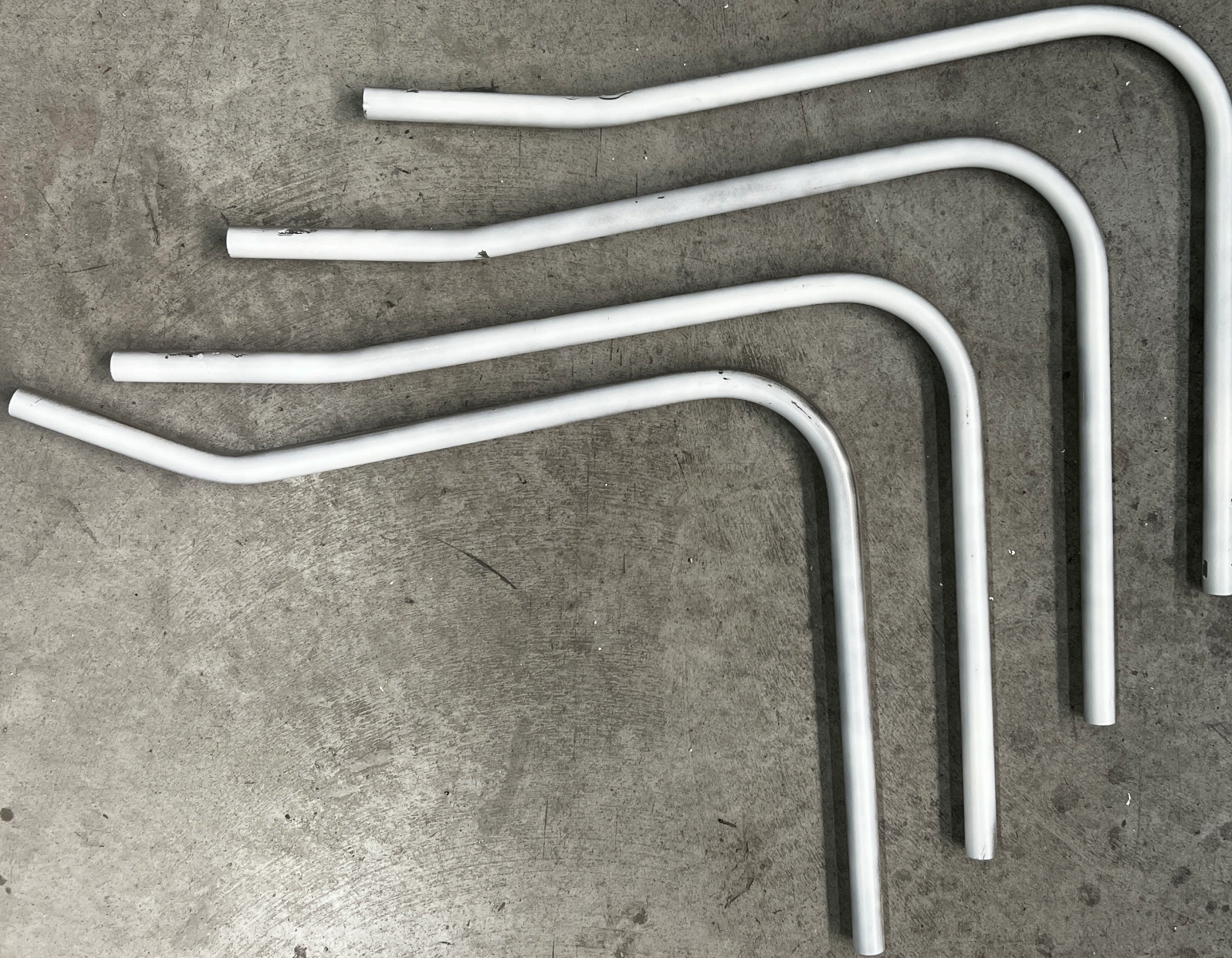


Figure 134. Deviation result of the fourth extrusion (manual overwrite)

Figure 135. On the right page | The four extruded tubes in order of extrusion (bottom to top)



D.5.2 Stress distribution

I simulated the user sitting in the wheelchair and the user performing a wheelie and compared the results. To keep my method of testing consistent, I used the same approach as for the preliminary simulations. To improve the accuracy of the results, I set the mesh settings to generate a finer mesh (Appendix c.1).

The load on the frames represents 8 times the maximum load of 120 kg. I chose to simulate a load this heavy to visualise the stress distribution more clearly.

Sitting

The Cross-Over design features tubing that is 3mm thinner than the Box frame throughout the entire frame. Despite this difference, the simulation shows that the stress distribution in the Cross-Over design is very similar to the distribution in the Box frame (Figure 137). In both designs stress concentrates on the seat where the load is applied and directly below it, where the seat connects to the camber bar.

The cross tube beneath the seat, to which the rigidifying tubes in the Cross-Over design are attached, displays a very even distribution. These seat bars lead stress away from the welded junctions of the frame, similar to the function of the classic diagonal cross bar in the Box frame design.

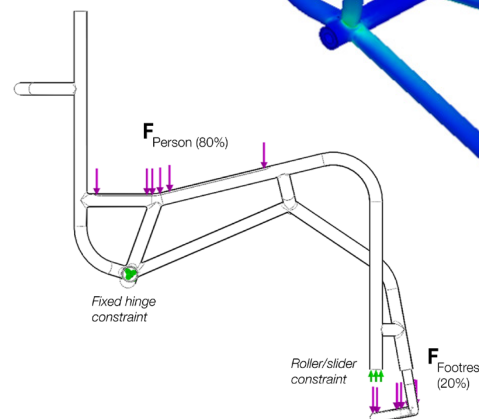


Figure 136. Forces and constraints on the frame simulating a person sitting in the wheelchair

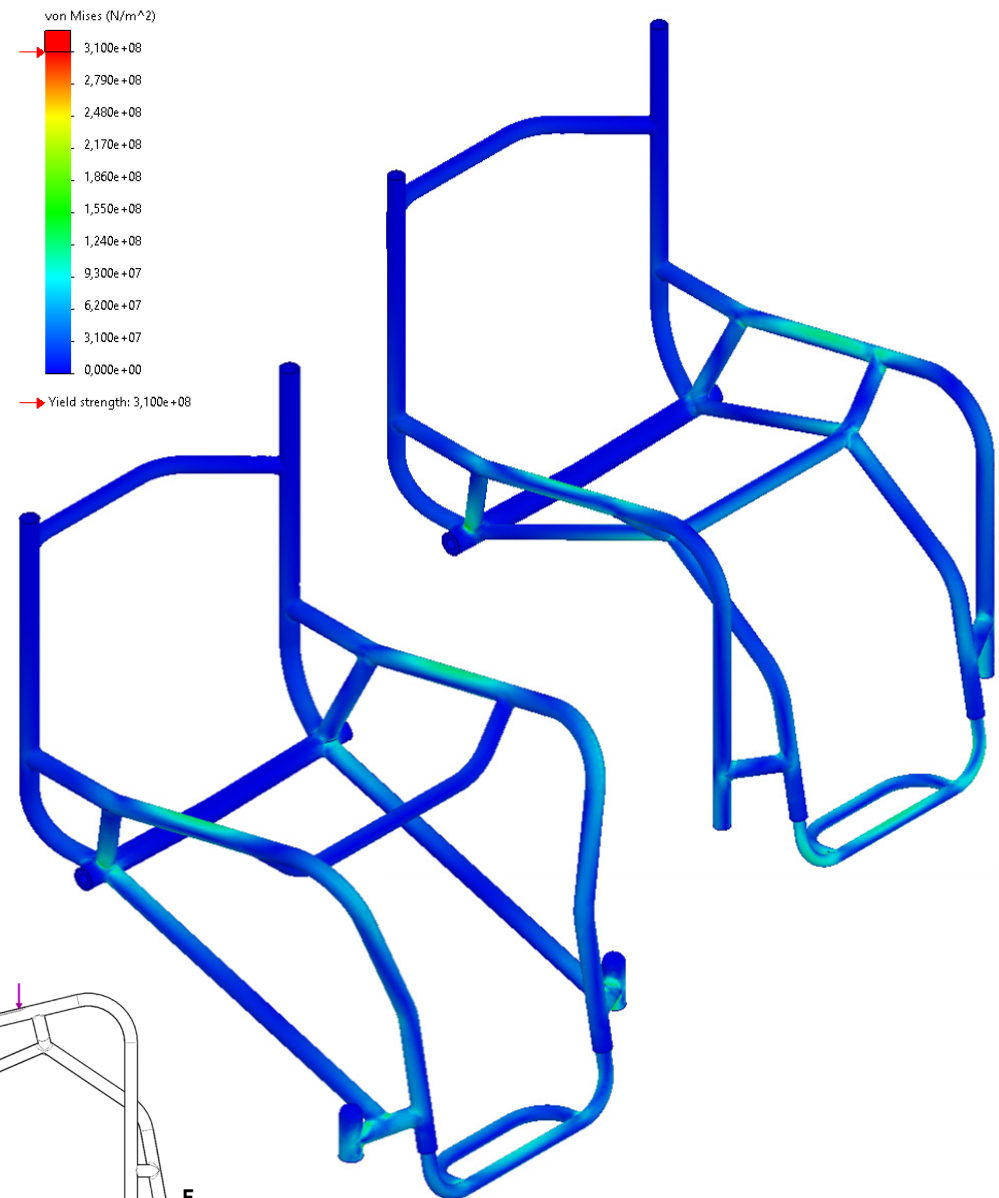


Figure 137. Stress distribution in the Box frame (left) and in the Cross-Over frame (right) | 80% of the load was placed on the seat (7680 N) and 20% on the footrest (1920 N).

Evaluation | Feasibility

Wheelie

To simulate the wheelie manoeuvre, the models are tilted by 15°. This tilt also shifts the center of gravity of the user more towards the rear side of the wheelchair. This causes the load on the seat to increase and the load on the footrest to decrease (Figure 138). Both frames show signs of fatigue around the welding junctions. This is highlighted in the circle in Figure 139. This can be explained by the constraint that holds the axle in place.

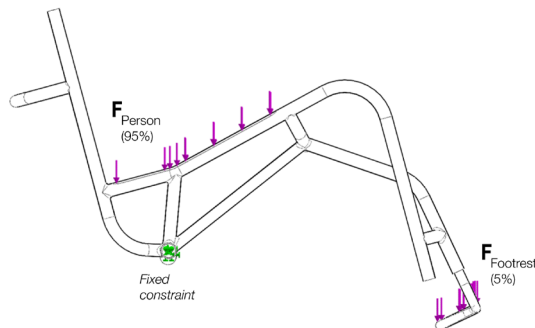


Figure 138. Forces and constraints on the frame simulating a person sitting in the wheelchair while performing a wheelie

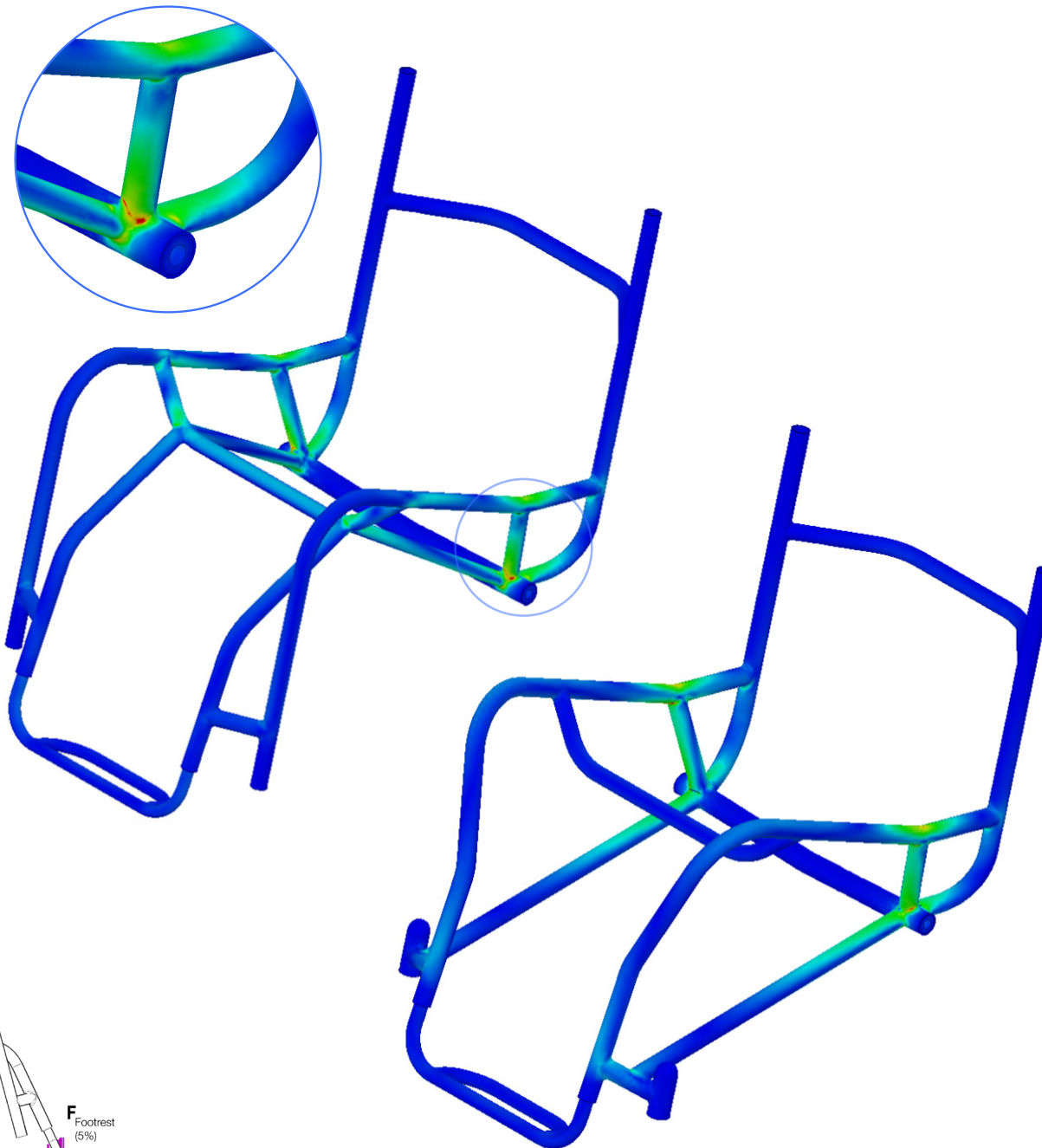


Figure 139. Stress distribution in the Cross-Over frame (left) and in the Box frame (right) | For this simulation the models are tilted 15°. 95% of the load was placed on the seat (9120 N) and 5% on the footrest (480 N). The scale used in this visualisation is the same as in Figure 102.

In the simulation of a user sitting, I used a *fixed hinge constraint* which allows for movement along the axis of rotation of the wheel. When simulating a wheelie this is not applicable, because the user actively holds the wheel in place to balance the wheelchair. The difference is the force used to keep the wheel in place, which is much higher in the simulation than it would be in real life.

It appears that the construction using the cross tube helps to disperse the stress more effectively than the cross bar used in the Box frame design. The construction in the Cross-Over frame allows for a more uniform stress distribution throughout the entire frame, rather than the construction of the Box frame where multiple tubes connect to the camber bar, causing a greater stress concentration.

Evaluation | Feasibility

D.5.3 Made-To-Measure

One of the requirements of the wheelchair frame is its ability to be customised to fit made-to-measure tailoring. To achieve this, I built the model parametrically in SolidWorks using equations. To test the model, I found an oddly sized made-to-measure frame of a competing manufacturer (Figure 140).

I used the image to roughly estimate the proportions. By changing the values in the parametric drawing (Figure 143), the CAD model automatically adjusts to preview the new design (Figure 141; Figure 142). Appendix c.6 shows the technical drawing of the customised frame.

This made-to-measure customisability test proves that the design is configurable to different body types. More testing of different configurations is required to verify whether the frame is customisable to fit all of the sizes in the list of requirements.



Figure 140. Oddly sized made-to-measure wheelchair frame by Wolturnus

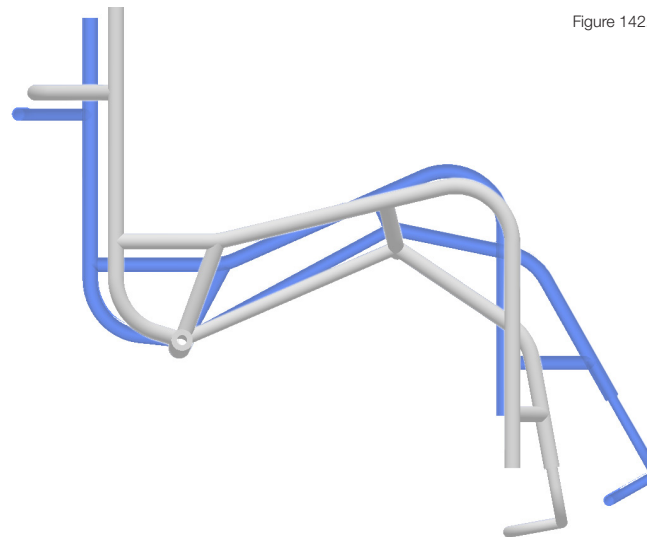


Figure 141. Comparative side profile of the made-to-measure frame | Blue shows the customised frame

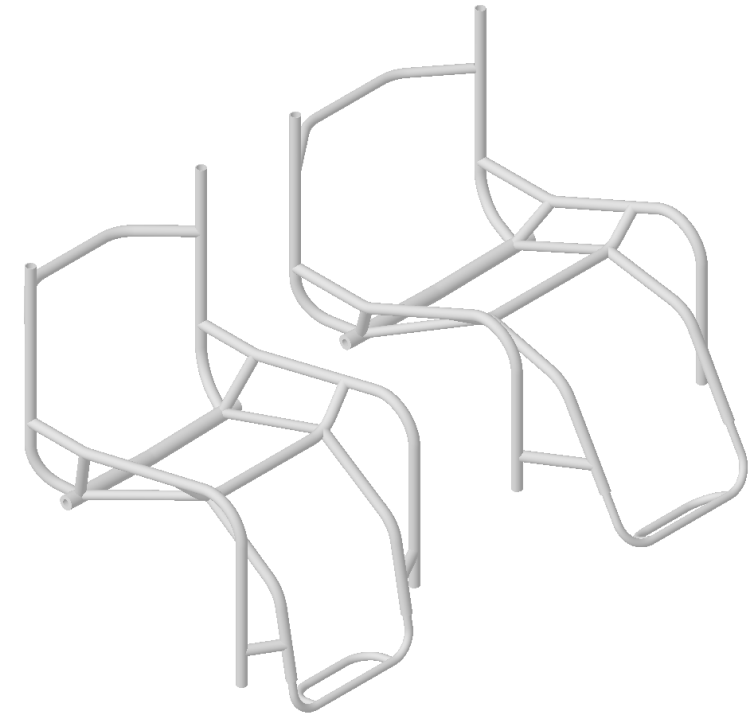
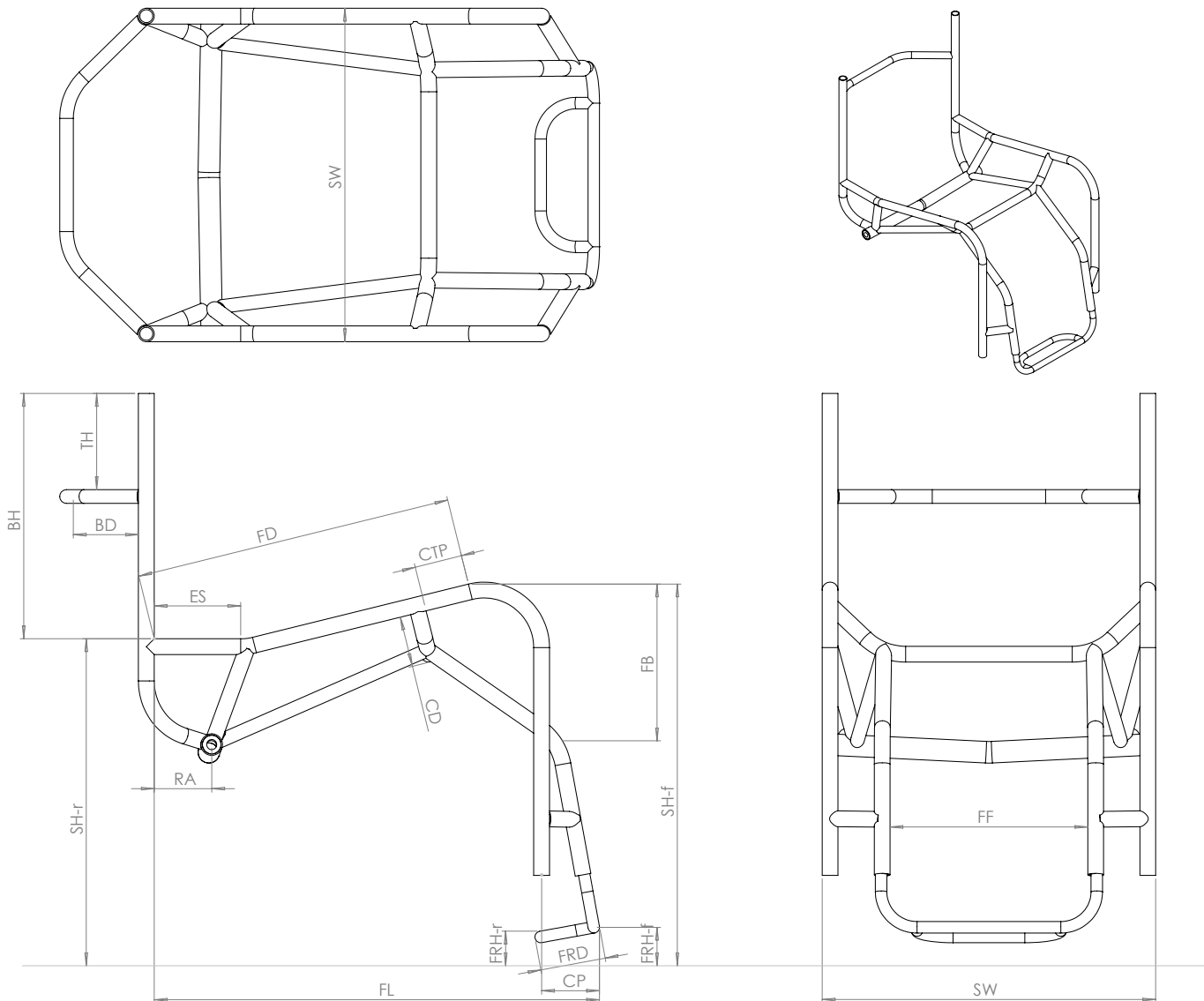


Figure 142. Side-by-side of the master model sizing next to the made-to-measure frame design

The parameters (Table 18) in the technical drawing that is used to manufacture the frame are the same as the parameters that are used for the frames of various competitors that I compared in the market analysis. This ensures that the frame is feasible to manufacture and also that the parameters are feasible to measure on the user.

Evaluation | Feasibility



SH-f	Seat height front
SH-r	Seat height rear
FD	Frame depth
RA	Rear axle placement
ES	Ergonomic seat length
CTP	Cross tube placement
CTD	Cross tube depth
FL	Frame length
CP	Castor placement
BH	Back height
BD	Back depth
TH	Back tube height
FRH-f	Foot rest height front
FRH-r	Foot rest height rear
FRD	Foot rest depth
FB	Front bend
FF	Front frame width
CW	Castor width
C	Camber angle
SW	Seat width
SF	Seat frame length

Figure 143. Technical drawing of the Cross-Over frame

Table 18. Parameters in technical drawing

Discussion

A. Analysis

User

To get insights from users, I visited two large conventions. In general, the wheelchair users that attend such conventions are outspoken and active. For example, most of the users I interviewed entered the obstacle parcour for fun or were involved in WCMX trainings. Therefore, these people may not represent all of the needs and preferences of average SCI wheelchair users.

Wheelchair provision

The stakeholder analysis is centered around the Dutch system of wheelchair provision. This system revolves around unique national reimbursement authorities. In the future, the factory may want to scale their production towards neighbouring countries.

Since the system of wheelchair provision is so dependent on the dynamics of the stakeholders involved,

these systems are likely to be organised differently and will require further research.

B. Synthesis

Reference Box frame

The concepts that were compared in the selection of the final concept are all compared with a reference Box frame design. This design is an estimation of what a Box frame could look like, but there is a wide variety of different types of Box frames available. It is possible that some of these frames perform differently regarding rigidity and stress distribution.

Transportability

The transportability of the different concepts was evaluated through side profiles of sketches and CAD models (Figure 144). This allows for fast visual assessment but doesn't account for the actual transportation experience. For improved assessment, the different concepts

could have been prototyped to evaluate the three-dimensional space improvements of each concept.

Subjectivity of selection

The criteria that are used to select the concept directions are only a small section of the total list of requirements. This selection is made based on assumptions of the previous analyses and the knowledge available to rate the different criteria. Although I tried to compare the concept directions, and later also the concepts variations, as equally as possible, the rating remains subjective.

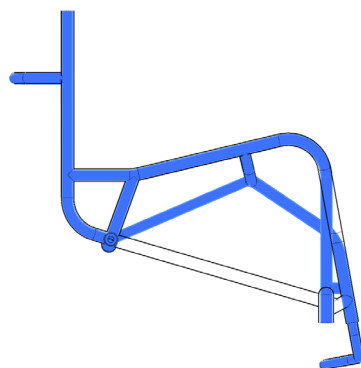


Figure 144. Assessing transportability from the side profile of the frame

C. Final Design

Made-to-measure

The Cross-Over frame is designed using the sizing parameters of existing wheelchair frames. Because of this, I assume that the dimensions of the frame will be just as easily customisable as existing frames on the market that use similar parameters. To test this assumption, I configured the frame to a custom variation. To ensure that all the sizes that are specified in the list of requirements in Appendix d.1 are indeed compatible, more variations need to be configured.

Estimated production time

The new design of the frame has not been produced yet in the PEZY factory. The production time estimation is based on an informal interview with one of the workers in the factory. Whether my claims about faster and more efficient production come true remains uncertain.

Estimated total weight

Because the frame has not been produced yet, the total weight estimation is based on the SolidWorks model and some off the shelf components such as the caster and rear wheels. The weight of the upholstery was estimated based on upholstery sold by competitors.

The total weight of the frame will ultimately be dependent on the configuration of the made-to-measure frame. The claim that the frame is 8,5% lighter than the Box frame is only applicable to the exact configuration that it is compared to. There may be configurations where the difference is larger or smaller.

Use

The lack of a physical prototype makes it impossible to evaluate the user experience of riding in the Cross-Over frame. The new design of the frame may also have implications for other user scenarios such as

Discussion

transferring or the amount of vibration through the frame riding over cobble stones.

Hardening treatment

The use of the AA7020 alloy of aluminium requires an expensive precipitation hardening treatment to regain the strength that was lost in the weldig process.

Footrest tube

Using Ø22mm tubes for the front frame of the wheelchair means that the tubes that shape the footrest have to be Ø16mm to fit into the tube (Figure 145). Based on the calculations of deflection I did for each available tube diameter (Figure 146), this is thinner than I would recommend. The stress performance analysis in chapter D.5.2 shows that the stress remains far below the yield strength of the material, but this only applies to scenarios that are similar to my simulation settings.

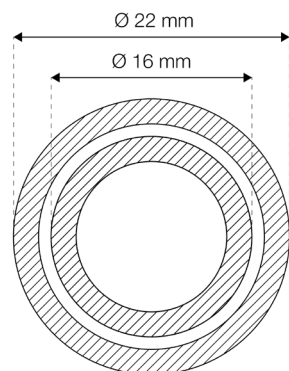


Figure 145. Illustration of the diameter of the footrest tube inside of the front frame tube

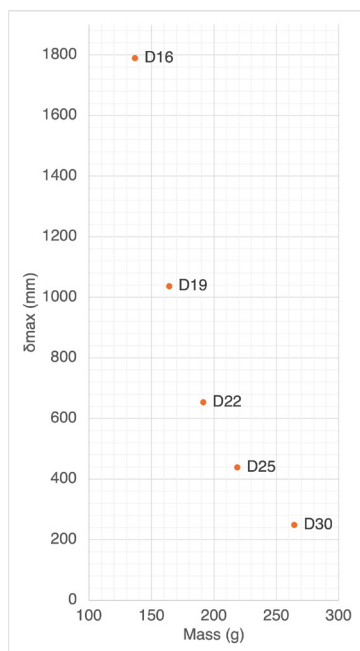


Figure 146. Graph of calculated deflection for the AA7020 aluminium alloy

D. Evaluation

User behaviour

Different users will have different user behaviour. Some users will be more careful with their wheelchair, but others may use it in more extreme scenarios. Therefore, it is impossible to simulate every possible load scenario that a frame will have to endure.

Simulation in SolidWorks

The stress performance of the frame is assessed by a simulation in SolidWorks. The load scenarios in these simulations are an estimation based on the weight of the user and the position of the frame. The results of simulations in SolidWorks

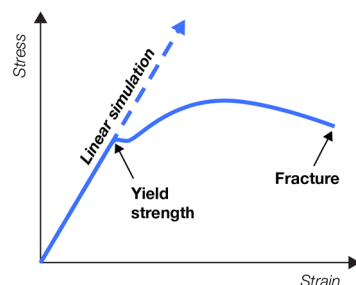


Figure 147. Elasticity curve

are calculated using linear elastic properties. This means that the material behaves as if it is infinitely flexible, rather than fracturing. Figure 147 shows this relationship. Normally, a material behaves linearly until the point where the yield stress is reached. From this point onwards the material will deform and ultimately fracture.

A linear relationship also means that a doubling of the forces applied will also generate twice as much stress in the frame. To my advantage, I used this characteristic to visualise more extreme results. In reality this relationship wouldn't be linear, so it is uncertain what would happen to the frame in the areas where the yield strength is surpassed: Could it deform or fracture?

Dynamic loads

The simulations I did on the frame are all done under static conditions. However, most of the time the wheelchair is used in dynamic

situations: dropping off curbs, riding over uneven terrains, going downhill etc. These types of scenarios can create peak stress in the frame that aren't accounted for in a static scenario of sitting in the wheelchair. In the current simulations, I only evaluated the stress distributions under a vertical load. How the frame would react to a sudden impact from a different direction has not been analysed.

Fatigue damage

The frame is intended to be used for roughly seven years. During this time the frame lives through daily manual propulsion, transferring, wheelies and more. The load that activities apply to the frame may not leave initial damage but could cause the material to degrade which causes the yield stress to lower over time. This can cause fractures in the material that are very difficult to replicate in a simulation that only accounts for a single moment.

Discussion

Weld quality

My simulations simulate the weldings as perfectly smooth fillets. In reality, the quality of the welds may differ from frame to frame. Examples of factors that influence the quality of the weld are the thickness of the weld, the temperature at which the material melted, the residual stress in the frame and the coverage of the weld. Imperfect welds can cause the frame to fracture at lower impacts than simulated in SolidWorks.

Influence of secondary components

In my assessment of the frame, I evaluated the performance of the ‘naked’ frame. In reality, the frame is never used bare, but always upholstered with cushioning, wheels and other accessories. All of these secondary components may influence the rigidity and the total weight of the wheelchair.

Recommendations

Turning the frame into a wheelchair

To keep this project feasible within the timeframe of a 100 working days, I chose to only develop the frame of the wheelchair. To produce a complete wheelchair, the following components need to be added:

- Upholstery
- Cushioning
- Rear wheels
- Caster wheels
- Accessories

All of these components are standard components that can be used off the shelf, but it may be desirable to research whether custom components can add value to the wheelchair.

Physical prototype

A prototype in the AA7020 material would allow for assessment of the strength of the frame through a double drum test (Ghosh et al., 2025). This type of testing is also required to get a wheelchair frame ISO certified. A double drum test is a fatigue test that is used to evaluate the endurance of the frame (Figure 148). Manufacturing the frame in the PEZY factory can be used to validate the production efficiency. This will also give a better indication to the production time for the new frame design.

Simulating dynamic scenarios

To evaluate the performance of the frame in dynamic scenarios, the frame should be simulated in different worst-case scenarios. Although such simulations will still be static scenarios of the dynamic situation, they might provide useful insights.

User testing

Ideally the frame should be prototyped to be tested by a spinal cord injured user. The weight of the frame in the right material may also give different results when testing the transportability in a car.

Made-to-measure

To evaluate the customisability of the frame, more configurations should be developed.



Figure 148. Double drum test (Ghosh et al., 2025)

Conclusion

The goal of this project was to design a custom active manual wheelchair frame for users with a spinal cord injury that combines the rigidity of a Box Frame with the transportability of an Open Frame. In addition, the design had to be manufacturable at PEZY while balancing customisability, production time and cost.

The user analysis showed that people with a spinal cord injury are generally very active wheelchair users who value their independence. Among stakeholders, there is tension between the type of wheelchairs that suppliers are willing to prescribe and what the user actually requires. Custom frames allow users to be more independent by offering a made-to-measure fit. Standardised frames are a mass-produced alternative. These frames are more affordable but lack the ergonomic benefits of a custom-made frame. This

identified an opportunity to design the frame at a lower price point by optimising the manufacturing efficiency.

The market and frame analyses confirmed the trade-offs between the existing frame types. Open Frames are light and easy to transport, but they are more prone to flexing, which reduces propulsion efficiency, durability and compatibility with hand bike attachments. Box Frames are much more rigid and durable, but also heavier and more difficult to transport without assistance.

In the synthesis phase, I translated the insights from the analyses into six concept directions that explored different ways to combine rigidity, transportability and manufacturability. Using a selection from the list of requirements, I chose the Minimal frame direction to diverge and developed twenty-one different

concepts through sketching and iterating in SolidWorks. The concepts were first narrowed down based on their performance in a stress distribution simulation. The six resulting concepts were assessed on criteria regarding design, performance and manufacturability.

The resulting 'Cross-Over' frame showed a similar quality stress distribution to the Box frame, while reducing the frame weight by over 8,5%. The frame is designed to be easier to lift over the driver's seat. This was also validated with a user. The Cross-Over frame construction is faster to manufacture by eliminating 3D-bent tubes and optimising the tube dimensions that require bending. This reduces the complexity of the manufacturing process and is compatible with the existing machinery in the PEZY factory.

The final design should still be validated through physical testing. The stress performance of the frame is simulated with simplified loading conditions, which are likely not identical to real-life scenarios. Regardless, the Cross-Over frame shows that better transportability of the frame does not have to

come at the cost of rigidity and strength (Figure 149). The final design offers a balance between performance, manufacturability and user needs, which could be an attractive solution for suppliers.

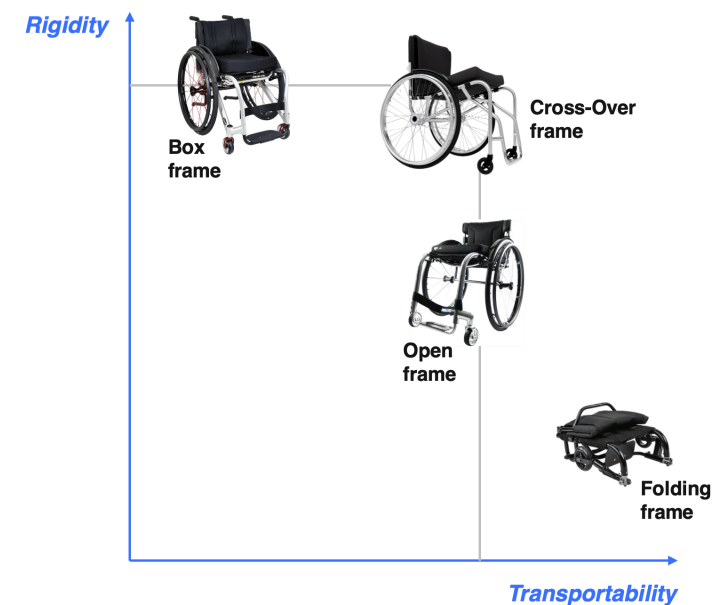


Figure 149. Positioning of the Cross-Over frame

Reflection

Generally, I tend to be quite perfectionistic. Before I commit to a design decision, I want to be certain that I have researched everything there is to know. This project originally started out as a research project to learn about the design of a good wheelchair frame. What I didn't fully realise then, was that in order to design a good wheelchair frame, you not only need to learn everything about the physical characteristics of the frame, but you must also understand everything about what it means to *use* a wheelchair. Without using a wheelchair yourself, this is an impossible goal. When you design something for a specific user group, you want to add value for that user group. However, when you don't understand the needs of the user, this becomes very difficult.

During the first half of this graduation project, I was mostly doing research to fill this knowledge gap.

I can absorb lots of information, but then it simply stays in my head. For me, this method works flawlessly, however as soon as I need to present my findings, this becomes a problem. I started this project with '*getting better at writing*' as one of my learning ambitions. Looking back at this, I find that the coherency of my writing has become better than it was before. However, I still struggle with the structure of my writing. I find it difficult to write in a way that describes the main objectives, without writing too much noise.

One of the biggest improvements in my writing in my opinion is the use of *goals*. I specified these for each of the analyses and I also tried to implement this in the synthesis phase. This helps to take the reader along in my findings. 'Taking the reader along' is still not something I'm particularly good at, but I think that I have improved this in these past six months.

Something else I have had to learn is that at some point, enough is enough. Because there was so much to learn in the world of wheelchairs, I found it difficult to decide when I had learned enough to finally start designing. Originally, my planning indicated that I would have been halfway through the synthesis phase by the time the midterm was scheduled. However, once the midterm rolled around, I still wasn't satisfied with the amount of research I had done and had to extend it even further.

All in all, I am very happy with the final design that I present. In the beginning we had discussions about the feasibility of a frame that combines both rigidity and transportability for these advantages would be too contradictory and may cause me to fail. I can say with certainty that it wasn't an easy design goal, but that makes me all the more proud that I managed to do it anyway :)

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a. Appendix | Analysis

a.1 Wheelchair users in the Netherlands

The data for this table is gathered from the sources below. Prevalence data of wheelchair use in the Netherlands is very scarce, so I converted prevalence data from other countries to the respective number of users in the Netherlands. Unfortunately, I couldn't find data for all wheelchair users. To estimate the number of users for these disability types I used ChatGPT.

Disability	Estimated users	Wheelchair type
Spinal Cord Injury ¹	12000	Active manual Custom
Multiple Sclerosis (MS) ²	4250	Active manual
Chronic Fatigue (e.g. Lyme)	1500	Active manual
Amputation	1500	Active manual Custom
Hereditary Spastic Paraparesis ³	300	Active manual
EDS	200	Active manual Custom
Hemiplegia (CVA) ^{4,5}	180000	Assisted manual
Huntington ⁶	1100	Assisted manual
Cerebral Palsy ⁷	6000	Electric
Amyotrophic Lateral Sclerosis ⁸	1200	Electric
Myotonic dystrophy (MD)	1000	Electric
Spinal Muscular Atrophy ⁹	700	Electric

Table 19. Prevalence of the disability types for the different permanent wheelchair users in the Netherlands and their respective wheelchair types

¹ (Handondersteuning Bij Dwarslaesie | de Hoogstraat Revalidatie, 2023)
² (Zajicek et al., 2007)
³ (Schröder, 2023)
⁴ (Şen & Kösehasanoğulları, 2024)
⁵ (RIVM, 2026)
⁶ (Hersenletsel-uitleg.nl, z.d.)
⁷ (Kerr et al., 2021)
⁸ (ALS Association, 2021)
⁹ (Rouault et al., 2017)

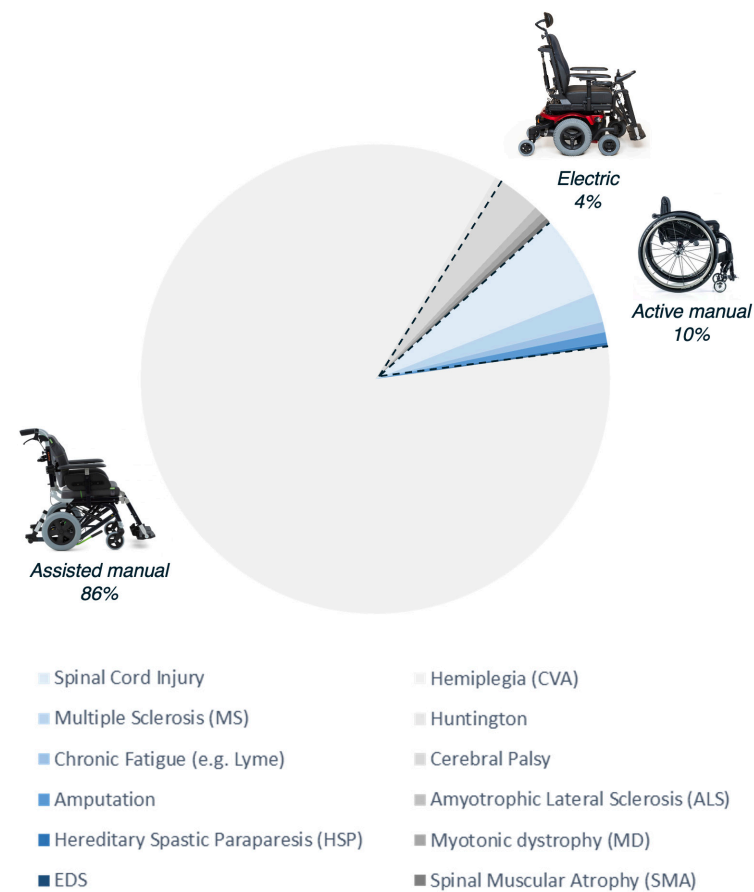


Figure 150. Permanent wheelchair users in the Netherlands

a.2 Stakeholders

	Interest	Influence
User	<ul style="list-style-type: none"> • Durability • Ergonomic performance • Ease of use • Ease of transportation • Delivery time • Look and feel 	<ul style="list-style-type: none"> • Advocating needs
Dealer	<ul style="list-style-type: none"> • Performance of the product • Good reviews / Reputation • Brand visibility 	<ul style="list-style-type: none"> • Ergonomic performance • Made-to-measure fit • Sales experience
WMO	<ul style="list-style-type: none"> • Low cost price 	<ul style="list-style-type: none"> • Assigning a budget to accommodate the needs of the user
Supplier	<ul style="list-style-type: none"> • Low cost price • Fast delivery time • Durability (less maintenance) 	<ul style="list-style-type: none"> • Connecting the user to the dealer
Municipality		<ul style="list-style-type: none"> • Budget / Allowance • Informing the user
Manufacturer	<ul style="list-style-type: none"> • Performance of the product • Low complexity of design • Brand visibility • Low cost price • Sales • Good reviews / Reputation 	<ul style="list-style-type: none"> • Performance of the product • Material quality
PEZY	<ul style="list-style-type: none"> • Sales 	<ul style="list-style-type: none"> • Qualitative design • Low complexity of design • Design Modularity • Cost price
Ergotherapist	<ul style="list-style-type: none"> • Ergonomic performance • Minimizing physical therapy 	<ul style="list-style-type: none"> • Informing the user • Advocating user needs • Supporting the user
Caregiver	<ul style="list-style-type: none"> • Ease of (secondary) use • Ease of transportation 	<ul style="list-style-type: none"> • Advocating user needs • Supporting the user
Knowledge institutes		<ul style="list-style-type: none"> • Informing the user • Influencing

Table 20. Summarised overview of the interests and influence of the analysed stakeholders

a.3 Market overview



Figure 151. The compared frames which are available in the Netherlands

a.3.1 Wheelchair specifications

Brand	Model	Price indication Wheelchair	Total weight (kg)	Transport weight (kg)	Max. carrying weight (kg)	Frame Material	Tube diameter (mm)	Frame type	Camber (°)
RGK	TIGA F2	€ 4.234,70	8	5,5	115	AL7020	30	Open & Box	0,1,2,3,5
	TIGA	€ 5.035,00	7,5	5	125	AL7020	30	Open & Box	0,1,2,3,5
	TIGA FX	€ 6.307,00	9	6,5	110	AL7020	30	Folding	0,1,2,3,5
	TIGA SuB5	€ 8.215,00	6	3,5	110	AL7020	30	Open	0,1,2,3
	HiLite	€ 5.936,00	7,5	5	125	Ti G2	25	Open & Box	0,1,2,3,5
	HiLite XTR	€ 4.870,70	7,5	5	115	Ti G2	25	Box	0,1,2,3,5
	MaxLite		7,2	4,7	100	Ti G2	19	Box	
	Octane		7,3	4,8	110	Ti G9	31,75	Open	
	Octane FX	€ 7.367,00	8	5,5	110	Ti G9	31,75	Folding	0,1,2,3,5
	Octane SuB5	€ 9.275,00	6	3,5	110	Ti G9	31,75	Open	0,1,2,3
	Veypr SuB5	€ 13.500,00	5,8	3,2	110	Carbon fibre	oval 29x36	Open	0,1,2,3
Wolturnus	W5	€ 5.533,20	9	6,5	150	AL7020	25	Box	1,3,5
	W5 Suspension		9	6,5	150	AL7020	25	Box	1,3,5
	Dalton		12,5	10	160	AL7020	25	Box	1,3,5
	Tukan		11,5	9	120	AL7020	25	Open	1,3,5
	Hawk		9,5	7	120	AL7020	25	Box	1,3,5
PEZY	FLOW A	€ 4.652,00	10,8	7,8	120	AL5086	25	Box	0,3,6
	FLOW Mono A	€ 4.542,00	10,8	7,8	100	AL5086	25	Open	0,3,6
	FLOW Easy A	€ 4.762,00			120	AL5086	25	Box	0,3,6
TNS	Activator ADL	€ 3.599,83	7,5	5		Aluminium	30	Open	
	Activator 2.5	€ 2.907,39	6	4,5		Aluminium	25	Box	
	Activator F.C.		7	5,5		Aluminium	30	Folding	
	Proval		6,5	4		Aluminium	15 x 30	Box	
Averages (rounded)		€ 6.000,00	8,2	5,7	120				

Table 21. Specifications of competing wheelchair frames by various brands sold in the Netherlands

a.3.2 Made-to-measure sizing

Brand	Model	Max Backrest height (mm)	Min Backrest height (mm)	Max Seat width (mm)	Min Seat width (mm)	Max Seat depth (mm)	Min Seat depth (mm)	Max Seat height back (mm)	Min Seat height back (mm)	Max Seat height front (mm)	Min Seat height front (mm)
RGK	TIGA F2	600	150	500	250	500	250	550	360	550	380
	TIGA	600	150	500	250	500	250	550	360	550	380
	TIGA FX	400	150	460	250	460	250	550	360	550	480
	TIGA SuB5	400	100	440	250	440	250	500	360	520	380
	HiLite	600	150	500	250	500	250	550	360	550	380
	HiLite XTR	600	150	500	250	500	250	550	360	550	380
	Octane FX	400	150	460	250	460	250	550	360	550	480
	Octane SuB5	400	100	440	250	440	250	500	360	520	380
	Veypr SuB5	400	150	440	250	440	250	500	360	520	380
Wolturnus	W5	500	250	480	320	500	250	520	300	520	300
	W5 Suspension	460	250	550	320	520	340	550	360	550	360
	Dalton	550	250	480	360	600	300	550	400	550	400
	Tukan	550	250	600	320	500	250	550	300	550	300
	Hawk	500	300	500	350	500	350	545	390	545	390
PEZY	FLOW A	500	350	525	365	500	350	590	440	620	450
	FLOW Mono A	500	350	525	365	500	350	610	430	620	450
	FLOW Easy A	500	350	515	365	500	350	610	430	580	470
Averages (rounded)		500	210	500	310	500	290	550	370	550	390

Table 22. Made-to-measure size range of competing wheelchair frames by various brands sold in the Netherlands

a.4 Provision of a wheelchair

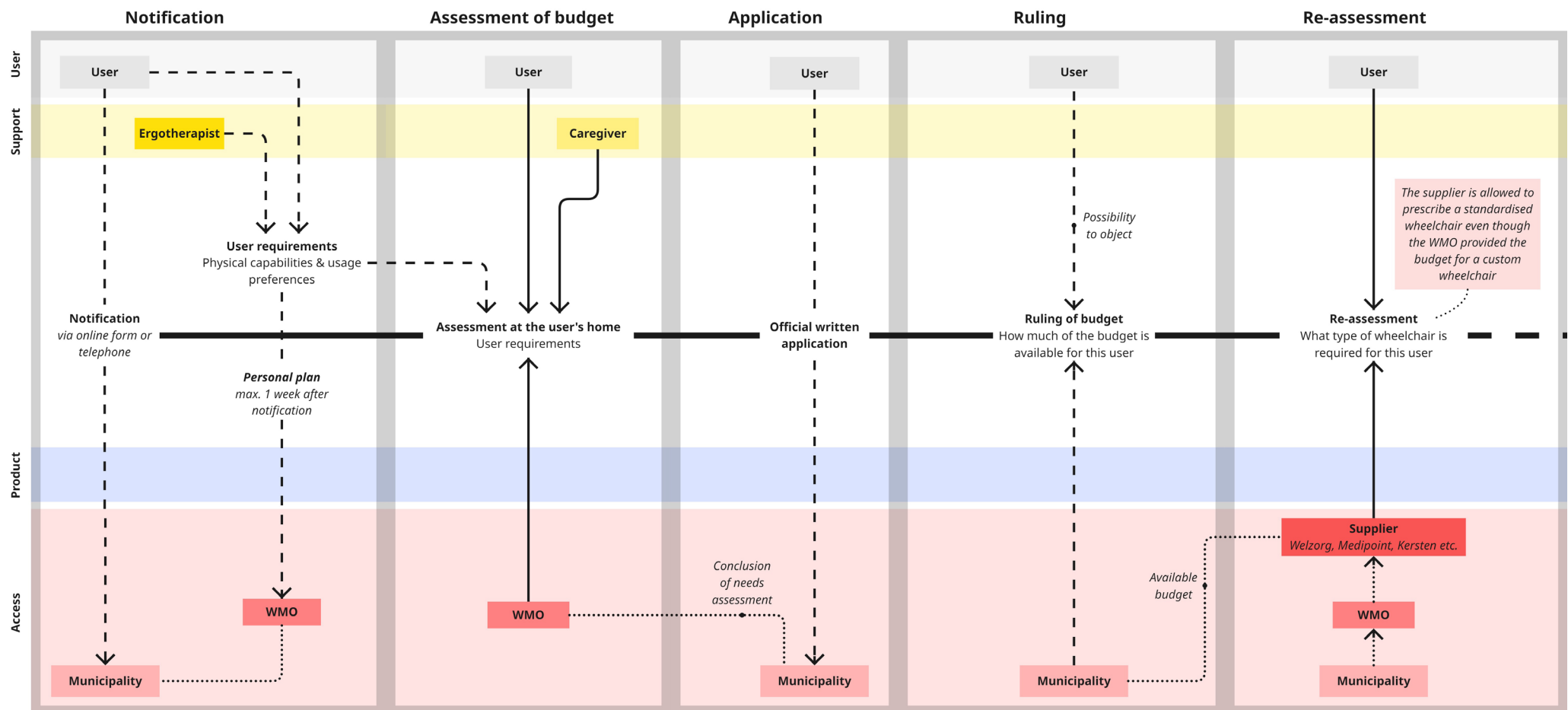


Figure 152. System overview of the stakeholders involved in the notification, assessment, application & ruling phases of a custom wheelchair

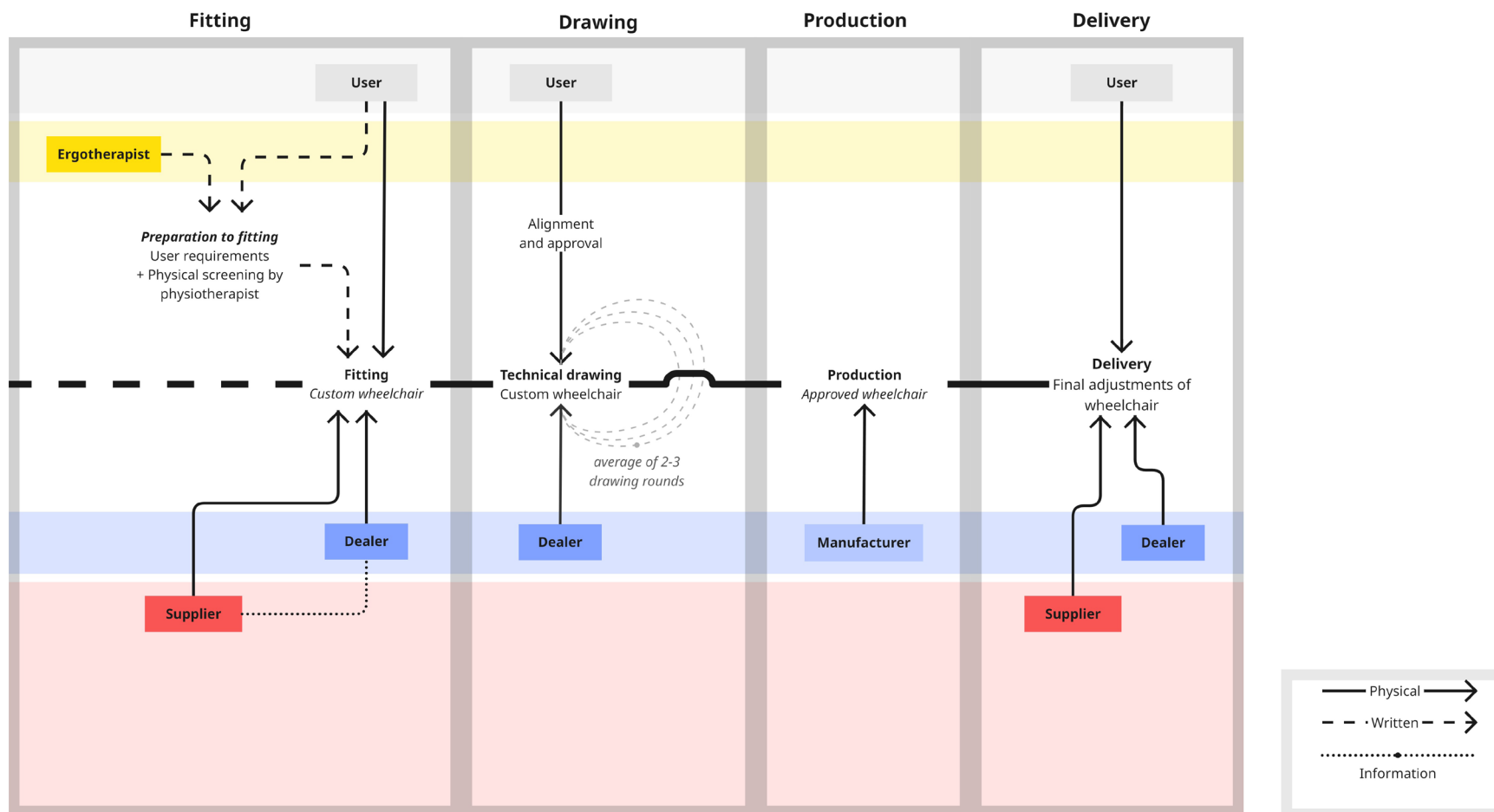


Figure 153. System overview of the stakeholders involved in the fitting, drawing, production & delivery phases of a custom wheelchair

a.5 Material properties

	Aluminium AA5086	Aluminium AA7020-T6*	Titanium Grade 9	4130 Cr-Mo Steel
Young's (elastic) Modulus	68 GPa	70 GPa	110 GPa	190 GPa
Elongation at Break	20%	10%	17%	18%
Fatigue Strength	120 MPa	130 MPa	350 MPa	660 MPa
Tensile Strength: Ultimate	270 MPa	390 Mpa	700 MPa	1040 MPa
Tensile Strength: Yield	110 MPa	310 MPa	550 MPa	980 MPa
Thermal Conductivity	130 W/m-K	86 W/m-K	8,1 W/m-K	43 W/m-K
Density	2700 kg/m ³	2900 kg/m ³	4500 kg/m ³	7800 kg/m ³
Strength-to-weight ratio	1,00E+05	1,34E+05	1,56E+05	1,33E+05
Base Metal Price (relative)	±1%	9,5%	37%	2,4%
Alloy Composition	Al: 93 – 96,3% Mg: 3,5 – 4,5%	Al: 91,2 – 94,8% Zn: 4,0 – 5,0% Mg:1,0 – 1,4%	Ti: 92,6 – 95,5% Al: 2,5 – 3,5% V: 2,0 – 3,0%	Fe: 97,3 – 98,2% Cr: 0,8 – 1,1% Mn: 0,4 – 0,6% C: 0,25 – 0,33% Mo: 0,15 – 0,25%



PEZY frame made with aluminium 5086 alloy (black coated)



Wolturnus W5 frame made with aluminium 7020-T6 alloy (natural anodised finish)

**Requires a precipitation hardening treatment after welding*



RGK HiLite frame made with grade 9 titanium alloy (natural finish)



Panthera U3 frame made with Cr-Mo steel alloy (black coated)

Table 23. Material properties of aluminium, titanium and steel alloys that are preferable to use for wheelchair frames

a.6 Calculation of tube mass and deflection

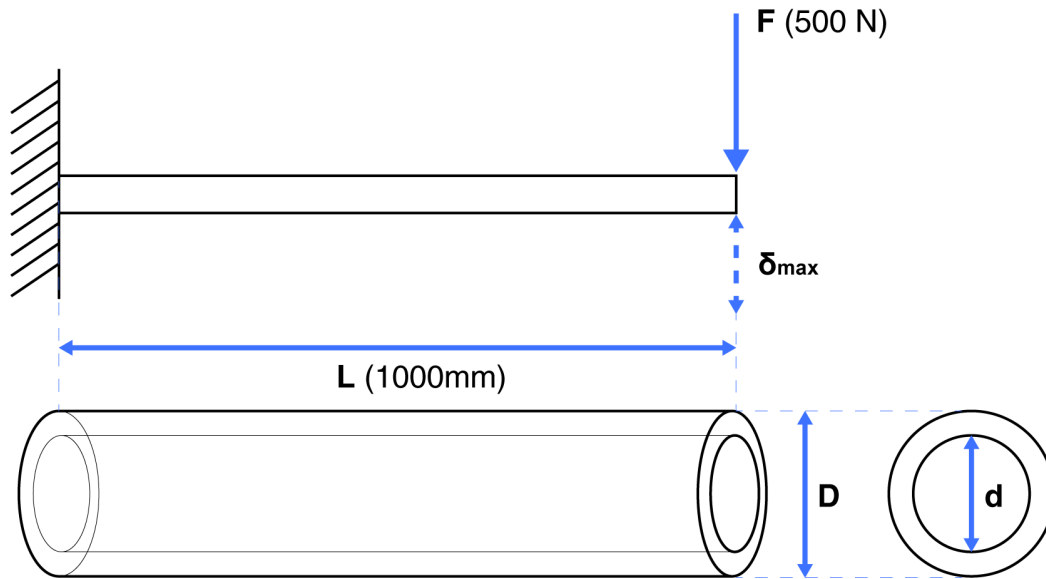


Figure 154. FBD of the calculation of deflection

Mass	$M = V \cdot \rho$
Volume	$V = \frac{\pi \cdot L \cdot (D^2 - d^2)}{4}$
Inertia	$I_{tube} = \frac{(D^4 - d^4) \cdot \pi}{64}$
Deflection	$\delta_{max} = \frac{F \cdot L^3}{2E \cdot I_{tube}}$

Table 24. Formulas for the calculations of mass and deflection

M	Mass (kg)	ρ	Density (kg/m ³) (Table 7)
V	Volume (m ³)	δ_{max}	Deflection at the end of the tube (mm)
L	Length of the tube (mm)	F	Force (N)
D	Outside diameter of the tube (mm)	E	Young's (elastic) modulus (N/m ²) (Table 7)
d	Inside diameter of the tube (mm)		

Table 25. Variables in the formulas of Table X

a.7 Tube mass and deflection

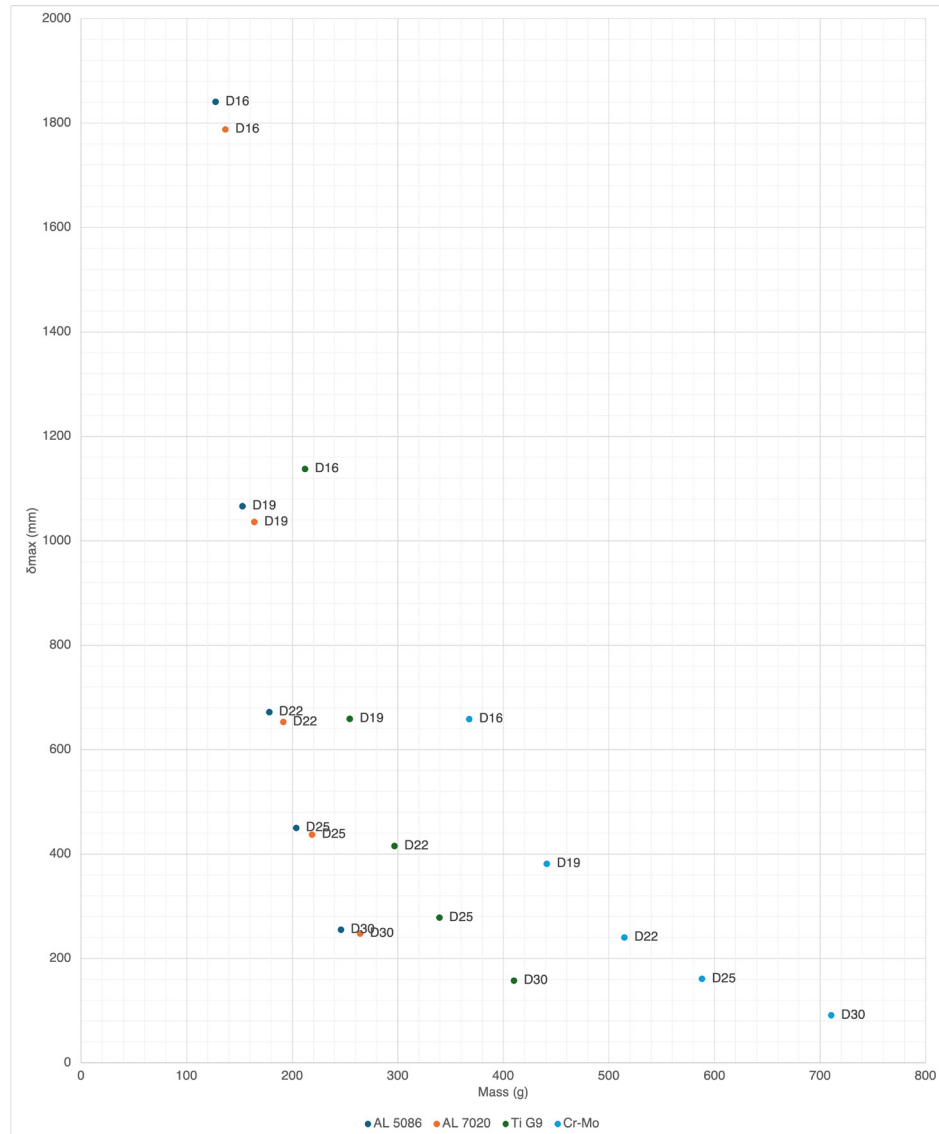


Figure 155. Mass vs. deflection of the different metal alloys

AA5086 (Aluminium)

Density	2700	kg/m ³
L	1000	mm
E	68000	N/mm ²
σ _y	110	N/mm ²
F	500	N

AA5086	Mass (g)	δ _{max} (mm)
D16 W2	127,2345	1841,112188
D19 W2	152,6814	1066,900909
D22 W2	178,1283	672,4165393
D25 W2	203,5752	450,70554
D30 W2	245,9867	255,6053042

Table 26. Mass and deflection of AA5086 Aluminium

Ti grade 9

Density	4500	kg/m ³
L	1000	mm
E	110000	N/mm ²
σ _y	550	N/mm ²
F	500	N

Ti G9	Mass (g)	δ _{max} (mm)
D16 W2	212,0575	1138,14208
D19 W2	254,469	659,5387437
D22 W2	296,88051	415,6756788
D25 W2	339,29201	278,6179702
D30 W2	409,97784	158,0105517

Table 27. Mass and deflection of Grade 9 Titanium

AA7020 (Aluminium)

Density	2900	kg/m ³
L	1000	mm
E	70000	N/mm ²
σ _y	310	N/mm ²
F	500	N

AA7020	Mass (g)	δ _{max} (mm)
D16 W2	136,65928	1788,50898
D19 W2	163,99114	1036,41803
D22 W2	191,32299	653,204638
D25 W2	218,65485	437,828239
D30 W2	264,20794	248,302295

Table 28. Mass and deflection of AA7020 Aluminium

Cr-Mo steel

Density	7800	kg/m ³
L	1000	mm
E	190000	N/mm ²
σ _y	980	N/mm ²
F	500	N

Cr-Mo	Mass (g)	δ _{max} (mm)
D16 W2	367,56634	658,92436
D19 W2	441,079609	381,83822
D22 W2	514,592877	240,65434
D25 W2	588,106145	161,30514
D30 W2	710,628258	91,479793

Table 29. Mass and deflection of 4130 Cr-Mo Steel

a.8 Construction strength

a.8.1 Simulation settings

The mesh quality was set to the coarsest option possible. Due to the relatively high complexity in the cylindrical tubes and filleted welds, this still resulted in a relatively detailed mesh. The mesh settings were kept the same for all following simulations.

The simulations of the preliminary ideation were performed with aluminium 5086 material properties. The simulations for the concept selection process were performed with aluminium AA7020 properties.

All simulations are displayed in the same colour range with 0 as the lowest end in blue and the yield stress in red.

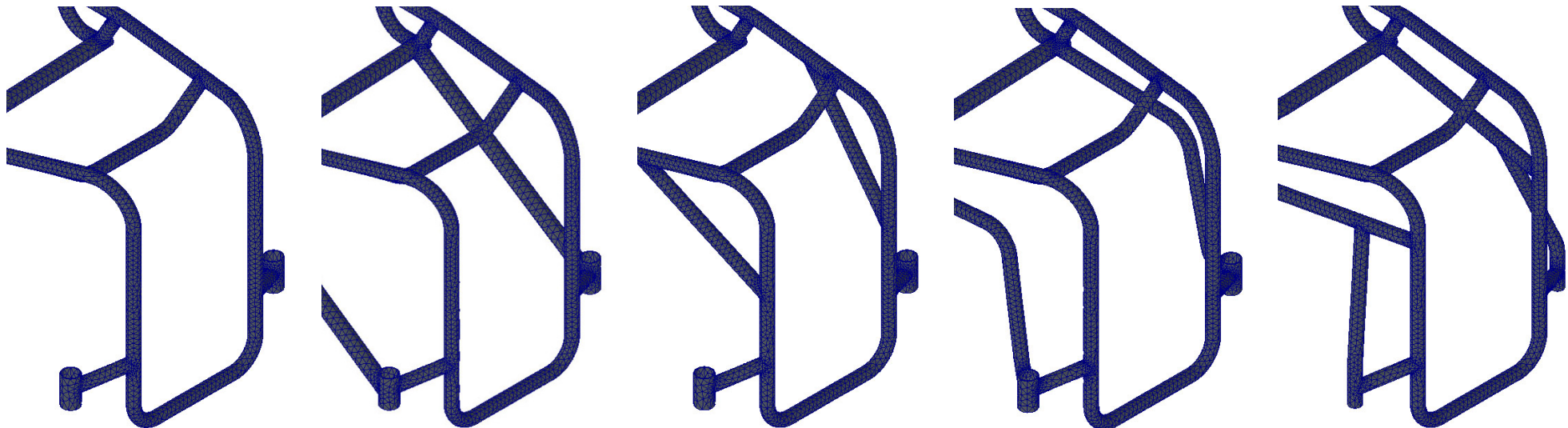


Figure 156. Meshes of the five preliminary designs (left to right): Open frame, Box frame, Corner frame, Minimal Box frame, Double frame



Figure 157. Box frame wheelchair with unfinished aluminium 5086 tubes

a.8.2 Results of scenario 1

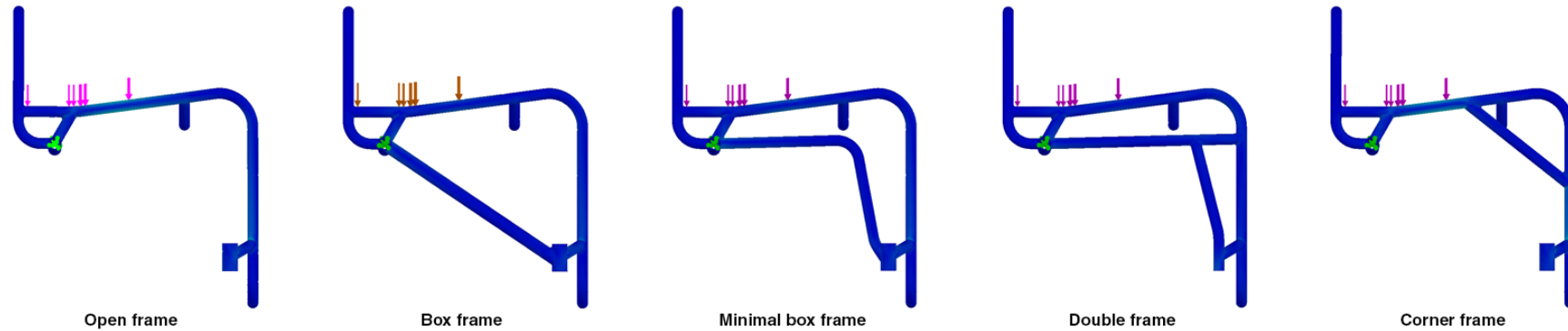


Figure 158. Simulation 1A with a distributed load of 120 kg (Fperson: 960N (80%), Ffootrest: 240N (20%))

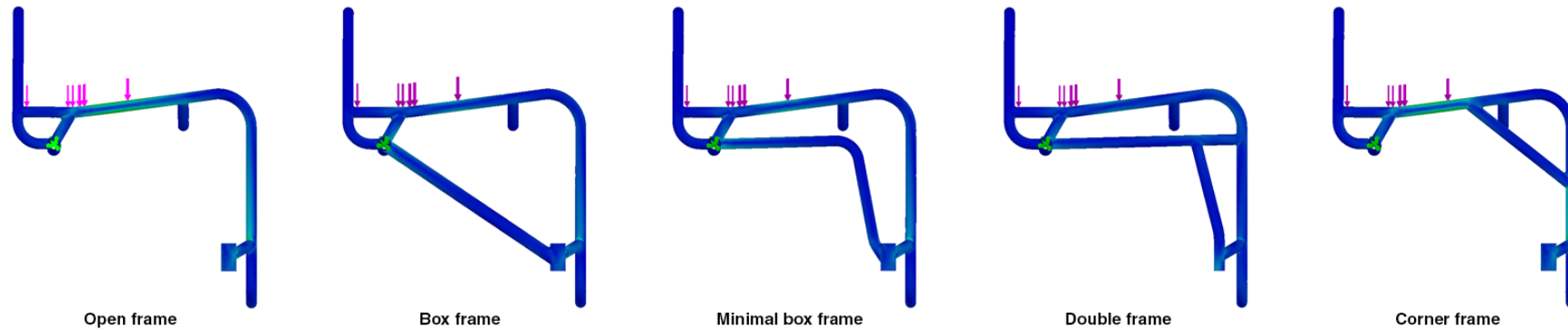


Figure 159. Simulation 1B with a distributed load of 240 kg (Fperson: 1920N (80%), Ffootrest: 480N (20%))

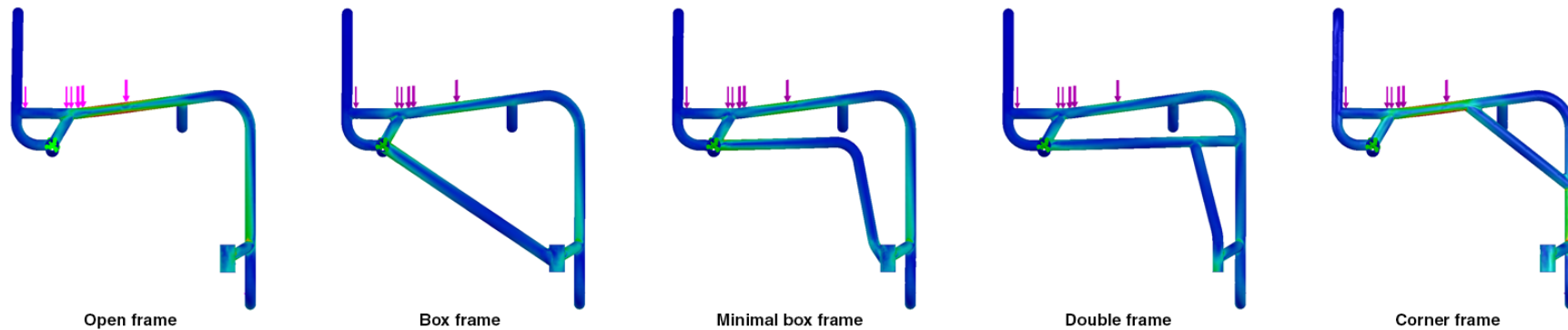
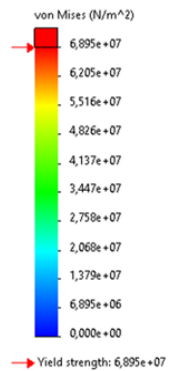


Figure 160. Simulation 1C with a distributed load of 480 kg (Fperson: 3840N (80%), Ffootrest: 960N (20%))



a.8.3 Results of scenario 2

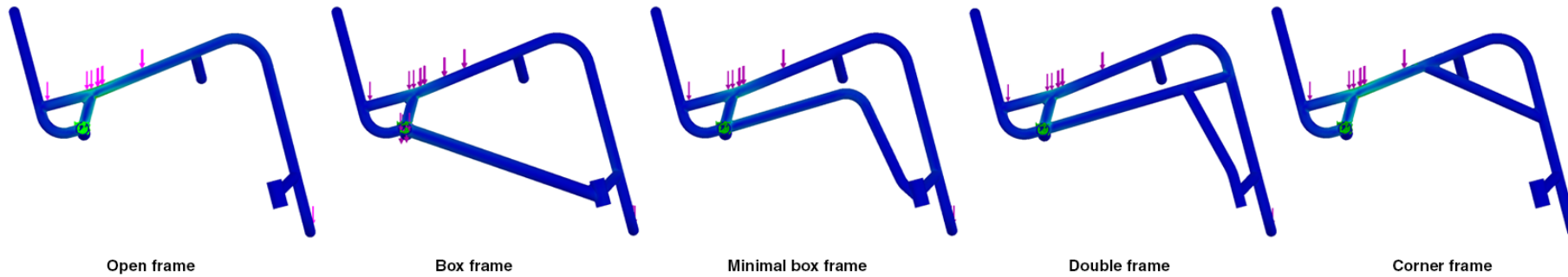


Figure 162. Simulation 2A with a distributed load of 120 kg (Fperson: 1140N (95%), Ffootrest: 60N (5%))

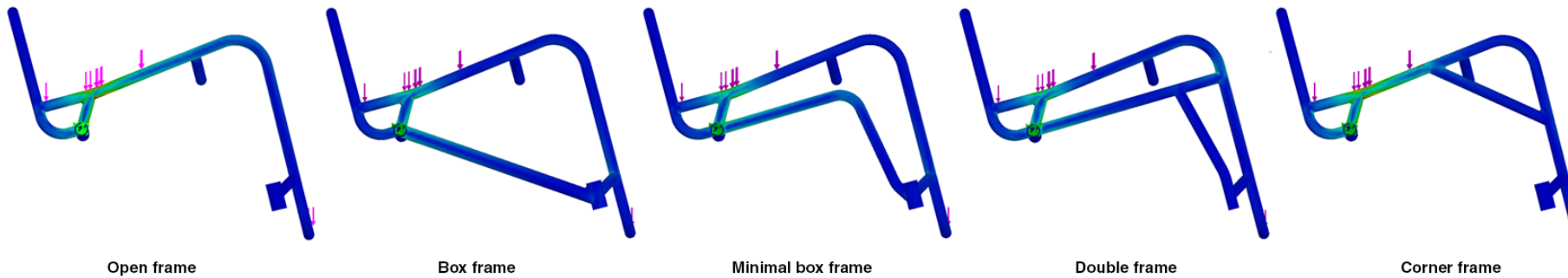


Figure 161. Simulation 2B with a distributed load of 240 kg (Fperson: 2280N (95%), Ffootrest: 120N (5%))

b. Appendix | Synthesis

b.1 Stress performance | Concepts

ID	Open	Box	A	B	C	D	E	F	G	H
Mass (g)	1784.07	2157.06	1958.82	2104.44	2069.27	2145.09	2181.37	2149.90	2087.60	1975.29
Weight saved (g)	-392.99	0.00	-198.24	-52.62	-87.79	-11.97	24.31	-7.16	-69.46	-181.77
Design	Isometric									
	Side view									
	Top view									

ID	Open	Box	A	B	C	D	E	F	G	H
Stress performance	0.5	3	1	2	2	3	3.5	3.5	0	1.5
Yield strength performance										

ID	Open	Box	A	B	C	D	E	F	G	H
Peak stress performance										

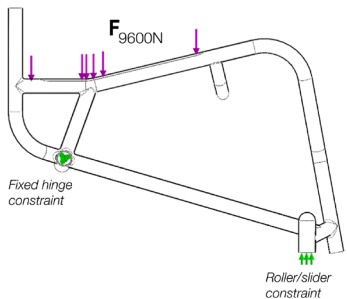
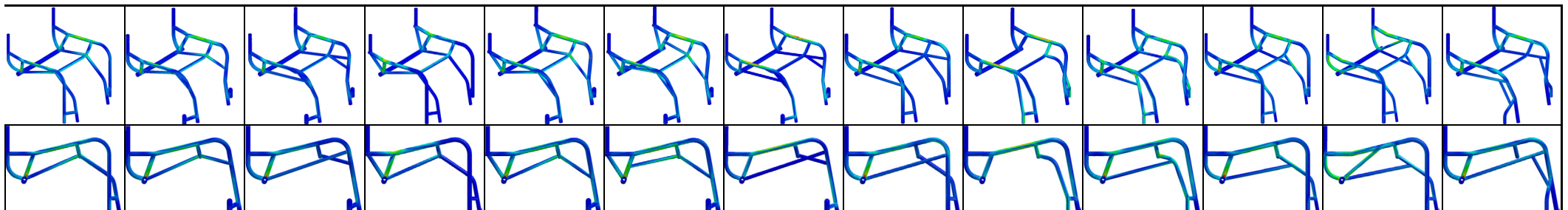
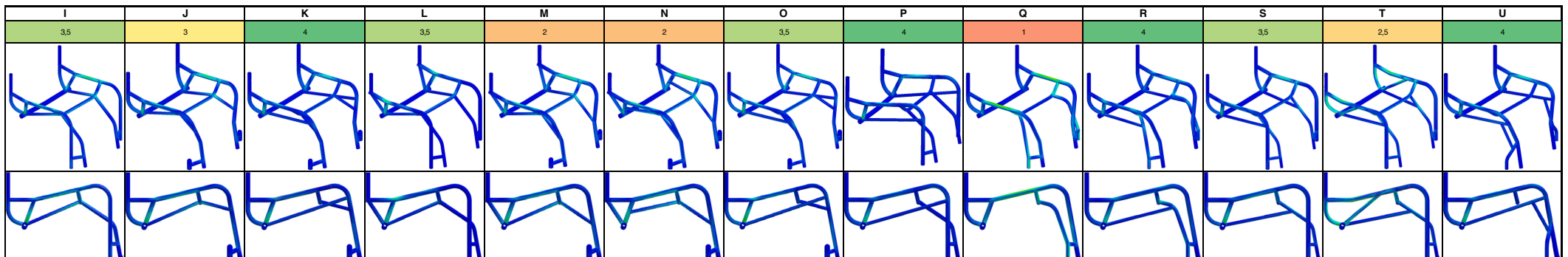
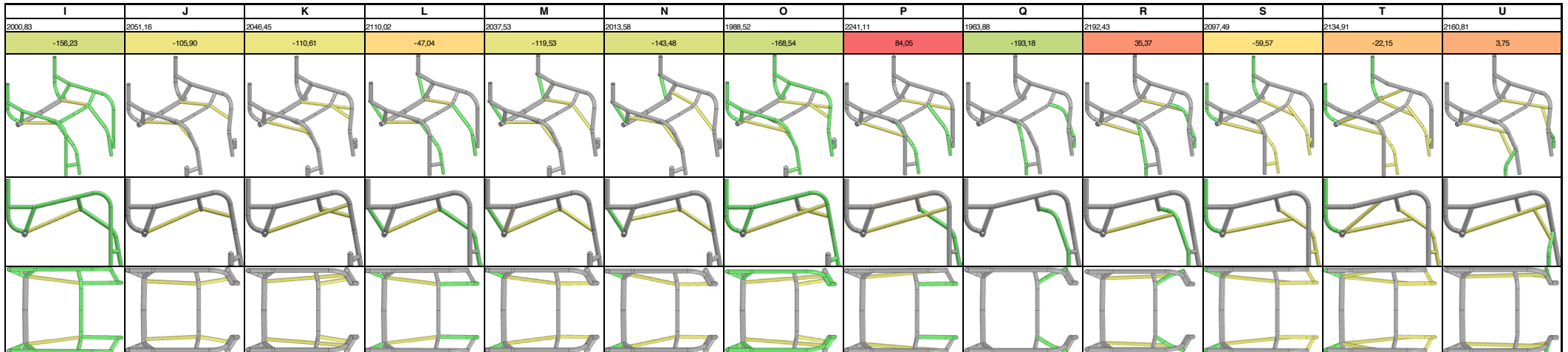


Figure 163. Simulation settings | Illustrated on Box frame design

Figure 164. Overview of the 21 designs with stress simulation results



b.2 Selection | Concept

<i>Made-to-measure</i>	All 21 designs should be customisable in the same way that the Box frame is, for they were designed with the Box frame as a reference.
Transportability	The transportability is difficult to assess without building the frame in real life. To make it quantifiable, I split the criterium into a criterium for the shape (subjectively assessed) and the weight (objective estimation in SolidWorks).
<i>Stability</i>	The experienced stability can't be tested without riding in the wheelchair. Therefore it is not assessed here.
Aesthetics	Subjective assessment based on the novelty of the shape and its recogniseability.
<i>Rigidity</i>	The rigidity of the frame is based on the material and how it is manufactured. All of the compared concepts are conceptualised with the same material and they are all fixed, welded frames. To validate the rigidity of the frame, a double drum test is required.
Stress performance	The stress performance is compared by applying an equal load vertical to the seat of each frame.
Feasibility	Assessment based on what I know about the manufacturing capabilities of the factory.
Complexity	Assessment based on what I know about the manufacturing efficiency of the factory.
Estimated cost	Estimated based on the total length of the tube material.

	Box frame	K	O	F	-	L	S
Weight saved (g) *	0,00	-110,61	-168,54	-7,16	-156,23	-47,04	-59,56
Total tube length (mm)	5145,04	5460,26	5460,26	5462,42	5462,42	5438,04	5575,6
Bent tubes							
<i>Total</i>	6	6	6	8	8	6	8
<i>2D</i>	4	4	4	8	8	6	8
<i>3D</i>	2	2	2	0	0	0	0
Straight tubes	8	10	10	6	6	10	6
Bending diameters	3	3	2	3	2	3	4
Cuts/Welds	18	22	20	20	20	22	20

Table 32. Weight, Tube length and Complexity of the concepts

Table 30. Reasoning for the criteria that were assessed in the rating of the concepts

	Criteria	Description	1	3	5
Design 40%	Transportability	The shape allows for easier transport by car	Similar to Box frame	A little better but not very convincing	Shape to Open frame
	Weight	How much does the design weight (estimate)	<50 grams lighter	50-150 grams lighter	>150 grams lighter
	Aesthetics	How attractive is the design	Not attractive	Boring, but not ugly	Interesting/attractive
Performance 25%	Stress distribution	Distribution of stress throughout the frame	Stress located at welds	Some areas are affected more than others	Perfect distribution
Business 25%	Feasibility	Can it be manufactured using in-house skills/tools	Requires training and/or new machinery (high investment)	Skills/tools not yet available but compatible with existing machines (small investment)	All skills/tools available. (no investment)
	Complexity	How difficult/time consuming is it to manufacture	More than Box frame	Similar to Box frame	Less than Box frame
	Material cost	Rough estimate	More than Box frame	Similar to Box frame	Less than Box frame

Table 31. Rubric for concept rating

c. Appendix | Final Design
c.1 Simulations

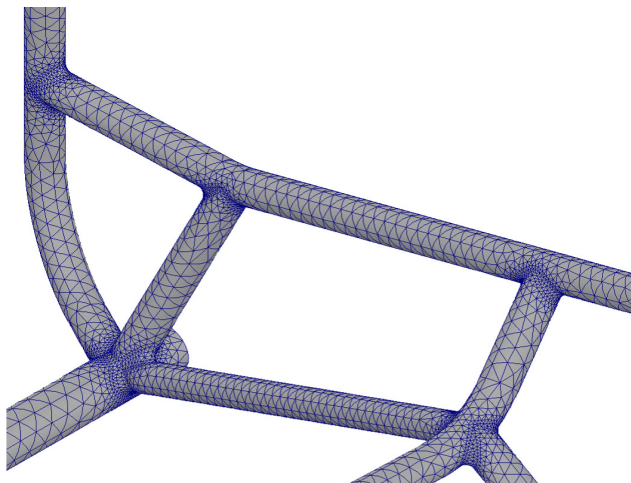


Figure 165. Mesh settings

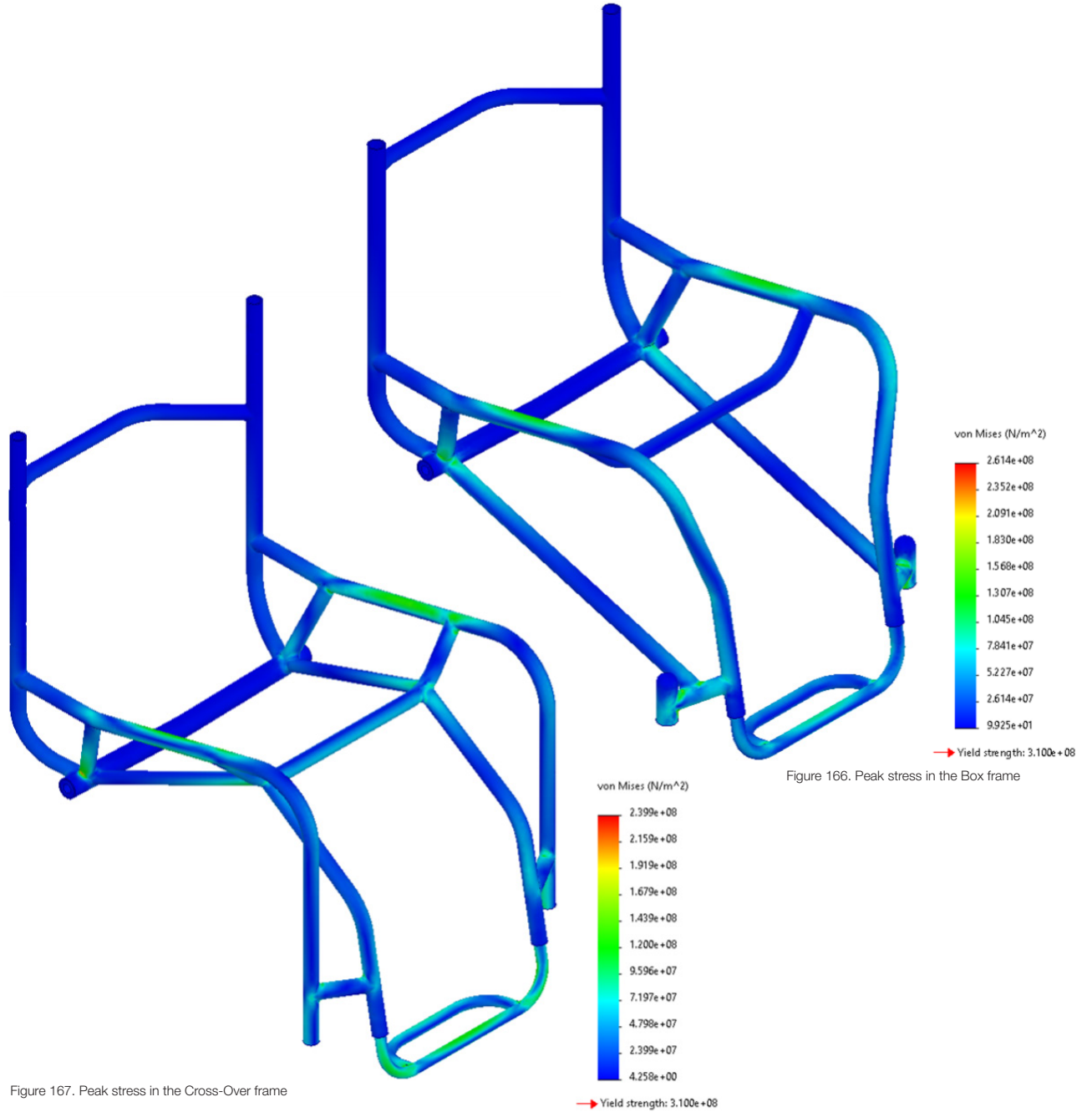


Figure 166. Peak stress in the Box frame

Figure 167. Peak stress in the Cross-Over frame

c.2 Components

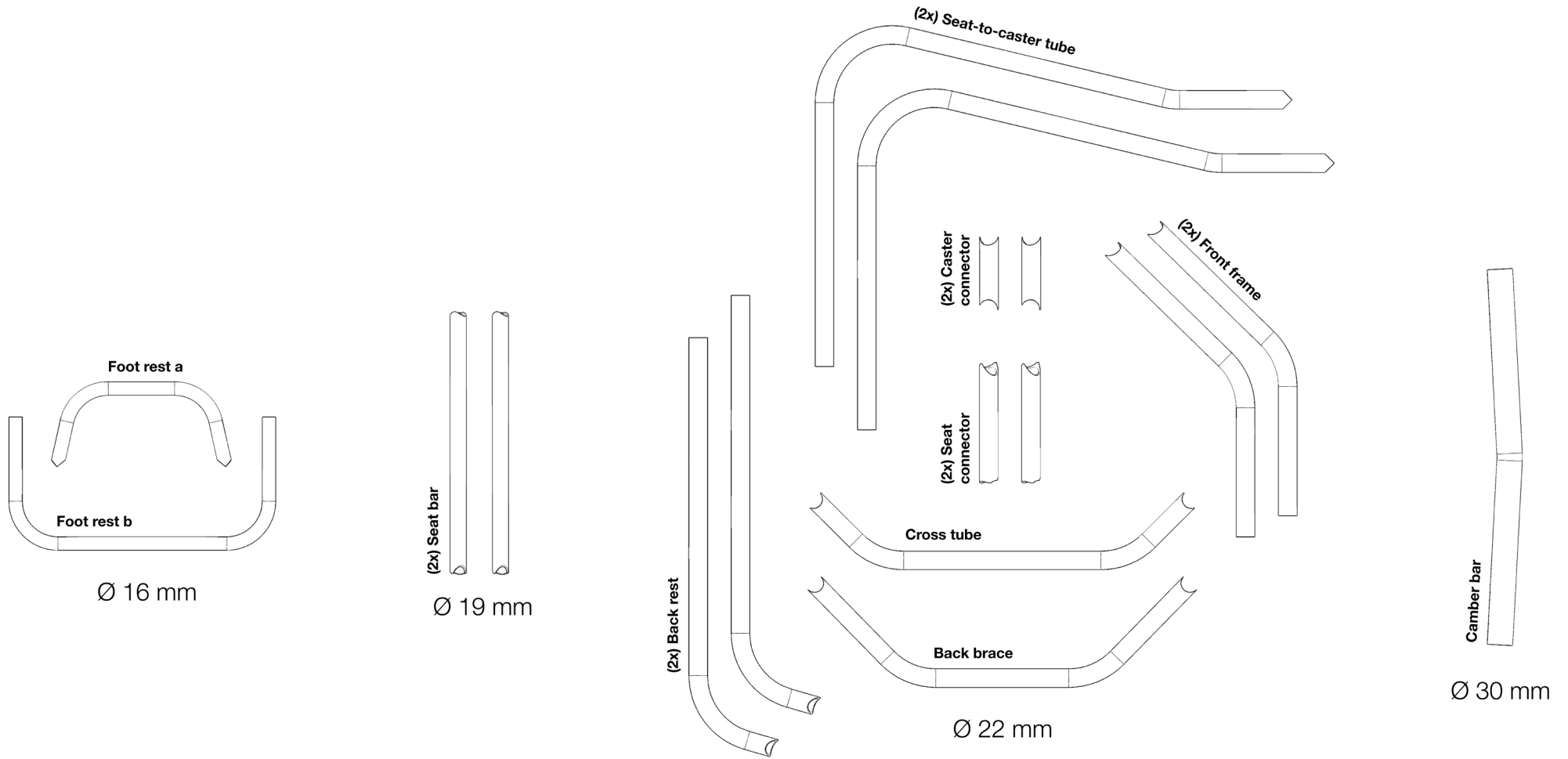


Figure 168. Indication of components and tube diameters in final design

c.3 Comparison of tube diameters

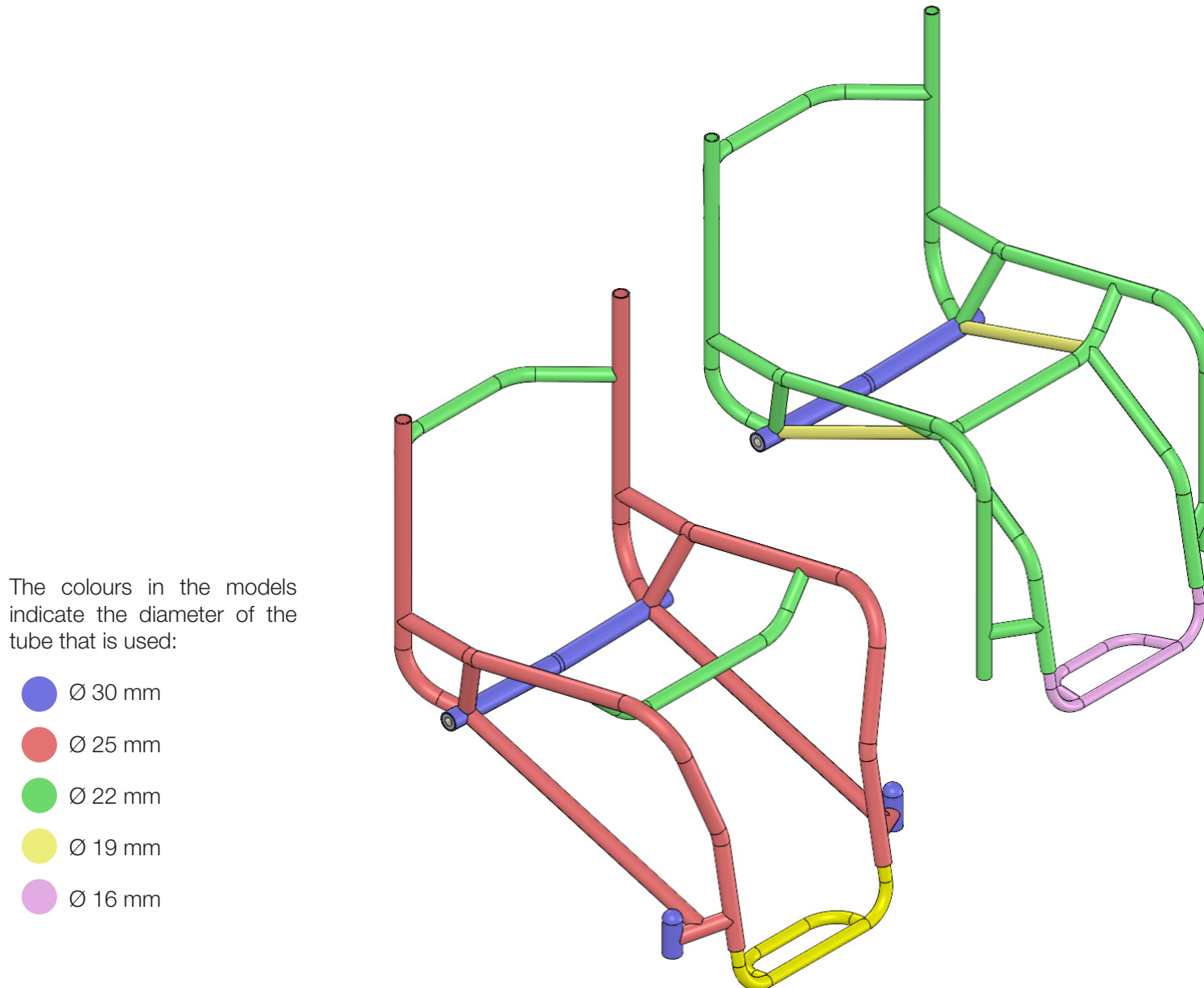
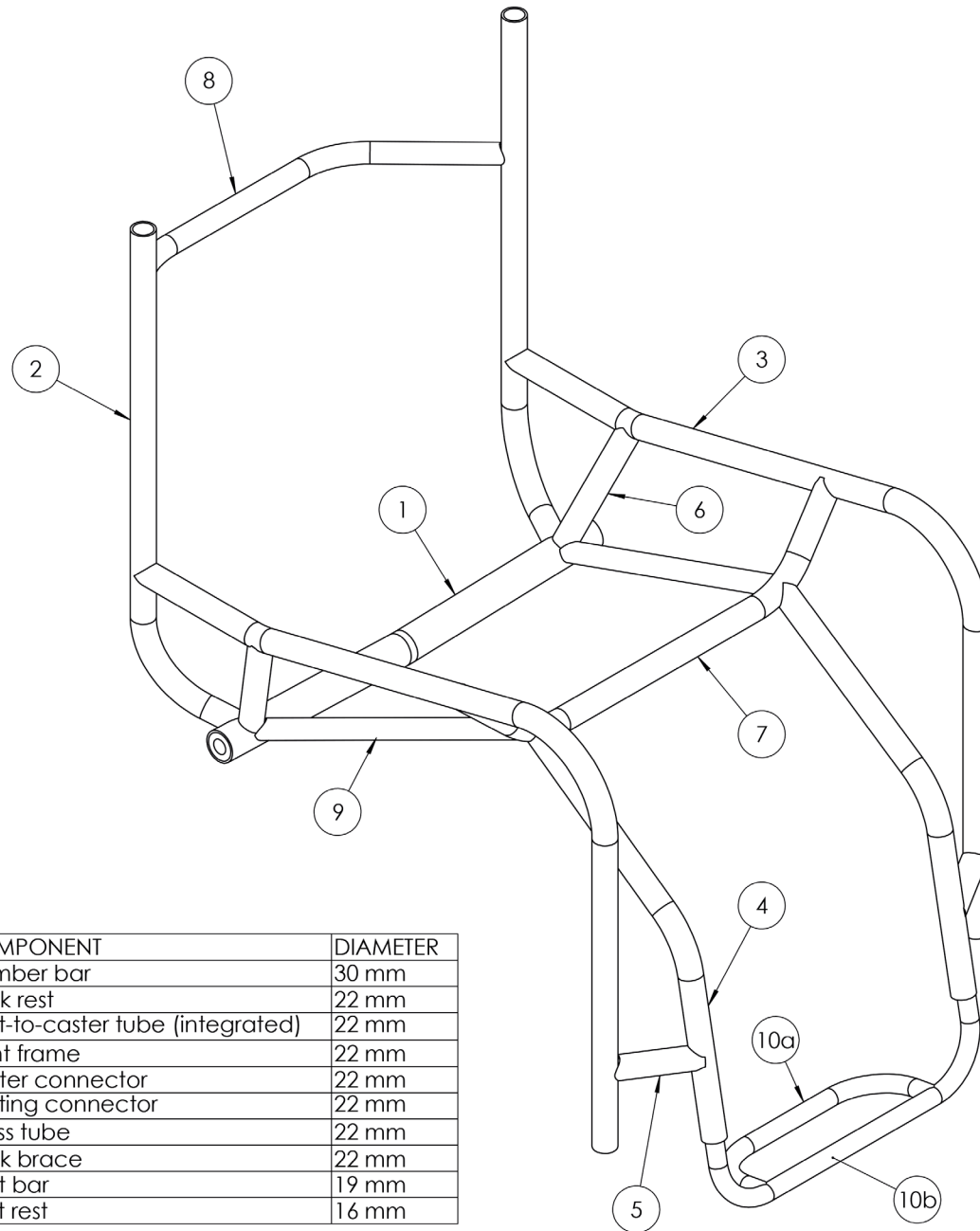


Figure 169. Indication of tube diameters in Box frame and final design

c.4 Production time estimation

<i>Cross-Over frame</i>						
Amount	Type	Component	Diameter	Length (cm)	Total length (cm)	Time (minutes) <i>Additional information</i>
						30 <i>Preparing the machine to bend 30 mm tubes</i>
1	Bent	Camber	30	44,6	45	5 <i>Produced in batches so no time is needed to program the machine. Can be cut to size</i>
						30 <i>Preparing the machine to bend 22 mm tubes</i>
1	Bent	Back brace	22	53,2	53	10 <i>Simple component, very little deviation</i>
1	Bent	Cross tube	22	49,8	50	10 <i>Simple component, very little deviation</i>
2	Bent	Backrest	22	54,6	109	10 <i>Simple component, very little deviation</i>
2	Bent	Seat to caster	22	92,1	184	20 <i>Complex component, will take more tries during the first few prototypes. After this, the factory worker will know which parameters to program in the machine to get more precise results.</i>
2	Bent	Front frame	22	42,6	85	10 <i>Simple component, very little deviation</i>
						30 <i>Preparing the machine to bend 16 mm tubes</i>
1	Bent	Footrest	16	55,7	56	10 <i>Simple component, very little deviation</i>
1	Bent	Footrest flat	16	30,7	31	5 <i>Produced in batches so no time is needed to program the machine</i>
2	Cut	Seat connector	22	15,0	30	1
2	Cut	Caster connector	22	8,6	17	1
2	Cut	Seat bar	19	32,8	66	1
					615 cm	173 minutes ±2,9 hours
<i>Box frame</i>						
Amount	Type	Component	Diameter	Length (cm)	Total length (cm)	Time (minutes) <i>Additional information</i>
						30 <i>Preparing the machine to bend 30 mm tubes</i>
1	Bend	Camber	30	44,6	45	5 <i>Produced in batches so no time is needed to program the machine. Can be cut to size</i>
						30 <i>Preparing the machine to bend 25 mm tubes</i>
1	Bend	Back brace	25	53,2	53	10 <i>Simple component, very little deviation</i>
2	Bend	Backrest	25	54,6	109	10 <i>Simple component, very little deviation</i>
2	Bend	Seat to front frame	25	93,4	187	40 <i>Complex component, the 3D bent shape makes it more difficult to scan the shape. Because there are more parameters that influence the bends, it is more difficult to program the machine.</i>
						30 <i>Preparing the machine to bend 22 mm tubes</i>
1	Bend	Cross tube	22	49,8	50	10 <i>Simple component, very little deviation</i>
						30 <i>Preparing the machine to bend 19 mm tubes</i>
1	Bend	Footrest	19	55,7	56	10 <i>Simple component, very little deviation</i>
1	Bend	Footrest flat	19	30,7	31	5 <i>Produced in batches so no time is needed to program the machine</i>
2	Cut	Seat connector	25	15,0	30	1
2	Cut	Cross bar	25	50,4	101	1
2	Cut	Caster connector	25	9,2	18	1
2	Cut	Caster	30	7,5	15	1
					650 cm	214 minutes ±3,6 hours

Table 33. Estimation of production time for the Cross-Over frame and the Box frame



#	COMPONENT	DIAMETER
1	Camber bar	30 mm
2	Back rest	22 mm
3	Seat-to-caster tube (integrated)	22 mm
4	Front frame	22 mm
5	Caster connector	22 mm
6	Seating connector	22 mm
7	Cross tube	22 mm
8	Back brace	22 mm
9	Seat bar	19 mm
10	Foot rest	16 mm

Figure 170. Indication of where components and tube diameters are placed in the Cross-Over frame

c.5 Technical drawing

- SH-f Seat height front
- SH-r Seat height rear
- FD Frame depth
- RA Rear axle placement
- ES Ergonomic seat length
- CTP Cross tube placement
- CTD Cross tube depth
- FL Frame length
- CP Castor placement
- BH Back height
- BD Back depth
- TH Back tube height
- FRH-f Foot rest height front
- FRH-r Foot rest height rear
- FRD Foot rest depth
- FB Front bend
- FF Front frame width
- CW Castor width
- C Camber angle
- SW Seat width
- SF Seat frame length

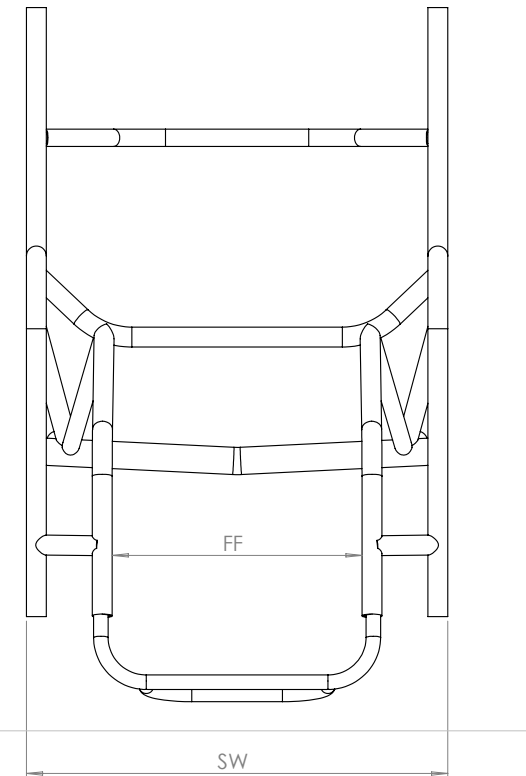
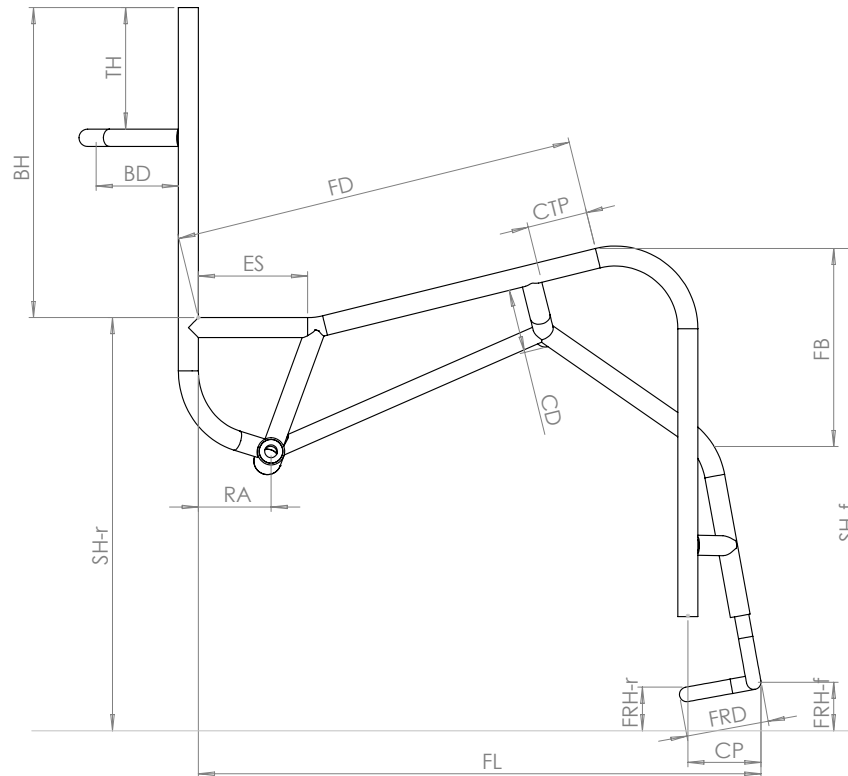
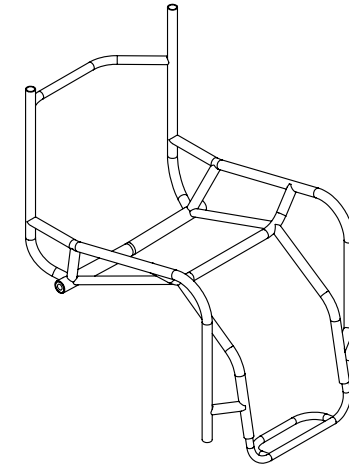
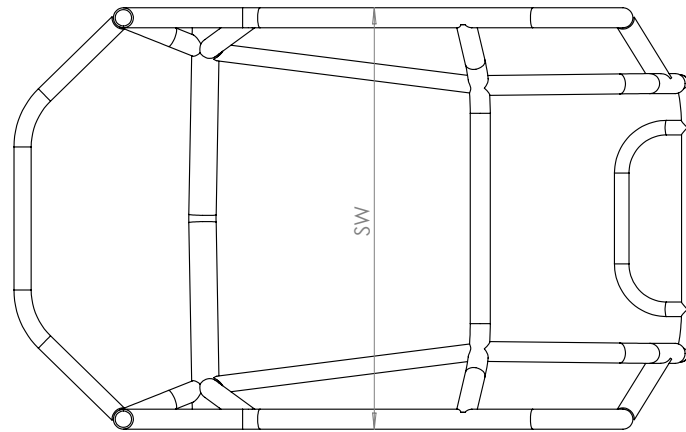


Table 34. Parameters in technical drawing

Figure 171. Technical drawing of final design

c.6 Technical drawing of a custom frame

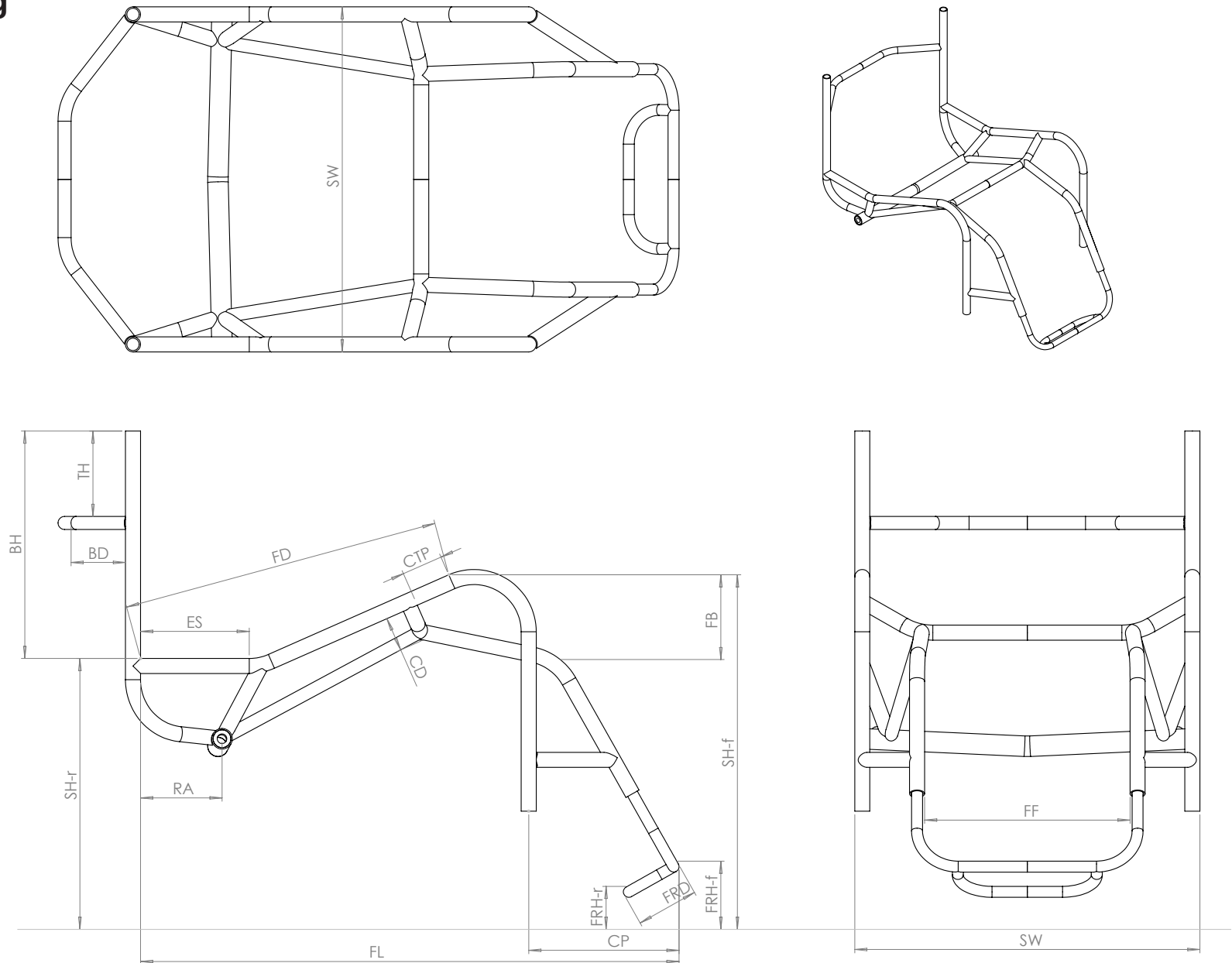


Figure 172. Technical drawing of a custom frame

d. Appendix | Evaluation

d.1 List of Requirements

ID	Keyword	Requirement	Assessment	MoSCoW	Additional notes	Reference
A. General						
A1 Product						
A1.1	Manual wheelchair	Manual wheelchair designed to be propelled and steered using handrims	The frame is a manual wheelchair	M		(International Organization for Standardization, 2008)
A1.2	Made-to-measure	Frame is custom designed and manufactured for use by a named individual occupant	The improved manufacturability of the frame makes it easier to bend custom tubes for individual users	M	User has limited core muscle control: User needs to be stable in the seat for they are unable to stabilise themselves	(RGK, z.d.; Van Breukelen, 2020); (Nederlands Normalisatie-instituut, 2022)
A2 Design						
A2.1	Active use	Design reflects active use	The frame is designed for active wheelchair use. The design is optimised for individual mobility by improving the transportability of the frame.	C	Also increases sense of ownership	(More et al., 2025)
A2.2	Recognisable	The design is recognisable / indistinguishable from similar products	The design is recognisable unique by crossing the caster over the front frame of the wheelchair.	M		
A3 Impact						
A3.1	Longevity	Designed to last for at least 7 years	Expected, but this can only be validated through a performance test with an aluminium prototype	S		
A4 Market						
A4.1	Pricing	Pricing is lower than current custom wheelchair prices: below €6000	Expected due to the improved manufacturability of the frame. This could save time, which would lower production costs.	S	Allows for increased interest of wheelchair suppliers; Prices range between €6000 and €8000	
B. User						
B1 Use aspects						
B1.1	Independent movement	User is able to independently use the wheelchair to move around in and around their house, at school or work and other (narrow) built environments	The frame has the same outer dimensions as the box frame, so the mobility experience in ADL use is expected to be the same as with existing wheelchair frames.	M		
B1.2	Manoeuvring environments	User can manoeuvre through & outside of built environments (permanent obstacles)		M	On the legs, pushbar, footrest or other parts of the wheelchair	
B1.3	Interaction with objects	User can interact with and manoeuvre around objects		M		
B1.4	Transfer	User can transfer (sideways) in/out the wheelchair	The frame has the same outer dimensions as the box frame and allows for space to place the hands, similar to the box frame design. Therefore expected to perform the same	M		(Nederlands Normalisatie-instituut, 2022)
B1.5	Independent use	User can lift/move the wheelchair independently	The frame is designed for improved transportability, by minimising the space used underneath the frame and reducing the overall weight of the frame.	M		
B1.6	Independent transport	User can transport the wheelchair independently by car		M	Frame can be lifted from the ground up, over the driver seat	
B1.7	Travel & Commute	User is able to travel and commute with the wheelchair		M	Frame fits within travel dimensions	
B1.8	Transporting small loads	User can transport small loads on the wheelchair	Expected, as the stress performance of the frame showed similar results to the box frame. Further testing recommended.	S		

C. Functionality						
C1 General (Wheelchair)						
C1.1 Dimensions						
C1.1.1	Total weight	Total weight of the wheelchair is suitable for active ADL use is below 15 kg	Improved. The frame is 233 grams lighter than the box frame, which can be lifted by the user.	M	Without causing pain or injury; The wheelchair frame should be light enough to lift it over the user with the wheels attached. Market (<7,5 kg)	(Wheelchair Skills Team, 2025)
C1.1.2	Transport weight	Transport weight of the frame can be lifted by the wheelchair user is below 6 kg		M	Average transport weight is 4-8 kg (no wheels/cushioning)	(Wheelchair Skills Team, 2025)
C1.1.3	Max load (user weight)	Wheelchair can transport a max load of 120 kg	The stress performance simulations in SolidWorks show that the frame is able to support at least 8 times the maximum load of 120kg with a performance similar to the box frame	M	RGK HiLite XTR: 115 kg Wolturnus W5: 150 kg	
C1.1.4	Wheelchair length	The maximum length of the wheelchair doesn't extend beyond 1200 mm	The dimensions of the wheelchair are dependent on the made-to-measure requirements of the user. The frame can be customised within a range of dimensions (C2) which will not extend beyond the ISO standardised measurements.	M	Full overall length	(International Organization for Standardization, 2008)
C1.1.5	Wheelchair width	The maximum width of the wheelchair smaller than 700 mm		M	Average adult seating width is 45-50 cm --> total width 65-70 cm	(International Organization for Standardization, 2008; Wheelchair Skills Team, 2025)
C1.1.6	Wheelchair height	The maximum height of the wheelchair below 1200 mm		M	Max occupied height is 1500 mm	(International Organization for Standardization, 2008)
C1.1.7	Turning diameter	Turning diameter of the wheelchair smaller than 1000 mm		M	The minimum diameter of a circular space required for the wheelchair to make a 180° turn (typically a U-turn)	(International Organization for Standardization, 2008)
C1.2 Transport						
C1.2.1	Train transport dimensions	Wheelchair can be transported by train; 150 x 70 x 137,5 cm	The dimensions of the wheelchair are dependent on the made-to-measure requirements of the user. The frame can be customised within a range of dimensions (C2) which will not extend beyond the maximum dimensions for public transport	M	NS	(NS Reizigers B.V., 2021)
C1.2.2	Public transport dimensions	Wheelchair can be transported by bus, metro or tram; 120 x 170 x 109 cm		M	Connexion, HTM, RET	(Connexion, z.d.; HTM, z.d.; RET, z.d.)
C1.2.3	Fixed transport	Wheelchair can be fixed to prevent movement while transporting in a vehicle	Expected. Requires additional component for attachment of straps	W	Wheelchair doesn't move around while the vehicle is in motion	
C2 Essential & secondary components						
C2.1 Backrest construction						
C2.1.1	Backrest depth	Backrest depth is customisable to 0.5mm increments	The frame is designed parametrically, using the same parameters as used to construct existing custom active wheelchair frames.	M	Lumbar depth (seating depth) is a critical dimension. 0.5cm can already have a noticeable effect.	(Van Breukelen, 2020)
C2.1.2	Backrest height	Backrest height: 200 - 500 mm		M	Dimensions based on averages in market overview & ergonomics; Backrest height shouldn't extend over 20 mm below the scapulae inferior angle.	(Cherubini & Melchiorri, 2012)
C2.1.3	Backrest frame	Minimises the development of kyphosis and lordosis	Expected to be similar to the box frame. The frame uses the same ergonomic seating construction as similar frames on the market. The final design of the frame was validated with a spinal cord injured user.	S	Seat & backrest frame shape	(Koontz & Druin, 2009; Van Breukelen, 2020)
C2.1.4	Folding backrest	The frame is compatible with a folding backrest system	Frame is not yet compatible due to the diameter of the backrest tube that is used. A folding system similar to existing hinges could be developed to accommodate this tube diameter.	C	Optional configuration, useful for transportation of the wheelchair by car	

C2.2 Seating construction & leg support						
C2.2.1	Seat width	Seat width: 300 - 500 mm	The dimensions of the wheelchair are dependent on the made-to-measure requirements of the user. This range is based on the average range of measurements used in similar competing wheelchair frames (market overview)	M	Dimensions based on averages in market overview; The width of the seat should be very precisely fitted to allow the user to lean forwards without losing contact with the wheelchair.	
C2.2.2	Seat depth	Seat depth: 250 - 500 mm		M	Dimensions based on averages in market overview	
C2.2.3	Seat height (back)	Seat height (back): 300 - 550 mm		M	Dimensions based on averages in market overview	
C2.2.4	Seat height (front)	Seat height (front): 300 - 550 mm		M	Dimensions based on averages in market overview; If SH is too high, user is unable to get their knees under tables	
C2.2.5	Seating frame	Seating frame allows for proper postural support	The frame uses the same ergonomic seating construction as similar frames on the market. The final design of the frame was validated with a spinal cord injured user, but was not yet tested with the user in the seat.	M	Ergo seat	
C2.2.6	Pelvic positioning	Ergonomic seat promotes neutral to slight anterior tilt of the pelvis		M	Equal weightbearing through the ischial tuberosities	(Koontz & Druin, 2009; Van Breukelen, 2020)
C2.2.7	Cross tube under seat	Frame is constructed with a cross tube under the front of the seat	Frame is constructed with a cross tube	M	For handbike attachment; cross tube should be placed 7cm backwards from the seat cushion. This tube can also be mounted afterwards.	Interviews
C2.2.8	Front frame	Frame provides sideways support to the legs	Frame provides sideways support between the front frame tubes above the footrest	M	Preventing movement and unwanted sideways leaning in the chair. Also makes turning with one hand possible	Interviews
C2.2.9	Footrest adjustability	Front frame is constructed with parallel tubes, allowing for height adjustments to the footrest	Front frame tubes are placed parallel, allowing for the option of footrest adjustability	M	Footrest slides into the tubes of the front frame, this is only possible if the tubes are parallel. Adjustability is desirable, because the height of different shoes can impact the way the user sits in the wheelchair.	
C2.2.10	Bare frame comfort	User sits comfortably when cushioning is removed for short distances	Frame performs similar to the box frame. This was considered out of scope	W	Useful in wet environments (swimming pool etc.)	
C2.2.11	Hand placement	The seat frame must allow space to place the hands during transferring.	The frame has the same outer dimensions as the box frame and allows for space to place the hands, similar to the box frame design. Therefore expected to perform the same	M		
C2.2.12	Obstruction	Wheelchair frame shouldn't obstruct reach of the user when bowing down to grab something	Expected. The frame has more empty space underneath the frame. To confirm this, a prototype needs to be built to allow for actual user testing	M		
C2.3 Camber bar						
C2.3.1	Center of gravity	The wheel axle can be placed in the appropriate place to the center of gravity	Axle placement is similarly configurable to existing custom frames	M	For general stability in the wheelchair and to perform wheelies	
C2.3.2	Fixed center of gravity	The wheel axle can be welded to fixate positioning	Concept is designed with a fixed axle position. To allow for adjustability, the axle to backrest connection would have to be slightly altered.	S		

C3 Related components						
C3.1	Lumbar support	Backrest is compatible with standard adjustable upholstery	Backrest construction remains unchanged compared to other active wheelchair frames. The diameter of the tubes is slightly thinner. Compatibility is expected.	S	Allows users with special upholstery needs (f.e. decubitus) to use the frame	
C3.2	Cushion compatibility	The seating frame is compatible with existing seating cushions	Seat frame construction remains unchanged compared to other active wheelchair frames. The diameter of the tubes is slightly thinner. Compatibility is expected.	S	Allows users with special upholstery needs (f.e. decubitus) to use the frame	
C3.3	Castor wheels	Castor wheels don't interfere with the footplate of the user	The dimensions of the wheelchair are dependent on the made-to-measure requirements of the user. The range of these measurements is based on the averages of similar frame types.	M		
C3.4	Leg strap	The frame is compatible with existing leg strap systems to support the calves	Expected. Requires additional component for attachment of straps	W	Used to increase the stability of the user	Interviews
C3.5	Handbike attachment	Frame is compatible with hand bike attachments	The frame is compatible with both hand bike systems. The placement of the camber bar and cross tube remain unchanged compared to existing frames. The front frame of the wheelchair is different, but the maximum seat width (C2.2.1) is compatible with the attachment range of front frame-connecting-hand bike systems	S	Either on the leg frame or beneath the seat on to a cross tube	Interviews
D. Manufacturing						
D1 Producability						
D1.1	Parametric design	Frame is parametrically modelled in SolidWorks	The frame is parametrically modelled in SolidWorks	S	Allows for easy manipulation of standard parameters	
D1.2	Customisability	Technical drawing of the frame can be easily adjusted for unique customisations	The CAD model can be altered by changing the values in the equations. This automatically alters the technical drawing.	M		
D1.3	Manufacturing time	The frame can be manufactured faster than the current frame types	The frame is constructed using only 2D bent tubes. These tubes are expected to be bent with minimal deviations. This reduces manufacturing time, compared to the box frame. Additionally, this design only requires the extrusion head of the machine to be swapped once. Which saves 30 minutes.	M	Time to assemble (build) the wheelchair below 5.5 hrs	
D2 In-house capabilities						
D2.1	Bending	Tubes can be bent using in-house bending machine	None of the tubes extend beyond 4800mm	M	Tube length doesn't extend beyond 4800 mm	
D2.2	Tube diameter	Tube diameters can be bent using in-house bending machine	The frame is designed with 30mm, 22mm, 19mm and 16mm tubes which are all compatible.	M	10mm, 16mm, 19mm, 22mm, 25mm, 30mm	
D3 Performance						
D3.1	Material	The frame can be bent and welded at the PEZY wheelchair factory	Aluminium AA7020 can be bent in the factory	M	Aluminium, titanium or steel	
D3.2	Material properties	The frame has similar or better material properties than competing frames	The material is the same as competing frames	M		
D3.3	Stress performance	The frame has similar or better stress distribution than the reference box frame design	The stress distribution of the frame is similar under the conditions tested in the report.	M		
D3.4	Increased load bearing	Frame can support increased load bearing during transfers or when carrying items	Expected, as the stress performance of the frame showed similar results to the box frame. Further testing recommended.	S		
D3.5	Increased impact	The wheelchair frame should be built to withstand increased impact on the wheelchair as the user goes down the stairs in wheelie position		S		

Appendix | Project proposal

Project Proposal form

IDE Master Graduation Project

In this proposal the agreements made between student and supervisory team about the student's IDE Master Graduation Project are set out. This document needs to be prepared for the Kick-off meeting and should be submitted in MyCase.

Name student Cécile Niejenhuis **Student number** 5265673

Project title A Convenient Wheelchair Frame For Spinal Cord Injured Users

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.

MSc programme Design for interaction Integrated Product Design Strategic Product Design

Other (in case of a double degree outside IDE): _____

Introduction

Describe the context of your project in the box below; 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)

People with a spinal cord injury (SCI) rely on manual wheelchairs for independent daily mobility due to (near) complete loss of leg function. For these users, the design of the wheelchair is critical. A custom-fitted frame enhances stability, durability and propulsion efficiency, allowing the user to move freely throughout the day, effectively replacing the user's legs. Opportunities to combine rigidity with transportability in the wheelchair frame would serve the interests of the user by improving independence and user experience.

The assessment of the user and reimbursement of mobility aids distributed through local dealers (Meyra, Welzorg, etc.) are controlled by the WMO. For the WMO, low prices and standardised products (thus widely applicable solutions) are preferred. Custom wheelchairs are expensive and can take up to 5 months to build, so faster production seems like a great opportunity for all stakeholders: Shortening the waiting time for the user and allowing the manufacturer to sell more wheelchairs in less time. Standardisation of components could keep cost down and makes production easier for the manufacturer, but poses a threat of lowered customisability of the wheelchair, negatively affecting users.

The complexity of designing a wheelchair frame is finding the balance between good design for the user, fast design for the manufacturer and affordable design for the WMO.

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Introduction (continued): space for images

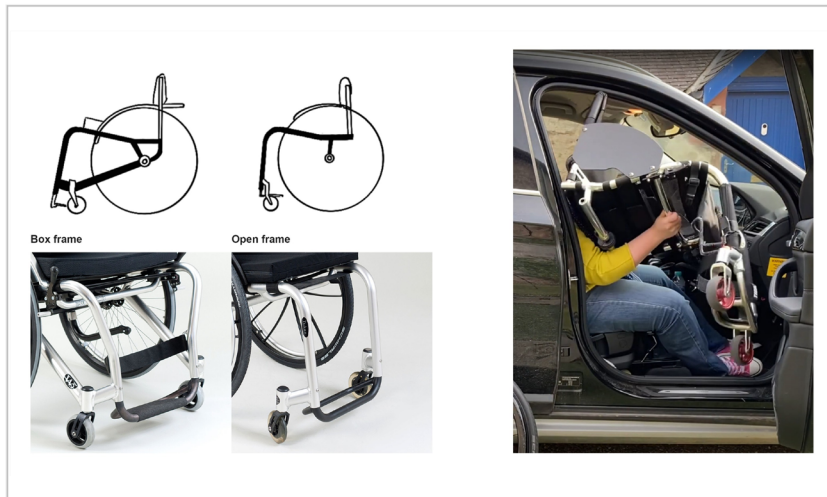


Figure 1: The 2 types of frames and transportation of open frame by car

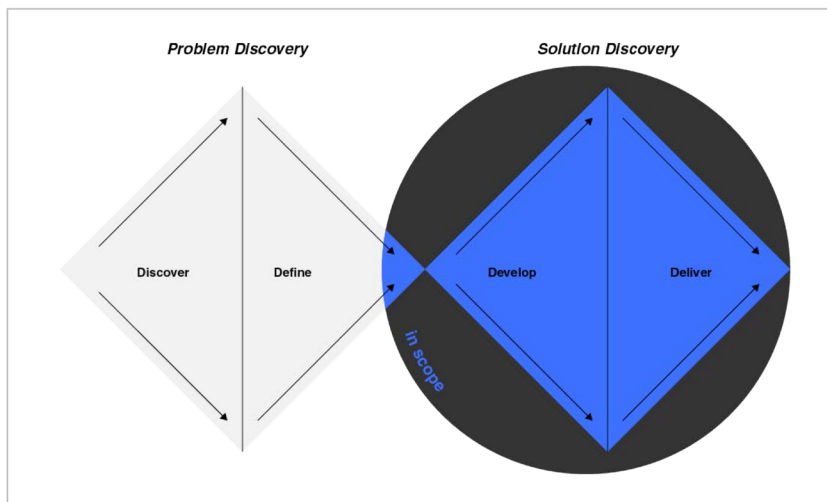


Figure 2: Double Diamond model with project scope (Design Council, 2004)

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)

Currently there are two types of rigid wheelchair frames offered on the market (figure 1): open-frames, preferred by people who travel by car, for they can lift the frame over the driver seat, and box-frames which are more rigid due to a crossbar that connects the front wheels to the rear wheel axle. Rigidity and therefore the strength of the frame is a vital factor in the riding experience and durability of the wheelchair. This means that the portability and independence offered by the wheelchair, comes at a cost of longevity. My goal is to design a wheelchair frame that accommodates different independent use scenarios, without compromising on rigidity. I want to design the frame with ease of assembly and customisability in mind to create a valuable solution for not just the user, but also the WMO and the manufacturer.

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 (Investigate/Design/Validate/Create), and you may use the format: (Investigate/Design/Validate/Create) a (what will be the deliverable → prototype/roadmap/process/intervention /approach/guideline/strategy/...) to (what should it do → create/understand/evaluate/validate/improve/execute/ analyse/...) (the objective → experience/value/process/product/...) for (whom → target group/client/...) in (what context).

"Develop a concept design of a manual, made-to-measure, wheelchair frame for lower body paralysed users that enhances the independence of the user and optimise the production process"

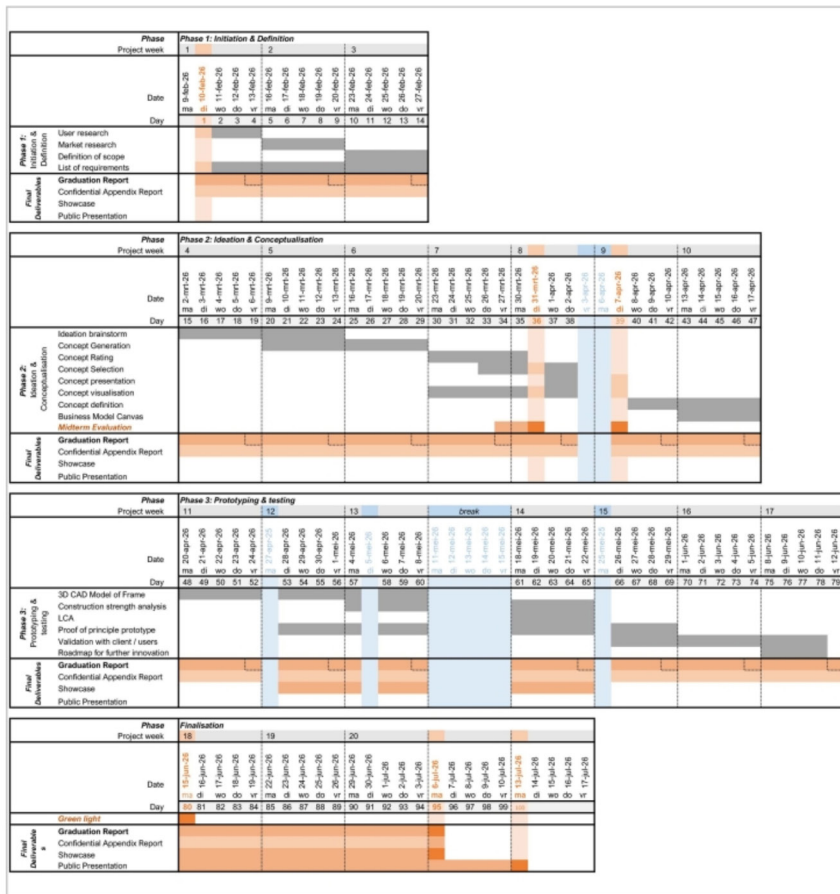
Explain your project approach to carrying out your graduation project and what research and design methods you plan to use to generate your design solution (max 150 words).

"Develop a concept design of a manual, made-to-measure, wheelchair frame for lower body paralysed users that enhances the independence of the user and optimise the production process"

My project planning will roughly follow the double diamond method (figure 2). Following my preliminary research, my planning starts near the end of the problem discovery phase. I will use the first weeks to finalise my problem definition. The following weeks I plan to work on 'solution discovery', through iterative cycles of ideation and conceptualisation. Around the time of my midterm, I want to present my concept directions and start the 'delivery' phase within my scope: defining my chosen concept and building a proof of concept prototype to verify with the involved stakeholders.

Project planning

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 the **Kick-off, Midterm Evaluation, Green Light** and **Finalisation** (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). Add (an image of) the planning in the box below. If it is not readable, you can add the planning as an attachment to My Case along with this Proposal.



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 (max 5) 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 (200 words max).

Since the start of my internship I have researched wheelchairs and interviewed a small number of wheelchair users as well as dealers of wheelchairs. I didn't know anything about wheelchairs but with everything I have learned so far, I am eager to put my preliminary research to use.

I am really looking forward to finally starting the actual 'design' phase of this project and hope to improve my prototyping skills. I like to build and visualise my designs so this project

I also want to work on my problem framing skills and I hope to get better at formulating requirements in a way that matches the complexity of my concept and such that I can test/validate my prototype. I also want to learn more about technical production processes and manufacturing methods to create a feasible concept, in which human measurements and ergonomics are integrated. The technical side of design has never been something I am confident about, but it is something I would like to get a little bit more comfortable with.

