CHALMERS

ALTER THE WHEELCHAIR

Development of a Rigid Frame Wheelchair for Developing Countries

Master of Science Thesis in the Master Degree Program, Industrial Design Engineering

CHRISTIAN BREMER
ERIK OHLSON

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg Sweden, 2013

Department of Product and Production Development
Division of Design and Human Factors

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Abstract

This master's thesis was conducted at the department of Product and Production Development at Chalmers University of Technology in Gothenburg, Sweden. The authors, who were also the two members of the project team, Christian Bremer and Erik Ohlson were at the project initiation students at the Master's programme Industrial Design Engineering.

The project was carried out in collaboration with Whirlwind Wheelchair International; a San Francisco based non-profit social enterprise dedicated to improve the lives of people with disabilities in the developing world. It was initiated to develop an adult active manual wheelchair compatible with the social, physical and economic conditions that currently characterize the situation in semi-urban environments in developing countries. The new wheelchair design should also promote an increase of social integration of people in need of wheelchairs in these contexts.

The project was characterized by a four-step process beginning in Gothenburg with a preparatory phase, covering planning and initial research. The second step was conducted together with Whirlwind at their headquarters in San Francisco, CA, which provided access to expertise and resources for designing, constructing and building a functional wheelchair prototype. This prototype was brought to Yogyakarta, Indonesia, for the third phase. During two and a half weeks, field trials and user studies were conducted together with UCP Wheels for Humanity Indonesia – a non-profit, Yogyakarta based non-governmental organization. Providing services within wheelchair provision and fitting for both young and adult users, UCP is the first of its kind in Indonesia. The fourth and final phase took place in Gothenburg where the feedback from these studies was translated into user requirements and technical specifications, which formed the base of the final result - a new wheelchair designed to accommodate the needs of wheelchair riders in semi-urban environments in developing countries.

This new wheelchair design has been embodied as a final prototype, which was produced both to portray the design but also to allow future testing and evaluation after the completion of this project.

Key words: product development, wheelchair, developing countries, Indonesia, field studies, prototyping.

Preface

This report presents a Master's thesis project of 30 ECTS for Chalmers University of Technology in Gothenburg, Sweden. The project was carried out in collaboration with Whirlwind Wheelchair International and the time frame was from October 2012 to April 2013. Whirlwind provided opportunities for building a functional wheelchair prototype at their headquarters in San Francisco, CA, and field studies in Yogyakarta, Indonesia, together with their partner organization UCP Wheels for Humanity Indonesia.

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Erik Ohlson

Christian Bremer

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There are also people, companies and organizations in Sweden that have made our project possible. Thank you Maria Samuelsson for sharing your knowledge in wheelchair fitting and distribution in Sweden. Thank you Jalle Jungnell for inviting us to Panthera for a deeper understanding of Swedish wheelchair development. We would also like to thank Decon Wheel for the rear wheels, Provexa AB for providing our prototypes with surface treatment and Mekpart AB for letting us use their tools and facilities. Thank you Jan Bragee for all the welding and Reine Nohlborg for all your help, and you both deserve a thank for putting up with us and our nagging. We would also like to direct a special thank to Ångpanneföreningen's Foundation for Research and Development and to Estrid Ericsson's Foundation. Your financial support have made this project possible.

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Christian Bremer & Erik Ohlson
Gothenburg, 2013

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1. Introduction

This chapter introduces the master thesis project behind this report. It describes the background, aim and delimitations of the project but also the project planning and process.

1.1. Background

Christian Bremer and Erik Ohlson initiated this project together with Whirlwind Wheelchair International during the fall of 2012. Its main focus is to develop an active adult manual wheelchair for semi-urban environments in developing countries. The project could be seen as a continuation of previous studies made by Christian Bremer, Erik Ohlson and Marika Olsson during the course *Reality Studio Kisumu at Lake Victoria* at the Department of Architecture, Chalmers University of Technology. Reality Studio involved a seven-week field study in Kisumu, Kenya, and the result was a project, named WEshare, which was focusing on developing a new type of wheelchair as well as strategies for wheelchair distribution that could facilitate the life situation of students at a secondary school for physically disabled in Kenya. The project result was a conceptual wheelchair design, named WEchair (seen in appendix I), based on the use scenario in Kenya as well as a proposal for wheelchair distribution in this specific context. It provides information on different needs in developing countries but the proposal remains to be further investigated and confirmed in order to introduce a working solution to the market. This project, however, did show many characteristics that remind of the problematic that are also facing the team of Whirlwind Wheelchair International.

In order to adequately be able to do authentic user studies with prospect users in their home environments, an additional organization has been involved. This organization, UCP Wheels for Indonesia, is one of Whirlwind Wheelchair International's partner organization and functions as a regional wheelchair distributor primarily around the city of Yogyakarta in Indonesia.

1.1.1. Whirlwind Wheelchair Int.

This master thesis project has been carried out in collaboration with Whirlwind Wheelchair International (henceforth Whirlwind); a San Francisco based non-profit social enterprise dedicated to improve the lives of people with disabilities in the developing world. Their most successful wheelchair in terms of number of users and inspiration for wheelchair producing companies in the developing world is the RoughRider, a long-wheelbase wheelchair designed to be used in semi-urban terrain in developing countries. Its rigid framework is mainly constructed by steel tubing, which creates the desired durable design at a low cost. The RoughRider has been developed based on extensive research and experience that has benefited the company over the thirty years of active work within the field of wheelchairs for developing countries. Whirlwind's organization includes a network of regional quality-certified manufacturers, which currently can produce 12 000 RoughRider wheelchairs per year. There are also small wheelchair shops across the developing world, which can produce many more under Whirlwind's public domain licensing program. (Whirlwind 2010a)

1.1.2. UCP Wheels for Humanity

UCP (United Cerebral Palsy) Wheels for Humanity began as "Wheels for Humanity" in a Studio City garage back in 1995, and delivered during that year 130 wheelchairs to people in Guatemala. Now UCP Wheels for Humanity is based in North Hollywood, California, and helps thousands of children and adults in need of wheelchairs in developing countries each year. Users in Mexico, Vietnam, Uganda, Costa Rica, Nicaragua, Brazil, Mongolia, Thailand, Ukraine, Zimbabwe and Indonesia all gain proper assistive equipment and thereby mobility through UCP Wheels for Humanity. (UCP Wheel for Humanity 2012)

UCP Wheels for Humanity Indonesia

UCP Wheels for Humanity Indonesia is a non-profit organization established in 2009. It is the first Indonesian organization of its kind and is based in Yogyakarta, where their main activities include wheelchair provision and fitting for both children and adults. UCP's long-term goal with their activities in Indonesia is to build an infrastructure, first of all regional but later national, that will provide appropriate equipment and responsible services for Indonesian people with disabilities indefinitely. (UCPRUK 2012)

1.1.3. Problem Definition

The basis of this project was formed around current problematic for wheelchair riders in developing countries, and primarily those in semi-urban environments. The alternation between rugged and urban terrain, difficult economic conditions and a lack of functioning service systems as well as education are all factors to consider. There is a tendency of people getting isolated in their homes because of their impairments, and disabled people in developing countries are generally less educated and less likely to be employment. By allowing these users to become more independent, they could possibly experience a significant elevation in self-confidence and tangibly perceive a personal contribution to the society.

The starting point of the project is Whirlwind's RoughRider. Its design is well suited for rural and less urban contexts but could mean a hardship for users in the growing urban and semi-urban environments in developing countries (trendwatching.com 2012). The RoughRider is quite heavy, which is ungainly when being lifted on top of buses or in cars for transport. It is designed to withstand a tough usage, which currently increases the weight and therefore aggravates these transport procedures. The RoughRider is folded by an x-brace under the seat and Whirlwind is currently not developing any rigid frame wheelchairs, something that according to themselves is asked for among their customers.

There is thereby a request for a rigid frame lightweight wheelchair with emphasis on durability and reparability, designed to be used in semi-urban environments in developing countries. The new product should, based on previous studies, hold some characteristics of the current RoughRider, such as long wheelbase and wide front castors. However, a number of challenges remain to be solved. How can an appropriate expression for a wheelchair in this use environment be found, and in what way should it provide comfort of the user and ensure his or her contribution to the society? Furthermore, the price of the wheelchair is of crucial importance, both in terms of initial purchase and maintenance. Hereby, keeping the costs low for manufacture and spare parts is necessary.

The idea is to provide an adequate assistive product solution that will help to generate an additional degree of freedom and facilitate social integration. Such solution may particularly help users to overcome certain obstacles and barriers, including an improved access to local public transport. This could counteract the tendency of people getting isolated in the society due to a potential impairment. Incapabilities related to disabilities would in such case be decreased and also provide greater possibilities for personal development.

Since there will be instant access to extensive knowledge about target group and use scenario through Whirlwind and the previously conducted wheelchair project in Kenya, this information will function as the primary starting point of the project. Basically, this means that the primary starting-point for the project is the needs identified by Whirlwind through recent projects, but will also include needs identified during WEshare. The ultimate challenge will focus on confirming the needs and translate it into new functionality in order to finalize the construction and develop it into a final prototype.

1.2. Project Aim

The project aim is to design an adult active manual wheelchair, which is compatible with the social, physical and economic conditions that currently characterize the situation in semi-urban environments in developing countries. Part of the project aim is also to strengthen the product range of Whirlwind, which will serve to increase their capability of providing customized wheelchair solutions for a comprehensive range of use scenarios in developing countries. In the longer perspective, this should become beneficial for the intended target group.

This is accomplished by addressing the following questions:

- How should a wheelchair be designed to increase the opportunities for social integration for active wheelchair riders in semi-urban environments in developing countries?

- In what way should a wheelchair be designed to differentiate from current products on the market and still fit into Whirlwind's product portfolio?

- Regarding the current market situation, how could a wheelchair be designed to promote innovative wheelchair development in developing countries, which ultimately would foster an industry modernization?

1.3. Project Goal

The project goal is to deliver one prototype that represents an embodiment of the project's final result. The end result should thereby be embodied as a final prototype to allow users and external expertise to further test and evaluate the result even after the project completion.

As this project setup will involve taking advantage of recent external data collection within the actual field of study, the goal is also to reach the end stages in the product development process and thereby gain more experience within the embodiment design phase.

1.4. Delimitations

The project goal is to develop a wheelchair prototype for adult users, which means that children and young people whose bodies cannot be considered fully developed are left out of the project scope.

The intended geographical context of the final solution's usage is semi-urban areas in developing countries, which means that the intended target group consists of wheelchair riders in this context. This will form the basis of requirements and there is no intention to primarily suit the needs of wheelchair riders in developed countries.

No preliminary information gathering located in the intended context will take place. The reson can be related to both financial issues and accumulated experiences from previous projects.

The primary focus will emphasize development of the framework according to its heavy influence on the total chair appearance. The upholstery will be developed as a part of the final solution and the intention is to use existing materials and not to apply project resources to develop new material solutions for this purpose. The rear wheels will not be subject for new product development and solutions provided by current wheelchair wheel manufactures will be used. The front castors are proved to function very well in the intended context and they will therefore be retained and not further developed in this project.

Developing a wheelchair for a developing context includes deep consideration into the economic situation around the chair. Technical functionality will here be regarded as more important than economical aspects since this project primarily is focused on developing a functional prototype. Economy will still be considered throughout the project in terms of material choice and manufacturing techniques, but is not given a major role according to the time span. Optimizing the final solution regarding economy could be more efficiently done in a later stage of the development process after the project's finalization.

This project will not include marketing or thereby comparable actions to facilitate introduction on the market. The main focus is on product development and the intention is to use Whirlwind's current distribution channels to spread this product to the intended target group.

1.5. Definitions

Developing country/less developed country: There is, according to the United Nations (UN), no established convention for the designation of "developed" and "developing" countries or areas in the United Nations systems. They also note that the designations "developed" and "developing" rather are intended for statistical convenience and not necessarily expresses a judgment of the stage reached by a certain country in their development process. The UN also explains that Japan, USA, Australia, New Zeeland and Europe all are considered developed regions or areas. (UN 2012) This project will address other regions as possible developing or less developed contexts.

Disability: According to Johan Borg (2011), definitions of disability tend to both vary and evolve to suit different purposes. Functional definitions often handle disabilities as a lack or restriction of bodily functions. Such definitions are often used in surveys to estimate various service needs. According to more relative definitions, disability appears in the relation between a person with impairments and an inaccessible surrounding. Such definitions are intended to turn the eyes from individuals with impairments to their interaction with the surroundings. According to administrative definitions, people with disabilities are categorized by the welfare state as being in need of or eligible for certain support. By using a more subjective definition, anyone who perceive themselves as disabled have a disability, regardless of the basis of such perception. The definition will not be further evaluated in this project, but simplified by primarily referring to the administrative definition when discussing disabilities.

Semi-urban area: The criteria for allocating certain areas to the rural or urban sector respectively differ in different countries. A rural area is often defined as an administrative district in which the population size is below 2 000 inhabitants. Other areas are called urban areas. However, certain definitions of rural and urban areas may lead to distinguish an intermediate category referred to as semi-urban areas (UN 2010). This definition is here refined to apply on people primarily living close to cities in developing countries.

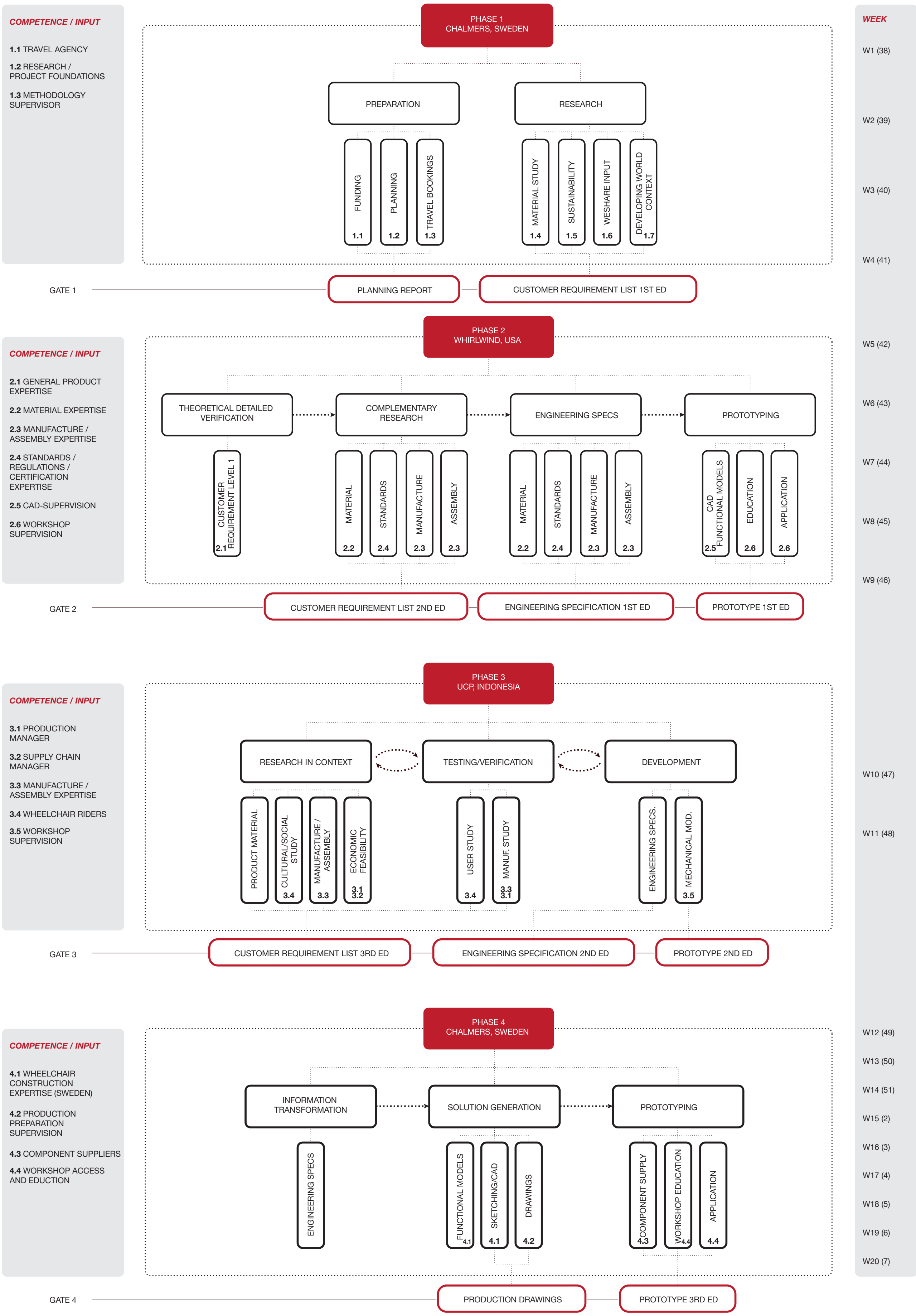
Target group: The intended target group includes adult wheelchair users in developing countries that are able to maneuver their wheelchair independently and without external assistance. The project is directed towards people with disabilities primarily affecting the lower limbs, such as paraplegia, parapares, amputation or polio-related impairments.

1.6. Overall Project Process

The following section explains the structure and planning of this project, which according to the extensive travels became crucial for the end result. An overview of the planning is shown in figure 1.1.

1.6.1. Planning

Including both Whirlwind and UCP in this project provided access to an extensive knowledge-base within the fields of developing, producing and distributing wheelchairs for and in developing countries. Extensive travel was required to be able to share this knowledge according to the geographic locations of these organizations. This increased the demands on a careful and accurate planning, including how unpredictable as well as expected problems should be handled. The time schedule was formulated together with a risk analysis formulated in a planning report, which was sent for feedback to both representatives at Whirlwind and at Chalmers University of Technology prior to the travel to ensure its reliability. The report also included specific project milestones that had to be accomplished at each geographic location to make sure that the project could proceed according to the plan.



▲ *Figure 1.1. Planning flow chart*

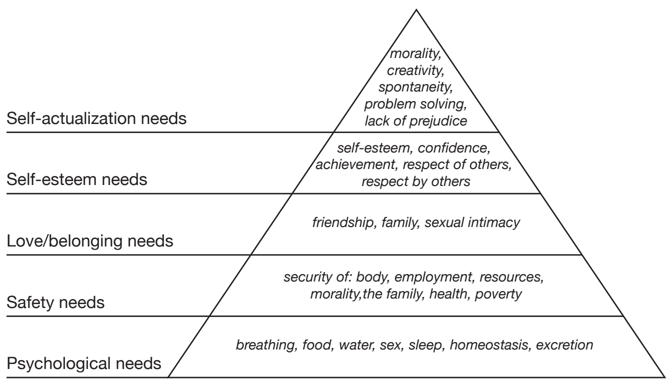
1.6.2. Process

The project was carried out through a four-step process initiated in Gothenburg with the preparatory planning phase, which also included literature studies and research. The second step was accomplished during one month in San Francisco together with Whirlwind where a functional prototype was designed, constructed and built. This prototype was then used during the third phase of the project where user studies where conducted during two and a half weeks in Yogyakarta, Indonesia, in close collaboration with UCP Wheels for Humanity Indonesia. The fourth and final phase took place in Gothenburg where feedback from these studies was translated into user requirements and technical specifications. This formed the base of the final result of the project – a wheelchair prototype for users in developing countries.

1.7. Sustainable Development

Conducting a project with high emphasis on providing help for people in developing countries, hence promoting integration between economically and socially separated societies, will serve to foster a globally sustainable development. The project also implies a cultural and national knowledge exchange, which would benefit the quality of the project as well as spreading knowledge about proper use of wheelchairs in the world. As a part of this globalization strategy the project would also serve as a contributor to increase the overall nationwide well being, independent of physical or psychological conditions. The project will thereby not primarily promote environmental or economical sustainable development but rather social sustainable development. There is, however, a need to also include environmental and economical aspects in order to reach an end result where sustainable development is achieved.

The global health issues approached by this project are located in contexts where the general behavior among people differs from the people in the industrialized world. Some of the differences can be explained with help from Maslow's hierarchy of needs, shown in figure 1.2 (Zastrow & Kirst-Ashman 2010). The welfare in the industrialized world facilitates the compliance of basic psychological and safety needs, which allows people to care for and manage sustainable development. The daily battle to meet these needs in developing countries decreases the possibilities of such behavior. By implementing sustainability in this project, there was a two-folded opportunity to facilitate this development among the intended target group. First of all, providing functional wheelchairs to the riders can possibly exclude some of the problematic to meet the basic and psychological needs. This allows users to reach higher levels in the hierarchy, which ultimately releases more time to take an interest in affairs beyond the personal sphere. Secondly, there is a possibility to avoid several mistakes previously made in the industrialized world. The historically rapid development without an extensive knowledge in sustainability have demanded developed countries to later adapt to a more sustainable behavior, which is proven to be problematic according to several reasons. By including sustainability already in this developing phase of the intended contexts, this project can possibly be part of preventing making similar mistakes in the developing world.



▲ *Figure 1.2 - Maslow's Hierarchy of Needs*

1.8. Report Outline

This report explains the complete implementation of the project. Its basic structure is, with a few exceptions, chronological but must not be read from cover to cover in order to be fully understood. The chapter division offers the reader to focus on specific sections of interest.

Chapter one introduces the project behind this report. It describes the background, aim and delimitations of the project but also the project planning and process.

The second chapter presents underlying theory, which means an introduction to wheelchairs, development of these products in a developing context and disabilities that may be addressed by this project.

The third chapter presents the project execution, alongside with chosen methods and tools. The chapter theoretically declares the chosen methods but also explains how they were implemented in this specific project.

Chapter four describes the initial research and analysis performed before building the functional prototype.

The fifth chapter describes the development and actual production of the functional prototype. This phase was carried through in collaboration with Whirlwind Wheelchair International at their headquarters in San Francisco, CA.

The content of chapter six is the most prominent results from the field studies in Yogyakarta, Indonesia. It also includes different aspects of the user group, which are fundamental for customer requirement prioritization.

The seventh chapter conatains a requirement list for the final wheelchair, which is based on insights and feedback throughout the project.

Chapter eight describes the synthesis, which is the final concept of the project. It is here visualized and described in terms of technical specifications.

The ninth is chapter describes the process of transforming the synthesis into the final prototype. This embodiment represents the end result of the project.

Chapter ten, which is the discussion, includes insights and thoughts on the complete project. The discussion is concluded with recommendations on further development for Whirlwind.

The eleventh and final chapter contains the project conclusions.

2. Theory

This chapter presents underlying theory, which means an introduction to wheelchairs, development of these products in a developing context and disabilities that may be addressed by this project.

2.1. Wheelchair Theory

A wheelchair is exactly what its name tells us – a chair with wheels. It is designed as an aid for people who are, either temporarily or permanently, not able to or have difficulties to walk. There are several variations of wheelchairs according to the widely diverse requirements from their users but what they all have in common is that they offer personal transport to people with walking difficulties.

2.1.1. An Introduction to Wheelchairs

Maria Samuelsson[1], Occupational therapist at Swedish Handicap Institute, confirms that wheelchairs can be divided into two main categories; electric and manual (figure 2.1). Electric wheelchairs are supported by one or several electric motors and are primarily used by people who need a higher degree of assistance to maneuver their wheelchairs, or by people who need an elecric outdoor wheelchair for longer and faster transportations. An electric wheelchair can be a chair entirely operated by electronic means and would in such case be controlled by an actuator operated by either the user or a caretaker. These chairs are commonly distributed to people with disabilities affecting both upper and lower extremities. An electric chair could also mean a manual wheelchair with specially developed wheelchair wheels containing electric motors that provide extra energy when the user pushes the hand rim. Such chair is maneuvered just like a manual wheelchair and the extra power allows users with less arm strength to push the chair independently. This means riding a wheelchair that does not share the visual appearance of the conventional electric chairs, since such chairs may have a negative psychological affect on users that would not identify themselves as electric wheelchair riders.

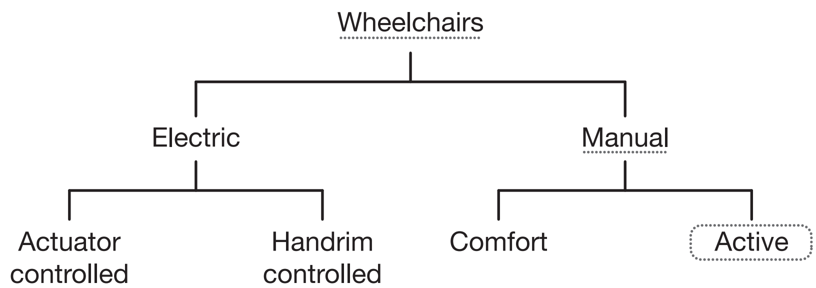


Figure 2.1 - Wheelchair division

1. Maria Samuelsson (Occupational therapist, Swedish Handicap Institute) interviewed by the authors March 14, 2013.

The manual wheelchairs are here divided into comfort and active chairs. Comfort chairs refer to wheelchairs that are equipped with adjustable seat and backrest, and are not primarily propelled by the user. Instead, an assistant or caretaker pushes the wheelchair using the handles placed on the backrest. These chairs often have smaller rear wheels since there is no requirement on the user reaching them for maneuvering. People in need of further support while seated or people that are not able to propel the wheelchair by own power are seen as primary users for this kind of chair.

The primary users of active wheelchairs, which also are the primary users adressed by this project, normally have impairment in motor or sensory function of lower extremities. What identifies these users is the ability to use the upper extremities, which allows them to fully maneuver the wheelchair by using the hand rims on the rear wheels. A functioning upper body eliminates the need of electronics and an extensive trunk support, which ultimately enables a more minimalistic wheelchair design. Still, there is a wide range of wheelchairs and riders in the industrialized world have an opportunity to find a wheelchair that accommodates their specific needs. Each manufacturer has an own way of designing and constructing the framework but there are two major kinds of active wheelchairs; rigid frames and foldable frames using an x-brace placed under the seat. Rigid chairs normally have a foldable backrest, which aligns with the seat once folded, while folding frames are folded by pushing the two sides together.

2.1.2. Wheelchair Mechanics

Wheelchairs are designed to enable mobility and activity. If they are not properly designed, they might create deficient sitting postures and malicious inactivity instead of the desired increase of freedom and mobility. Moreover, small obstacles that never cause problems for someone with walking ability may be devastatingly difficult to master in a poorly designed and fitted wheelchair. Proper design and fitting means that an active lifestyle can be achieved and obtained, and the ability to freely move around is an important part of a social life. For a wheelchair user, this means the ability to ride a wheelchair. This is not only dependent on design specific features but also mechanical properties, which in some cases are changeable. (Engström 2002)

Characteristics to consider are the wheelchairs rolling resistance, weight distribution, wheelbase, camber angle, caster angle, toe-in and toe-out. The rolling resistance means that all four wheels always have a braking effect, certainly the casters. To withstand a rugged terrain, casters should have a comparably small diameter but still a large contact area to the ground. The preferable material is soft without having too much elasticity (Ibid.). What also affects the casters total influence on the rolling resistance is the weight distribution. Engström (Ibid.) describes how a longer wheelbase makes it possible to decrease the weight on the front casters without reducing rearward stability, which is also confirmed by both Jalle Jungnell[2], Owner and Construction manager at Panthera AB, and Ralf Hotchkiss[3],

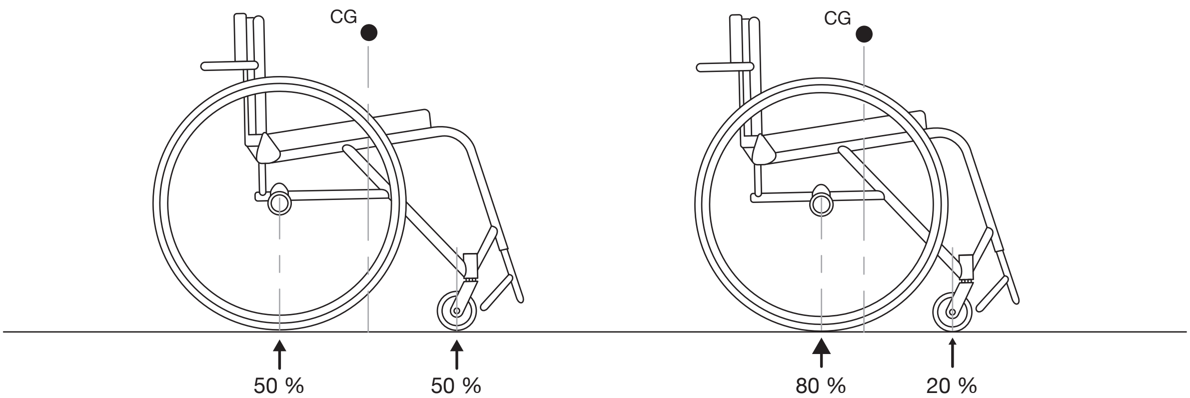
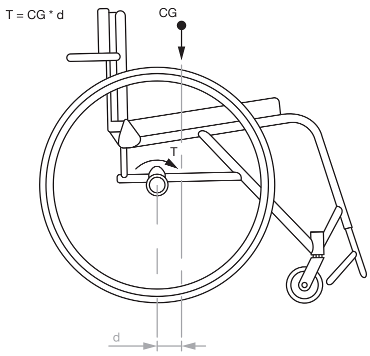


Figure 2.2 - Weight distribution

2. Jalle Jungnell (Owner/Construction manager, Panthera AB) interviewed by the authors October 3, 2012
3. Ralf Hotchkiss (Co-founder, Whirlwind Wheelchair International) interviewed by the authors October 20, 2012.

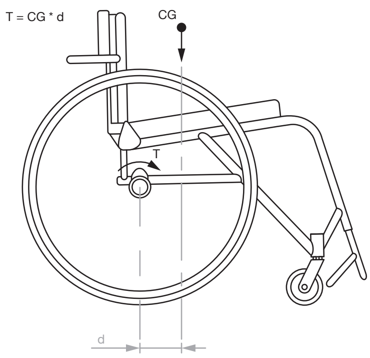
Co-founder of Whirlwind. Thus, the distance between the center of gravity (henceforth COG) and the front casters will be greater than the distance between the COG and the rear wheels. Decreasing the weight distribution on the casters further implies that the wheelchair becomes easier to turn. However, the same effect can be also achieved by decreasing the distance between the rear wheel axle and the COG which can be seen in figure 2.2.

What is also dependent on the COG is the ability to balance the wheelchair on the rear wheels. To avoid a situation where there is a risk of falling over backwards, the user is seated in a position where the COG is located in front of the rear wheels. As can bee seen in figure 2.3, the COG is estimated to be close to the user's bellybutton (Lemaire et al. 1991).



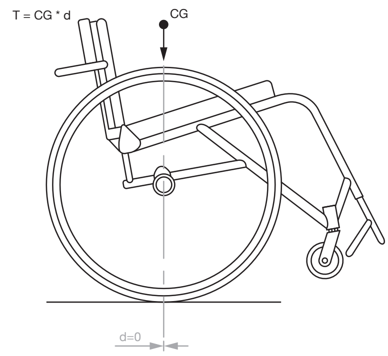
▲ *Figure 2.3 - Rear wheels in front position*

The distance (d) between the center of gravity and the rear wheels creates a torque (T), which ultimately is counteracted by the ground to create equilibrium. This force on the casters can be translated as the weight distributed here.
If the rear wheels are moved back, the COG's location relative the rear wheels is altered and a larger torque is generated according to the larger distance (seen in figure 2.4). This results in more force on the front casters.



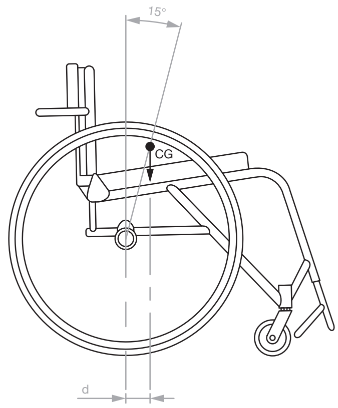
▲ *Figure 2.4 - Rear wheels in back position*

No torque is generated if the chair is tilted backwards so that the COG is vertically aligned with the center of the rear wheels. The horizontal distance is eliminated, which results in a balancing equilibrium (figure 2.5).



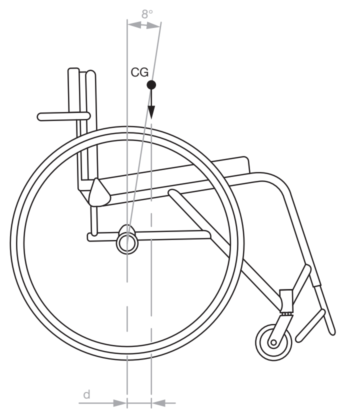
▲ *Figure 2.5 - Balancing equilibrium*

This backward tilting angle is here referred to as the balancing angle. It is dependent on both the horizontal and the vertical location of the COG. A larger balancing angle is created by either a lower center of gravity or by moving the rear wheels backwards (figure 2.6).

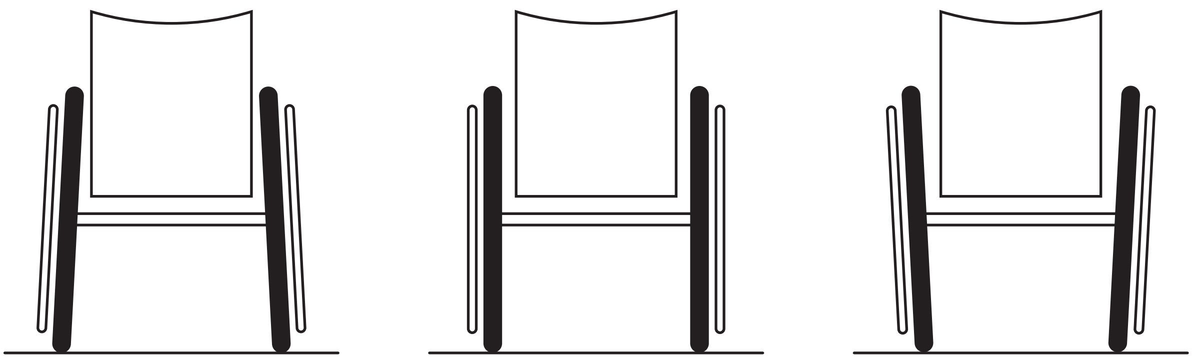


▲ *Figure 2.6 - Low center of gravity*

A smaller angle is consequently created by a higher COG or by placing the wheels closer to the user (figure 2.7).



▲ *Figure 2.7 - High center of gravity*



▲ *Figure 2.8 - Camber*

The leaning angle on the rear wheels that often can be seen on wheelchairs is called camber. The main purpose of camber is to facilitate course keeping. More camber provides more stability and the chair can easier stay on the right course (see figure 2.8). The disadvantage of a large camber angle is instead the enlarged chair-width. The camber's main benefit is found when riding on slopes that lean to one side. By leaning the upper body in the same direction as the slope, it is possible to prevent the change of course that is caused by the leaning ground. The camber also contributes to increased ergonomics when riding the chair. The handrims are placed closer to the body, which decreases the static load on the arm muscles (Engström 2002).

2.1.3. Developing World Wheelchairs

Wheelchairs developed for a developing context differs from standard wheelchairs in a number of ways. The most prominent difference is the price to the end customer. Poverty, both as a result of developing countries' economic situation and social exclusion due to disabilities, means that many users in these countries cannot afford to purchase wheelchairs without external financial support (Bremer, Ohlson, & Olsson 2012). This means that wheelchair riders in developing countries are very dependent on support, either donated chairs or monetary donations. This relationship heavily decreases the possibility to use expensive materials and carbon steel is, according to its outstanding durability in relation to its price (Ashby & Johnson 2009) the most commonly used material. Steel also has a further advantage in developing contexts. Wheelchair maintenance is in developed countries usually handled by a service network, where the user can submit the wheelchair and have it repaired by experts. The situation is different in developing contexts where the user is completely responsible for the maintenance. There are examples of service networks in these contexts, where one example is UCP Wheels for Humanity Indonesia, but these examples are few and a more common situation is one where the user must repair his or her wheelchair at a local workshop. It is therefore important to ensure that the wheelchair design is compatible with maintenance at such shop. One thing that must be considered is the availability of welding techniques. The tooling and skills required to weld other materials than steel and its alloys is according to Hotchkiss[4] rarely found in developing countries and by choosing carbon steel as the main material, the users are given a possibility to repair the wheelchair in the local surroundings.

The material choice also affects the ability to produce these products in developing contexts. Chosen materials must be easily available through either domestic production or a cheap and simple import. Steel meets these requirements, which makes it suitable for production at these geographic locations.

There are, beside the material choice, a number of visual and technical differences that differentiate developing world wheelchairs from standard solutions. The overall accessibility for wheelchair users in developing countries is very poor. The less developed context means riding rugged terrain, rough roads and urban areas with very limited accessibility. This puts higher demands on developing world wheelchairs to master the rougher riding environment in terms of safety

4. Ralf Hotchkiss (Co-founder, Whirlwind Wheelchair International) interviewed by the authors October 20, 2012.

for the user and riding comfort. The accessibility is not offered in the society and must thereby be offered through the wheelchair design.

This is solved in a number of ways depending on both the context and the company developing the solution, but some general differences can be seen. Wheelchairs for the developing world commonly use rear wheels that reminds of mountain-bike wheels to handle the rough terrain. The distance between the front casters and the rear wheels is also extended to prevent users from falling forward, which is one of the most prominent reasons for injuries among wheelchair riders (Armstrong et al. 2008). The length of the wheelbase and the size of the front casters differ among the producers and this is also dependent on which context the chairs are developed for. Still, it is generally easier to manage obstacles in a wheelchair with a longer wheelbase. The longer wheelbase creates an extended lever between the rear and front wheels, which basically means that the wheelchair must be less angled compared to managing an obstacle in a wheelchair with a narrower wheelbase (Engström 2002).

The tough economic climate and the requirements on handling rough terrain mean a number of trade-offs for wheelchair designers. There is a major challenge to make an affordable chair that meets the needs of durability and is both producible and repairable in a developing context. There is currently a major hardship for the end users to afford new wheelchairs, which is why there are many examples of charity organizations providing chairs to disabled people in these contexts. This economic climate also affects the producing companies and there is a high pressure on keeping the final price of the wheelchairs very low. This means that some wheelchair producers focusing on developing countries have a problem with their chairs not being self-sufficient. The small income generated by these products is sometimes not enough to cover the costs of developing and producing the wheelchairs. This is partially remedied by governmental support in countries where the developing companies are located. (Bremer, Ohlson, & Olsson 2012)

2.1.4. The RoughRider

Whirlwind currently provides one wheelchair model - the RoughRider. It is according to them their answer to expensive fragile wheelchairs that unnecessarily limit access (Whirlwind 2010b). The RoughRider is designed to easier handle rough and rugged riding conditions, which has been proven in over 25 countries where wheelchair riders are in need of equipment withstanding the rough use environments. The RoughRider is primarily used as a daily-use chair in developing countries and as a backup chair in industrialized countries when there is a need for off-road features.

The most obvious difference between the RoughRider and a conventional chair for use in industrialized countries is the wheelbase, which on the RoughRider has been extended 50% (figure 2.9). This provides stability and prevents users from tipping forward. The longer wheelbase has also been accompanied with Whirlwind's signature caster wheel. Compared to a conventional caster, this solid rubber wheels roll easier over obstacles like grass, mud, rocks or lightly packed sand.

The RoughRider is produced by Dharma Healthcare in Tangerang, Indonesia. The framework is constructed from steel tubing, which has several advantages for a developing world wheelchair. Steel has an outstanding durability to cost ratio (Ashby & Johnson 2009), especially compared to other metals extensively used by the wheelchair industry. This decreases the price for the end user, which is not only desired but also required to make the chair affordable for the target group. Steel also increases the possibility to repair the frame in local workshops or bicycle shops since it can be welded using available welding techniques in these developing contexts. The reparability is also enhanced through a usage of bearings, tires, tubes, wheel parts and hardware that can be found in local bicycle shops, motorcycle shops or hardware stores around the world.

The RoughRider is equipped with a twelve-degree seat angle designed for the user's comfort but also to prevent the user from falling forward in the case of sudden stops. What also prevents the user from injuries in rugged environments is the toe-protecting footrest. The chair is foldable

▲ *Figure 2.9 - Left: the RoughRider, right: 50% extended wheelbase*

by an x-brace placed under the seat and this folding is primarily used for storage and transport. The RoughRider can be ordered in five different seat widths (12.5", 14", 15.5", 17" & 18.5"), each with three different seat lengths (14", 16" & 18"). It is also possible to adjust the backrest height, the footrest position and the rear wheel position to customize the characteristics to fit each specific user.

One of the major issues with the current product is its weight. The steel framework and robust components are all contributing to the chair's off-road characteristics but are also adding weight to the product. The current weight is more than 20.5 kg, which is over twice the weight of a typical active wheelchair used in industrialized countries and more than four times as heavy as the world's lightest wheelchairs (Panthera AB 2012a).

2.2. Disabilities

This section primarily explains the most occurring disabilities among the intended user group. The most prominent difference between developing and developed contexts is poliomyelitis, which thanks to vaccine is largely eliminated in developed countries. A thorough analysis of the mentioned diseases' relevance for the project and how they affect the usage of wheelchairs in developing contexts is described in Chapter 6.3.

2.2.1. Spinal Cord Injuries

A spinal cord injury (SCI) refers to an injury to the spinal cord caused by a trauma instead of a disease. The symptoms can vary widely depending on where the spinal cord and the nerve roots are damaged and patients can experience pain, incontinence or paralysis depending on the injury. (Apparelyzed 2012)

Paraplegia

Paraplegia is medical terminology for impairment in motor or sensory function of lower extremities (often paralysis), which could include both torso and pelvic organs. Paraplegia is often the result of a spinal chord injury or a congenital condition. The part of the spinal canal affected in paraplegia is either the thoracic, lumbar or sacral regions. A partial paralysis of the lower limbs is called parapares, which also could include muscle weakness or a limited movement. In case of all four limbs being affected by paralysis, it is called tetraplegia or quadriplegia. (Ibid.)

Tetraplegia

Tetraplegia is similar to paraplegia but means that all four extremities (arms and legs), pelvic organs and torso are affected. It is caused by an injury to the cervical region of the spinal canal, which results in partial or total loss of motor and sensory functions. (Ibid.)

2.2.3. Poliomyelitis

Poliomyelitis, often referred to as polio or infantile paralysis, is a viral disease that is spread from person to person via the fecal-oral route, often as a result of insufficient sanitation and hygiene. However, about 99% of infections are either inapparent or very mild. In rare cases, the virus enters the central nervous system, preferentially infecting and destroying motor neurons, leading to muscle weakness and acute flaccid paralysis. People in primarily developed countries are vaccinated against the virus at an early age and it only remains in a few countries. The virus can, however, spread to other countries. (Melnick 2012)

2.2.4. Amputation

Amputation is removal of a body extremity by trauma, prolonged constriction or surgery. When used as a surgical measure, amputation is used to control the disease process or pain in an affected limp. Examples of such diseases are malignancy and gangrene. Amputation may also be used as a preventive action for these issues. A special case is congenital amputation (acongenital disorder) where constrictive bands have cut off fetal limbs prior to birth. (NHS 2012)

3. Execution and Methods

The methodology has primarily been characterized by the latter phases of the product development process. Additional methodology has, however, been included to cover further parts of the product development cycle. This chapter theoretically explains the chosen methods but also explains how they were implemented.

3.1. Phase 1 - Chalmers, Sweden

The initial project phase took place in Sweden, primarily at Chalmers University of Technology, and included a project planning, a risk analysis and initial data collection.

3.1.1. Planning

The planning was implemented prior to the travels. The extensive work abroad increased the importance of a detailed planning, which in turn meant an inclusion of supportive methods. There were a number of important gates and these were identified and explained in a planning report, which was written during the project's initial planning phase. It included a chart (figure 1.2), visualized as a combination of a Gantt chart and a flow chart, explaining the time plan, gates to complete at each geographic location and resources needed. The main purpose was to clarify what needed to be completed at each location and how to reach these goals. This planning formed a basis for a risk analysis where potential risks of failure and ways to solve such issues were formulated.

Gantt Chart

Gantt chart is a bar chart developed by the American mechanical engineer and management consultant Henry Gantt in 1910 (Wilson 2003). A traditional Gantt chart illustrates starting and finishing dates of elements and tasks in a project. Gantt charts can possibly also show the dependency and relation between these different tasks to determine which must be completed before the following can be initiated.

Flow Chart

A flow chart is a graphical representation of a process, using annotated geometric figures connected to each other with lines or arrows (Mind Tools Ltd. 2012). The process is thereby documented and additional symbols are used to represent operations, equipment, data etc. The flow chart may through its implementation describe the relation between certain tasks or processes and determine which of theses must be completed before the next can be started.

3.1.2. Risk Analysis

Some risks related to long distance communication, traveling and working in developing country context had to be considered and backed up with secondary options in case of unexpected problems. Potential risks were identified and briefly explained as follow.

Traveling Complications

In the unlikely event of denied entry in Indonesia or USA, the work process would significantly change. This would have meant a new type of working arrangement where the project would have to be continued in Sweden earlier than planned. The project would, however, still have been feasible although it would have required intensive distant collaboration with Whirlwind and UCP Wheels for Humanity Indonesia. There would also have been a greater probability that the final result of the project would be questioned according to the inability of meeting the prospect users. Possible flight delays could have posed similar but smaller difficulties.

Inadequate Knowledge
Our gained knowledge from the WEshare project could have turned out to be insufficient, which would imply a significant change of the final wheelchair design. In case of such problematic occurring, there was a little time to compensate for this shortcoming if the problem would be identified at an early stage in San Francisco. Considering the possibility that this kind of problem would have been encountered during the field study in Indonesia, there would have been a need to prepare a secondary option besides studying the functional prototype. If the new solution would have turned out to be completely malfunctional, bringing a RoughRider to the test site would have allowed a continuation focusing on evaluating the RoughRider's functionality instead. In addition, this would have been regarded as valuable information as it would have helped to determine the actual value of a new solution. If the users not would had accepted the new design, there would not have been any reason to develop it further without considering this additional input.

Guidance
Due to several reasons, there was a risk of us encountering a lack of guidance and supervision in both USA and Indonesia. This could possibly have occurred in USA due to in-house projects at Whirlwind, causing a lack of excessive time for their employees. This could possibly have caused delays in the prototyping work and eventually ending up in uncompleted material at the time of starting up the field study. This risk had to be considered and prevented by preparing workshop skills prior to the arrival in San Francisco. In addition, there was need for a backup time during the prototyping phase to be able to compensate for these possible issues. Similar issues could also have occurred during the testing phase in Indonesia. This would however imply extensive focus on user studies, which require small technical means and little workshop support.

Bottlenecks
Several problems with bottlenecks could have occurred in relation to supply chains. This was chiefly relevant during the first and second prototyping phase where the progress of the project was heavily dependent on standard part supplies such as wheels, casters and brakes. To prevent a project stopper, there was an ambition to contact as many suppliers as possible prior to manufacturing the prototype. This significantly reduced the risk of encountering heavy delays.

Financial Issues
In the event of insufficient funding for the project, there would be a need to reduce the amount of expenses until further financial support could be identified. The ambition was, however, to not interfere with the quality of the final solution.

3.1.3. Data Collection
The initial project phase mainly involved literature studies, with the main purpose to broaden the knowledge base before visiting the partner organizations in both the United States and Indonesia. These studies were also complemented with an open and unstructured interview with Maria Samuelsson, Occupational therapist at Swedish Handicap Institute. The reason was to include Swedish wheelchair expertise at an early stage in the project process. This contact could later be used to discuss and evalue the project's final result.

A minor benchmarking, including both state of the art technology and wheelchair development in developing countries, also complemented the literature studies. The included chairs cover a broad range of active wheelchairs for both developed and developing contexts, which ultimately could generate interesting input for the project continuation.

Literature Studies
The purpose of a literature study can be to describe the current state of knowledge or to collect domain knowledge about a specific field (Bohgard et al. 2009). In this project, it have meant a deeper search for literature written on wheelchair development, assistive device development in developing contexts, cultural differences, and public transportation in developing countries.

Unstructured Interviews

According to Jordan (1998), an interview means that the investigator compiles a number of questions that are asked directly to the participants. There are three different kinds of interviews – unstructured, semi-structured and structured.

In unstructured interviews, the investigator will ask the participant a number of open-ended questions. This will give the participants the opportunity to steer the discussion in the direction they find important. This is beneficial when the investigator has little idea on what issues to concern prior to the interview. This became reality in the case of interviewing Maria Samuelsson, and the open approach gave an opportunity to steer the discussion towards interesting subjects as it went along.

Benchmarking

Before embarking new product development, it may be beneficial to evaluate existing products on the market to understand the state of the art in the preferred field. Benchmarking is a method of comparing preferably your own business to industry best or practices from other industries (Ibid.). Commonly measured dimensions are quality, cost and time. This method may provide comparative values that make it possible to generate specifications to the product about to be developed.

The idea behind this benchmarking was to briefly study manual active wheelchairs, designed for both developing and developed contexts, that individually hold different but yet interesting characteristics. Six chairs designed for developing and five chairs designed for developed contexts were included in the study. The overall goal was to identify how these chairs differs from each other. It was done by comparing them in two different graphs, named “usage context” and “chair characteristics”. The measured aspects were developing/developed and urban/rugged in the usage context graph, and expensive/affordable compared to weight in the chair characteristics graph. Each chair was placed in the graphs according to their specific characteristics, which provided a visualization of the differences between chairs designed for the respective contexts. Studying this range of active chairs should also allow a certain degree of inspiration on how to solve specific detail problems during the project implementation. The included chairs and the actual result of this study can be seen in chapter 4.2.1.

3.2. Phase 2 - Whirlwind, USA

The second project phase included further data collection, which later led to idea generation and ultimately constructing a functional prototype. This project phase was conducted during one complete month in close collaboration with Whirlwind in San Francisco at their headquarters in San Francisco, CA.

3.2.1. Data Collection

The data collection was primarily characterized by further interviews and scenarios set up and conducted by the project team members. The interviews where once again unstructered in their nature and the reason was the close collaboration with the Whirlwind staff. The geographic location of the project allowed short and unplanned question sessions as well as more thorough discussions on certain issues. This iterative and continuous process constantly strengthened the production underlay of the functional prototype. The interview subjects varied with the different issues but the majority of these sessions were held with with Whirlwind employees, and primarily Matt McCambridge (Director of Product Development), Ralf Hotchkiss (Co-founder) and Aaron Wieler (Product Designer).

The scenarios were set up in order to gain knowledge within basic wheelchair mechanics and functionality as well as general design challenges related to wheelchairs in both developed and developing contexts. These were conducted together with Ralf Hotchkiss, who has more than 30 years of experience in both riding and developing wheelchairs.

Scenarios

The scenarios were designed primarily based on the input from experienced wheelchair riders and conducted prior to the ideation phase. The scenarios were conducted by the project team in order to understand some of the problematic wheelchair riders might face during their regular life. They included common riding challenges that may be particularly related to the context of a semi-urban area in developing countries. Some of the elements that where included can be briefly described as riding in stairs, climbing curbs, climbing ramps and inclined surfaces, riding on rough terrain, riding on rear wheels and riding on sideways leaning paths. Both wheelchairs designed for developed and developing countries were used to identify and understand the difference in appearance and performance.

3.2.2. Concept Development

The concept development in San Francisco required idea-generating methodology. Brainstorming was extensively used initially when designing the prototype. This method allowed the project team and representatives from Whirlwind to easily create and share ideas. Also morphological matrixes were included in forming the concept. The main reason was the modularity in a wheelchair design where different solutions on each part may be combined into different wheelchair concepts.

Each concept was visualized - first through sketching and then using computer aided design software - to facilitate the communication of the ideas between the project team members and the Whirlwind employees. The software made it possible to show moving features, such as folding backrests and alternating seats. Also, it provided a possibility to rotate the models and observe them in different angles. All models were also presented in images of similar quality, which decreased the risk of preferring one solution to the other due to a varying presenting quality.

These ideas were later evaluated using both group discussions, including the complete Whirlwind workforce[1], and Pugh evaluation matrices. The combination between empirical and non-empirical methods created a solid decision underlay.

Brainstorming

Brainstorming, developed by Alex Faickney Osborne in 1941, was designed to encourage a group to express and share ideas (Michalko 2006). Critical judgment on these ideas is saved until later to not inhibit the creativity. Ideas are offered by everyone and these may be listed, combined improved and changed into various other solutions. At the end of the session, the group agrees on one final resolution.

This project phase included two different variations of brainstorming. The first, which was also primarily used, is similar to what is described above. The participants were limited to the two members of the project team. The second version was used when additional input was required, according to the complexity of the problem to be solved. Matt McCambridge and Aaron Wieler from Whirlwind were invited to join the session, which broadened the knowledge base of the brainstorming crew. This variant sometimes included an additional trigger in terms of a brainstorming grid. The grid was drawn with 25 boxes, and each of them had to be filled with a new solution to the problem before the next could be initiated. This required quick solutions to reach the goal of 25 different and individual results, but also promoted one of Brainstoming's fundamentals - quantity breeds quality (Ibid.).

Morphological Matrix

A morphological matrix allows products or concepts to be divided into sub-parts or sub-functions, and then imaginary assembled in a new order or with new parts from other concepts achieve a change. New ideas are generated through various combinations of parts, or functionality, from the old solutions (Ibid.). A wheelchair's modularity makes it quite suitable for methods as morphological matrix. Using it in the idea generation phase allowed different ideas to be combined and evaluated before one final concept was chosen.

Sketching

Sketching is an adequate tool for exploring, visualizing and communicating ideas during product development. Depending on the level of refinement, it covers a range of different purposes but is in basic a rather time efficient visualizing method (Österlin 2007). The rapidness of sketching was considered very suitable for quickly sharing ideas on individual parts among the people involved in the idea generation. To ensure the feasibility in certain detail solutions, the need of producing a more realistic underlay became

1. Ralf Hotchkiss (Co-founder), Marc Krizack (Executive Director), Matt McCambridge (Director of Product Development), Aaron Wieler (Product Designer), Keoke King (Marketing Director), Kaleen Canevari (Quality Systems Engineer), Laura Harrington (Project Administrator), Nancy Carroll (Office Administrator)

more significant. This is where computer aided modeling was included, which fulfilled these requirements.

Computer Aided Design

Computer aided design (CAD) is a tool to build three-dimensional objects using a computer software (Johannesson 2004). There is a number of different CAD-software and ideas may be visualized, explored and evaluated in several different ways. By using different software, it is possible to test characteristics such as shape, dimension, color, construction and durability. Furthermore, most CAD-software can provide photo-realistic images through rendering modules.

In this poject, there was a need of finding software where ideas rapidly could be visualized and communicated to Whirlwind's team in a language they would understand. Also, there was a need to produce drawings for the actual production of these ideas. This led to the selection of sketching and computer aided modeling as the two main communication tools.

CATIA v5 from Dassault Systèmes was chosen as modeling software according to its possibility to create construction drawings as well as computer models for rendering purposes. Keyshot 3 from Luxion Inc. was later used for rendering photo realistic visualizations of the concepts.

CATIA (Computer Aided Three-dimensional Interactive Application) is a multi-platform commercial computer modeling software developed by the French company Dassault Systèmes. CATIA is capable of addressing the complete product development cycle and facilitates collaborative engineering through its multidisciplinary modules. Examples of these are Mechanical Design, Machining and Ergonomics Design & Analysis (Dassault Systèmes 2013).

Keyshot 3 is a standalone three-dimensional rendering and animation system, which is entirely CPU-based and has been designed to decrease the complexity of rendering realistic images (Luxion Inc. 2013). Keyshot supports most popular file-formats from three-dimensional modeling software and is used by engineers, designers and computer graphics professionals to render realistic images and animations.

Pugh Matrix

The Pugh matrix is a quantitative technique used to rank multi-dimensional options of an option set. A set of requirements or criteria is established in a basic decision matrix and each potential solution can then be decomposed, scored and summed to gain a total score. The requirements and criteria might also be weighted according to their importance but this would result in a slower selection process.

This method was very useful when evaluating different framework options during the creative stage of this project. A Pugh matrix might prevent subjective opinions by offering a more objective way of evaluating different criteria. It also allows different requirements or criteria to be compared to each other, which was valuable at this point of the project. The framework options were at this point not fully developed and it was chosen to evaluate general design properties by comparing two solutions to each other instead of including further options and using one solution as a reference model. Each of the chosen critera was given a certain weight, which represented the level of importance. This made it possible to include requirements of different importance in the comparison.

3.2.3. Prototyping

The concept development resulted in a concept which was embodied at Whirlwind's workshop by the project team and Whirlwind. Whirlwind's staff got a dual role where they both acted manufacturers and tutors. They were responsible for the production aspects but a large part of the process also meant teaching the project team members how to build a wheelchair prototype. The reason was basically to accelerate the second prototyping phase, where the precense of Whirlwind would be downgraded to video calls and e-mail conversations.

The prototyping primairly included manufacturing techniques as welding, tube bending, laser cutting, water-jet cutting and drilling.

3.3. Phase 3 - UCP, Indonesia

The third project phase once again meant a new geographic location and a new continent. Meeting UCP Wheels for Humanity in Yogyakarta, Indonesia, enabled field trials and extensive user studies.

3.3.1. Theoretical Prototype Evaluation

Prior to the principal test phase with actual users, the functional prototype was carefully evaluated based on internal testing. It was analyzed and evaluated primarily through a modified version of a Failure Mode and Effect Analysis (FMEA) (see appendix II). The scope of the analysis was extended to include a human factors consideration and the modification was inspired by the approach of a Predictive Use Error Analysis (PHEA). The modified FMEA was conducted prior to the empirical studies to fulfill the following two purposes. First of all, it was beneficial in terms of usability. Understanding what mistakes could be done and what effects this could have increased the possibilities of preventing such events through minor design changes. Secondly, it was important to identify possible dangers with the prototype. Situations where users could possibly harm themselves could be avoided by being aware of potential risks. Considering the fact that the prototype were to be tested by real users, the latter was of crucial importance. When a handicap is underlying, the wheelchair rider's ability to use their fully intact body functionality is invaluable. Therefore a malfunction in the prototype leading to an injury would be completely unacceptable.

Failure Mode and Effect Analysis

FMEA (Failure Mode and Effect Analysis) is a systematical and proactive method for identifying and preventing potential failure modes of a product. The FMEA approach was first formally conducted within the aerospace industry and is nowadays a key tool to prevent safety accidents and incidents from occurring (Mikulak, McDermott, & Beauregard 2009). FMEA is applicable during early product or process design stages as well as on already existing products. Through the use of FMEA, user safety and customer satisfaction may be substantially increased. The process of FMEA is initially based on brainstorming in order to identify potential defects and failure modes of the process or the product. Sequentially, these defects are systematically analyzed to capture potential effects, severity, occurrence, detection, appropriate action and estimated improvement.

Predictive Human Error Analysis

PHEA is a useful method for conducting a structured and systematic analysis of a task that a user must perform when using an interface. The method was originally developed for evaluating a screen-based interface with a step-by-step procedure needed to solve the task (Bohgard et al. 2009). However, the method may also be used for evaluating a non screen-based interface such as hand-tools. The method aims to answer the following questions – *What can the user do wrong? What happens if the user does something wrong?*

3.3.2. Field Study

The field study in Yogyakarta was mainly characterized by empirical studies. The testing sessions were conducted with 22 test subjects who all had various disabilities primarily affecting the lower limbs. This means polio-related impairments, amputation, paraplegia and parapares. Each user got to ride the prototype, and the time span varied from 30 minutes up to approximately one and a half hours depending on the conditions of each session. Involving users enabled an opportunity to include further methodology developed for usability purposes. Field observations took place as a major source of information, and it was complemented by interviews, this time semi-structured. They were primarily used during or after the observations and the interviews were conducted on the test subjects. Discussing certain issues and learning from user's experience through focus groups also enlarged the amount of feedback from the testing and evaluation phase.

A minor aesthetics study was also conducted. It was done by showing pictures of different types of wheelchairs, designed both developed and developing countries, and discuss each user's perception of the chairs. After this, renderings of the prototype was shown in different color settings to create an understanding for color preferences within the tested user group.

The tests involved some difficulties regarding understanding, according to language barriers. An interpreter was used for each of the interview sessions because of this insufficient level of understanding between the interviewees and the project team. Language barriers and previous experiences with using questionnaires made this an inappropriate method for this part of the project. Instead, questionnaires were used as an underlay for discussion during the interviews.

As a result of various mobility limitations for target users, the external part of the field study was primarily dominated by home visits. This variation implied a unique test environment for each user, which potentially would have an impact on the test results. To the most extent possible the use tests were conducted with the same characteristics and procedures. However, due to various environmental characteristics some differences came out to be unavoidable. The mentioned home environments were different in several ways. Some test subjects lived in urban conditions with relatively well-developed infrastructure. Others lived on farms, which meant a more rural context with fewer paved roads, and there were subjects who lived deep in the woods with very limited opportunities to get into the city.

To control the impact on the output, the field studies where primarily conducted using a semi-structured and open-ended approach as described above.

Field Observations
Jordan (1998) explains how field observations involves watching users using a product in the environment they would normally use it. This adds an ecological validity, which would be lacking in evaluations conducted in a usability laboratory. The idea is to understand how the product performs under natural conditions without imposing boundary constraints that would arise with a set evaluation protocol.

It is very important that the investigator make sure that the impact of his or her presence is minimal (Ibid.). Users might consciously or subconsciously change their behavior if they are aware of being observed. This was important to consider during the field observations in. The sessions were documented with both photographs and video recordings, which both may affect users' behavior. A possible solution is to use a hidden camera but such approach raises ethical questions (Ibid.). It was chosen to inform the users of the intention to document the session and ask for permission to do so.

The field observations were as explained combined with interviews, according to Jordan's recommendations (Ibid.), to expand the information collected about the user's experience.

Semi-Structured Interviews
In a semi-structured interview, the investigator has a clearer idea of what issues to focus on prior to the interview. This means that the investigator will stick more to an agenda to ensure that certain issues or questions are covered and answered (Ibid.).

In this stage of the project, semi-structured interviews provided an opportunity for a more systematic analysis than what would be possible with unstructured interviews. It was also an attempt to ensure the feedback collected from the test sessions. Pre-defined questionnaires (see appendix III) were used as underlay and the answers were documented using pen and notepad.

Questionnaires
Questionnaires are usually printed lists of questions and there are two general kinds – fixed-response questions and open-end questions. These are generally sent to a lot of people and one great advantage with questionnaires is that once they are designed and checked for validity and reliability, they can be copied and sent to many people at a little extra cost. There is, however, an issue that only a small proportion of them usually are completed and returned (Ibid.). Since this project is aimed at a large market where wheelchair users all over the developing world are included, it could have been very useful to gather information using this method. There was, however, difficulties with both language barriers and with finding appropriate users to answer the questionnaires. So instead of sharing these with users all over the world, it was decided to formulate a questionnaire to use as an underlay for the coming interviews.

Focus Groups

Jordan (Ibid.) describes focus groups as a group of people gathered together to discuss a pre-defined subject. The group usually consists of a discussion leader and a number of participants. This could for example include users' experience of a product, their requirements regarding a product, information about the using context or usability problems that are associated with the usage. The agenda is usually rather loose to allow the participants to lead the discussion into the direction they wish. The leader's role is rather to ensure that all participants get room to take part in the discussion.

The project included two different focus groups, one containing four test subjects and one containing three wheelchair riders employed by UCP. The agenda was loose but consciously guided on processing experiences and impressions of the prototype.

3.4. Phase 4 - Chalmers, Sweden

The fourth and final project phase closed the travel loop and brought the project back to Gothenburg. Here, the feedback from the field study was analyzed and translated into customer requirements. These requirements formed the basis of the final concept generation and the final prototype.

3.4.1. Analyzing Field Study Feedback

The analysis of collected data was heavily reflected by the wide variety of input formats. The usage of literature, interviews and observations put demands on a method that was able to transform all this data into requirements for the final design. This is the background on which KJ-analysis was chosen.

KJ-Analysis

KJ-analysis is a method used to organize large amounts of data. It was initially developed by the Japanese anthropologist Jiro Kawakita to be used for analyzing verbal information collected during field studies. The KJ-analysis serves two primary purposes – to generate one simple and holistic view comprising all the relevant data from the field study, and to effectively communicate the result to its readers. The method is utilizing a hierarchical approach and serves to group the data into different categories and hierarchical levels. (Bergman & Klefsjö 2012)

The information collected during the field studies was sorted together in columns for each user, and information from photos, video recordings, observations and interviews were all gathered here. These gatherings were then translated into customer requirements that represented the content of each category. The result of the method was the requirement list presented in chapter seven.

3.4.2. Final Concept Generation

When generating the final concept, there was a great focus on changing already existing solutions from the functional prototype. This, once again, made brainstorming a useful tool. There was a clear idea on what should be achieved and thereby changed on the functional prototype, which reduced the need of methods where a different mindset is promoted to increase the degree of innovation through the method implementation.

Both conventional brainstorming and the brainstorming grid previously described was used again. The participants were the two members of the project team and further expertise was not included at this stage.

3.4.3. Prototyping

The experiences from constructing and building the functional prototype in San Francisco was a major benefit when producing the final prototype. Previous planning and methods were here adopted to fit the second prototype iteration.

This prototyping was made in the mechanical engineering prototype workshop at Chalmers University of Technology. The inclusion of the university provided a high degree of workshop expertise and several operations were performed or supervised by either Jan Bragee or Reine Nohlborg, Research Engineers at Applied Mechanics. This allowed manufacturing techniques as welding, milling and lathing. Some operations, however, required the inclusion of another mechanical workshop and Mekparts AB in Mölndal supported this project in those cases. This included bending the framework tubing and appropriately notching the tube endings.

The final prototype's framework was powder coated by the Swedish surface treatment company Provexa AB. The inclusion of a professional business for this purpose ensured the quality of the coating and would eventually extend the life span of the prototype.

3.4.4. Final Result Evaluation

The final result was primarily evaluated based on the comprehensive requirement list. The reason was to evaluate to what extent the requirements, which were determined through thorough research, had been achieved.

Using a comprehensive set of requirements developed through the completion of all project phases, each requirement were evaluated based on the corresponding functionality of the final prototype. Thus, it could be determined if the final result were satisfactory in terms of the technical specifications.

4. Initial Research and Analysis

Chapter 4 describes the initial research and analysis performed prior to building the functional prototype. Implementation of methods as well as analysis and results is presented chronologically.

4.1. Literature Studies

The literature studies were included to understand and learn from current and previous research within the field of assistive devices for developing countries. These studies involve important factors of consideration but are also confirming the need of sufficient assistive equipment for each specific context.

4.1.1. The Need of Sufficient Wheelchairs in Developing Countries

There is current research confirming the need of sufficient assistive devices in developing countries. People in developing countries generally enjoy human rights to a much lower extent than people in countries with richer economies (UNDP 2000) and disability often increases this gap (Parnes et al. 2009). The Convention on the Rights of Persons with Disabilities claims that people in need of assistive devices must be able to access it to ensure their full and equal enjoyment of all human rights and fundamental freedoms (UN 2007).

Several studies, similar to each other but in different developing countries, have shown that people with disabilities in these contexts generally are less educated and less likely to be employed (Eide & Kalameri 2009; Loeb et al. 2008; Eide & Loeb 2006; Loeb & Eide 2004; Eide et al. 2003; Eide, van Rooy, & Loeb 2003). A study by Susan Shore and Stephanie Juillerat (2012) further confirms this by showing that lack of mobility inhibits wheelchair users to integrate with society, resulting in limited access to employment and education. Ways must be found to prohibit this development and there is previous research showing that wheelchair users with improved mobility seem to get better opportunities in the society (May-Teerik 1999). However, the access to wheelchairs and other assistive devices is very limited in many countries and the World Health Organization (WHO) estimates that 1% of the world population is in need of a wheelchair (Armstrong et al. 2008), whilst only 5-15% of the people living in low and middle income countries requiring assistive devices have access to it (WHO 2012). This means that approximately 70 million people are in need of a wheelchair and that most of those living in low and middle-income countries lack access to it. Previous research has also pointed out that assistive devices incompatible with the environment may end up being abandoned by the user (Saha et al. 1990).

What is stated in this section can be seen as implications on that there is a need for wheelchairs compatible with each specific context. What must also be understood and considered is that wheelchair distribution is a prominent factor to provide all these users with sufficient equipment.

4.1.2. Public Transportation in Developing Countries

Previous research has shown that most of the least developed nations are dealing with problems regarding basic public transportation rights such as personal mobility and environmental access. Further national development usually means reaching beyond these issues but there are also many developing countries struggling with a proper focus on public transportation to provide it on a satisfying level to their citizens. These problems are also further enhanced among disabled people. (Venter, Rickert, & Maunder 2003)

The issues of access to assistive devices and affordability of public transport are still major challenges in many developing countries (Ibid.). This is definitely consistent with the experiences gained by the project team during the WEshare project (Bremer, Ohlson, & Olsson 2012). Furthermore, previous observations in Kenya also highlighted other issues among disabled people. It is, according to the difficulties linked to wheelchair riders, common that these people are not accepted on public transport. Accepting a wheelchair rider means that the rider needs assistance to get on board the bus, vehicles which rarely are accessible for disabled. This occupies time, which the driver otherwise could be used for earning money. Wheelchair riders also demand more space than other passengers, meaning that the driver will lose income if the wheelchair rider does not pay an additional fee for bringing the chair. Finally, it is also quite common that other passengers do not consider that there are disabled people among them. This means that vehicles often are filled before a wheelchair rider has an opportunity to get on board.

All these issues may not be solved through a product-specific solution such as a wheelchair, but can be one step towards a change. It is reasonable to believe that infrastructural changes are about to take place in many developing nations. The question is perhaps rather *when?* than *if?*. It is, however, still difficult to speculate when such change would take place, which evokes a wheelchair design adapted for the current context even if a more preferable situation would be the converse. A society designed after its inhabitants.

4.1.3. Cultural Aesthetic Differences

The Dutch researcher Geert Hofstede (Hofstede, Hofstede, & Minkov 2010) outlines five dimensions to describe national cultures and how these can be differentiated from each other. The dimensions include *power distance, individualism, masculinity, uncertainty avoidance* and *long-term orientation.* They are here linked to aesthetic preferences in different national cultures, which is considered important when designing a product suitable for various national contexts.

Power Distance (PDI)

Power distance basically explains the extent to which people accept that power is, and even should be, distributed unequally (Ibid.). USA and many northern European countries generally have low power distance cultures, whilst South American and Asian cultures tend to have comparatively high power distance cultures. In high power distance cultures, it is accepted and even expected that wealth and authority go side by side. Status symbols and privileges are expected and popular, quite contrary to low power distance cultures where these are frowned upon. (Jordan 2000)

Individualism (IDV)

Individualism declares the extent to which people tend to separate themselves from others in the society (Hofstede, Hofstede, & Minkov 2010). In individualistic cultures, people are generally brought up to look after themselves and their closest family. People in collectivist countries function differently and they are born into extended families and their identities are based on the belonging of a social network rather than a single individual. Northern European and North American countries are generally individualistic, whereas South American and Asian countries tend to be more collectivistic. (Jordan 2000)

Masculinity (MAS)

Dominant values in masculine cultures are material success and progress, which implies that things and making money are very important. This completely counteracts to feminine cultures where caring for others, preservation and warm relationships are more important. (Hofstede, Hofstede, & Minkov 2010)

Sweden belongs to one of the world's most tender cultures according to Hofstedes (Ibid.) studies, and the welfare society is seen as ideal here. The higher value on modesty is in contrast with the tougher and more masculine perception of valuing ambition and assertiveness. (Jordan 2000)

Uncertainty Avoidance Index (UAI)

Uncertainty avoidance describes the extent to which people feel threatened by ambiguity (Hofstede, Hofstede, & Minkov 2010). USA, UK and Scandinavian countries do all have a low uncertainty avoidance index. In these countries, uncertainty is accepted as normal and people tend to accept it as it comes. This is contrary to high uncertainty avoidance cultures, such as Japan and many South American countries, where this uncertainty is seen as a threat that must be fought. High uncertainty avoidance countries are often conservative and may worry about changes in society, while low uncertainty avoidance cultures are more tolerant to change. This ultimately leads to that low uncertainty avoidance societies put a higher value on youth. (Jordan 2000)

Long-Term Orientation (LTO)

Long-term orientation is treating the extent to which people are future orientated (Hofstede, Hofstede, & Minkov 2010). North American countries and the UK are short-term oriented countries, which means that they want instant rewards for their efforts. It can partially be translated into that people tend to spend money they make quickly and are buying the latest things regardless if they can afford it or not. Most of the Asia Pacific countries are long-term oriented countries and these people generally save a considerably higher share of their incomes and may be more critical regarding purchases. (Jordan 2000)

Conclusion

Jordan (Ibid.) claims that by correlating the cultural dimension scores of countries, it is possible to cluster them into cultural groupings. Traditionally, manufacturers have generally clustered their markets geographically. An implication of Jordan's study is that if aesthetic preferences are linked to culture, these geographical approaches become flawed. The UK does, for example, score closer to North American countries in the cultural dimensions than to its geographical neighbors.

A challenge when involving cultural differences in design and human factors is to investigate whether or not there are systematic links between a country's position on a cultural dimension and aesthetic preferences within that country. This is particularly prominent in multi-national companies who are active on different geographical markets.

So how do this theory apply to this project? The answer is perhaps not obvious but finding an appropriate visual appearance on a product for a global market means crossing over many smaller cultural groups. It could mean that the end result must be consistent with all the different end users' preferences but it could also mean to create a design, which is causing as little cultural errors as possible. Finding an expression that would be accepted by everyone is challenging and could perhaps be replaced by finding an expression that is neglected by as few people as possible.

The fact that the testing and evaluation phase of this project should take place in Indonesia must also be considered. The cultural dimension differences compared to Sweden and the United States are significant, as can be seen in figure 4.1. This is important to consider according to several reasons. The general perceptions held by Swedes are different from the other two and it is important to understand and accept that there must be room for cultural clashes and misunderstandings, but also a great amount of respect. What is obvious in a Swedish context might be perceived in a complete different way in the United States or Indonesia.

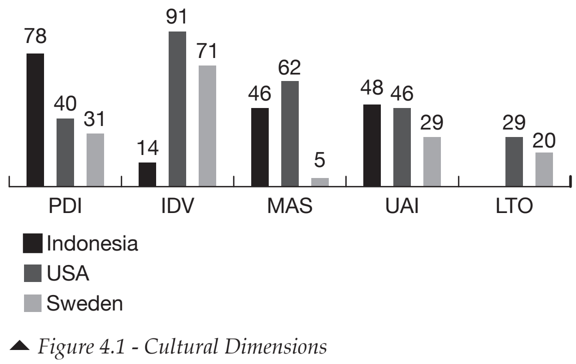


Figure 4.1 - Cultural Dimensions

4.2. Further Data Collection

The opportunity to spend time at three different geographic locations, each with a different expertise within the fields of academic projects, wheelchairs and developing contexts, required different data collection methodology for each location.

4.2.1. Benchmarking

It is impossible to accommodate the needs of all users with just one kind of wheelchair. Disability, riding context, economy, manufacturability, reparability and distribution are all factors of importance when designing a wheelchair. By benchmarking current solutions in both developed and developing contexts, there was a hope to find strengths and weaknesses in different solutions but also opportunities for this project and ultimately create an understanding for how wheelchairs are designed in different contexts.

The choice of wheelchairs for this analysis was based on what type of user characteristics they were designed for. It was chosen to include chairs accommodating the needs of active adult users in both developed and developing countries to understand their differences. These different wheelchairs have been chosen to cover certain developing world characteristics, such as rugged terrain and semi-urban environments, but also wheelchairs that accommodate the needs of similar users in developed countries. In addition, it was chosen to also include wheelchairs that cover state-of-the-art technologies in the fields of both lightweight and rugged terrain wheelchairs.

Developing Context Wheelchairs

Whirlwind RoughRider: A complete description of the RoughRider is found in chapter 2.4.1. In short it is an x-brace folding rough terrain wheelchair designed for developing countries. It has a 50% longer wheelbase than conventional wheelchairs and large solid rubber casters, which provides the neccessary rugged terrain characteristics for users in developing countries.

There is, according to the inclusion of Whirlwind, a wide knowledge on the RoughRider and it is therefore suitable as a reference model in this study. The Roughrider can be seen in figure 4.2.

Free Wheelchair Mission GEN_2: This is currently the cheapest developing country wheelchair available. It is sold at less than USD 72 and designed to accommodate a variety of user needs (Free Wheelchair Mission 2012). This second-generation Free Wheelchair Mission chair is especially designed for use in rugged terrain of under-resourced and rural areas. Its low cost includes manufacturing and shipping to some of the globe's most remote corners and the concept of Free Wheelchair Mission is to provide needing users with wheelchairs at no cost for the client. The result is a simple wheelchair with fewer adjustment options, which is not ergonomically optimal, but it gives poor people in need of wheelchairs an opportunity to get a device to facilitate their life situations

This chair, which can be seen in figure 4.3, earned its place in this study as a low-cost wheelchair for the developing world.

▲ *Figure 4.2 - RoughRider US Edition*

▲ *Figure 4.3 - Free Wheelchair Mission GEN_2*

▲ *Figure 4.4 - Harmony*

Harmony: The Indonesian manufacturer Dharma Healthcare produces the Harmony and its frame is constructed by double Ni-chrome plated cold rolled steel tubing (Dharma Healthcare 2012). It has an archetypal wheelchair appearance with separated durable footplates, large plastic molded front casters and vinyl upholstery. The Harmony comes in two different seat widths (16" and 18") and may be folded through an x-brace placed under the seat. The chair, shown in figure 4.4, was included in this study according to that it is commonly distributed to users in the intended contexts.

Leveraged Freedom Chair (developing): This chair has a different way of transmitting force from the rider's arms to the wheelchair, which can be seen in figure 4.5. Instead of pushing the rear wheels like a conventional wheelchair, LFC riders push on levers. This is according to the developers more efficient and the LFC is designed to allow the user to travel five kilometers a day in the chair (Global Research Innovation and Technology 2012).

▲ *Figure 4.5 - Leveraged Freedom Chair (developing)*

Riders can "shift gears" by sliding their hands up and down the levers to either provide more torque or travel faster. The levers can also be removed and stored on the chair, which makes it possible to use the LFC like a conventional wheelchair. This may be convenient in certain situations and perhaps particularly indoors. The LFC is produced in mild steel, which is locally available in most developing contexts. All moving parts are bicycle parts and this enables the LFC to be repaired at local bicycle shops. The LFC has a large single front caster, which is placed in front of the footrest. This prevents the rider from falling backwards when encountering obstacles and provides additional stability.

The Leveraged Freedom Chair for developing countries has taken place in this study according to its innovative approach on wheelchairs for developing contexts.

Motivation Active Folding: The British developer Motivation's Active Folding is designed for a semi-urban context in developing countries and is described as an active style wheelchair (Motivation 2012). It has two medium sized front casters and two bicycle wheels in the back to negotiate uneven ground without losing the good maneuverability in urban and indoor environments. Conventional bicycle wheels and bearings are used so that they are easily replaced and repairable at local bicycle shops.

The Active Folding, displayed in figure 4.6 represented a very active developing context wheelchair in this study.

▲ *Figure 4.6 - Motivation Active Folding*

Motivation Rough Terrain: The Rough Terrain has a similar visual appearance as the Leveraged Freedom Chair. The main difference is that the Motivation Rough Terrain is propelled using conventional hand rims instead of levers. It has some similarities with Motivation's Active Folding and is also partially built from bicycle parts to facilitate maintenance in local workshops (Motivation 2012). The frame is mainly made from steel with additional components in aluminum and stainless steel.

The Rough Terrain, shown in figure 4.7, represented a developing world wheelchair designed for people living in areas with primarily rugged terrain.

▲ *Figure 4.7 - Motivation Rough Terrain*

Developed Context Wheelchairs

Etac Cross Active: The Cross Active is a very versatile chair in terms of both adjustability and additional accessories, which are used to individualize the total performance (Etac Sverige AB 2012). The Cross Active is very stable for a foldable chair according to its double x-brace. The framework is constructed by steel and aluminum and the great ability to adjust measures creates a chair suited for a wide set of users.

The Etac Cross Active, which can be seen in figure 4.8, was included in this study to represent an industrialized version of wheelchairs like the Harmony and the RoughRider. This can be translated to an active adult wheelchair, which is foldable through an x-brace solution placed under the seat.

▲ *Figure 4.8 - Etac Cross Active*

Leveraged Freedom Chair (industrialized): The industrialized version of the LFC is based on the developing world version but has been equipped with a refined design and high-end materials to suit the needs of wheelchair users in primarily the United States. It allows riding over uneven surfaces and rough terrain to a wider extent than conventional wheelchairs. This chair is still under development and is not yet available on the market but the idea is that the income of this chair will help funding the developing world version (Global Research Innovation and Technology 2012).

The industrialized version of the LFC was used in this study since it represents state-of-the-art technology within the field of rough terrain wheelchairs. It is displayed below (figure 4.9).

▲ *Figure 4.9 - Leveraged Freedom Chair (industrialized)*

▲ *Figure 4.10 - Panthera X*

Panthera X: The Swedish wheelchair developer Panthera's model X is according to themselves currently the lightest wheelchair in the world (Panthera AB 2012a). Its framework is produced in carbon fiber and all details are made as light as possible, which includes a carbon fiber-reinforced titanium footrest. The total weight is 4.4 kilograms, which is evenly distributed between the rear wheels and the rest of the chair.

Panthera X, shown in figure 4.10, represents state-of-the-art technology within the field of lightweight wheelchairs and was therefore included in this study.

Quickie GT: GT, from the American developer Quickie Wheelchairs, is also considered a lightweight wheelchair but is mainly made out of aluminum. It has a rigid frame and the backrest may be folded to decrease the total size of the chair when transported. This creates a lightweight wheelchair with the flexibility to meet a wide variety of user needs (Quickie Wheelchairs 2012a).

▲ *Figure 4.11 - Quickie GT*

The Quickie GT, which can be seen in figure 4.11, was included in this study since it is a lightweight rigid frame wheelchair for developed contexts constructed using relatively affordable materials.

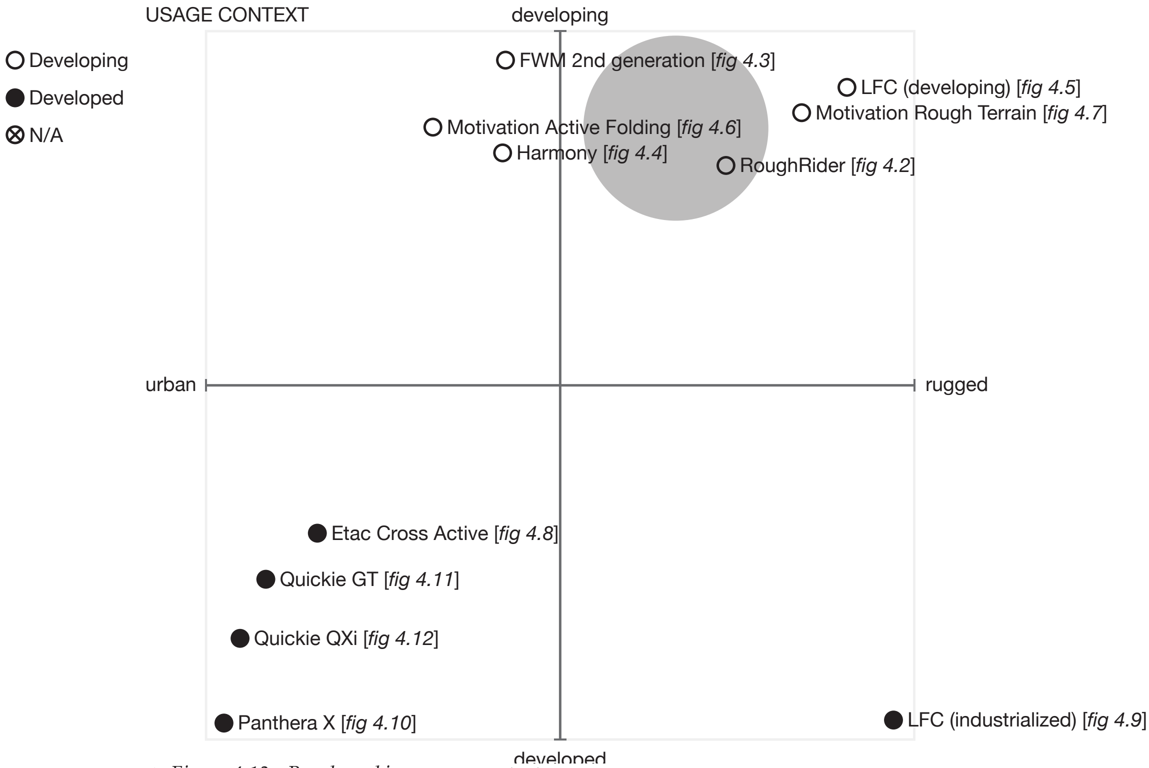
Quickie QXi: QXi is an ultra light x-braced wheelchair made from aluminum (Quickie Wheelchairs 2012b). It shares a number of functionality with more conventional x-braced chairs and Quickie has managed to combine this with a very low weight. Most adjustments can be done using only one tool to reduce adjustment and setup time.
It offers a great choice for riders preferring the x-brace framework to rigid frames.

The QXi, shown below in figure 4.12, earned its place in this study by showing state-of-the-art technology in X-braced wheelchairs.

▲ *Figure 4.12 - Quickie QXi*

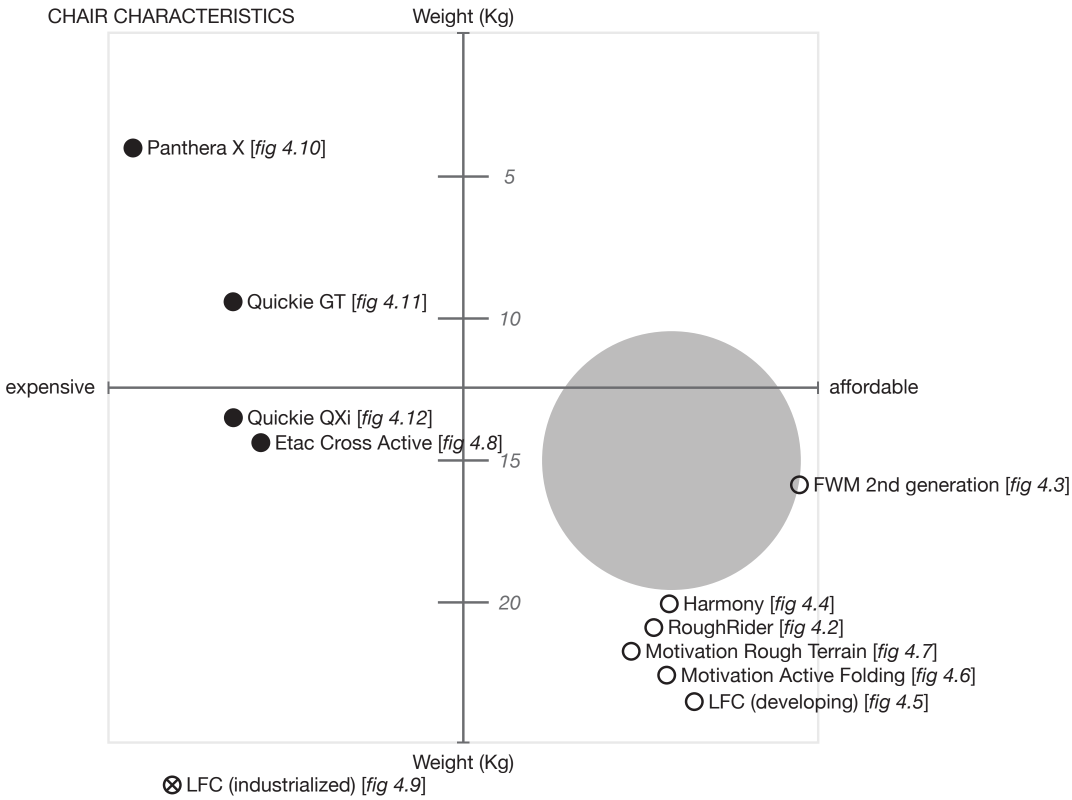
Results

This benchmarking, visualized in figure 4.13 and 4.14, should rather be seen as giving a general understanding of different active manual wheelchairs in both developing and developed contexts than a thorough analysis of the current market situation. The first and perhaps most obvious understanding is the difference in weight and cost between wheelchairs for developing and developed contexts. The extensive usage of steel in developing world chairs enables affordable and durable chairs. However, this causes heavier chairs and most developing world chairs have a total weight of between 20 and 25 kilograms. The economic conditions in developed countries enables a usage of more expensive and complex lightweight materials, which ultimately means more expensive but also lighter chairs. A lighter



▲ *Figure 4.13 - Benchmarking, usage context*

▼ *Figure 4.14 - Benchmarking, chair characteristics*



chair is preferred over a heavier chair considering maneuverability. Less muscle power is needed, which means that the user gets a simplified handling procedure but also an extended endurance.

Considering the usage context, the following conclusion can be made. There are two general types of active manual wheelchairs – chairs designed for rugged terrain and chairs adapted for more urban environments. There are few hybrid models that can handle both the rugged terrain and urban environments, including tight passages and indoor riding, to a satisfying level. The closest example is possibly the RoughRider, which would not perform as good as the Rough Terrain or LFC in rural contexts but does with its extended wheelbase have an improved ability compared to more urban chairs. The same kind of argument can be used for the RoughRider's ability in pure urban contexts. It is not as adapted as the urban chairs but would manage tight spaces better than the pure rugged terrain chairs.

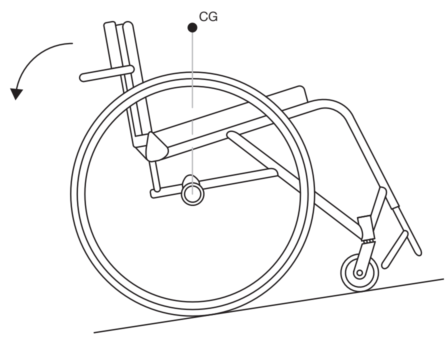
This opens an opportunity for this project. As can bee seen in the figures, two grey circles indicate interesting market potential. There are currently no developing world chairs that handle both rugged and urban terrain, which characterizes the situation in semi-urban environments, while still being lightweight and affordable. Since this project is aimed at a user group living in semi-urban environments, there is definitely a sense in keeping similar riding characteristics as on the RoughRider.

4.2.2. Wheelchair User Scenarios

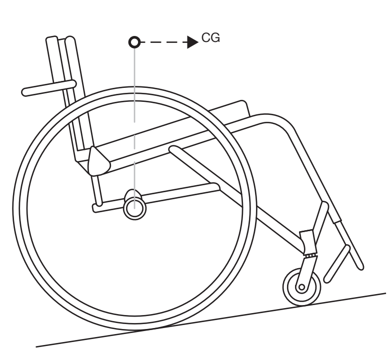
Producing wheelchairs includes multi-layered issues and for a person with fully functioning body limbs, it is extremely hard to imagine how everyday life as a wheelchair rider is. Before carrying on with further data collection, it was decided to set up small-scale scenarios. As can bee seen in figure 4.17, both chairs designed for developed and developing contexts were used.

The outcome of these scenarios was not measureable in terms of qualitative or quantitative data, but rather formed an emotional basis on which the further development work could be built. The awareness of how different kind of wheelchairs, especially the RoughRider compared to conventional lightweight solutions, acted in varying terrain enhanced the understanding of the casters and longer wheelbase. These have a major advantage when riding anything but flat ground. The width of the casters floats over both soft ground and minor obstacles in a way that allows the user to challenge him- or herself to choose routes that normally cannot be run by wheelchairs. More conventional wheelchairs with smaller casters placed behind the footrest get stuck in soft ground, but minor obstacles can also mean a dangerous situation according to that the shorter wheelbase may cause the chair to tip forward if the casters run into something. Also, an additional understanding for how the total weight of the chair affects the riding performance was provided. A lighter chair is according to the experience easier to maneuver.

Another major insight was made here. Riding steeply inclined hills is considerably difficult. The center of gravity is translated back and the rider is likely to fall over backwards if too much power is transmitted to the rear wheels (figure 4.15). This may be counteracted by sitting at the front end of the seat (figure 4.16), which can be seen as incredibly difficult for paraplegics.



▲ *Figure 4.15 - Risk of falling backwards*



▲ *Figure 4.16 - Translate center of gravity*

▲ *Figure 4.17 - Scenario testing (Left: Erik riding a Quickie. Right: Christian riding a RoughRider)*

▼ *Figure 4.18 - Consultation with Ralph Hotchkiss at Whirlwind*

4.2.3. Wheelchair Expertise

This research phase included both visits at the Assistive Device Central in Mölndal, Sweden, and conversation via video-calls and email-conversations with Whirlwind staff. This was also later enhanced by Whirlwind's constant presence during the development and production of the functional prototype (see figure 4.18). The inclusion of wheelchair development expertise significantly speeded up some processes. It has meant an ability to clarify uncertainty regarding specific issues but also an extra dimension of confidence. There has been an ability to evaluate solutions with experienced developers at an early stage, which has reduced the risk of serious errors later in the development process.

The close collaboration with Whirlwind has definitely affected decisions regarding the functional prototype. This can bee seen from two different perspectives. It has been important to develop a product in which Whirlwind are interested. Getting help and feedback from people with their knowledgebase has been both important and very helpful, and the opportunity of getting such help is probably related to the enthusiasm among the expertise. This basically means that the input from Whirlwind has been seen as very important but this could not aimlessly be considered as absolute facts and was be evaluated and confirmed just like any other information.

Whirlwind's Director of Product Development, Matt McCambridge[1], promoted development of a rigid frame wheelchair with a lower weight than the RoughRider. Whirlwind still wanted the end result of this project to hold similar riding characteristics as the RoughRider and there is strong connection between Whirlwind's product identity and the front casters – a Whirlwind innovation the company truly believes in and intend to retain.

4.3. Conclusions

The main conclusion from the initial research is that there is definitely a need for people to get involved in wheelchair development for developing countries. It is important that more resources are used in the developing world to be able to increase the quality of wheelchair services here .

Regarding the prototyping, it was decided to retain the riding characteristics of the RoughRider. Still, some technical properties were decided to change. The intention was to keep the extended wheelbase and the casters but to change the framework structure to offer an alternative solution. This included a rigid framework without the x-brace construction and an ambition to construct a lighter chair. Achieving a more lightweight chair would have to mean a new framework, using less tubing or a lighter material. Using another material than steel could, however, potentially mean problems connected to finance or maintenance in the intended contexts.

These conclusions formed the basis of a preliminary requrement list (figure 4.19). The intention was to initiate a summary of the requirements identified in each part of the project. This list could then later be expanded to eventually become a full list of requirements.

PRELIMINARY REQUIREMENTS

No.	Specification	wish/requirement
1.	Retain RoughRider riding characteristics	wish
2.	Retain Roughrider wheelbase	req.
3.	Retain Roughrider casters	req.
4.	Provide rigid framework	req.
5.	Framework weight must not exceed 20 kg	req.

▲ *Figure 4.19 - Preliminary requirement list*

1. Matt McCambridge (Director of Product Development, Whirlwind Wheelchair International) interviewed by the authors October 20, 2012.

5. Functional Prototype

This chapter describes the development and actual production of the functional prototype. This phase was carried through in collaboration with Whirlwind Wheelchair International at their headquarters in San Francisco, CA.

5.1. Ideation

The initial research confirms the need of a lightweight wheelchair for developing countries.
As mentioned, it was also important to use the advantages of specific characteristics on current wheelchairs for developing countries. The decision to keep the long wheelbase and its casters in combination with the delimitations of the project led to the following.

It was decided to focus on primarily designing a new framework in this initial idea generation. The reason was mainly the framework's heavy influence on the final solution's appearance. The modularity of a wheelchair made it possible to later generate specific solutions for each of the remaining details without being too controlled by the framework appearance.

5.1.1. Framework Brainstorming

A brainstorming session with the project team as the two participants was held. The main focus was on generating ideas on how to achieve a lightweight wheelchair framework, which should retain the riding characteristics of a long wheelbase wheelchair. Four feasible ideas were chosen for presentation and further evaluation.

Idea 1

The first idea, displayed in figure 5.1, shows a rigid box frame. The seat tubing and the tube connected to the caster barrel create a box-shape to provide stability to the construction. The foot support is attached to the extended seat tube, which decreases the number of loose-end tubing and saves space. The backrest has an extended folding, which minimizes the folded size and efficiently utilizes the framework's shape.

Idea 2

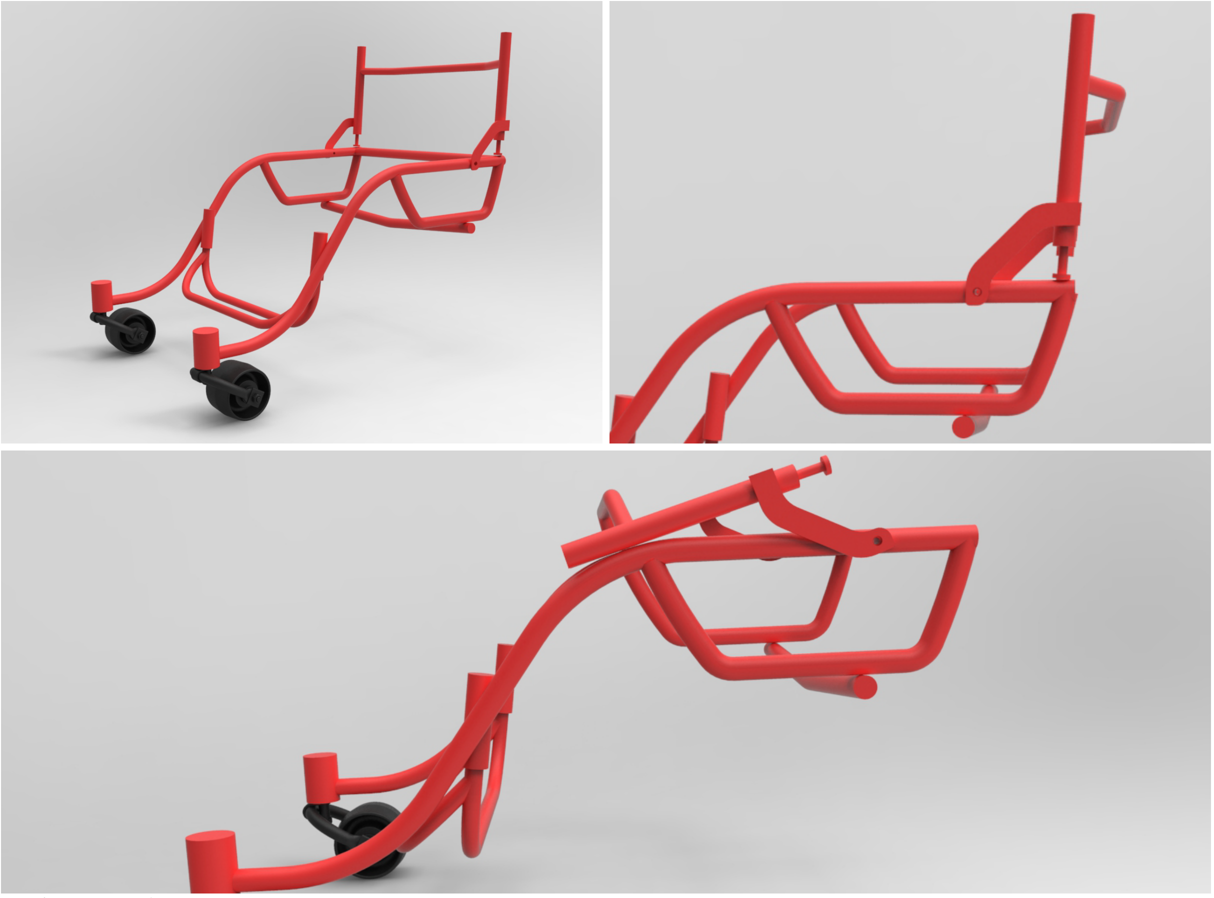
Idea number two, seen in figure 5.2, is also a box frame where both the seat and lower tubing is connected to the caster barrel. The tubing is bent in a more complex manner to allow further flexibility, which could be beneficial when riding in rugged terrain. The footrest is attached on the extended seat tubing to allow a step-less horizontal adjustment. The backrest has a conventional folding mechanism where it aligns with the seat in folded position.

Idea 3

Idea three can be seen in figure 5.3 and it is constructed as a mono-frame. There is only one main tube that reaches all the way from the seat down to the caster barrel. This decreases the total weight by using less tubing, but also increases the frame flexibility. The construction under the seat still provides the step-less rear axis positioning and the footrests may be horizontally adjusted through the attachment tubes placed on the framework.

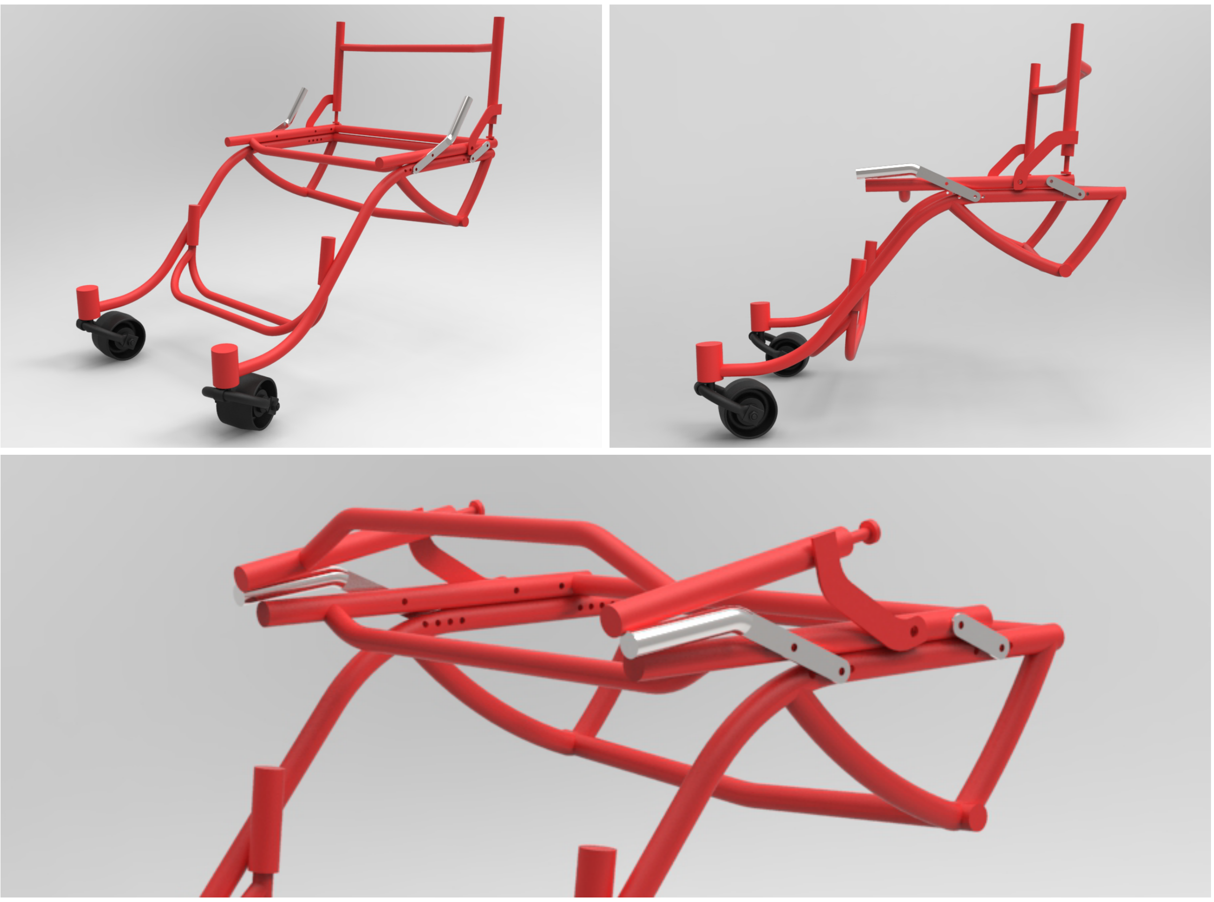
▲ *Figure 5.1 - Idea 1*

▼ *Figure 5.2 - Idea 2*



▲ *Figure 5.3 - Idea 3*

▼ *Figure 5.4 - Idea 4*



Idea 4

The fourth and final idea, shown in figure 5.4, is an attempt to take further advantage of the longer wheelbase. This idea has a moving seat where the COG may be altered. The idea is built on a mono-frame construction but could also be applied to a box frame solution. The thought is to allow the user to alter the position of the seat by own means while riding. By grabbing the handles and pushing forward, the seat will flip over and take a new position. Through this procedure, the COG is moved approximately ten centimeters forward. This has its major advantage in steep slopes where there is a risk of the user tilting backwards due to the inclination.

5.1.2. Idea Presentation & Evaluation

These four ideas were presented to eight Whirlwind employees[1] for feedback and further evaluation. Including Whirlwind was important from two different points of view. They could contribute through important feedback according to their extensive knowledge, but also by being involved in the decision making.

Since computer-aided material was used as communicative media, there was a concern that the audience might perceive the images as finished concepts rather than ideas. This was considered and prevented by two main factors. First-of-all, CAD software is used at Whirlwind and that means that there is already a habit within the company to look at concepts generated digitally by computers. Secondly, it was chosen to remove side protections, rear wheels and seat fabric from the presentation images to emphasize the fact that these were frame idea sketches rather than finished concepts.

The evaluation was based on discussions among the project group and Whirlwind employees. One major concern was the level of innovation. Considering the fact that this is an academic project, there is perhaps an even greater opportunity to test and evaluate solutions that are previously not tested by current wheelchair companies. This caught the interest of the evaluators. The longer wheelbase allows an alternating COG to a much wider extent than what would be possible on a conventional chair with a shorter wheelbase. Also, this is a solution unknown to the intended user group and this project was a great opportunity to test and evaluate such solution.

There was also a discussion regarding box frame or mono-frame construction. The hypothesis was that the visual expression of a mono-frame solution would be perceived differently than a box frame in a developing context, which increased the interest in testing and evaluation a mono-frame wheelchair. Especially since box frames currently are ridden by many users in developing contexts and it is quite common that old chairs are donated from industrialized countries. The individual comments on each concept were as follows.

Idea 1

The tube connecting to the caster barrel would presumably need a bigger diameter to withstand the twisting forces in a developing context. Also, the footrest is placed too close to the user's body. This means that it must be moved closer to the casters to fulfill its purpose properly. The extended folding has a potential but the brackets connecting the backrest to the framework would either have to be larger to efficiently function as dirt protection, or smaller to make room for external protection.

Idea 2

Once again, the footrest would have to be located closer to the casters. Furthermore, it is a simple and feasible design with its main disadvantage in the rather complex bends of the seat tubing. It would mean a difficulty to produce it in factories in developing countries according to the advanced bending tools needed to achieve such bends efficiently. It is, however, a clever use of existing tubing, since no additional tubes are required for attaching the footrest.

Idea 3

The mono-frame is, as previously described, interesting according to its different visual appearance compared to other wheelchairs for developing countries. Also, it would probably be lighter than a box frame construction, since less tubing is needed to accomplish the framework.

1. Ralf Hotchkiss (Co-founder), Marc Krizack (Executive Director), Matt McCambridge (Director of Product Development), Aaron Wieler (Product Designer), Keoke King (Marketing Director), Kaleen Canevari (Quality Systems Engineer), Laura Harrington (Project Administrator), Nancy Carroll (Office Administrator)

Though, it would probably need a bigger tube diameter to withstand horizontal, vertical and twisting forces applied during maneuvering. The footrest is once again placed too close to the user's body and the attachment to the framework must be reconsidered in order to function properly.

Idea 4
This idea is shown with a fixed rear wheel position but it would be beneficial to allow the rear wheels to be repositioned, and thereby gain more versatility in the chair's performance. The alternating seat mechanism has great potential in combination with the long wheelbase, but must be redesigned so that it is possible to maneuver by the targeted users. However, the idea of keeping the construction simple means a possibility to achieve this functionality and still keep the production at a low cost.

Decision
There was a decision to develop the alternating seat from idea number four further. It could at this point not be fairly evaluated according to the need of further development, but there was still one very interesting aspect to this idea. On a wheelchair with a shorter wheelbase, it would be very hard to achieve an alternating seat since a forward seat motion would probably cause the rider to fall over forward and out of the chair. The decision to keep the longer wheelbase of the RoughRider enabled a logical opportunity - a possibility to evaluate an alternating seat in combination with a long wheelbase. The idea was at this point not particularly developed and included a thought of alternating the center of gravity rather than a technical solution on how to achieve this.

5.1.3. Requirements Update
The ideation led the project to a point where there was a need to update the preliminary requirement list before developing the idea further. The characteristics of the added requirements were predominated by accessory compatibility, such as brake and footrest attachment, but solving the idea of an alternating seat was also of major interest. It was also noted during the evaluation that there is a need for hip support and adequate mud protection. As can be seen in figure 5.5, the requirements were at this point still general and not translated into engineering specifications. They were also not given any weighting or importance, and were just divided into wishes or requirements according to the characteristic of each specification. Specifications 1 - 5 (faded in gray) are kept from the preliminary list, while number 6 - 15 were added here.

UPDATED REQUIREMENTS

No.	Specification	wish/requirement
1.	Retain RoughRider riding characteristics	wish
2.	Retain Roughrider wheelbase	req.
3.	Retain Roughrider casters	req.
4.	Provide rigid framework	req.
5.	Framework weight must not exceed 20 kg	req.
6.	Provide an alternating seat	req.
7.	Provide adequate footrest attachment	req.
8.	Provide footrest adjustability	req.
9.	Provide adequate brake attachment	req.
10.	Allow backrest to fold	req.
11.	Minimize unfolded size	wish
12.	Minimize folded size	wish
13.	Allow stepless rear wheel position adjustment	req.
14.	Provide hip support	req.
15.	Provide adequate mud protection	req.

▲ *Figure 5.5 - Updated requirement list*

5.2. Concept Development

The requirements did not yet include framework design, and the seat alternation could be adapted to both a box frame and a mono-frame wheelchair. Two separate framework concepts were delevoped further, visualized by sketches (figure 5.6) and finally evaluated.

5.2.1. Concept Generation

The idea behind the refined box frame was to create a tight and light expression but still benefit from the construction's increased stability and durability. It would also provide an obvious location to attach the brakes.

The mono-frame would have its primary advantages in the lighter expression and lighter total weight provided by the decreased amount of tubing. The compressed framework design would, however, leave less space to attach additional accessories, such as the brakes.

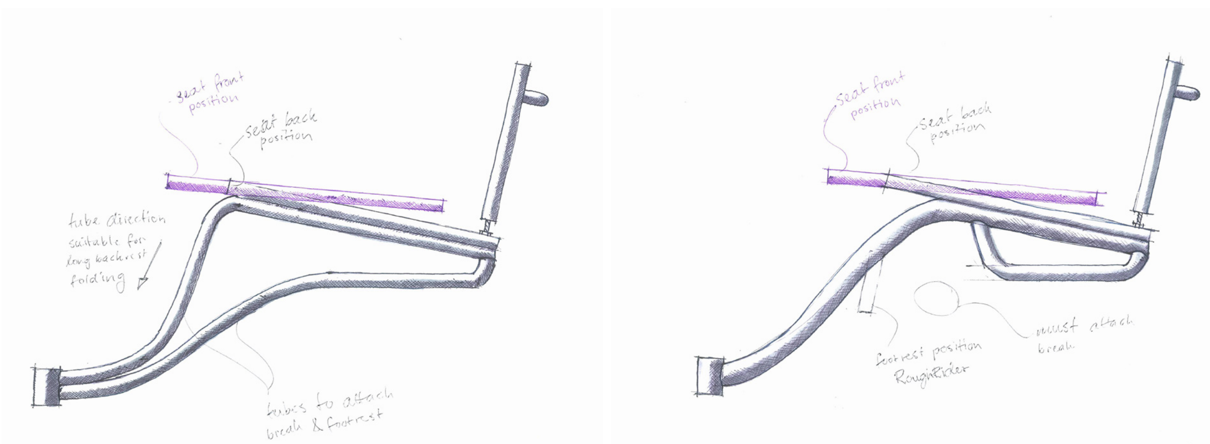
5.2.2. Concept Evaluation

These two different frameworks were evaluated by using a modified Pugh evaluation matrix (seen in figure 5.7). It is a comparison between the mono-frame and the box frame concepts and the evaluated aspects are based on the updated requirement list in figure 5.5. However, some aspects have intentionally been excluded from the evaluation according to that both concepts were considered to fulfill these requirements to an equal and satisfying level. The aspects in the evaluation matrix were instead slightly changed, compared to the list of requirements, to better evaluate which of these two concepts was better suited for being embodied as a prototype for the field trials in Indonesia.

Each of the evaluated aspects was given a weight according to their importance for the upcoming prototype. Every aspect was then evaluated and given a score. "0" means that the two concepts are considered equal. If one of the concepts is considered better than the other, that particular concept is given the score "1". If one of the concepts is significantly better than the other, it is given the score "2". The score is then multiplied by the weight to receive a total score. The final score is given by comparing both concepts' total scores. The weighting might seem odd for some aspects but they were at this point based on their importance for the prototype, not for adequately accommodating the user needs on an actual product. This means that some issues could be overseen and a good example of this is repairability in a developing context. Such aspect is crucial for the final product but not for the prototype. The field trials in Indonesia includes good access to both workshop, tools, and staff, meaning that repairability issues could be taken care of.

As can be seen in the matrix, the footrest attachment was considered to be equal for both concepts, while the mono-frame allows a bigger range of footrest adjustability. The brake attachment would be problematic on the mono-frame according to the lack of sufficient attachment points for the current RoughRider brakes.

The current shape of the two frameworks means that there is more potential in supporting the alternating seat on a box frame according to the



▲ *Figure 5.6 - Box and mono frame concept sketches* different radius on the main tubing, which can be studied in the sketches in figure 5.6. There was at this point a wish to use an elongated folding backrest and such solution woul be easier to accomplish on the box frame, according to the recently mentioned radius. The durability was also considered higher in a box frame because of its supportive structure. The frame flexibility, which is beneficial when riding in rough terrain, would however be better in a mono-frame wheelchair.

A mono-frame would demand less tubing, which would mean a lighter construction and there was confidence in that both solutions would provide enough strength to withstand the trials in Indonesia. The mono-frame would, according to its slimmer design, have a smaller folding size but that was not a major concern for a functional prototype. Instead, it was considered more important to find available material and be able to produce it at Whirlwind's workshop. Since there was more knowledge on how to construct a box frame and on how such construction would behave in the intended context, the box frame scored higher than the mono-frame in these two categories. The repairability was not a major concern here, since the testing phase in Indonesia would mean good possibilities to repair the prototype within the facilities of UCP Wheels for Humatiy.

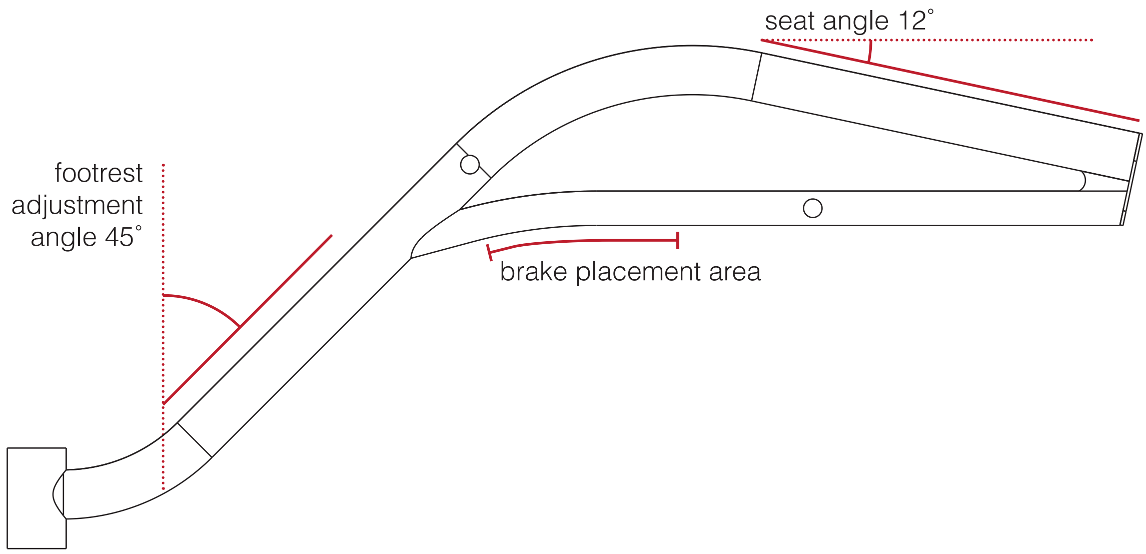
The two most important factors were the possibilities of adequate testing and innovation. The limited knowledge of mono-frame constructions and the fact that there are currently no such solutions available to users in developing contexts made such solution very interesting. That is also why the mono-frame was given high scores here. The final aspect, aesthetics, was considered to be too subjective to benefit either of the concepts.

The evaluation shows that the mono-frame concept scores slightly higher than the box frame according to the chosen criteria. By studying this further, it becomes clear that the box frame earns a lot of its points according to the ease of producing a prototype and secureness. It is a safe choice where certain characteristics already are

EVALUATION MATRIX

No.	Aspect	Weight	Score	Total
1.	Footrest attachment	0.2	0	0
2.	Footrest adjustabilty	0.4	M: 1	M: 0.4
3.	Brake attachment	0.6	B: 2	B: 1.2
4.	Seat support	0.7	B: 2	B: 1.4
5.	Elongated folding backrest	0.4	B: 2	B: 0.8
6.	Frame durability	0.5	B: 1	B: 0.5
7.	Frame flexibility	0.4	M: 1	M: 0.4
8.	Strength/weight ratio	0.6	M: 1	M: 0.6
9.	Folded size	0.4	M: 2	M: 0.8
10.	Material availability	0.7	B: 1	B: 0.7
11.	WWI workshop manufacturability	1.0	B: 1	B: 1.0
12.	Reparability in developing context	0.2	B: 1	B: 0.2
13.	Possibilities of adequate testing	1.0	M: 2	M: 2.0
14.	Innovation aspect	1.0	M: 2	M: 2.0
15.	Aesthetics	0.6	0	0
TOTAL SCORES		*Box frame: 5.8*		*Mono-frame: 6.2*
PREFERRED SOLUTION		***MONO-FRAME***		***+0.4***

▲ *Figure 5.7 - Evaluation matrix: B = box frame, M = mono-frame*



▲ *Figure 5.8 - Framework refinement*

▼ *Figure 5.9 - Seat mechanism*

known. The mono-frame offers a solution with less known factors but with a higher innovation aspect. One major reason of trying a mono-frame concept was thoroughly discussed here. If the mono-frame structure would be tested in Indonesia and is proven to fail, there is always the possibility of going back to a box frame later in the development process. The reverse situation would demand a higher amount of workload later in the process according to the, in that case, untested and uncertain mono-frame construction. Based on this discussion, the mono-frame was chosen as the concept to develop further from this stage. Using the mono-frame would not only mean testing the mono-tube framework but also a new kind of footrest adjustment angle.

5.2.3. Defining Concept

The concept definition included a further refinement of the framework (figure 5.8) and defining all parts of the wheelchair in order to produce a prototype production underlay.

Seat Mechanism

One of the main issues to solve at this point was the seat mechanism (figure 5.9). The idea was to construct a mechanism that would move the seat ten centimeters forward and simultaneously change the seat angle from twelve degrees backwards in the back position to four degrees backwards in the front position. Twelve degrees is the current seat angle on the RoughRider, which in this concept was chosen to be the same for evaluative reasons. A backwards tilted seat also provides pelvic stability and decreases the risk of falling forward (Engström 2002). Four degrees in the front position was based on that it should provide a close to horizontal position but still prevent the user from falling forward. This would, except from gaining a benefit going uphill, allow the user to come closer to tables and also offer a more active sitting position when working at a desk. If the seat would translate more than ten centimeters, it would be difficult to reach the rear wheels and thereby hard to propel them to maneuver the chair. Also, it was important to keep the popliteal-footrest distance in both front and back positions. This would allow the user to maintain the sitting ergonomics without having to adjust the footrest height.

It was decided to keep the mechanism simple and feasible in terms of prototype production. This was perceived as more important than users being able to translate the seat with own means. Then, it would be possible to evaluate whether there is a point of having a translating COG or not. The translation would thereby have to be done by assistance from either the evaluators or other people attending the testing procedure.

Footrest

There was a great opportunity to lower the weight of the footrests compared to the RoughRider. The initial idea of producing a footrest similar to what is used on lightweight wheelchairs in developed countries was rejected early in this ideation phase according to the lack of toe protection. It is according to Hotchkiss[2] common that people in less developed contexts ride without shoes and it is thereby important to offer some kind of protection for their feet. Wounds in the feet could lead to serious infections and in very severe cases even death.

There was a decision to keep a toe and foot protection similar as on the RoughRider. There were, however, still some issues to be solved. The amount of material in the foot supports currently increases the total weight. The attachment to the adjusting tube requires a relatively large amount of material to counteract the leverage from the feet and this causes an addition to the total weight. This is also further increased by the fact that there are two separate footrests. These are not supported by one another, which also requires stand-alone support and increases the footrest weight. The footrests are also not stabilizing the framework since they are not connected. This means this support must be integrated elsewhere in the frame, which possibly increases the total weight of the chair. These individual footrests were rejected considering the prototype according to the frame stability. One of the major advantages with a rigid framework is the complete frame stability and this can be further increased by one complete footrest instead of two separate. The disadvantage is of course the lack of individual adjustment for the feet.

2. Ralf Hotchkiss (Co-founder, Whirlwind Wheelchair International) interviewed by the authors October 20, 2012

▲ *Figure 5.10 - Footrest*

▼ *Figure 5.11 - Folded backrest*

There was also one additional thought on the footrest adjustment. Many available footrest solutions on the market are only vertically adjustable. There was here an idea to evaluate a footrest adjustment that is simultaneously translating in horizontal and vertical direction. People with shorter legs and thereby a need for a higher footrest position would according to anthropometrical studies not only have shorter knee height but also a shorter buttock-popliteal length (Pheasant 2003). This implies that a beneficial adjustment would include both the upper and lower part of the legs.

The footrest proposal (figure 5.10) included an adjustment along the framework's main tubing, which enables simultaneous horizontal and vertical adjustment. The idea was also to offer a similar vertical adjustability as on the RoughRider but to complement it with the horizontal movement.

Seat and Backrest

The initial thought was to diverge from the non-folding upright backrest used on the current RoughRider and instead go for an elongated folding backrest as seen in figure 5.1. This, however, showed to be problematic according to the wishes on such functionality. There is a determined need for fenders and these would need to fold away together with the backrest to satisfy the requirement on minimized folding size. That would in turn mean that the upholstery would interfere with the frame, and that the backrest would interfere with the brake attachment. Such problems could be solved through a significanlty more complex wheelchair design, but a more convenient solution is to use a folding backrest, aligning with the seat in folded position, as seen on conventional rigid frame wheelchairs. The fender may thereby be attached to the backrest and fold away as the backrest aligns with the seat (figure 5.11). Adding a crossbar reaching between the two backrest tubes ensures that both fenders are folded simultaneously.

The upholstery used for both seat and backrest will be taken more or less completely off a RoughRider. There was at this point no idea to search for other solutions, since the possible benefit probably not would correspond to the time spent on finding such solutions. It was decided to use a similar pendent seat as on the RoughRider, which would provide the prototype with a functional solution.

Fenders

The fenders include multi-layered problematic. They should adequately protect the user from mud and dirt but there are also other factors to consider. Some users need the fenders to also provide support for the hips and others occasionally sit on them to be able to reach further up. In the case of a folding backrest, which is the most likely way of handling foldability for a rigid framework, it would be preferred if the fenders would fold away when the backrest is folded. All these issues were solved by making the fenders lower than normal, which allowed a mud protection that the user could sit on, since its upper edge aligns with the rear wheels. The fenders were also attached to the backrest and seat, which allows them to fold away once the backrest is folded forward.

Brakes and Brake Attachment

The mono-frame concept would mean a difficulty to attach a regular RoughRider brake to the framework. Using off-the-shelf parts could be beneficial in a latter stage of this project where Whirlwind actually could use similar parts for different wheelchair models, which ultimately would decrease the total production costs. Evaluating the mono-frame would however mean that regular RoughRider brakes could not be attached in a satisfying way. It was therefore chosen to use scissor brakes, which were activated by reaching in under the seat and pulling levers. Such brakes are not optimal for the prospect user group but fulfilled the need of a functional brake at this stage of the project. If these brakes later would have been proven not to work, there was a great opportunity of changing them at a latter stage of the project.

Material

The opportunities to deselect steel as the primary material for the framework are very limited according to available workshop maintenance in developing contexts. This basically leaves carbon steel or some kind of steel alloy for the prototype. One interesting alloy was particularly discussed during the early part of the material selection process. A steel alloyed with chro-

▲ *Figure 5.12 - Concept*

mium and molybdenum (4130 steel), referred to as chromoly (Metal Suppliers Online 2012), is interesting for a developing world wheelchair. It is already commonly used for wheelchair applications in developed contexts according to its excellent strength to weight ratio. It is not as easy to weld as standard 1020 carbon steel but can be welded using all conventional methods, such as brass welding, MIG-welding or TIG-welding and welders in developing countries would probably overcome the posed problematic. The amount of chromium in chromoly is not enough to provide the steel with the corrosion resistivity found in stainless steel. Using chromoly would open a possibility to use thinner wall thickness in the framework tubing, which would decrease the total weight of the chairs. Chromoly was thereby chosen as main material for the framework. Even though this, considering end production, would mean a higher cost, it was interesting to take advantage of the opportunity to evaluate an extensive usage of a new material. This could also be helpful when trying to further define the need of a lightweight wheelchair.

Final Design

The final prototype design (figure 5.12) was constructed according to the given specifications using CATIA V5. Computer generated models allowed quick evaluations and minor testing sessions to ensure certain functionality. This was proven to be very beneficial in terms of finding optimal locations of holes, size of fenders, and how to design the framework to reach the given criteria.

5.3. Prototyping

The production of the functional prototype was not only dependent on the final concept proposal. This proposal also had to be adapted for both available material and tooling to ensure that it could be produced at Whirlwind's prototype workshop. It also included determining what size the functional prototype should be manufactured in. This decision was based on the following two requirements: It had to fit as many as possible of the intended testing group and still be large enough to fit the project team members, which would allow the widest variety in evaluation methods. This includes both theoretical expert evaluation methods and empirical studies.

Finding an appropriate size for the Indonesian testing group, without having a possibility to take their measurements in advance, meant basing these measurements on anthropometrical data. The difficulty to find sufficient data on Indonesian wheelchair riders required another approach. It was chosen to work with a data substitute as close to Indonesian wheelchair riders as possible, in this case anthropometrical data collected at National University of Singapore (Chuan, Hartono, & Kumar 2010). The dataset, seen in figure 5.13, is rather small for an anthropometrical study (345 male and 132 female Indonesian subjects) but is still providing information about an Indonesian population. The population of the study is university students, which most likely are not equal to general wheelchair riders but the data still represents an anthropometrical dataset that is considered precise enough for the purpose of choosing an appropriate prototype size.

The measure of importance was considered the hip breadth, which would determine the seat width of the prototype. It was here chosen to work with standard RoughRider seat widths, and in this case the size closest corresponding to the anthropometrical measures. It is impossible to use one seat width satisfyingly corresponding to a complete population. In the datasets described in the table below, the 50th percentile is similar for all four groups. According to the wish of fitting as many users as possible, it was decided to use the seat width fitting the 50th percentile

Hip breadth	(mm)			*(in)*		
Percentile:	**5th**	**50th**	**95th**	***5th***	***50th***	***95th***
Indonesian male	280	350	430	*11.0*	*13.8*	*16.9*
Indonesian female	290	350	450	*11.4*	*13.8*	*17.7*
Chinese Indonesian male	300	350	440	*11.8*	*13.8*	*17.3*
Chinese Indonesian female	300	340	420	*11.8*	*13.4*	*16.5*

▲ *Figure 5.13 - Anthropometry table: Hip Breadth for Indonesian Adults*

▲ *Figure 5.14 - Prototyping*

of these groups. The largest measure is 350 mm, which corresponds to 13.8". Pheasant (2003) suggests that 10 mm should be added to such measure in contexts where thin clothing can be assumed to be used. In such case, the measure increases to 360 mm or 14.2". This means that a 14" seat width would be appropriate according to the following. The seat width is measured between the two seat tubes and there is a small distance between the seat tubing and the fenders, meaning that the distance between the fenders in a 14" seat actually is 14.3". A 14" seat width would thereby be appropriate for most people in the targeted user group.

The next step was to evaluate whether the project team members could fit in a 14" chair. The evaluation showed that a 15.5" seat width would be optimal but a 14" seat was wide enough to allow the team members to ride the chair and conduct previously mentioned evaluation methods.

5.3.1. Optimization

The first step towards making reality of this prototype was to optimize the concept for being produced in the facilities of Whirlwind. This primarily meant adjusting the radii of the bends on the framework tubing. The available tube bending tooling included a roll bender and a tube bender using dies. The chromoly also showed characteristics, which made it significantly harder to bend than 1020 steel tubing. These issues complicate situations where tight radii are used and required a more thoughtful prototyping process. These issues could be eliminated through the usage of a more clever design. It was important to keep the main aim with the prototype, which here became producing a model that users could actually try and evaluate. It was important to keep the visual aspect as close to the initial idea as possible, but not as important as achieving a prototype users could actually ride. The technical aspects were thereby considered to be worth more than the purely visual. This eventually meant slight changes to all radii on the chair although none of them were considered to play a significant role in the prototype's visual appearance. The balance between achieving the technical properties together with the desired appearance could thereby be found without major concerns.

5.3.2. Drawings

Once the CAD-model had been optimized, there was a need to create production underlays in terms of primarily drawings. Considering the rapid process of producing a prototype of this kind (a physical representation that technically must perform like an actual wheelchair), it was also important to include an effective plan of how to build this model. Only one prototype was planned, which promoted a different way of producing compared to if more than one chair were about to be produced. One single prototype evoked an idea of using drawings in scale 1:1. The idea is basically that each part can be compared to the actual size drawing to rapidly evaluate the fitting (upper left picture in figure 5.14). The drawings were also attached to large wooden panels where cylindrical pins were placed. This provided the panels with a third property – function as a welding jig. This triple functionality would not be as convenient for producing more than one prototype but did in this case an excellent job as a drawing, evaluating tool and welding jig simultaneously. This also suited the use of CATIA v5, through which it was possible to generate 1:1 drawings.

5.3.3. Production

The main challenge considering the prototype production was achieving a straight construction. This includes achieving exact tube bends a well as welds with as little framework skewing as possible. This was counteracted by using a three-dimensional welding jig (center picture in figure 5.14). It was also important to maintain an efficient way of working because of the tight time schedule. These factors promoted a building procedure where Whirlwind employees, who are used to building wheelchair prototypes, took on a major responsibility but also acted educating as a preparation for the final part of the project. This, since the final phase would include producing another prototype without the presence of Whirlwind employees. The inclusion of wheelchair prototyping expertise was not only beneficial in terms of a faster process and education but also in terms of improving the quality of the physical prototype.

The production also meant encountering obstacles that unconsciously had been overseen earlier in the concept development process. The importance of not only rapid but also functional solutions was crucial. A similar attitude as previously described was used here. It was considered more important to achieve a technically working solution than something that visually would correspond to the compuder-aided renderings. This was reflected in the use of pre-fabricated parts, such as the footrest and rear wheel axel attachments, but also in the seat locking mechanism. It demanded an immediate solution to a problem that previously had not been considered.

Producing the prototype also gave some important lessons regarding the actual production of a wheelchair. The most visually pleasant solutions are rarely equal with the simplest manufacturing processes. This created trade-off situations where it was important to find compromises with acceptable visual expressions as well as manufacturing processes. This was especially prominent in the connection between the two tubes in the side-frame. The appearance of the weld connecting the two tubes is heavily dependent on the angle with witch the lower and thinner tube connects to the larger.

The prototype is also not optimized for a simple mass-production, which can be understood by observing the construction. The number of welds could be decreased through optimization work, and there are possibly several other details that would benefit from deeper consideration. The ease of manufacturing one single prototype and technical functionality was here more important than achieving an optimal design considering economy and mass production. The final weight of the prototype is 16 kg, which is 4,5 kg lighter than the current RoughRider.

Figure 5.15 shows the functional prototype fully assembled, figure 5.16 displays the functionality of the translating seat and figure 5.17 explains the foldability.

▲ *Figure 5.15 - Functional prototype fully assembled*

▲ *Figure 5.16 - Functional prototype with seat in back position (left) and front position (right)*

▼ *Figure 5.17 - Functional prototype folded with rear wheels detached*

▲ *Figure 6.1 - Paraplegic test subject riding uphill in front position*

6. Field Study

The content of this chapter will initially present the most prominent results from the field study in Indonesia. In the following section, different aspects of the user group are presented, which are fundamental for customer requirement prioritization.

6.1. Population

Various disability characteristics represented in the test group allowed the trials to embrace and evaluate the whole set of functionality included in the prototype. Different spinal cord injuries, such as paraplegia and parapares, as well as poliomyelitis and amputees, were all represented to a certain extent among the 22 test subjects. The age of the users were varying substantially within the range of 9 to 60 years old, which is not completely in accordance with intention described in section 1.4, but still considered as satisfactory since the majority of the test subjects were adult users. However, for a few young users the prototype turned out to be slightly oversized which had to be considered during the output data analysis.

6.2. Component Evaluation

The feedback received during the evaluation was rather characterized by the profile of each user. Disability, independent physical needs and social engagement are different examples of factors that typically would generate certain preferences in terms of assistive devices. However, in the following section, a general description of the most prominent user feedback is briefly given for different functionalities of the product.

6.2.1. Framework

For a major part of the trial population, the fact that the prototype was substantially lighter than currently used chairs such as the Harmony or previous versions of the RoughRider was heavily appreciated. The feedback was presumably based on the experience derived from maneuvering operations. It became clear that many users were encountering challenging riding tasks every day, which had to be overcome in order to interact with the society outside of their homes. From this understanding, it becomes important to emphasize features of wheelchairs that could be used to facilitate overcoming these challenges. As an example, the endeavor of creating a lightweight chair should be further pursued. An example of these challenging tasks is found in figure 6.1, where a user has taken advantage of the translating seat to maneuver the functional prototype on inclined ground.

The investigation also highlights the importance of the large wheelbase. Several users pointed out that the large wheelbase contributed to increased safety and mobility when riding in outdoor terrain. When used in an indoor environment, however, it was expressed that the large wheelbase had a negative effect on accessibility.

The use of chromoly did not reveal any significant gain in terms of user experience. Nevertheless, focus groups with production representa-

▲ *Figure 6.2 - Double amputee test subject riding ramp in front position* tives disclosed that the use of this material rather should be considered as a long-term solution that will facilitate the task of building an even lighter chair as a result of reduced wall thickness. In addition, it was clarified that the currently used production techniques at Dharma Healthcare's factory would not yet be able to process this material for building wheelchairs. Particularly, chromoly requires special tooling to accomplish tight-radius bends - a challenged identified already during the prototype stage.

6.2.2. Transport and Foldability

As a result of various needs - distances to travel, access to vehicles and available assistance - the attitude towards the prototype folding mechanism came to vary substantially. In order to understand the challenges and potential leverage points, it was important to define some different transportation scenarios that represents the situations encountered during the trials.

The major part of the trial population did not make any significant travelling outside of their residential property. In most cases, this part of the population is strained by physical limitations and poor access to transportation services. They are often settled in the semi-urban areas at a significant distance from any public transportation connection.

Therefore, it can be concluded that the mobility of these users is strongly dependent on three prominent factors - level of independent travel, access to vehicle and access to relatives or friends who can provide assistance. The first factor - *independent travel* - is about their ability to move around independently using their personal assistive device. Some users are able to travel several kilometers only propelling their wheelchair if the roads are accessible enough. Others may be strongly limited by their both physical condition and poor equipment, which strictly limits their area of freedom to solely become their private house or property. This accessible area may, in some cases, become even smaller as a result of inaccessible stairs or steep ramps that may be too inclined for the rider to climb. An example is shown in figure 6.2. A steep ramp at the entrance prevented this user from getting into his own house using his own wheelchair. The translating seat on the functional prototype helped him to move the COG forward, which allowed him to master the ramp by own means.

The second factor - *access to vehicles* - is the access to personal modified vehicles, which can be used to travel both short and long distances on rough terrain or poorly maintained roads. In this case, long distances may refer to a range - from one or two up to several tens of kilometers. In general, people in this context are more comfortable with travelling long distances using simple means than what is normally accepted in industrialized countries. The most common way of transportation is by a personal motorbike. As oppose to regular cars, motorbikes are relatively affordable. According to a focus group discussion, owning a car is normally associated with wealthy people.

Motorbikes are frequently modified to accommodate the needs of wheelchair riders. With affordable means, sometimes financed by sponsorship, a two-wheeled motorbike can be reconstructed to become a three-wheeled. For riders who are able to rely on some support in lower limbs, a trike design is normally enough. This means a symmetric axle holding two rear wheels is installed to replace the single rear wheel. This trike design requires the user to leave the wheelchair and transfer to the normal seat when riding the motorbike. If this is not possible, which normally is the situation for a paraplegic, another common approach is to attach a sidecar (seen in upper left picture in figure 6.3). Thus, the user is allowed to ride the vehicle while sitting in the wheelchair. By installing the steering components on the sidecar, the vehicle is easily maneuvered without having to transfer from the wheelchair. The prominent advantage with both the trike design and the sidecar is that both can be operated without assistance, provided that the modification is adequate for the individual needs. In rare cases, such as for one user that was part of the study, a modified car may be used for independent transportation. This, however, requires relatively demanding modifications and high level of physical ability from the user. From this case, it was also revealed that an important advantage with an x-brace chair is the possibility to load the chair on a leveled surface only using one hand. This feature made it possible for a wheelchair rider to hold on to a supporting structure as the chair was loaded.

▲ *Figure 6.3 - Personal and public transportation trials*

The third factor - *access to relatives or friends who can provide assistance* - is the access to people in the proximity who may access vehicles that is able to meet the needs of the wheelchair rider provided assistance for entry or egress is given. Most often, cars are used for this purpose but may also include modified or regular motorcycles. However, the requirement of human assistance is uncompromisingly adding delimitation in terms of reduced freedom. Particularly, the access to this category of assistance is strongly limited in certain areas.

6.2.3. Public Transportation

Even though none of the users that were part of the study had direct access to public transportation nodes, it became relevant to study the current public transportation system to identify possible causes and future opportunities. Focus groups and scenario investigations indicated several issues that could be related to different ways of transportation.

Local City Buses

The public transportation in Yogyakarta comprises several types of formal transportation subsystems for bus and train transit. One of the most developed formally operating companies within the inner city is called *Trans Jogja,* and is using modern high-floor buses with specially designed platforms. Building platforms that match the level of the threshold on the buses solves the lack of low-floor buses. However, it was observed that ramps built to make the platforms accessible are often very steep and require assistance for wheelchair riders to climb (visible in the centre picture in figure 6.3). On most platforms, this kind of human assistance is made available as a result of continuously staffed ticket booths. However, since not all platforms are providing ticket service and may not be accessibly designed, passengers using wheelchairs need to know at what locations it is appropriate to enter or exit the bus in order not to get stranded. In addition, the general impression of the climate was experienced as relatively harsh. Passengers using wheelchairs were not frequently prioritized during the entry procedure, which may tend to induce significant stress and discomfort for the wheelchair rider when travelling. As expressed by several test participants, it is also common that passengers using wheelchairs are often denied entry on certain buses. This is possibly a result of a complicated and time consuming boarding procedure, sometimes also combined with limited assistance availability and lack of space for loading the wheelchair.

Intercity Trains

In addition to bus transit systems there is a train service for intercity travels. In terms of accessibility, the scenarios in the study revealed no critical shortcomings that would cause any major difficulty for a wheelchair rider to overcome independently. Accessible platforms and available assistance provided the circumstances needed for a trip to be achieved independently. However, some factors still contributed to a stressful and demanding environment, which may result in keeping wheelchair riders from using the transportation service. As an example, there were no designated areas for wheelchairs to be positioned in the train. Hence, wheelchair riders had to position in the open area adjacent to the doors where they also would be constrained from further movement due to narrow aisles (upper right in figure 6.3). As a result, every sequence of embarkation and disembarkation would induce a feeling of personal discomfort and stress as the wheelchair rider would experience being an obstacle delaying this process.

Informal Transportation

In addition to major bus companies operating in the inner city area, there is a range of more informal ways of transportation stretching from smaller manual transportations to private minibuses (lower left in figure 6.3). The becak, for example, is a small bicycle taxi for two passengers driven manually by a pedaling driver. In the trials, it was clarified that fitting both the rider and the wheelchair in one becac was not possible. However, if two becaks were hired to carry two passengers each, it turned out possible to fit the wheelchair wheels in one of them, as the other becac would carry the chair. It should also be pointed out that in addition to the becak, there are also motorized vehicles that are based on the same concept - trike design with a wide seat for several passengers.

Based on experiences gained during the Indonesia trials as well as during the WEshare project in Kenya, the existence of different trike design

▲ *Figure 6.4 - Test subject with an x-brace folding chair in a becak*

▼ *Figure 6.5 - Fenders in back and front positions*

transportation vehicles may vary depending on the location. However, it can be concluded that trike design vehicles are compatible with carrying both the wheelchair and the rider if the passenger area is slightly bigger than what is offered in a becak. During the public transportation investigation, the becak turned out to be the only vehicle that did not allow the chair to be stored along with the passenger in one vehicle (figure 6.4). Nevertheless, the study pointed out that this actually was possible when using an x-brace Quickie chair.

For minibuses, the question whether it is possible to fit both the chair and the rider is strongly dependent on the amount of passengers in the vehicle. However, the trials confirmed that a passenger with a wheelchair could easily fit in the minibus if two seats were available. It was concluded from the studies that a wheelchair solution, which easily can be folded to fit in a conventional passenger seat (lower right in figure 6.3), is desirable. As a result, the space needed for the wheelchair to be loaded would be compatible with several public transportation vehicles, no matter of the existence of a designated cargo area.

Fenders

Several shortcomings for the fenders were pointed out from a user perspective during the trials (fenders displayed in figure 6.5). In the attempt of using the fenders as support during position alteration, the material turned out to be of insufficient stability. In addition, the lack of a stable supporting structure to be used during transfer became particularly critical. Thus, the hypothesis stating that small fenders would imply the use of the more stable wheels as supporting structure turned out to be incomplete. As was not entirely unexpected, this behavior ascended as a consequence of the unwillingness to come in contact with the dirty tires. As another result of the material selection, the backrest folding mechanism quickly turned out to cause an apparent wear pattern on the fenders.

The size of the fenders contributed to additional issues. The relatively small size of the fenders provided a poor dirt protection, even though the chair was primarily tested during dry conditions resulting in a relatively small amount of mud. The wheelchair also failed to keep loose clothes from becoming dirty from the tires, also presumably entailing the small size if the fenders.

Furthermore, the trials revealed that the fenders in some cases contributed to keep the rider's legs in place, meaning that these users have an additional reason to include fenders on their wheelchairs. The fenders are attached to the seat and not the main framework, which means that they move along with the seat if the position is altered. They do thereby inhibit transfer procedures even in the foremost seat position.

Other factors that would contribute to maintaining the desired leg position would also be the adaption of wheelchair size, footrest height and selecting an appropriate cushion. The small size fenders, however, would have a significant negative effect on the ability to completely meet the requirements of this functionality.

6.2.4. Seat Angle

Several users argued that the twelve-degree angle of the seat did not meet their personal needs and preferences. Consequently, a significant part of the participants that owned a RoughRider preferred to use another chair if they had one available. If not, it was common that makeshifts were used to compensate for the steep angle. Towels or clothes were crumpled and placed on the rear end of the seat to flatten out the angle.

The main issue, captured from several users, emphasized that a significant discomfort was perceived as a result of the steep angle. It was argued that with an increased seat angle, an increased load would be applied to the buttocks. This would in turn tend to cause pressure sores. This notion was presented several times from both physiotherapists and users, and may also be an effect of local knowledge sharing. However, as many users were not riding the RoughRider at the time of the evaluation, it was hard to assess the actual scenario where this problem occurred. To validate the accuracy of this notion, stating that an increased angle would cause pressure sores was therefore difficult.

Some aspects of this matter, however, were explicitly captured from the evaluations. For instance, several paraplegics are storing their

▲ *Figure 6.6 - Test subjects during trials* urine bags in their lap. A more appropriate way of storage is with a strap on the user's leg. By doing so, the low level storage ensures that urine can flow continuously without interruptions. On the contrary, storing the bag on the lap will occasionally create a reverse flow and consequently cause the functionality of the bag to be reduced. The steeply inclined seat amplifies this effect, which prevents the urine bag from fulfilling its purpose. Another aspect of the steep angle is the ability to keep the urine from leaking down on the ground. In the case of urine leakage, it is, according to the evaluation, desirable for every user to keep this on the seat to the most extent possible.

Another aspect, primarily derived from observations in the study, embraces the reduced reachability at workstations due to the heavily tilted posture. Furthermore, this position tends to deactivate the upper body of the rider when performing everyday tasks. As previously explained, an increased seat angle provides additional pelvic stability and that is particularly useful when riding in rough conditions. However, this effect is achieved at the expense of a reduced freedom of movement for the upper body. This effect also plays a significant role at the event of a transfer. To gain free space for a transfer in front of the rear wheels, the user is required to slide forward on the seat. As the seat is heavily inclined, the effort needed to perform this task is significantly more demanding than what would be needed in the case of a reduced seat angle. Therefore, there is a need to further evaluate the advantages and disadvantages with the 12-degree seat and find an optimal solution for the intended user of the project. It should be pointed out that the acceptance of the product is of crucial importance. Even if the seat angle would be physiologically beneficial, it will not be accepted and concurrently benefit the rider unless there is confidence in using the product. If that would be the case, there is a need to change the mental model of the product. This could be achieved in two ways - either by an actual design modification or by education and training for the current product.

Alternating Seat

As oppose to the hypothesis describing two prominent functions of the flipping seat, the study disclosed three major advantages - easier to climb steep ramps, improved working position and facilitated transfer. The latter turned out as having a considerable impact on the ease of transferring, wherefore it may be considered as the most prominent contribution from the alternating seat. A twelve-degree angle often causes a major barrier, which has to be overcome in order to perform a transfer.

By altering the seat position to the foremost, the seat becomes considerably separated from the position in between the rear wheels. Based on domain knowledge within wheelchair usage, gained from scenarios and trials (see figure 6.6), it has been clarified that normal transfer procedures primarily involves sideways translation of feet and legs followed by the upper body. Hence, removal of sideways-located physical barriers such as wheels and fenders would substantially facilitate the transfer. In order to fully evaluate this functionality and test its potential value, the fenders were detached during several testing sessions. This enabled users to transfer from the seat in front position without being distracted by the fenders.

Regarding hill climbing, there is evidence that the COG translation actively prevent the user from falling backwards when climbing hills or heavily inclined surfaces. Moving the seat, however, introduces some significant complications in terms of ability to propel the wheels. In order to climb a steep ramp, additional arm force is required to overcome the increased resistance caused by the increased angle of riding surface. The distance to the hand rims is also increased as the seat is moved, which consequently aggravates the propelling of the wheels. Roughly, it may therefore be assumed that the maximum power that can be transmitted to the rear wheels is dependent on the length of seat translation. Increased distance means reduced power and vice versa. Supplementary, the power that can be applied on the rear wheels without causing the wheelchair to tilt backwards is heavily dependent on the position of the COG. As an example the greatest power, generated by a rearmost seat position and presumably a COG far back, implies a high probability of falling backwards.

▲ *Figure 6.7 - Assistant pulling on backrest*

▼ *Figure 6.8 - Feet placement on footrest*

Although the previous statement is probable, there are additional factors to be considered. According to the study, there are basically two ways of moving the COG (provided the wheel axle is fixed) - by upper body control or by moving the seat. As the ability of controlling upper body is significantly reduced for a paraplegic rider, according to the reduced or completely lost ability to use the abdominal muscles, the possibility of moving the seat would be likely to have significant value for these users. It was revealed that some users were unable to change the seat position independently, which is required to benefit from the functionality of the moving seat. Particularly, observations showed that users with polio and amputations generally managed to perform the seat movement with less effort compared to users with paraplegia.

Due to the participants' infrequent engagement in activities involving work at a desk, the possibility of evaluating the moving seat in the context of working postures was notably limited. Therefore, only a few turned out to benefit from this - one user running a TV-repair service, a group of young students as well as another user working administratively. For TV-repairs, the most prominent advantage turned out to become the substantially improved reachability. It was revealed that for adult users it was sometimes difficult to fit legs under the table, which was challenging for both rearmost and foremost position. For the students, the foremost position substantially contributed to sit closer to a school desk. Nevertheless, the possibility to come close was often dependent on the cross rib that normally was constructed close to ground level in order to stabilize the desk.

6.2.5. Backrest

Riding in a developing terrain - highly characterized by unpaved pathways, high curbs and steep ramps - is compared to industrialized context very challenging without assistance. In fact, the study showed that riding completely independent is extremely rare. Instead, riders are frequently assisted by someone pushing the backrest, lifting the chair using the backrest crossbar or pulling the wheelchair backwards to overcome an obstacle. In order for this assistance to be performed without causing any significant force impact to the rider, the backrest has to lock when set in riding position. As can be seen in figure 6.7, the backrest of the prototype unintentionally folded when it was pushed by an assistant. In addition, there is a need for distinct push handles to increase the cognitive recognition for secondary users. As was also clarified during the scenarios in San Francisco, a separated push handle may be advantageous for providing support as the upper body is twisted. By locking one arm around the handle, the upper body can be stabilized even in relatively challenging postures.

Furthermore, the trials revealed a considerable deterioration of the upholstery as a result of heavy backpacks attached to the backrest. Particularly, this was a behavior that primarily occurred for students in school. However, the field study embraces the importance of supporting the upholstery as it is exposed to heavy loads.

Several users also point out that they experienced the backrest as too low. It was recognized that this experience was particularly common among paraplegics with a high spinal cord injury. However, it is hard to conclude whether this experience has arisen as a result of long-term use of a chair with a higher backrest, or actually derives from a physiological need. The need for a certain backrest height is however subjective and thereby varying with each individual user.

6.2.6. Footrest

It was recognized that a majority of the users had a tendency to position their feet on the toe protection tube instead of behind it (see figure 6.8). Thus, the initial intention to protect the feet from injuries would prove to fail. In addition, supporting the feet by the toe protection tube would also cause an ergonomically inappropriate footrest angle. There are several possible reasons to why this behavior may occur. A factor that presumably had a substantial influence on the feet position is the size of the chair. It is also important to take into account that the size of the chair may have caused certain behaviors that might not be representative for the actual use scenario, as the trials were limited to a one-size prototype. However, disregarding the size, there is still evidence that the footrest plate was not big enough to provide stable support for the complete length of the foot.

It has therefore been concluded that a probable reason for the inappropriate foot position among several users is the undersized plate.

Regarding the footrest adjustability, the trials revealed some shortcomings in terms of adjustability. An insufficient range of vertical adjustability, lack of horizontal adjustment as well as a lack of independently adjustable footrests were all contributing to the fact that several customer needs could not be accommodated. In addition, the range of different needs turned out to be considerably extended as a result of limited joint functionality and other disease-related symptoms. It is therefore important to understand who is the primary target user for this product in order to optimize against the project goal. As an example of specific needs, a rider with one or two amputations would benefit from separately detachable footrests, while a rider with limited joint movability or different length on legs would benefit from independently adjustable footrests.

6.2.7. Cargo

Crutches, small personal valuables, drinking water, bulky bags for collecting empty bottles and urine bags were all examples of cargo that several riders were carrying on their wheelchair. As captured from these users, there are currently no good options for attaching even small items to the wheelchair without having to carry them on their lap or in the seat. Such behavior might have an ergonomically negative impact. Some users solve this problem by attaching a backpack on the backrest. Using a backpack would however introduce other concerns such as translation of the COG - difficulties to reach stored items as well as a reduced ability to look after personal valuables. It may therefore be concluded that there is a clear need of including a cargo holder for relevant items. In the case of valuables, the cargo holder should be placed so that it may easily be surveilled and subsequently protected from theft. Similarly, the change of COG should be observed and minimized in the case of attaching heavy items.

6.2.8. Aesthetics

As a result of few opinions and being fairly subjective, the study in aesthetic preferences provided a limited and somewhat scattered result. However, some conclusions derived from currently existing wheelchair designs may be presented to function as guidelines for the aesthetical design development.

An attitude based on the Swedish users' preferences was used as a hypothesis when conducting the study. According to Jalle Jungnell[1], owner and construction manager at Panthera AB, Swedish riders may be characterized by a clear desire for products based on a minimalistic and discrete design. Black, grey and other discrete wheelchair colors are frequently preferred as they enable the user to create an own expression by freely selecting clothes and accessories without risking an aesthetical interference with the wheelchair design. In other words, by making a wheelchair design that is discrete and minimalistic characterized by neutral colors and a framework with an almost non-existent contribution to the overall expression, an increased freedom for personal expression is given to the user.

As the feedback gained from the Indonesia trials conveyed a different attitude, the hypothesis turned out as incomplete. In order to strengthen the well-being of a wheelchair rider there is evidence from the study that emphasizes the use of bright and non-neutral colors. As oppose to neutral colors, bright elements in the living environment would function as a catalyst for triggering an effect of encouragement, brightness and harmony. According to the study, achieving this effect is a way to diminish the presence of everyday burdens and challenges that may appear as insurmountable for a person in a wheelchair.

A similar pattern were discovered when investigating the shape and construction of the wheelchair. It was pointed out that a wheelchair with an expression of agility, lightness and simplicity - typical characteristics for active Swedish wheelchairs - would typically not be preferred among the participants in the study. As stated among the users, agility or related characteristics would convey an expression of instability and poor ability to withstand the rough conditions of the local context. On the contrary, other wheelchairs with a design that reminds of the RoughRider - particularly expressing rigidity and stability - evoked a significant desire among users.

1 Jalle Jungnell (Owner/Construction manager, Panthera AB) interviewed by the authors October 3, 2012

Sponsors

Based on the fact that external sponsors largely finance the wheelchair distribution, there are some important limitations in the color selection for the wheelchairs. As external financing organizations have the desire to stay visible on the market, the chairs are frequently branded by producing the chairs in a color that is specific for the individual organization. Two typical wheelchair colors in the Indonesian context are blue, representing LDS – The Church of Latter Day Saints providing thousands of RoughRider wheelchairs annually, and yellow representing UCP Wheels for Humanity Indonesia. As a result of this system, the current possibility of freely selecting a color for assigned wheelchairs is strictly limited.

6.3. User Group Evaluation

In the process of finding a target group that would significantly benefit from using the new prototype, the characteristics of each participant in the trial were studied to find out whether the specific user would be an appropriate primary target for the new wheelchair. The main characteristic of consideration was the seat position alternation. The outcome from this analysis is graphically presented in figure 6.9.

In terms of the seat alternation, there is evidence that a majority of the population is localized in the range of 30-45 years old. For paraplegics, 75% of the participants within this range are considered to be primary target users for this wheelchair. As the corresponding figure for the poliomyelitis category is 40%, there is reason to conclude that paraplegia is the most important concern of this project. Several factors that are considered a contribution to this conclusion will be analyzed in the following section.

Transfer

It can be recognized that a major part of the potential primary target group in the age span 30-45 is located within the less active spectrum. However, this conclusion tends to antagonize the hypothesis stating that the alternating seat would primarily address the needs of active users. Initially, the most prominent advantage with the seat alternation was assumed to be the possibility to climb hills with the seat in front position, which significantly would reduce the risk of falling backwards. It was also assumed that this functionality would benefit users that normally were challenged by rough riding and consequently could be considered as active users. However, this hypothesis turned out to be incomplete. Rather, this analysis shows that a considerable amount of the population that obviously would benefit from the alternating seat are less active.

This can be explained as the flipping seat substantially facilitates an independent transfer. As can be seen in the figure 6.9, this functionality was primarily useful for users with limited upper-body control possibly caused by an intermediate or high paralyzing injury, sometimes combined with a less active lifestyle. Evidently, there is a significant probability that the less active lifestyle is also partly generated as a result of the injury. Therefore, introducing functionalities that will reduce the perception of being immobile, there is a chance of helping riders to become more active. Particularly, a considerable improvement of the situation may be to be able to transfer from the bed to the wheelchair. Subsequently, the user's level of freedom becomes substantially improved.

Polio and Paraplegia

The reasoning concerning level of activity is further described in figures 6.10 and 6.11, where a simplified model describes the personal development towards an increasingly active lifestyle. Additionally, the figures presents the major underlying factors for this development as divided into three categories - external, internal and the actual disability. While all factors collectively contributes to the overall development towards an increased activity, they are also inwardly dependent as described in the figure. The internal factors are assumed to be dependent on the external factors as, for instance, knowledge is driven by education. Subsequently, the importance of external factors are dependent on the underlying disability. For instance, increased limitations due to a certain disability may result in increased need for assistance.

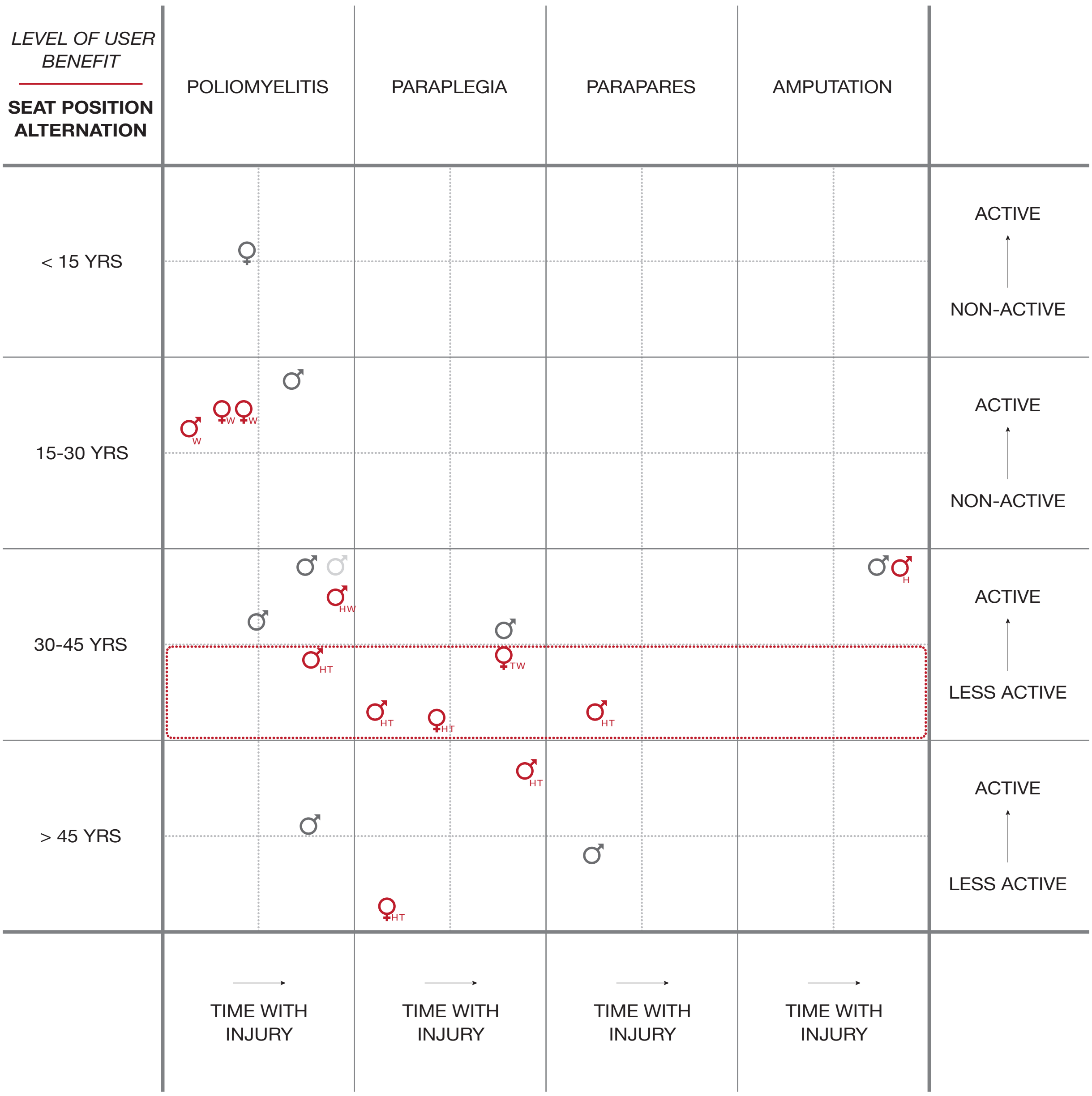
As the example illustrates, the importance of appropriate equipment and assistance is less for a wheelchair rider with polio compared to a rider

Which users would experience a significant increase in social integration and personal freedom when using the seat alternation functionality incorporated in the chair?

- evident benefit
- small benefit
- nonexistent benefit

- ♀ female
- ♂ male

- H benefits when hill climbing
- T benefits when transferring
- W benefits when sitting at workplace



▲ *Figure 6.9 - User group mapping*

with paraplegia. This means the access to proper equipment and assistance is more critical for a paraplegic rider.

Moreover, the studies revealed that the development process towards increased activity is more demanding for a paraplegic rider compared to a rider with polio, which is visualized in the figures by the starting point and the rate of change for the independency development curves. This also correlates with the comparatively high need for aids and assistance for paraplegics. There is, however, a theory that the ultimate level of activity may be achieved to an extent that is independent of disability characteristics. It can be seen that for a paraplegic to achieve this level of activity, the overall need for equipment and assistance will be comparatively higher.

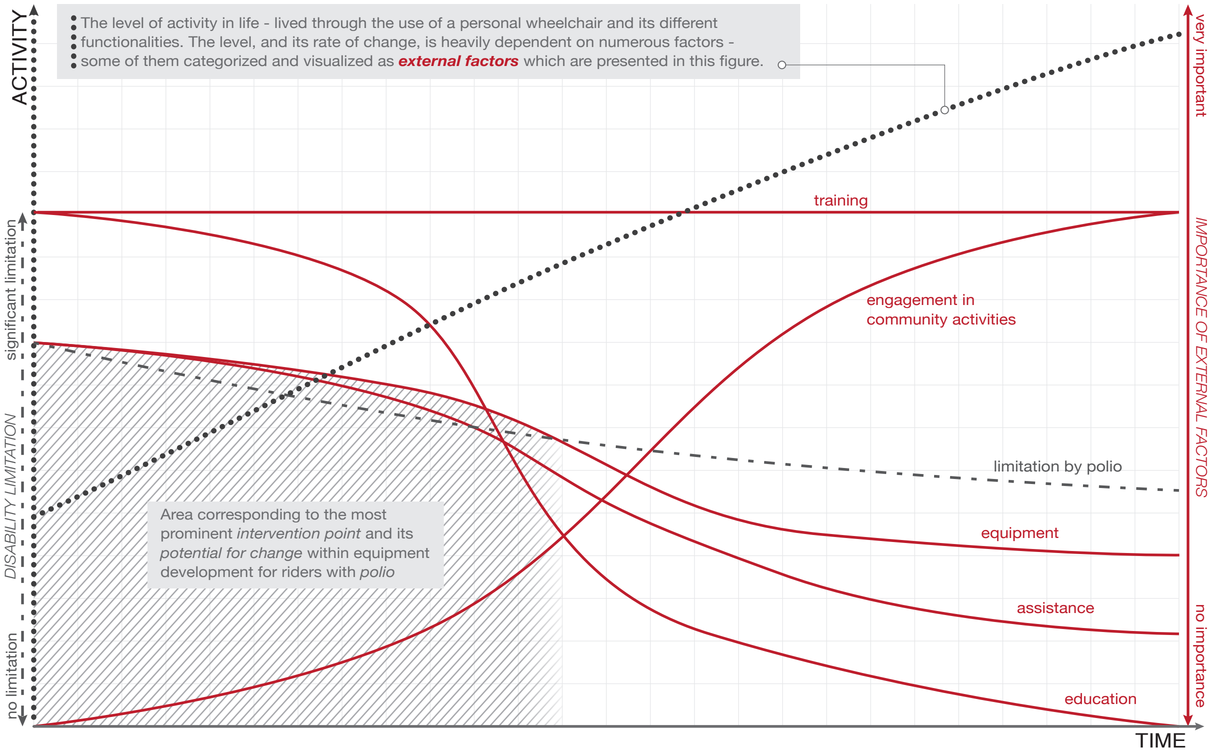
It should be pointed out that the figures are representing a *theoretical model* on what is needed for an increased activity among wheelchair riders. Considering the current situation, the trials revealed that the level of available equipment, education and assistance is rarely meeting the actual needs of the users. For instance, users that are known to the society are normally not educated or ever challenged to test their limits. As a result, internal factors such as self-confidence, physical ability and knowledge is not developed as desired. When this development is delayed or even not exist, the level of activity - and therefore the level of integration into the society - is substantially reduced.

In order for this project to intervene with great leverage, it is necessary to isolate and look at the importance of equipment and its magnitude over time. Studying the grey area in figures 6.10 and 6.11, it may be concluded that the the most significant need appears during an early phase of the development process for users with paraplegia. It may be concluded that this significant need partly derives from the inability to perform an independent transfer. Thus, a functionality such as the alternating seat may constitute a significant leverage in terms of equipment needs for these users.

Assuming the starting point is sorted out, there are still some uncertainties concerning the selected primary target group. As pointed out, the challenges that these users need to overcome in order to integrate with the society normally exceeds the demands for users with a less confining disability. Therefore, it becomes critical to understand the holistic picture of these challenges in order to increase the capability of addressing critical needs of this user group. As the accomplishment of this task would require a wide range of users, it seems reasonable to question whether relevant representatives from the user group of paraplegia have been considered in the evaluation of this project. Particularly, since the access to a large amount of users and range if various characteristics have been relatively limited. There is, however, evidence to assume that as a result of limited community space for development and growth, many users with paraplegia characteristics might not yet have been discovered by the society. Until this happens, there is an incredibly small probability that an appropriate wheelchair can be issued and an even smaller probability that a social integration will take place for these users. Consequently, there would be an aggravation in the task to include these users in the user evaluation for this project. This reasoning also poses uncertainties to the data reliability from the trials, but simultaneously provides additional arguments for exploring the complexity of the situation and trying to meet the needs of known users. Ultimately, a solution may trigger the discovery of currently unavailable people who are in need of help.

The trials also revealed that once a user is identified, there is a following process dedicated to finding an appropriate wheelchair for the user. However, it appeared during the study that this process might not be currently appropriate corresponding to its relevance. For instance, a significant factor which is currently not fully considered once a wheelchair is assigned, is the prospective possession of the chair. As the needs of a user alternates over time, the greatest challenge becomes to assign a wheelchair that will meet the user's future needs, which may not yet be revealed during the first chair assignation.

Specifically, it is difficult to know what kind of rider the user will become. Selecting an inappropriate chair might therefore result in critical future limitation as it cannot easily be exchanged once new skills are developed.



Disability
The extent to which the specific disability reduces the physical capacity of the individual, which in turn has an impact on the activity development. Additionally, it has a direct impact on several external factors.

External factors
Fundamental drivers that have a significant impact on the speed of development towards increased activity and the presence of internal factors. As visualized, their importance differs over time. There is a hypothesis stating that these factors primarily drives the personal development up to a certain level after which the internal factors will dominate.

Internal factors
Enables personal development beyond the level of fundamental drivers, although the development of these factors are strongly dependent thereof.

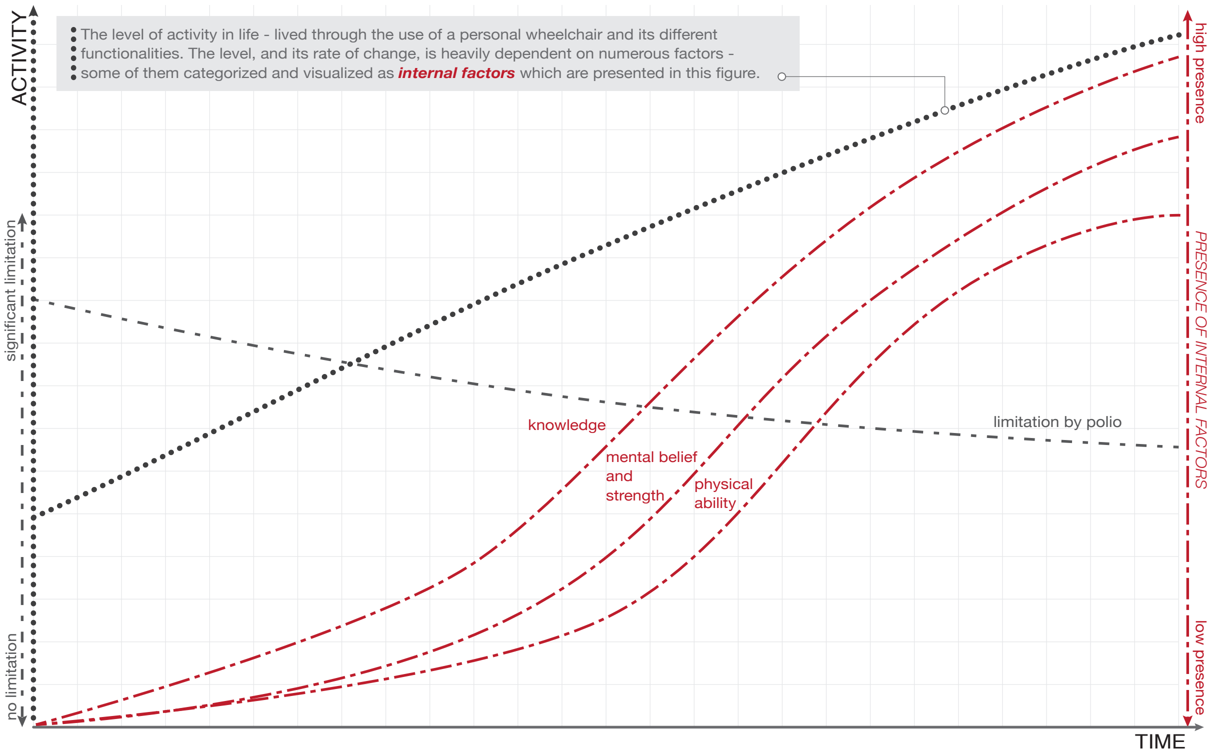
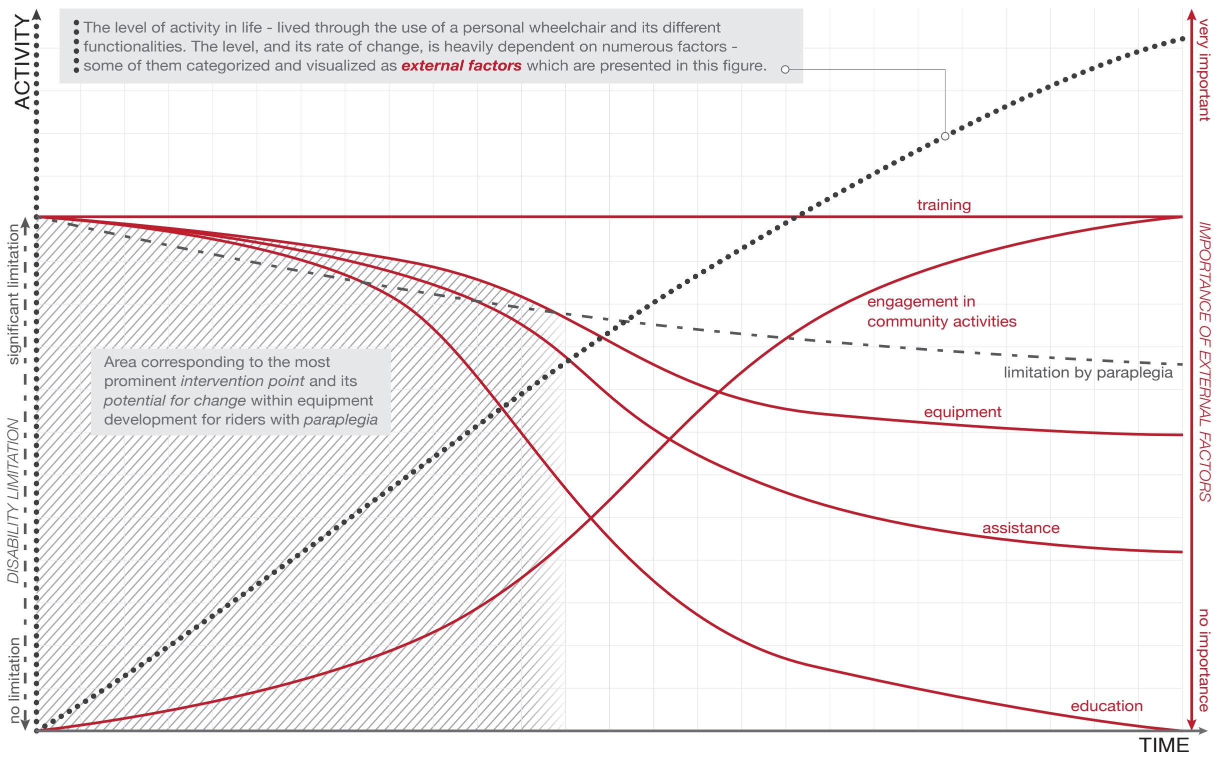


Figure 6.10 - Visualizing the personal development towards an increasingly active life for wheelchair users with poliomyelitis. An investigation to idenify potential points of leverage in terms of wheelchair design. The shaded area in the graph represents the need for functional equipment in the very beginning of the learning process. Consequently, this area reveals a potential intervention point for this particular project.



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Internal factors
Enables personal development beyond the level of fundamental drivers, although the development of these factors are strongly dependent thereof.

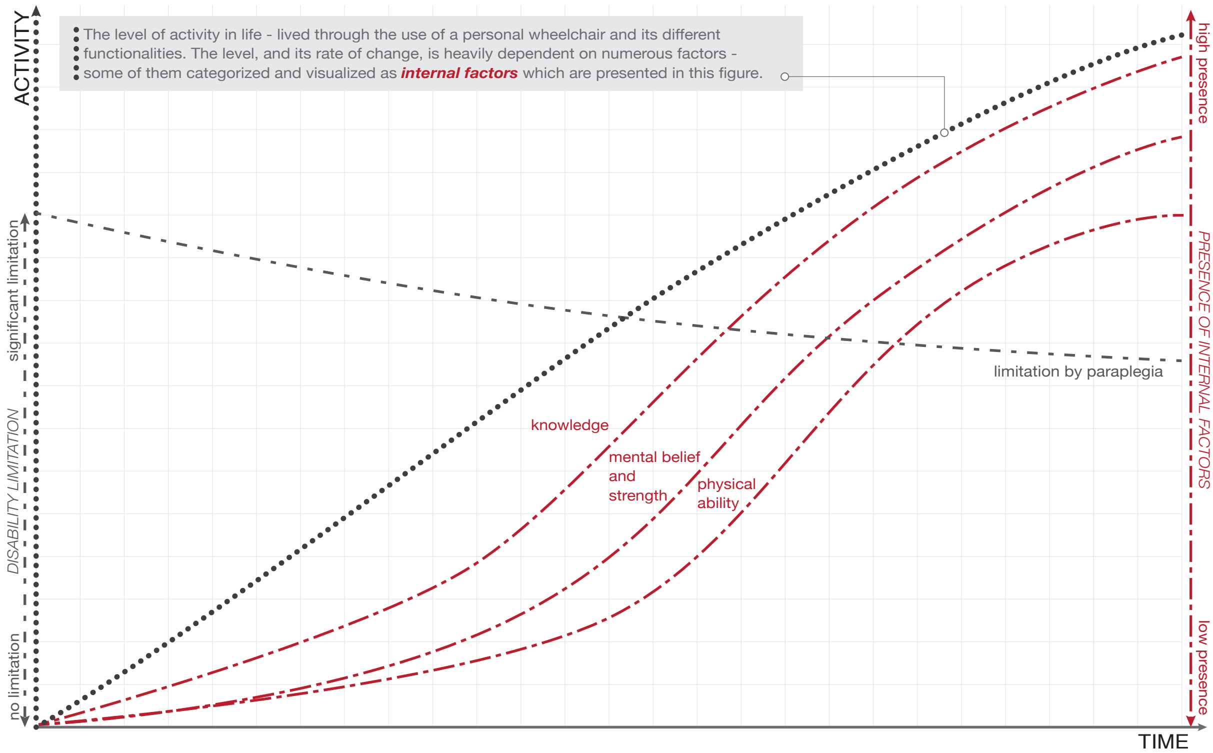


Figure 6.11 - Visualizing the personal development towards an increasingly active life for wheelchair users with paraplegia. An investigation to idenify potential points of leverage in terms of wheelchair design. The shaded area in the graph represents the need for functional equipment in the very beginning of the learning process. Consequently, this area reveals a potential intervention point for this particular project.

▼ *Figure 7.1 - Requirement list*

LIST OF REQUIREMENTS

No.	Requirement	Weight
0.	*GENERAL*	
0.1	Total cost must not exceed USD 150	req.
0.2	Follow WHO guidelines	req.
0.3	UV-radiation, corrosion and temperatures -15°C - 50°C must be resisted	2
1.	*FRAME*	
1.1	Provide clues for folding mechanism	1
1.2	Minimize folded size	3
1.3	Minimize width	4
1.4	Minimize weight	4
1.5	Provide grip for loading	2
1.6	Provide stand alone folded solution for vertical storing on flat surface	1
1.7	Emphasize compatibility with attachment on modified motorcycle	2
1.8	Provide easily detachable rear wheels	5
1.9	Provide rigid framework	req.
1.10	Construct with a monoframe design	3
1.11	Use the same wheelbase as on the RoughRider	req.
1.12	Use locally available material (low carbon steel)	5
1.13	Use locally repairable material (low carbon steel)	req.
1.14	Must withstand 400 000 cycles of standardized ISO 7176-8:1998 testing (2x ISO req.)	req.
1.15	Provide a life span of at least 10 years	5
1.16	Allow medium weight cargo to be carried safely	3
1.17	Allow loads < 5kg to be applied on the back of the chair without falling over	5
1.18	Counteract caster barrel twisting	3
1.19	Endeavor frame flexibility	2
1.20	Allow aesthetic personalization to increase conscious handling	1
1.21	Use Ø22 (1.0 mm wall thickness) and Ø32 mm (1.5 mm wall thickness) tubing	4
1.22	Minimize use of shoulder bolts	3
1.23	Prevent corrosion from local scratches to spread	1
1.24	Seal construction cavities to protect inside of tubing	5
2.	*SEAT*	
2.1	Allow user to alternate seat position 100 mm in horizontal direction	req.
2.2	Ensure a smooth seat alternation	3
2.3	Protect frame from wear during seat alternation	4
2.4	Provide a 4-degree seat angle in front position	req.
2.5	Provide a 7-degree seat angle in back position	req.
2.6	Allow cushion to attach to the seat	5
2.7	Provide a locking mechanism for both front and back positions	req.
2.7	Allow framework design include both a moving seat and a fixed seat option	5

7. List of Requirements

The output from the testing and evaluation phase in Indonesia was translated into a thorough requirement list, seen in figure 7.1. This chapter will present these requirements and highlight their meaning for the project continuation.

7.1. Requirement Division

The previous versions of the requirement list presented general specifications, which have been used as an underlay for pursuing the project. The feedback and input given by the trials was analyzed through a KJ-analysis, which ultimately translated this information into new requirements. This means that the former requirements have further determined and specifically formulated but also complemented by additional requirements. The extensive amount of new requirements promoted a division of these to create a structural overview. This division also clarifies that a wheelchair could be seen in different perspectives - either as one complete product or as many smaller, which together create a whole.

A number of requirements have been addressed to each part of the wheelchair, and these have for the first time also been provided with weighting to determine their importance for the end product. The requirements that have been weighted as "Req." are considered most important and then follows a descending scale, where the grading "5" is given to the most important wishes and "1" to those that are considered least important.

7.2. General Requirements

The general requirements, starting at number 0, are separated from the others according to their importance for the complete solution rather than just individual part. These requirements must be completely fulfilled except for withstanding UV-radiation, since different resistance would be required in different contexts. This could allow a certain degree of freedom when designing the final wheelchair, depending on what context it is designed for. A context that exposes the chair to heavy sunlight might for example never provide temperatures below zero centigrades.

7.3. Framework Requirements

The framework requirements, starting at number 1, are mainly characterized by wishes to accommodate various user needs. What must be satisfyingly achieved is a rigid framework with the same wheelbase as the RoughRider that withstands standard ISO-testing (ISO 7176-8:1998). The RoughRider is tested to withstand 400 000 cycles of the ISO-testing procedure (basically a bumpy threadmill with 13 mm bumps), which is twice the ISO requirement, and the aim is to provide similar characteristics in this new wheelchair.

The new chair must also be constructed from material that is locally repairable in the intended contexts, an aspect that is more important than using locally available materials. Maintenance and repairability is extremely important according to the insufficient distribution and maintenance networks in developing countries. Thus,

No.	Requirement	Weight
2.8	Promote an improved body posture when working at desks	5
2.9	Keep the popliteal-footrest distance in both front and back positions	req.
2.10	Allow user to grab seat during transfer	req.
2.11	Provide a confirmation of if the seat is locked in position or not	5
2.12	Facilitate the seat alternation	5
2.13	Position locking mechanism so that it is easily reachable in both front and back positions	5
2.14	Ensure alternation mechanism levers to rotate past their pivot for both positions	5
2.14	Provide RoughRider seat widths (12.5”, 14”, 15.5”, 17” and 18.5”)	req.
2.15	Provide RoughRider seat depths (14”, 16” and 18”)	req.
2.16	Minimize weight	5
2.17	Minimize the amount of moving parts	3
2.18	Use locally available material (low carbon steel)	5
2.19	Use locally repairable material (low carbon steel)	req.
2.20	Use Ø22 (1.0 mm wall thickness) and Ø32 mm (1.5 mm wall thickness) tubing	4
2.21	Minimize use of shoulder bolts for cost optimization	3
2.22	Prevent corrosion from local scratches to spread	1
2.23	Seal construction cavities to protect inside of tubing	5
3.	*FENDERS*	
3.1	Protect user from dirt	5
3.2	Allow user to propell wheels, using handrims, freely without being distracted from fenders	5
3.3	Make sure that fenders do not inhibit transfer procedure	5
3.4	Support legs to maintain correct leg posture	5
3.5	Ensure fenders do provide support for hip joint and proximate area	5
3.6	Allow user to propell wheels, using tires, freely without being distracted from fenders	4
3.7	Provide transferring support	4
3.8	Withstand horizontally applied load	4
3.9	Withstand vertically applied load (sitting user)	4
3.10	Provide support for user when changing body posture	4
3.11	Allow fenders to be detachable	req.
3.12	Minimize weight	4
3.13	Minimize folded size (contribution to chair’s folded length, height and width)	4
3.14	Ensure ease of manufacture	5
3.15	Ensure ease of assembly (symmetry, number of attachment points)	5
3.16	Maximize durability with robust design and material	5
3.17	Use ductile material to prevent creation of hazardous chips in case of breakage	5
3.18	Ensure complete compatibility with backrest folding mechanism	4
4.	*BRAKES*	
4.1	Ensure that activated brakes prevent weels from moving	req.
4.2	Ensure that brakes are easy to activate/deactivate with hand impediments	5
4.3	Position brake within reach for the user	5

it also becomes desirable to minimize the use of expensive and rarely available parts such as shoulder bolts.

In addition, the folded size becomes an important emphasis as it will contribute to the extent of which the rider is able to utilize public transportation services for increased social integration. The preferred tube dimensions are based on the proved durability during the trials in Indonesia. Since no additional optimization work is included in this project, these dimensions will be used. Consequently, an increased compatibility with the components of the previous prototype is achieved.

7.4. Seat Requirements

These requirements starts at number 2 and are heavily influenced by the presence of the alternating seat. It adds complexity and thereby also an increased number of requirements. These are mainly characterized by ensuring the functionality of the alternation but also that users not are exposed to anything undesirable because of the seat movement mechanism.

What also can be seen are direct links to the user feedback and one example is the new seat angle, which has been changed according to customer requirements during the testing in Indonesia.

7.5. Fender Requirements

Fender requirements starts with number 3 and the only actual fender requirement was that they should be removable. Additionally, an improved dirt protection, adequate transfer facilitation and proper body support is emphasized. Several other entries are resulting from highly subjective opinions and individual habits and has been given similar scores (3.6-3.10). As a result of selecting plastic for the first fenders, there is an additional emphasis on wishes related to material properties and manufacture.

7.6. Brake requirements

These are found under number 4. No brakes should, according to the delimitations of the project, be further developed and these requirements should rather be seen as guidelines to follow when choosing brakes for this product. In a latter stage, these requirements could be used as an underlay for developing new brakes to suit this product. The most important factor was, however, to ensure that the chosen solution actually would prevent the wheels from moving when being activated.

7.7. Backrest Requirements

Found under number 5, the most prominent result from the field study regarding the backrest was the inability to lock it in position. This prevented assistants from helping the users in problematic situations and was further enhanced by the backrest's insufficient ability to offer the assistants an adequate location to place their hands. This resulted in two major requirements, saying that the backrest should be lockable in unfolded position and that it must provide push-handles for occasional use.

7.8. Footrest Requirements

The footrest requirements, found under number 6, are particularly formulated to treat an anatomically correct feet positioning and the footrest adjustment range. The idea behind it is to allow as much positioning freedom as possible for the feet, which would increase the possibilities for each individual user. The field studies also showed that it is rare with users requiring footrests that are individually adjustable for each foot.

7.9. Rear Wheels Requirements

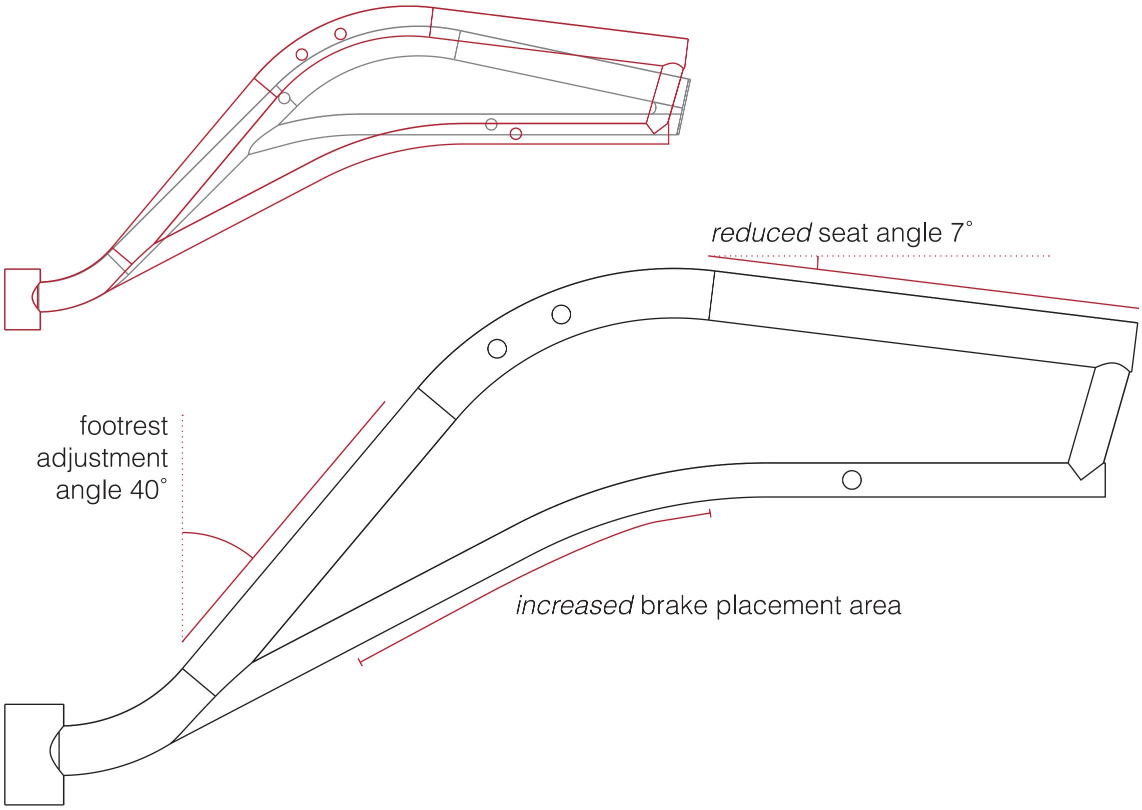
The rear wheels, found under number 7, are not subjects for further development and these requirements can, just as in the case of the brakes, be seen as an underlay for choosing a proper solution. The requirements of the rear wheels demands a certain adjustment range and quick-release functionality. The three-degree camber angle was proven to function well during the field studies and will thereby be kept.

7.10. Storage Requirements

The storage requirements are found under number 8 and is not considered to be of major interest for the new solution's total performance. Adding a storage is rather seen as a wish to enhance the total user experience and increase the positive perception among users. Finally, the intention is to improve the functionality of the chair.

4.4	Minimize the use of springs and other complex parts	2
4.5	Minimize the number of components	2
4.6	Ensure that brakes do not inhibit user from propelling wheels freely	5
4.7	Prevent accidental locking	3
4.8	Minimize folded size	3
5.	*BACKREST*	
5.1	Allow backrest to lock in unfolded position	req.
5.2	Provide backrest in three different heights (14”, 16” and 18”)	req.
5.3	Provide attachment options for large volume cargo	1
5.4	Resist the load of a standard backpack without causing upholstery deformation	3
5.5	Position seat locking mechanism so that it does not interfere with an attached backpack or other cargo on the backrest	3
5.6	Include push-handles	req.
5.7	Minimize weight	4
5.8	Minimize folded size	5
5.9	Allow backrest to easily fold and align with seat	5
5.10	Use locally available material (low carbon steel)	5
5.11	Use locally repairable material (low carbon steel)	req.
5.12	Use Ø22 (1.0 mm wall thickness) and Ø32 mm (1.5 mm wall thickness) tubing	4
5.13	Minimize use of shoulder bolts for cost optimization	3
5.14	Prevent corrosion from local scratches to spread	1
5.15	Seal construction cavities to protect inside of tubing	5
6.	*FOOTREST*	
6.1	Adapt adjustment to the anthropometric relation between upper and lower leg	5
6.2	Set lowest position to lowest RoughRider position	req.
6.3	Extend the adjustment range compared to the RoughRider	3
6.4	Allow individual adjustment for both feet	1
6.5	Provide perpendicular leg-support in relation to footrest	5
6.6	Maximize positioning freedom in the horizontal plane for the feet	4
6.7	Ensure a correct foot placement on footrest	4
6.8	Align footrest parallel to seat in back position	req.
6.9	Ensure a anatomically beneficial foot position	5
6.10	Provide a rapid and easy adjustment for footrest height	5
6.11	Allow user to sit on footrest	5
6.12	Minimize footrest size	4
6.13	Ensure that the footrest never extends beyond the turning radius measured from casters	req.
6.14	Minimize the amount of moving parts	4
6.15	Minimize wear on frame when performing adjustment	4
6.16	Prevent interferrence with frame or footrest tubing during lateral transfer	4
6.17	Minimize weight	5
6.18	Use locally available material (low carbon steel)	5
6.19	Use locally repairable material (low carbon steel)	req.

6.20	Use Ø22 (1.0 mm wall thickness) and Ø32 mm (1.5 mm wall thickness) tubing	4
6.21	Minimize use of shoulder bolts for cost optimization	3
6.22	Prevent corrosion from local scratches to spread	1
6.23	Seal construction cavities to protect inside of tubing	5
7.	*REAR WHEELS*	
7.1	Keep RoughRider limit positions and adjustment range (80 mm)	req.
7.2	Provide 3 degrees of camber	req.
7.3	Provide easy adjustment for horizontal position	4
7.4	Minimize wear on frame when performing adjustment	4
7.5	Provide a fixed and connected axle between the rear wheels	req.
7.6	Provide spacebetween the handrim and the tires to freely propell wheel	5
7.7	Use standard quick-release connections Ø12 or Ø12.7 mm	req.
8.	*STORAGE*	
8.1	Allow user to store smaller personal items on the chair	2
8.2	Protect smaller personal belongings from theft	1
8.3	Provide storage for smaller personal belongings without translating the COG	5
8.4	Allow a urine bag to be stored below waist level	3



▲ *Figure 8.1 - Updated framework*

▼ *Figure 8.2 - Walter*

8. Synthesis - Walter

The requirement list helped the project into its final stage. The synthesis describes the process of transforming the requirements into the final concept, which later was used as an underlay for producing the final prototype. The synthesis has been named Walter, which basically sums up the project - alter the wheelchair.

8.1. General

The major step during this part of the project was transforming the defined requirements into actual solutions for the final concept. This transformation primarily meant adjusting solutions on the functional prototype but also included adding new functionality, which according to the testing in Indonesia was needed. What has also been considered is the conclusions from chapter 4.1.3, which is discussing cultural, and there primarily aesthetic, differences. There are obvious difficulties with being consistent with the different preferences of all individual users. The final design should thereby be as aesthetically customizable as possible within the frames of still providing adequate functionality. The framework has, considering this, been designed to cause as little cultural aesthetic errors as possible through a close to archetypal expression. The customization could instead be solved through different color choices.

8.2. Framework and Seat

The framework underwent some changes compared to the functional prototype, and these accounted for the largest differences between the two chairs (figure 8.1). Its functionality directly affects both brake and footrest attachment but also the seat angle. The previous idea of using scissor brakes was rejected during the testing according to a lack in functionality. Instead, RoughRider brakes were used and their performance during the testing meant that they were retained in this synthesis. This also meant that the framework had to be adjusted so that these brakes adequately could be attached to the frame. The result is a different shaped lower framework side tube, which now attaches below the footrest attachment instead of above. The difference becomes a lower and more angled brake attachment, which extends the area where the brake can be placed and reduces the problem of the brake falling back onto the tire when balancing on the rear wheels. This also extends the footrest adjustment range and the disadvantages are instead primarily found in the aesthetic preferences.

One of the ideas behind the mono-frame design was to evaluate its visual expression in the Indonesian context. The verdict was positive and there are implications from the study saying that the design provides the desired combination of being both robust and lightweight. The changes to the framework make it closer to a box construction, which can be seen in figure 8.2. The prediction of possibly going back to a box frame has come true, primarily according to the brake attachment difficulties. The diameter difference between the upper and lower side frame tubes is however kept to emphasize the perceived impression of a mono-frame construction. The large diameter of the upper tube also promotes robustness, which according the aesthetics study is beneficial.

▲ *8.3 - Seat in back position*

▼ *8.4 - Seat in front position*

What has also affected the final framework design is the seat angle. The previous seat angle, a backwards tilt of twelve degrees, was adopted directly from the RoughRider. This did, however, not agree with the user experiences identified during the studies. Several users expressed a concern over the risk of pressure sores but also a direct discomfort with the steeply inclined seat. The seat angle was hereby decreased to seven degrees. A less steep seat angle would according to Maria Samuelsson[1] provide a more active sitting posture and still provide pelvic stability to some extent. Seven degrees is also currently used by the Swedish wheelchair developer Panthera AB for a majority of their chairs (Panthera AB 2012b). The four degree angle in the foremost position is kept since it was proven to satisfyingly function during the trials. The seat alternation is facilitated through two detachable levers (figure 8.3). The seat is altered by pushing them (figure 8.4), and this facilitation increases the opportunities for all users to independently take advantage of this feature.

Taking the design to the next phase also required a consideration for customized sizes for several components. Generally, various sizes are achieved by cutting different tube lengths before welding the frame. However, some tube lengths may retroactively and permanently be adjusted to smaller sizes by cutting the ends. This is a non-reversible process and is only possible with access to adequate tooling. This may be performed for the seat depth, where the related upholstery may be shortened by folding the foremost fabric and locking it backwards using a velcro fastener.

Walter also meant a change in the footrest adjustment. The radius of the major bend on the larger diameter framework tubing was changed to create a 40-degree angle. This would, according to the testing and evaluation, suit the user group's adjustment needs better. However, the range of stepless adjustment is still dependent on the seat depth, which also determines the angle of the lower leg relative the footrest. This angle must be maintained in order to keep an appropriate foot position. The distance to the footrest also changes slightly when alternating the seat position. Depending of the combination of footrest position and seat depth this change may vary between 3 mm and 46 mm. However, large differences are relatively rare as it may result from improbable settings, such as a high footrest combined with the largest seat depth (18").

Minimizing the folded size for easy stowing also raises two considerations. According to the studies, stowing on a regular flat surface may also be complemented by situations where the chair is placed in a regular passenger seat. Keeping an adequate clearance under the backmost part of the framework therefore becomes an important measure in addition to minimizing folded height, width and length.

8.3. Backrest

The main issue with the backrest was its inability to lock it in position. There are several solutions for how to solve such issue among wheelchair producers but there is one additional requirement here. Springs may possibly cause problems regarding maintenance if they break in a developing context and are therefore undesirable. This is reflected in the synthesis by adding a backrest locking mechanism without springs. It is an eccentric lock an may be seen in figures 8.9 and 8.10. This mechanism will not be as rapid to lock and unlock as a spring and that is based on experiences from both Kenya and Indonesia, which indicate that most users do not fold their chairs very often. On this background, it was decided to offer a lockable and folding backrest where durability and manufacturing costs are considered more important than a rapid folding procedure.

8.4. Footrest

The footrest's primary task is to support the feet of the user, but it is also acting as a support and holds the two frame sides together. The supporting functionality has been kept in this final synthesis and the area where the feet are

Foot length	(mm)		
Percentile:	**5th**	**50th**	**95th**
Indonesian male	220	250	290
Indonesian female	210	230	260
Chinese Indonesian male	110	250	280
Chinese Indonesian female	210	230	260

▲ *Figure 8.5 - Anthropometry table: Foot length Indonesian Adults*

1. Maria Samuelsson (Occupational therapist, Swedish Handicap Institute) interviewed by the authors March 14, 2013.

supposed to be placed is enlarged according to findings during the empirical studies. The former footrest did not offer enough room to adequately hold larger feet and was thereby enlarged. The total area is now extended to a length of 260 mm, which according to figure 8.5 should accommodate the needs of Indonesian riders. This means that the foot rest support the major part of the feet of all Indonesian dataset groups of the study, which is according to applicable recommendations (Engström 2002). The footrest plate will through color and material be distinguished from the toe protection tube to encourage the user to place the feet on the plate instead of the tube.

8.5. Fenders

In order to achieve a transfer facilitation, the fenders were modified to maintain a backmost position during the seat position alteration. However, an additional transfer facilitation in terms of smaller fenders would tend to contradict an improved dirt protection. As this contradiction was accompanied by other diverging wishes, three different fenders proposals were developed and evaluated against the requirements in figure 8.6. All three proposals are larger than the fender used on the functional prototype, which is here considered the reference fender. Fender 1

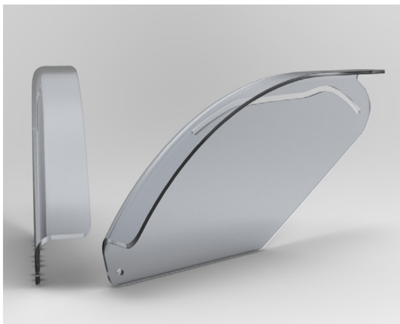
▼ *Figure 8.6 - Fender evaluation*

EVALUATION MATRIX

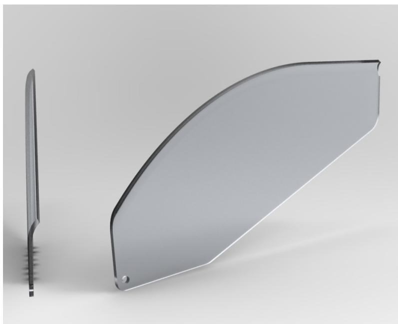
			Fender 1		Fender 2		Fender 3	
No.	**Aspect**	**Weight**	**Score**	**Tot.**	**Score**	**Tot.**	**Score**	**Tot.**
1.	Protect from dirt	1.0	1	**1**	0.8	**0.8**	0.6	**0.6**
2.	Propelling handrims	1.0	1	**1**	1	**1**	1	**1**
3.	Propelling tires	0.2	-1	**-0.2**	-0.5	**-0.1**	0	**0**
4.	Thigh support	0.6	0	**0**	0.2	**0.12**	0.2	**0.12**
5.	Hip joint coverage	1.0	0	**0**	0	**0**	0	**0**
6.	Transfer facilitation	1.0	1	**1**	0.7	**0.7**	0.7	**0.7**
7.	Transfer/posture alteration support	0.4	0	**0**	-0.5	**-0.2**	0	**0**
8.	Horizontal load resistance	1.0	0	**0**	0	**0**	0	**0**
9.	Vertical load resistance	1.0	1	**1**	-1	**-1**	-1	**-1**
10.	Folding mechanism compatibility	0.4	-1	**-0.4**	-0.3	**-0.12**	0	**0**
11.	Weight	0.6	-0.3	**-0.18**	-0.2	**-0.12**	-0.2	**-0.12**
12.	Folded size	0.6	-1	**-0.6**	-0.6	**-0.36**	-0.3	**-0.18**
13.	Ease of manufacture	1.0	-1	**-1**	-1	**-1**	0	**0**
14.	Ease of assembly	1.0	-1	**-1**	-1	**-1**	0	**0**
15.	Durability	1.0	0.8	**0.8**	0.5	**0.5**	0.5	**0.5**

TOTAL SCORES **Fender 1: 1.42** **Fender 2: -0.78** **Fender 3: 1.62**

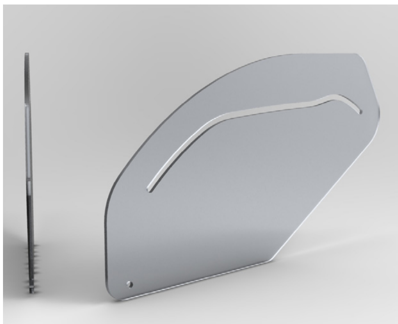
PREFERRED SOLUTION ***FENDER 3*** ***+0.2 vs. FENDER 1*** ***+2.4 vs. FENDER 2***



▲ *Fender 1*



▲ *Fender 2*



▲ *Fender 3*

is suppossed to be bent over the tire and provide a flex to be supported by the tire when the user grabs onto it. Fender 2 has a slighter bend, which is there to increase the mud protection compared to the reference. Fender 3 has a similar expression as the reference but is larger to provide better dirt protection.

Each requirement was weighted on a scale measuring from 0 to 1, and given a score compared to the reference. "-1" means poorer functionality, "0" is considered equally good and "1" is better than the reference. As showed by the evaluation, the third proposal was selected. This was primarily due to decent and well-known functionality combined with an ease of manufacture. However, proposal number one also presents satisfactory characteristics which may provide both adequate dirt protection and transfer facilitation. Yet it was deselected due to uncertainties concerning manufacturability and limited compatibility with the backrest folding mechanism.

8.6. Rear Wheels

The functional prototype was built using conventional wheelchair wheels, primarily designed for riding on flat ground. The suggestion is to replace these by wheels made for rugged terrain with a hope to increase the riding experience.

The studies in Indonesia also confirmed the need of individually customizable hand rims. The distance between the actual wheels and the hand rim has been a subject of discussion. Some users prefer a large distance while others are using a different technique where this distance can be decreased.

8.7. Storage

The need to carry around personal items was identified already during the WEshare project. The WEchair takes advantage of the removed x-brace and the thereby freed volume under the seat, which allowed the inclusion off a small pocket for loading small personal items. By positioning the pocket under the seat, the load will not heavily interfere with the chair's COG. (Bremer, Ohlson, & Olsson 2012)

This idea has been kept in Walter and it is according to the identified need of carrying small personal belongings at a safe place. Smaller goods are usually carried in a bag placed on the backrest, which in crowded places could be attractive targets for pickpockets. Adding a small storage unit under the seat would allow the user to keep smaller belongings out of reach for others. A limited storage volume but still a more secure location for small valuables.

8.8. Material

The intended material for this final concept is low carbon steel (also referred to as mild steel). The chromoly previously described is according to Hotchkiss[2] and Indriyanto[3], Technical Specialist at Whirlwind, not sufficiently available in the intended contexts. The hardship of bending the thinner tubing causes additional problems regarding manufacturing. The manufacturability in less developed countries is considered very important and is a factor that heavily could increase the feasibility of the end result. The uncertainty of using chromoly is currently considered too large but it should be further evaluated according to its future potential. The ability to build a similar but lighter construction is very interesting and might be possible in a close future, if the use of chromoly is spread in the developing world. The material must become available and affordable, but it is also important to develop usable manufacturing techniques for the producers. Using chromoly might be a good alternative if these requirements are fulfilled.

8.9. Color

The current situation leaves little opportunities for the user. Charity and distributing organizations are currently defining the colors of the wheelchairs provided through their systems and the user is not able to pick a color of his or her choice. In a user-centered development, it would be beneficial to allow the user to personalize their own chair by choosing their own color. The empirical studies also implicates that there is a wish among the users to do so. The final suggestion is thereby to allow the users to define their

2. Ralf Hotchkiss (Co-founder, Whirlwind Wheelchair International) interviewed by the authors October 20, 2012.
3. Indriyanto (Technical Specialist, Whirlwind Wheelchair International) interviewed by the authors.November 28, 2012.

own color of each wheelchair delivered. The user requirement is thereby seen as more important than spreading knowledge about different organizations through the color of the wheelchair. This branding is currently also done by placing logotypes on primarily the backrest of the chairs. Allowing the users to choose the color would not interfere with such branding.

The insufficient studies of color means that no suggestions will be left on what actual colors should be available for the users. The project goal of producing a prototype has instead meant that the focus on colors was applied on the final prototype. The main framework and footrest are given a red color and the definition of red was decided by the availability with the surface treatment supplier Provexa AB. Remaining parts are black, since the contrast between these two colors allows the side frames to stand out and describe the form expression of the chair. Red was chosen according to its general perception as vivid, powerful and physiologically activating (Nilsson 2004).

8.10. Surface Treatment

The functional prototype did not include a surface treatment but such processing is regarded necessary for the final concept. There is a requirement on a life span of at least ten years. This puts a demand on a corrosion resistant surface treatment and a chair in mild steel will face a tough situation considering a rough usage in possibly both rainy seasons and very humid climate. There are definitely applicable surface treatments to overcome the problem with a corroding frame, but there is also one further issue that must be considered. The tight economic situation requires a process that holds the right characteristics to a low cost. This becomes a matter of trade-offs and the wish for the most suitable process must be compared to the cost of using it.

There is a wish to meet the requirements of a ten-year lifespan and this means that critical points on the frame must be identified and located. These are found where a detail is rubbing against the surface. This includes the attachments of the footrest, rear wheel axel and brakes as well as the seat locking mechanism and the area where the large angle adjustment bolts in the backrest hit the framework. What must also be considered is how often these hits or rubs occur. All three of the attachments described represent adjustments that usually is set once and then not adjusted for a very long time. The angle adjustment screws and particularly the seat locking mechanism are in that sense considered more critical. The biggest challenge is found in the seat locking, which include a gripping area that will slide against the cross-tube in the back every time the seat is locked or unlocked.

Provexa AB, a Swedish surface treatment company that consider themselves as one of northern Europe's leading surface treatment suppliers (Provexa AB 2011), was contacted for consultation. Provexa's Technical Sales Stefan Wiborg[4] explained the benefits of suggesting powder coating for the final concept. The method offers an opportunity to first apply a first layer (primer), which later is covered with a top coating. This dual protection would provide a good corrosion resistance at a, with Swedish measures, low cost. This cost should, however, be further confirmed by a possible manufacturer in the intended context. The powder coating would also withstand the applied external impact of parts rubbing against the surface to a greater extent than conventional painting methods.

8.11. Technical Specifications

In order to present a comprehensive set including measures, adjustability and sizes that are technically available, a technical specification was formed (figure 8.7). It includes major features of the synthesis and some of them that have not yet been physically constructed, such as alternative chair widths and heights. Rather, these features will result from a prospective alteration of the design to accomplish various sizes of the chair. These alterations have been considered, but not tested, during the project and may therefore require further evaluations for a complete implementation.

4. Stefan Wiborg (Technical Sales, Provexa AB) interviewed by the authors February 26, 2013.

▼ *Figure 8.7 - Technical specifications*

TECHNICAL SPECIFICATIONS

No.	Feature	Specification
1.	Alternating seat	Two different seat positioning options facilitating hill climbing and providing easy transfer with locking fenders. Includes push levers and locking mechanism.
2.	Seat and backrest width	Available as 12.5” (318 mm), 14” (356 mm), 15.5” (394 mm), 17” (432 mm) and 18.5” (470 mm). Measured from the outer side of the seat tubes. The seat width also drives the measure of the backrest width, which is uncompromisingly matched. The seat width is determined at time of manufacture and is therefore not adjustable. Prototype size: 14”.
3.	Seat depth	Available as 14” (356 mm), 16” (406 mm) and 18” (457 mm). Measuring from the foremost seat tube ending to the backrest tube. The measure is semi-adjustable and may be permanently shortened if the initial size is larger than 14”. Prototype size: 16”.
4.	Seat angle	The backmost seat position may be locked and secured at an angle of 7 degrees. Similarly, the foremost position provides a seat angle of 4 degrees.
5.	Backrest height	A non-adjustable measure available as 14” (356 mm), 16” (406 mm) and 18” (457 mm). Measuring from the top of the seat tube to the upper backrest tube ending. Prototype size: 14”.
6.	Backrest angle	Starting at a 90 degree angle measuring from the seat, the backrest offers stepless adjustment within a range of ±8 degrees. It may be securely locked in position independent of backrest angle setting.
7.	Toe protecting footrest	The footrest adjustability range for different seat depths measured in the backmost seat position are established as 266-428 mm (14”), 297-424 mm (16”) and 299-425 mm (18”). The ranges corresponds to the distance between the top of the seat tube ending to the backmost ending of the footplate.
8.	Overall length	Maximum length is 1080 mm, measured with the footrest set to the lowest position and the rear axle set to the backmost position. Correspondingly, the minimum length is 940 mm.
9.	Overall width	Measuring between lowest part of tires. 590 mm (12.5” seat width), 625 mm (14”), 660 mm (15.5”) and 700mm (18”)
10.	Foldability	The chair folds by detaching the quick-release rear wheels and by folding the backrest which concurrently lowers the fenders. Stowed on a passenger seat, the chair will occupy a space measuring 790x630 mm seen from sideview. If placed on a flat surface the corresponding space will measure 860x450 mm. The folded width is 510 mm (14” seat width).
11.	Rear wheels	Accommodates for 24” rear wheels with an interchangeable quick release hub axle.
12.	Rear axle	Adjustable within a stepless range of 100 mm. Allows for a COG adjustment which may be used to achieve optimal balance and ease of pushing. The axle provides a 3-degree rear wheel camber, which may also be slightly adjusted by clamping the axle at different positions. This adjustment will also affect the level of toe in and toe out.
13.	Front casters and caster barrel	Uses Whirlwind’s WideFlex casters, a standard bicycle hub and bearing. The caster barrels holds a neutral 90 degree angle relative the ground.

No.	Feature	Specification
14.	Wheelbase	Measuring from caster hub in a forward riding position to the rear wheel hub, the wheelbase ranges between 490 and 660 mm depending on rear axle position. This provides a wheelbase that is approximately 50% longer than the wheelbase on a conventional wheelchair.
15.	Turning radius	1280 mm - 1440 mm depending on rear axle position.
16.	Tension adjustable back	Seven individually adjustable straps to provide optimal posture support for a broad range of users.
17.	Upholstery	Washable Whirlwind RoughRIder upholstery.
18.	Framework	Rigid frame with single tube caster barell attachment.
19.	Total weight	19 kg

▼ *Figure 8.8 - Rear wheels removed and backrest folded*

▲ *Figure 8.9 - Seat locking mechanism in back position*

▼ *Figure 8.10 - Seat locking mechanism in front position*

▲ *Figure 9.1 - Final prototype*

▼ *Figure 9.2 - Final CAD-model*

9. Final Prototype

This chapter describes the process of transforming the synthesis into the final prototype, which is here also evaluated. This embodiment represents the end result of the project and offers an opportunity for external stakeholders to further reflect the project result.

9.1. Manufacturing

The final prototype (figure 9.1) was, just as its forerunner, built with a 14” seat width. The intention of fitting an Indonesian population was not as prominent for this prototype since no further field evaluations were planned. Such evaluations would, however, be possible for the final prototype if it would be produced with a 14” seat width. Additional information, provided by Whirlwind, further confirms this size. Ralf Hotchkiss, founder of Whirlwind, currently uses a 14” RoughRider and there is a wish to allow Hotchkiss to personally ride and evaluate this prototype.

The iteration between the functional prototype and the synthesis and meant a number of design changes to satisfyingly correspond to the user requirements, but also constructional changes to further facilitate the manufacturing. Producing the final prototype also meant using a different set of tools compared to what was available in the workshop in San Francisco. This required some additional customizations and adaptions on the final proposal to make it manufacturable with the available tooling.

The most significant adaption is found in the bends of the side frames. These three radii on each of the two sides became smaller than intended, which gave the prototype a slightly different visual appearance than the computer-aided concept (figure 9.2). These changes do not affect the technical functionality according to that no critical measures for the wheelchair had to be changed to manufacture the prototype.

As a result of complications in the welding process, the footrest attachment mechanism was also slightly modified. Attaching a tube onto a steel plate requires the TIG torch to fit in a very small in order to make a durable weld. In order to comply with manufacturing feedback and be able to finish the prototype this steel tube was replaced with a more compatible square pipe. This exchange slightly changed the overall expression of the prototype but is regarded as an incitement of evaluating the initial solution rather than a final proposal.

The TIG welding process also triggered other minor design features to be modified. Particularly, tube connections located close to tube endings were required to either be located adjacent to endings or with a significant margin to ensure keeping the end profile intact. In cases where the tube were supposed to be plugged, keeping the endings in appropriate shape were highly desired. Consequently, some connections were modified to fit the new requirement. However, some connections were intentionally kept unmodified in order to keep the adjustability range for the rear axle.

▲ *Figure 9.3 - Prototype with seat in back position*

▼ *Figure 9.4 - Prototype with seat in front position*

COMPLEMENTARY LIST OF MANUFACTURING REQUIREMENTS

No.	Requirement	Weight
9.1	Allow at least 5 mm between connecting tube and tube endings to facilitate welding.	4
9.2	Prioritize bends instead of welds to minimize cost	5
9.3	Allow appropriate space for welding torch in welded connections.	5
9.4	Use 90 degree T-connections to minimize length of welds.	3

▲ *Figure 9.5 - Complementary list of manufacturing requirements*

The different set of tooling also provided new possibilities to make a more precise and less rough prototype. The use of lathes and milling machines primarily allowed the final prototype to accurately correspond to th e initial design, developed in CAD. This consistency also allowed better functionality in terms of appropriate ranges of adjustability as well as finished surfaces with a minimized risk of injury.

The collected feedback from the final prototyping phase were eventually documented as a complementary list presented in figure 9.5. This list, primarily characterized by manufacturing aspects is considered as a complement to the initial set of requirements presented in chapter seven.

9.2. Surface Treatment

The prototype was, in accordance with the synthesis, powder coated. Based on currently available tooling for the RoughRider surface treatment, selecting this process also for the new prototype will guarantee the application feasibility. There is also a future interest of evaluating the powder coating functionality and its compliance with the new functionality of the wheelchair. Particularly, critical zones such as friction surfaces resulting from stepless adjustability will contribute to undiscovered evaluation novelty. In order to create an appropriate foundation for further improvement of the surface treatment, selecting powder coating is the one option that should be initially evaluated since it currently serves as the most available process and therefore the most economically feasible.

9.3. Theoretical Evaluation

The prototype is evaluated based on the requirement list presented in chapter seven. As successively developed throughout the project, this specification contributes as a comprehensive basis of the evaluation that will help to determine whether or not the prototype is an adequate representation of the project goal.

Fixed Seat

To a large extent, the systematical evaluation shows a satisfactory coverage for the engineering specification. However, for various reasons some aspects have been disregarded. One important example is the decision not to propose how the chair can be modified to become a rigid, lightweight and large wheelbase chair with a fixed seat. Despite several indications on a significant need for this solution, the selection of the primary target group has been a dominating factor for solely emphasizing the development of a functional alternating seat. By disregarding the fixed seat option for this prototype, an increased amount of resources in terms of time and competence could be spent on developing a thorough solution with regards to the primary target group. However, as there is an extensive relevance within the development of a fixed seat option, this remains to be investigated in the future.

Footrest

The evaluation also emphasizes the footrest as an important second concern. This is primarily based on the adjustable range and its deviation from anthropometric relations. Comparing the 40-degree adjustment angle with anthropometric variations for upper and lower leg, it can be noticed that the there is a poor compliance. In fact, the anthropometric relationship, set as 5:6 for lower and upper leg (Chuan, Hartono, & Kumar 2010), is the inverse of what is used for the prototype. However, this deviation can be explained by the result from the trials, which highlighted the need to move the footrest closer the front of the chair. In turn, the riders would be encouraged to position their feet more accurately from an anatomically beneficial point of view. To

▲ *Figure 9.6 - Christian riding prototype uphill with seat in back position*

▼ *Figure 9.7 - Christian riding prototype uphill with seat in front position*

accommodate this need, also supported by the observation saying that some users were unable to appropriately bend their knees, the anthropometric ratio was slightly disregarded.

As can be derived from the angle and position of the frame tube for footrest adjustment, the evaluation further shows that the construction may constitute as an obstacle for the rider when making a transfer. This particularly becomes an issue when trying to move feet and legs sideways out from the chair. However, the frame design is a result of contradictory demands and may not easily be changed without interfering with remaining functionality. This functionality should therefore be further evaluated to find out whether it is a major problem for the overall functionality.

Alternating Seat

The alternating seat also constitutes some complications when combined with different seat depth options. The intention to keep identical distance between footrest and seat becomes physically impossible with the current design as the seat depth varies. Therefore, the construction is made such that the distance is identical for the 16” seat depth and consequently varies slightly when selecting a different seat depth.

Fenders

Driven by demands of being lightweight and dynamic, the fenders constitute as potential weakness of the chair. This particularly arouses as a result of disregarding force impact resistance in order to decrease weight and facilitate manufacture. As the fenders are also enlarged to improve its dirt protecting functionality, the area of exposure to critical impacts is also increased.

Theoretical suppositions claims that the natural flexibility of the polycarbonate plastic will increase the durability of the fenders as they may be supported by adjacent structures, such as the rear wheels when exposed to critical forces. However, the empirical support for this hypothesis is currently limited and the sensitivity to externally applied forces therefore remains to be completely investigated before taking any further action.

As the size of the fenders is increased there is also a risk of interfering with a smooth and easy transfer. Presumably, this effect is relatively small since the extended area of the fenders primarily not interferes with the intended transfer space.

Friction Surfaces

Another important concern is the fact that the final prototype, compared to the RoughRider, includes several friction surfaces that are critical subjects to wear and tear. As the intended surface treatment method is critically sensitive to dents and scratches this becomes particularly relevant. In order to minimize the risk of a serious corrosion failure, protective rubber films are used where possible. It is also known from trials that the kind of adjustments that causes critical wear are infrequently made in the intended context. As a result, there is a presumption stating that the new wheelchair will not be significantly critical in terms of corrosion resistance. However, this remains to be further evaluated and potentially subject to improvements in order to find better solutions for clamping and surface treatment methods.

10. Discussion

This chapter considers insights and thoughts on the complete project. The discussion includes the project's final outcome but also the process leading to this result. The discussion is concluded with recommendations of further work for Whirlwind.

10.1. Final Result

The project goal was not only to develop a prototype but also to ensure its compatibility with the social, physical and economic conditions that currently characterize the situation in semi-urban environments in developing countries. The project has shown that there are many subjective factors affecting these conditions. It is therefore problematic to define the project success regarding this in specific. By including the project aim it is easier to clarify the future purpose of including this kind of wheelchair to the market.

The project aim treated the opportunities of social integration and such problematic is hard to accomplish through only wheelchair design, and if only wheelchair design is considered it is still impossible by only implementing one specific wheelchair. The wide variety of user characteristics requires a range of different wheelchair solutions to accommodate the personal needs of all different users. The strength in this project is rather the addition to the existing solutions. The alternating seat offers a solution that is currently not available to the prospect user group, and by extending the product range there is definitely a possibility to increase the opportunities of social integration. By providing this wheelchair design to users that would benefit from its functionality, these users could possibly strengthen their own abilities. Such development would positively affect social integration for these users in specific, but not solve the overall problem. Wheelchair design must therefore be complemented with education, community development and other activities to facilitate the life situation of wheelchair riders in the intended context.

The final result, especially considering the final prototype, can also be discussed in terms of detail solutions. The idea to test and evaluate a principle has definitely overruled optimizing detail solutions. This leaves a lot of improvement potential but there is also some room for concern here. Some mechanical details have been chosen according to its known and reliable functionality and are also rather expensive. Replacing those with more affordable solutions is indeed possible but would also affect the preciseness and probably the life length of the product. It becomes clear that this solution's functionality is optimized for its intended context, while economy aspects need to be further considered. The question here is whether it is possible to still provide the same, or at least a very similar, functionality at a lower cost using cheaper solutions? It probably is, but there is a significant need for further expert evaluations and optimizations to both clarify the main issues and determine how to solve them.

10.2. Process

The process is of major interest, especially regarding that this project has gone from an idea to a physical prototype within a very limited amount of time. It should also be considered that the project is based on previous field study, which gave input and partially excluded some of the early phases in conventional design process.

10.2.1. Planning

This project did, as previously described, require a thorough planning. The successful implementation of the travels is perhaps a direct result of this planning but that is probably only one of several reasons. It was difficult to define all necessary resources prior to the initiation of the project and several insecurities in the planning were actually solved as the project went along. The risk analysis was definitely an additional safety factor, and there was a plan on how to react on certain problems. None of these actions had to be implemented since the project came to follow the intended plan. A question that should be raised is thereby; to what extent would these backup plans actually solve the potential issues?

The time in San Francisco was not spent exactly as planned and the plan was slightly modified so that the construction work was moved forward in time. The reason was to gather more input before a complete concept was presented and embodied. There was a possibility to do so according to the amount of time planned at Whirlwind's facilities. Such approach would have been far more difficult in Yogyakarta, where there was less time planned. Encountering problem there would have meant meeting fewer users for testing procedures, which ultimately would have caused a lack of empirical input. This would have required another way of gathering information to fill these presumed gaps in the analysis. A likely approach would have been including more theoretical input and this would probably have affected the final result of the project - possibly in a solution that would be less appreciated by the intended users.

The choice to visit Indonesia and partially base the project on previous studies in Kenya should definitely be considered. The input from WEshare did probably affect the complete project but perhaps the initial phases in particular. Those studies formed the basis of the problem definition and the final result is probably more affected by the evaluation phase in Indonesia than the experiences from Kenya. The visited context in Yogyakarta is more developed and it is interesting to consider how this affected the outcome. Conducting an evaluation phase in another developing context could have given another outcome of the project. Since there is an overall goal of providing this technology to the "developing world", it would have been beneficial for the project to include more than one less developed context for these testing and evaluation steps of the process. This would have provided an increased validity to the result and a more reliable outcome to develop further for Whirlwind. There is of course a theoretical possibility to include further locations in the next iteration, where the final prototype should be evaluated. There is, however, a possibility that the lack of geographical spreading could provide further difficulties in later development stages. Still, there are very few specific details on the final design that have been developed only considering Indonesia, which should minimize the risk of such problematic occurring.

There were several factors determining the travelling possibilities in this project. The collaborating organizations' possibilities to accept two students, given knowledge, and financing the trips have all been prominent issues. This basically means that the trips were planned to give as much valuable results as possible within the given frames. It can still be discussed if there would have been any possibility of getting better results if these problems could have been overseen. As already mentioned, it would have been interesting to complete similar testing and evaluation studies in other developing contexts. An even more interesting solution would perhaps have been if the first prototype could have been constructed at a location with prospect users. The alternating seat was based on problems identified in the United States and if there would have been a possibility to interact with users at that point, this idea could have been confirmed earlier in the process. This would have decreased the level of uncertainty and improved the working efficiency. This risk was not considered a prominent issue at that point, since there was actually an idea on how to accomplish the evaluation stage even if the alternating seat idea would have failed. Still, it should be considered that such approach was perhaps only possible since this is a student project. The monetary loss would not have been severe for any of the involved parties in case of a project failure at that point. Instead, the scope and the agenda of the testing and evaluation phase would have to change. It would still provide the necessary knowledge to pass the graduation, but perhaps not end up in a new wheelchair design. If a company would have done this project instead, this approach could have been very expensive in case of a project failure. It is thereby probably worth investing in appropriate field studies prior to the actual development work to avoid having to correct potential mistakes later in the process, which probably would be more costly.

10.2.2. Execution

The implementation of this project and its planning has been very successful and there have, as mentioned, been few errors causing problematic situations. It is not only a result of a thorough planning but also that the inclusion of external expertise has given a very positive result. This became clear especially during the testing and evaluation phase in Indonesia, where the support provided by UCP should be highlighted. Their input heavily facilitated the testing and evaluation procedures, but their effort has also affected these analyses. The testing phase was conducted with users provided through use UCP. The main advantage has been effectiveness, where little resources have been put on searching for users and valuable project time has instead been put in preparing the tests. This has, however, also meant that the opportunity to pick users with certain characteristics has been very limited. This means that the outcome of the tests reflects the included users, who may not fully represent an optimal user group for this specific chair. This variety of users has instead given an opportunity to evaluate what type of user that is suitable for this solution. This approach has probably been beneficial for the project result since there was no clear definition on this before the project phase in Indonesia. Still, it means that there is a lack of empirical studies on appropriate users riding a wheelchair with an alternating seat.

There is another factor regarding the empirical studies that must be mentioned here. All users riding the prototype only got the chance to ride it for approximately one hour. This means that obvious problems were identified and that most of the studies are based on first impressions. It is possible that there are several problems that were never discovered because of the limited time for each trial. It is also possible that potential positive feedback was overseen because of this. The translating seat is an example of chair characteristics that possibly could be perceived very different when using it for a longer time span. A problematic first try can potentially be developed into a smoother maneuver with some exercise.

A wheelchair is used for more than 16 hours a day by some people and this wheelchair concept should definitely be given longer testing sessions where users could use it as their primary chair for a longer time.

10.3. Methods

The large amount of empirical studies has resulted in a very user-centered design process. Whether this should be seen as positive or negative is not obvious given that the user's desires and expectations not always can be equated with scientific studies or the opinions from medical expertise. The users' current position in developing countries differs from their fellow wheelchair riders in industrialized countries. In a market-driven situation, companies must adapt their development after user wishes and requirements to avoid losing market share to a competing business. A shortage of companies developing wheelchairs for users in developing countries, the tough economic situation for people in the developing world, and the difficulty of disabled people to fully integrate with the society all affect the user's situation considerably. Their ability to affect the producers is very limited and this opens an opportunity for this project - to develop a conceptual chair with high focus on users' whishes and requirements. Both theory and medical expertise have been involved in this project but the result should be further confirmed with respect to both of these in case of a continuation.

The choice of specific methods can be discussed but is harder according to several reasons. Each method is chosen with respect to the task to be solved but also factors as personal experiences and secureness with each method have been considered. The methods chosen have given an effective way of working and have not caused unnecessary delays because of confusion of how to implement certain methods, or uncertainty about what results they may provide. There are possibly methods that would provide an even better, more relevant or more confident result but the efficiency provided by the chosen methods have, given the tight time schedule, been considered more important than searching for alternative ways of working that may have given an improved result.

10.4. Further Development

The final result of this project should not be considered as a finished product proposal, but rather as a concept under development. This project has taken this idea to a clear embodiment stage but there is still a lot of work left before this idea can be implemented on the market. The next natural step would be to evaluate the characteristics of the final prototype to clarify whether it provides the desired results. The feedback from the testing and evaluation has changed the wheelchair design and these changes should definitely be evaluated.

There is also a major challenge of making this chair producible. The current prototype has not been optimized regarding neither economy nor manufacturing. The lack of calculations of the possible price to the end customer also leaves a gap that must be filled with information. The economical factors have consciously been left out of the project scope but is a very important factor considering that this is a solution developed for less developed contexts. It would, however, be interesting to see whether there is a market for this solution in more developed contexts as well. This is a new solution to the market and there might be a potential marked in industrialized countries as well. Similar approaches, with one solution for developing and one for developed countries based on the same technology currently exist among other wheelchair producers. There might be a similar opportunity with this solution, and such possibility should be evaluated. It could extend the possible incomes for Whirlwind, which in the end could finance further wheelchair development for developing countries.

10.5. Recommendations

Bringing this final proposal from its current prototype stage to an actual implementation on the market definitely needs some further work. These recommendations describe the actions that are considered required for this project to be further developed.

- The prototype must be evaluated during longer trials. There has not been any evaluation on how a longer use of this technology affects the user's perception of the chair. Such test could evoke new areas of interest for further development or confirm the current solution.

- The final proposal must be optimized considering both manufacturability and economy. The knowledge of the current chair's cost is regarding producing a prototype and not large-scale production. The manufacturability is of course connected to the costs but the ease of production should also be further considered. This should also include optimal tubing dimensions and weight optimization.

- This technology should also be introduced to more markets, primarily in other developing contexts. This would evaluate whether this technology is applicable all over the developing world or if there is something making it more suitable for certain areas. This should also include industrialized context to evaluate the future potential of this technology in such context.

11. Conclusion

The final result is a new wheelchair concept, developed for semi-urban environments in developing countries. It has been embodied in a prototype, which can be treated as a fully functional wheelchair and be both ridden and evaluated. It has been developed considering the current situation in semi-urban environments in developing countries and is seen as a contribution to social integration for suitable users according to that it provides necessary functionality to let these users overcome obstacles they currently cannot independently manage. This is an accomplishment of the project aim but it is important to consider the discussion about what must complement a wheelchair design to achieve a satisfying level of integration for these people.

The new technology implemented through this project is definitely seen as a differentiation from currently available solutions on the market, which may have an competitive advantage. The alternating seat alongside with the rigid framework mean a possible complement to the current product range of Whirlwind. This enhancement is not only due to the final concept but also the insights regarding the prospect user group. This study provides information that could be used to further develop current and future products for disabled people in developing contexts.

By basing this final design on a rigid framework, which is currently successfully used by several wheelchair developers in industrialized countries, there has been a technology adaption from an industrialized context to a developing context. As this technology has enabled new technical opportunities, it has been possible to introduce and evaluate new and innovative wheelchair solutions. Building the alternating seat, based on the industrialized version of the frame and proving its user benefit, demonstrates a distinct example of the inherent potential for both modernization and innovation in the developing world. Thus, based on the development of an adapted technology, the result of this project can be regarded as a source of inspiration for taking the wheelchair industry of the developing world one step further.

Even though this project has given a satisfactory result, there is still a lot of work remaining before this technology could be fully introduced to the intended user group. The final result means developing, testing and evaluating a new kind of wheelchair technology, and the insights given by this project can hopefully be used to further develop and increase the possibilities of wheelchair users in the developing world.

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Figure 8.5 - Chuan, TK, Hartono, M & Kumar, N (2010) Anthropometry of the Singaporean and Indonesian Populations. *International Journal of Industrial Ergonomics.* Vol. 40, Issue 6, pp 757-766.

Appendices

Appendix I - WEchair
Appendix II - FMEA/PHEA
Appendix III - Field Study Questionnaire

Appendix I - WEchair

Appendix II - FMEA/PHEA

	Key Process Step or Input	Potential Failure Mode or Error	FMEA/ PHEA	Potential Failure Effects	SEV	Potential Causes	OCC
	What is the Process Step or Input?	*In what ways can the Process Step or Input fail?*	*Potential failure mode or human error?*	*What is the impact on the Key Output Variables once it fails (customer or internal requirements)?*	*How Severe is the effect to the customer?*	*What causes the Key Input to go wrong?*	*How often does cause or FM occur?*
1	Move seat position	Forget to unlock seat	PHEA	None	1	Human errror, inexperi-ence	4
2	“	Get stuck with fingers in the handle or pinch fingers	PHEA	Possibly pinch or scratch fingers	3	Human errror, inexperi-ence	1
3	“	Try to pull seat for-ward by using the lock handle	PHEA	Backrest folds slightly	1	Human errror, inexperi-ence	5
4	“	Seat bolt breakage	FMEA	Decreased seat stability. Can pos-sibly lead to more bolts breaking, causing the seat to fall off.	8	Poor bolt quality. Too high force load on seat. Nuts not tightened properly.	1
5	“	Weld failure in seat construction	FMEA	Decreased seat stability, Could lead to further weld failure or bolt breakage.	8	Poor welds. Too high force load on seat.	1
6	“	Scratch thumb on fender when moving forward	PHEA	Cut in hand/finger	4	Human error. Sharp edges on fender.	3
7	“	Forget to lock seat in front position	PHEA	Fall into back position (pretty immediate action)	1	Human errror, inexperi-ence	6

Current Controls	DET	RPN	Immediate Actions Recommended	Actions Taken	User Communication	SEV	OCC	DET	RPN
What are the existing controls and procedures that prevent either the Cause or the Failure Mode?	*How well can you detect the Cause or the Failure Mode?*	*Risk Priority Number (Severity x Occurrence x Detection)*	*What are the immediate actions for reducing the occurrence of the cause, or improving detection?*	*Note the actions taken. Include dates of completion.*	*How should this failure be communicated to the users?*	*Failure mode svereness after completed action*	*Failure mode occurrence after completed action*	*Failure mode detection after completed action*	*Risk Priority Number (Severity x Occurrence x Detection)*
None except for that the seat is not moving	1	4	None	No action completed 2012-11-21	Show how the moving seat procedure is done through demonstration. No further communication. Interesting to see whether the users understand this functionality or not.	1	4	1	4
Grip on the handle. Handle on one side. Bar on the backrest prevents hands from getting there.	1	3	None	No action completed 2012-11-21	Only basic demonstration. Interesting to observe if anyone actually manage to injure themselves since the severeness is low.	3	1	1	3
Most common among first time users. Failure not likely to occur again after first failure.	3	15	None	No action completed 2012-11-21	Only basic demonstration. Interesting to observe users trying to use the seat functionality.	1	5	3	15
Nuts tightened by Erik and Christian. Observe tests so that we can intervene if something seems wrong.	4	32	Visual inspection prior to each test ride. Daily check of the wheelchair to make sure that nuts are tightened. Oil moving bolts.	Action noted 2012-11-21	Tell users to pay atention to abnormalitites and make sure to contact Christian and/or Erik if something deviates from normal.	8	1	2	16
Observe testing procedures which allows us to intervene if something seems wrong.	4	32	Daily visual inspection.	Action noted 2012-11-21	Tell users to pay attention to abnormalitites and make sure to contact Christian and/or Erik if something deviates from normal.	8	1	2	16
None	1	12	Round fender edges.		Only basic demonstration. No further information on the fender edges after they have been rounded.	3	2	1	6
None except for seat falling back into back position.	1	6	None	No action completed 2012-11-21	Only basic demonstration	1	4	1	4

8	“	Forget to lock seat in back posistion	PHEA	Seat instability	1	Human errror, inexperi-ence	6
9	“	“	PHEA	Worst case scenario: going down a steep hill and hits an obstacle at the end causing the seat to flip and ultimately throws the user out of the chair.	8	Human errror, inexperi-ence	1
10	“	Stop mechanism breakage	FMEA	Seat is allowed to move further towards front or further towards back.	1	Component wear. Poorly tightened bolts.	1
11	“	Pinch hand or fingers between seat and frame tube when moving back	PHEA	Finger pinch causing hand injuries, loss of finger/hand functionality.	10	Inappropriate finger po-sition combined with acci-dental seat movement. Possibly concurrent with seat locking procedure.	1
12	“	Open tube ends (scratch fingers etc.)	FMEA	Reduced finger functionality due to bruises or cuts.	3	Slippery locking handle causing inappropriate finger position.	2
13	Fold the chair	Handle can't really be folded	FMEA	Increased folding size	1	Poor design	10
14	“	Scratch on the fend-ers when unfolding the backrest	PHEA	Cut in hand/finger	3	Human error. Sharp edges on fender.	2
15	Transfer	Fender breakage	FMEA	Possibly cuts in buttock or hands	8	Human error, poor fender design, material failure.	1
16	“	Forget to lock seat before transferring	PHEA	Seat will move backwards and it is possible that the user will not get in and fall on he ground.	6	Human error, inexperience	2
17	“	Forget to lock brakes before transferring	PHEA	Chair will not stay in position	2	Human error or perhaps a wish from the user not to lock the brakes	1
18	“	Brake failure	FMEA	Chair will not stay in position but the user will definitely not be aware of this since he or she probably tried to lock the chair's position.	2	Material breakage. Nuts not tightened properly.	4
19	“	Forget to lock brakes before transferring out	PHEA	Chair will not stay in position	2	Human error or perhaps a wish from the user not to lock the brakes.	1
20	“	Forget to lock seat before transfering out	PHEA	Seat will probably fall back into rear position before transfer is initiated	2	Human error, inexperience	4
21	Pop a wheelie	Fall over backwards	PHEA	Can lead to severe injuries even though a smaller injury is more likely.	5	Human error, inexperi-ence. Wheel axle in wrong position.	1
22	“	Backrest breakage du to material or weld failure (primarily brackets)	FMEA	User can fall backwards depend-ing on level of failure and level of trunk control.	5	Bolt breakage. Material failure. Poor welds.	1

None	5	30	None	No action completed 2012-11-21	Only basic demonstration	1	4	5	20
None	5	40	If a client goes on a ride without locking the seat, Erik or Christian will intervene.	No action completed 2012-11-21	Basic demonstration and extra notification if needed	8	1	1	8
None	1	1	None	No action completed 2012-11-21	None	1	1	1	1
Grip on the handle	6	60	Mark out critical areas with colored tape. Provide detailed instructions on how this can be avoided.		Detailed instructions on where not to put hand or fingers during seat operation. Make sure to inform this is a prototype and not a consumer ready product.	10	1	2	20
None	5	30	Weld a backplate to remove sharp edges.	Action completed 2012-11-22	None	1	1	5	5
None	1	10	None	No action completed 2012-11-21	None	1	10	1	10
None	3	18	Round fender edges		Only basic demonstration	1	2	3	6
None	7	56	Observation when testing transfers. Remove fenders in some tests		Further information before attempting any transfer procedures	8	1	2	16
Locking handle angle. Haptic feedback if the seat is fixed in position or not.	2	24	None	No action completed 2012-11-21	Basic demonstration and observation during transfer testing to make sure that all actions are taken prior to the transferring attempt.	6	1	1	6
Visual and haptic feedback from brakes. Chair will move if not locked in position.	1	2	None	No action completed 2012-11-21	Basic demonstration of brakes	2	1	1	2
None	3	24	Daily brake check by Christian and Erik.	Action noted 2012-11-21	None	2	2	3	12
Visual and haptic feedback from brakes. Chair will move if not locked in position.	1	2	None	No action completed 2012-11-21	Basic demonstration of brakes	2	1	1	2
None except for seat falling back into back position	4	32	Observation of transfer testing.	Action noted 2012-11-21	Basic demonstration and extra notification if needed	2	1	2	4
Flip seat into front position in situations where risk of falling over backwards is increased.	2	10	None	No action completed 2012-11-21	Chair setup should be in accordance with user needs	5	1	1	5
The backrest has some backup in fender attachment.	1	5	Daily visual inspection	Action noted 2012-11-21	None	5	1	1	5

23	Encounter obstacles	Footrest plastic failure	FMEA	Users can cut their feet on sharp edges. Feet might fall down to the ground.	5	Material failure when bumbing into something	1
24	“	Caster assembly breakage (weld failure, individual part failure etc.)	FMEA	Castor falls off causing frame tube to fall into the ground, which ultimately might harm the user.	5	Failure in individual parts or assembly. Poor welding.	1
25	Accelerate	Fall over backwards	PHEA	Can lead to severe injuries even though a smaller injury is more likely	5	Rear wheel axle in the wrong position. Push wheels too hard in combinaiton with a faulty technique.	1
26	“	Scratch fingers/hands against fender	PHEA	Cuts in hands/fingers	3	User pushes on wheels istead of handrims	2
27	“	Forget to fold brakes away and injure hands	PHEA	Cuts or bruises in hands or fingers	4	Human error. Long handrim strokes.	3
28	“	Forget to lock seat in position (front position)	PHEA	Fall into back position (pretty immediate action)	1	Human errror, inexperience	6
29	“	Fingers get stuck in between spokes	PHEA	User might injure hands and /or fingers	5	Human error, inexperience. No spoke protection.	1
30	Activate/ deactivate brake	Fail to completely activate brake	PHEA	Wheels will not be locked in position	1	Human error, inexperience. Brakes are located at a difficult position and might be tough to lock for some people.	4
31	“	Pinch finger in brake mechanism	PHEA	Minor finger injury	3	Human error, inexperience. Brake placement.	1
32	“	Brake attachment failure	FMEA	Brake does not lock wheel properly. Brake gets loose or falls off.	3	Poor brake attachment. Spacers in wrong material.	3
33	“	Scratch fingers/hands on seat tube	PHEA	Smaller sctraches to lower arms.	3	Poor brake placement. Too sharp edges on seat tubes.	6
34	Further errors	Rear wheel breakage (fall off)	FMEA	Wheelchair falls over, causing user injuries	8	Material failures in wheel assembly. Poor quick release attachment.	1
35	“	Footrest sliding	FMEA	User's feet loose grip with the foot support	3	Screws not tightened enough	1
36	“	Framework weld failure	FMEA	Could lead to part separation - ultimately leading to that a rider may fall in high speed. The worst kind of breakage would appear if one of the major monotube welds failed.	10	Poor welding	1
37	“	Locking mechanism failure	FMEA	Can cause potential problems if failing while seat is locked in front position.	2	Material failure	1

None	4	20	Daily check by Christian and Erik to assure the condition	Action noted 2012-11-21	None	5	1	2	10
None	2	10	Daily check by Christian and Erik to assure the condition.	Action noted 2012-11-21	None	5	1	1	5
Flip seat into front position in situations where risk of falling over backwards is increased.	2	10	None	No action completed 2012-11-21	Chair setup should be in accordance with user requirements.	5	1	1	5
Handrims	2	12	Round fender edges	-	None. After rounding the edges, potential injuries are so small that it would be more interesting to see how people in general uses the wheels and handrims.	2	2	2	8
Brakes are placed far down	2	24	None	No action completed 2012-11-21	Only basic demonstration	4	2	2	16
None except for seat falling back into back position	1	6	None	No action completed 2012-11-21	Only basic demonstration	1	4	1	4
None	1	5	None	No action completed 2012-11-21	None	5	1	1	5
Haptic feedback from the brake when activation has been successively accomplished	2	8	None	No action completed 2012-11-21	Basic demonstration	1	4	1	4
None	1	3	None	No action completed 2012-11-21	Basic demonstration	3	1	1	3
None	2	18	Daily brake check by Christian and Erik. Possibly change the PVC spacer to a rubber spacer if there is an obvious problem.	Action noted 2012-11-21	Basic demonstration of brakes and extra notification if needed	3	2	1	6
None	2	36	Grind down the sharp tube ends.	Action completed 2012-11-22	Basic demonstration of brakes and extra notification if needed	2	3	1	6
Feedback in quick-release button if the wheels are attached or not	3	24	Daily check by Christian and Erik to assure the condition	Action noted 2012-11-21	Basic demonstration and extra notification if needed	8	1	2	16
None	3	9	Daily brake check by Christian and Erik	Action noted 2012-11-21	None	3	1	2	6
None	3	30	Daily visual inspection. An unlikely failure but it is very important to be aware of the possibility of such breakage since the effect would be severe.	Action noted 2012-11-21	None	10	1	2	20
None	1	2	None	No action completed 2012-11-21	None	2	1	1	2

Appendix III - Field Study Questionnaire

1. Basic riding

1.1 Compared to your current chair, how would you rate the overall performance for ***smooth grounds***?

[A LOT WORSE (1) – A LOT BETTER (5)]

1.2 Compared to your current chair, how would you rate the overall performance for ***rough grounds***?

[A LOT WORSE (1) – A LOT BETTER (5)]

1.2 Compared to your current chair, how would you rate the overall performance for ***indoor environment***?

[A LOT WORSE (1) – A LOT BETTER (5)]

1.3 Did you ever feel any ***discomfort*** when entering, leaving or riding the chair?

[YES ☐ NO ☐]

If yes, where could you feel discomfort?

____

2. Advanced riding

2.1 How would you rate the procedure needed to ***move the seat forward***?

[IMPOSSIBLE (1) – VERY EASY (5)]

2.2 How would you rate the procedure needed to ***move the seat backward***?

[IMPOSSIBLE (1) – VERY EASY (5)]

2.3 Compared to your current chair, how would you rate the difficulty of ***climbing the slope***?

[A LOT HARDER (1) – A LOT EASIER (5)]

2.4 Compared to your current chair, how would you rate the difficulty of ***going down the slope***?

[A LOT HARDER (1) – A LOT EASIER (5)]

1.3 Did you ever feel any ***discomfort*** when changing the seat position?

[YES ☐ NO ☐]

If yes, where could you feel discomfort?

____

3. Transfer

3.1 Compared to transferring from the seat in ***back position***, how would you rate the difficulty of transferring from the seat in ***front position***?

[A LOT HARDER (1) – A LOT EASIER (5)]

3.2 ***[WITHOUT FENDERS]*** Compared to transferring from the seat in ***back position***, how would you rate the difficulty of transferring from the seat in ***front position***?

[A LOT HARDER (1) – A LOT EASIER (5)]

4. Working station

4.1 Compared to having the seat in ***back position***, how did you experience the ***posture*** when working at a desk with the seat in ***front position***?

[VERY UNCOMFORTABLE (1) – VERY COMFORTABLE (5)]

5. Transport

4.1 Compared to your current chair, how did you experience the ***transportation*** of the prototype?

[A LOT HARDER (1) – A LOT EASIER (5)]

4.2 Compared to your current chair, how did you perceive the ***weight*** of the prototype?

[A LOT HEAVIER (1) – A LOT LIGHTER (5)]

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