Master Thesis

Designing for Mars: extraterrestrial full-body washing

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Division of Machine Design • Department of Design Science

Faculty of Engineering LTH • Lund University • 2013

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Preface

This Master's thesis is the final element of a long and winding path of education, awarding me with the almost as long and winding title *Master of Science in Mechanical Engineering and Industrial Design*. The thesis was carried out in the spring of 2013 at the Faculty of Engineering at Lund University, and in collaboration with engineers and architects at NASA's *Lyndon B. Johnson Space Center* in Houston, Texas. The objective of the thesis was to design a full-body washing system that can provide good personal hygiene for space explorers on Mars.

First of all I want to thank Molly Anderson and Larry Toups from NASA for making this possible, for showing tremendous support and interest for the thesis. I am very grateful for all the help I have received during the last months. I hope my work will be of help for you and your work, if not in its entirety perhaps some theories or assumptions could be valuable. I do know that I have learned a great deal throughout the work, and it gives me great satisfaction to be able to share the acquired knowledge and experiences. Thank you for inviting me to Johnson Space Center, and specifically to Molly for taking such good care of me during my visit.

Per Liljeqvist, a great teacher and my thesis supervisor, who showed great faith in me when he introduced me to Larry Toups. Thank you for, in a fun and instructive manner, educating me throughout the years and for all the help with the thesis.

Danny Marquez, my Houston *chauffeur*, a good friend and inspiration.

Filip Zezovski Lindh, my friend and confidant, who has shown great interest in my thesis and patiently listened to my theories, facts, and genuine babble.

Cristina Castañon, my girlfriend and consultant regarding everything from grammar to design. Thank you for motivating me and keeping me sane through my rough and tedious struggles.

Live long and prosper.

Lund, July 2013

Miro Söderberg Sert

Abstract

NASA is currently working toward the goal of landing humans on Mars. One challenge this mission is faced with is the lack of technology or procedure that could provide the explorers with means to maintain good personal hygiene. In collaboration with NASA engineers and architects the task of this thesis was to design a prototype for a nozzle and a conceptual water heater for a Martian full-body washing system.

The thesis was conducted mostly based on a conventional design methodology: a literature study, a benchmarking, a function analysis and an iterated design process. There were also some unconventional elements in the methodology, such as a function dissection, a personified target group and an aesthetical analysis of the environment.

Extreme environments and conditions require extreme design, so in other words, a re-designed shower will not suffice. No contemporary or historical full-body washing method proved satisfactory for this kind of mission, but a combination of showering and sponge bathing emerged as an efficient way to execute full-body washing. However, for the moment there is no design or technology that can provide this. Examples of design drivers are reliability, repairability, efficiency, smart stowage capabilities, autonomy, self-sufficiency and minimal logistical needs.

Several nozzle concepts were generated, evaluated, improved and evaluated anew only to be improved even more. Eventually, a 22 gram nozzle that combines washing methods was designed. It is efficient, reliable, repairable and can provide smart stowage capabilities The design is not yet ready for use - further research is needed - but in conclusion, maintaining good personal hygiene on Mars is definitely feasible.

Keywords:

Mars, NASA, product development, design, extreme environments, repairability, washing, hygiene

Sammanfattning

Introduktion

NASA förbereder sig för att sända en besättning astronauter till Mars; en fjärran, främmande och hotfull miljö som ingen människa hittills har besökt. En svår designutmaning är frågan om hur astronauterna ska kunna upprätthålla god personlig hygien.

I samarbete med ingenjörer och arkitekter från NASA är uppgiften i detta examensarbete att designa ett helkroppstvättssystem för användning på en framtida Marsbas. Utgångspunkten för detta system är att det består av tre delar: ett munstycke, en vattenvärmare och själva utrymmet där tvättningen kommer att ske med nyss nämnda verktyg. Mer exakt ör uppdraget att designa en fungerande prototyp av munstycket; en konceptuell och inspirerande design av varmvattenberedaren; medan själva utrymmet inte kommer att designas, dock tas stor hänsyn till det när de andra delarna utformas. Fokus ligger på munstycket.

Samarbetet med NASA var främst med Molly Anderson och Larry Toups som är Life Support Engineer respektive Habitation Lead vid NASA:s *Lyndon B. Johnson Space Center* (JSC). Ett veckolångt forskningsbesök vid JSC genomfördes i syfte att undersöka den aktuella frågan.

Metodologi

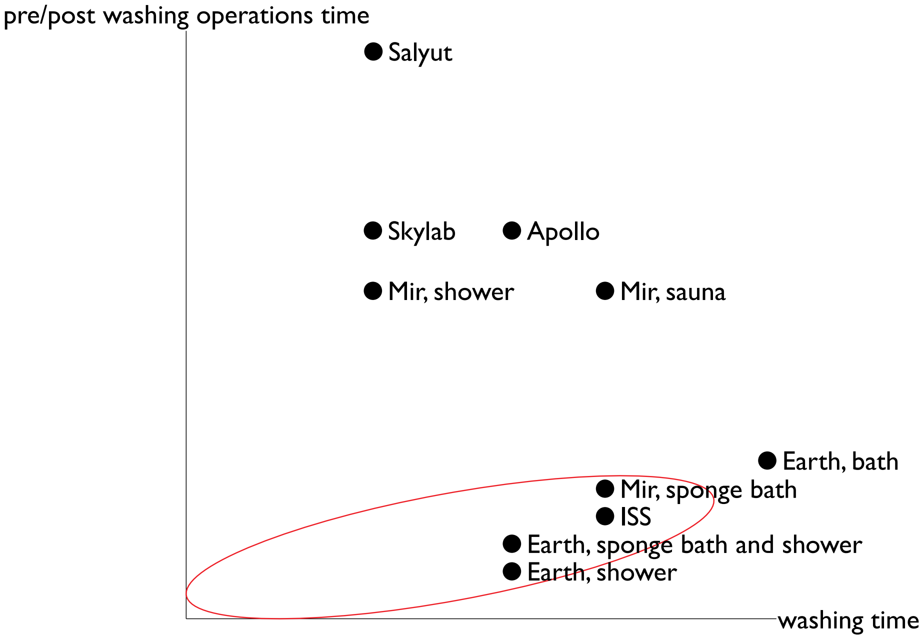
Analysdelen genomfördes mestadels baserat på konventionell designmetodologi: litteraturstudie på de generella förhållanden som en Marsfärd medför, benchmarking av kulturella och historiska tvättprocedurer och -teknologier, samt en funktionsanalys. Det fanns också några mer okonventionella inslag, bland annat en målgruppsanalys som tilläts representeras av en person, en estetisk analys av den miljö där designen kommer att placeras, samt en *funktionsdissektion* som rationaliserar helkroppstvättningens funktioner och procedurer.

Designprocessen för munstycket inleddes med två omgångar konceptgenerering och *concept scoring*, därpå utvecklades konceptet enligt mönstret: tillverkning av prototyp, test av prototyp, utvärdering av test och design av ny prototyp. Denna process upprepades tre gånger för munstycket. Utveckling av varmvattenberedaren upphörde vid det konceptuella stadiet.

Analys

På alla rymdstationer har det funnits problem med helkroppstvättningen, under vissa uppdrag har astronauter till och med vägrat att tvätta sig. Det finns alltså ingen teknik eller procedur som kan användas för ett uppdrag till Mars.

Astronauterna kommer troligen spendera cirka 500 dagar på Mars yta, där gravitationen är 38% av jordens. Tidsfördröjningen mellan Jorden och Mars kommer variera från tre till tjugotvå minuter, och en akut hemresa är inte genomförbar. På grund av dessa och många andra förhållanden bör designen vara: hållbar, reparerbar, effektiv, självständig, självförsörjande, ha minimala logistiska behov, ha stort antropometrisk omfång, ha låg massa för reservdelar och underhållsutrustning.

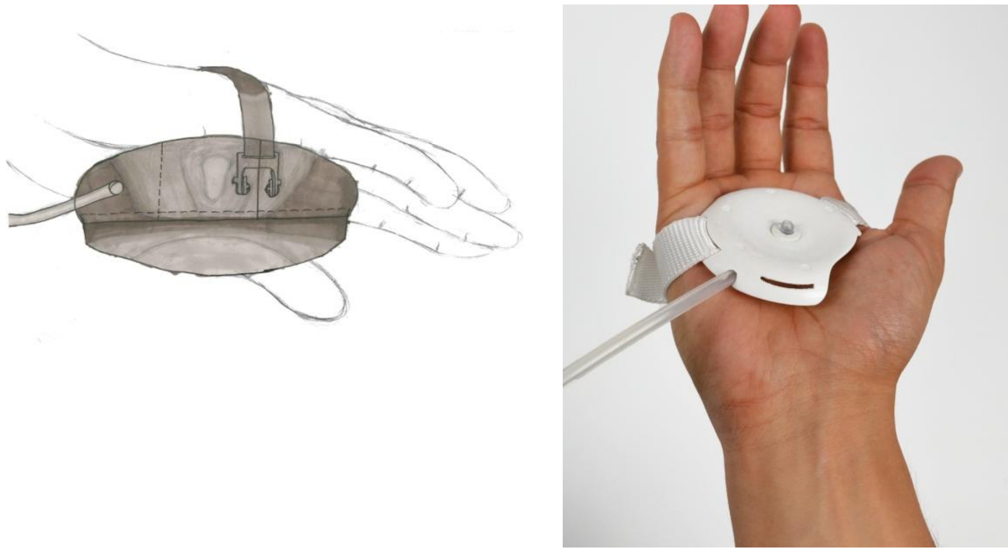


Figur 1 Diagram som jämför tvättiden med tiden för förberedelse och efterarbete hos jordliga och utomjordliga tvättsystem.

Kort tvättid och ännu kortare tid för förberedelse och efterarbete är verkligen ett effektivt samband; den röda ellipsen i diagrammet ovan ringar in detta område. De fyra tvättsystemen inom detta område har dock sina nackdelar: att duscha på jorden kräver stora mängder vatten, att tvaga sig på Mir och ISS kräver stora mängder förbrukningsvaror, och vad gäller att kombinera tvagning och duschning så finns det helt enkelt ingen teknologi som kan tillhandahålla den proceduren på Mars.

Munstycket

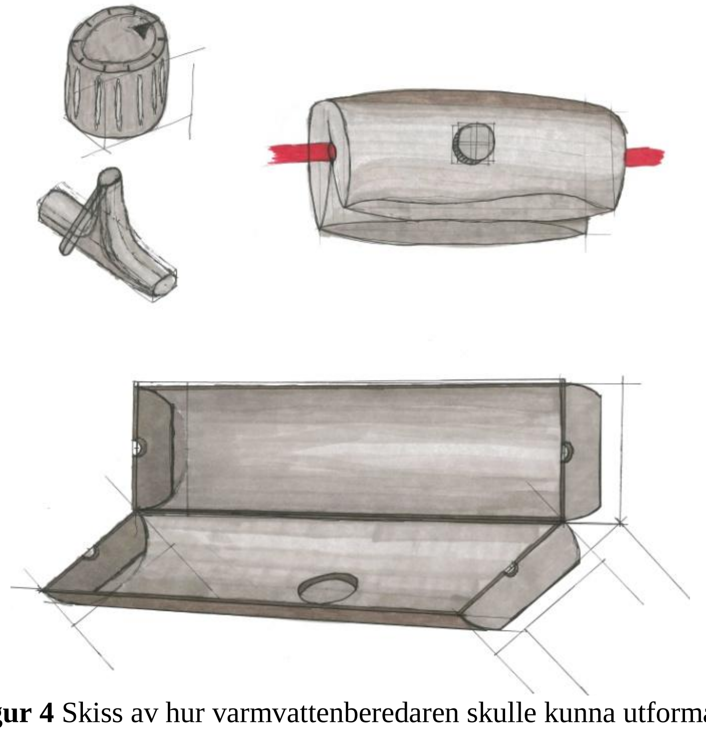
Munstycket såg till en början ut enligt figur 2, men efter en lång designprocess blev den alltmer avskalad, lättare att förpacka, enklare att reparera, skönare, enkel i utformning och funktion, se fugur 3. Dess slutliga vikt och maximala tjocklek blev 22 gram respektive 2 mm.



Figur 2-3 Det ursprungliga munstyckekonceptet och den slutgiltiga prototypen.

Varmvattenberedaren

Idén bakom varmvattenberedaren var att den framförallt skulle vara mobil, hållbar och reparerbar. Dess utveckling avstannade dock tidigt i det konceptuella stadiet. Figur 4 visar hur ett av dessa koncept såg ut.



Figur 4 Skiss av hur varmvattenberedaren skulle kunna utformas.

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1 Introduction

This chapter offers a brief background to the problem as well as an introduction to NASA, which is the guiding body for this thesis. The problem statement and objectives of the thesis are described and the working process is explained.

1.1 Background

1.1.1 NASA

The National Aeronautics and Space Administration (NASA) is the United States government agency responsible for the nation's civilian space program and for research on aeronautics and aerospace. Although probably most famous for the moon landings, the agency has for many years pioneered in many fields of technology and science. Their vision is "to reach for new heights and reveal the unknown so that what we do and learn will benefit all humankind" [1]. Over the years, much of NASA's research and inventions have indeed come to benefit humankind. An annually released publication, called Spinoff, features the past year's successfully commercialized NASA technology; some of which have direct benefit to the public sector [2]. The act of applying space technology to more down-to-earth applications is called space technology transfer [3]. The European Space Agency (ESA) has stated that investments in the space industry end up benefitting the general society twenty fold [4].

This thesis was conducted in cooperation with NASA, more specifically in cooperation with Molly Anderson and Larry Toups, Life Support Engineer and Habitation Lead, respectively, at NASA's Lyndon B. Johnson Space Center (JSC). A one-week research visit to JSC was carried out in order to explore the issue at hand.

Back to the vision, "to reach for new heights and reveal the unknown so that what we do and learn will benefit all humankind". There are many things to be learned through exploration, and many things to be learned just by trying to explore. As the challenges of space exploration are so extreme, the designers must reject conventional solutions to what would have been simple problems on Earth. NASA's next exploration goal is expressed as follows: "NASA is designing and building the capabilities to send humans to explore the solar system, working toward a goal of landing humans on Mars" [5].

1.1.2 Mars

Visible with the naked eye, the exploration of Mars began at least four thousand years ago, and it will continue for many years to come. So far, NASA has explored Mars with several kinds of unmanned missions: flybys, orbiters, landers and rovers. An ongoing mission is the *Curiosity* rover. The success rate of Mars exploration missions is 42%, which is the lowest rate for any category of exploration missions [6]. The ultimate goal of these exploration missions is to find out if life ever existed on the planet [7].

For human exploration missions to Mars there will be some great challenges. Due to the extreme conditions, and although many problems arise while travelling to and from Mars, this thesis will revolve around the stay on Mars. Examples of problematic Martian conditions are the high radiation levels, the temperature variations, the irregularities of solar power, the isolation, the logistical difficulties, the long stay and the partial gravity. These conditions, which will be analyzed in chapter 3.1, influence all aspects of the habitat design; one important aspect is the explorers' personal hygiene.

1.1.3 Personal hygiene

Personal hygiene involves the procedures and practices one performs in order to keep clean. The main effect of keeping clean is maintaining good health. In a NASA publication, called *Human Integration Design Handbook* it says that good personal hygiene "can enhance self-image, improve morale, and increase the productivity of the crewmember". It is further explained that body odor is recognized as a "predictable source of interpersonal conflict" [8, p. 499].

Personal hygiene procedures and practices are culture- and gender-specific. The Mars exploration crew will be of mixed cultural background and gender. A procedure that all crewmembers feel comfortable using, or a full-body washing system that is flexible in how it is used, are two possible approaches to this challenge. Either way some degree of flexibility is a must, since different areas of the body are washed in different ways and frequencies. Based on a summarized operations timeline for the ISS crew in the article *Waste and Hygiene Compartment for the International Space Station*, [9, p. 4] four critical areas of the body are hereby identified as the face (including the hair and the mouth), the armpits, the hands, and the perianal (genital and anal) area. These are illustrated in figure 1.1.

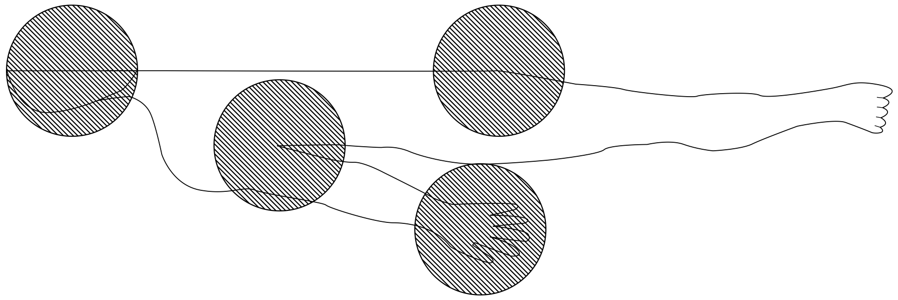


Figure 1.1 The four critical areas of body washing.

Besides holding some important organs, the hygiene of the face is important because it strictly relates to one's perceived cleanness. The same goes for the hair and the mouth. Halitosis could, just like body odor, be a source of interpersonal conflict. Furthermore, substandard oral hygiene can lead to conditions which are only solvable through surgery. On a Mars exploration mission this of course ought to be avoided. Face and hair washing is a regularly performed procedure and is not performed in connection to any particular activity. Oral care is usually performed before or after eating or drinking.

The bodies' apocrine sweat glands are all located in the armpits and the genital area. That is the kind of sweat gland that gives off a secretion that, when broken down by bacteria, cause the virulent kind of body odor [10, p. 199]. The washing of the armpits can be performed in connection to exercising but it can also be part of a daily washing routine.

The perianal area is principally washed after body waste activities. This washing is not performed very thoroughly; it serves more as a clean-up. Due to the apocrine sweat glands and the body waste activities, thorough washing of these parts is usually performed on a daily basis.

The hands are frequently in contact with various objects and need to be washed regularly.

This thesis will not revolve around any specific critical area, but of the hygiene of the skin, the human body's biggest organ, which encompasses all critical areas. Essentially, the only way to keep the entire skin clean is through full-body washing. In Sweden as well as in the United States, the conventional full-body washing practices are either bathing or showering.

1.2 Problem statement

NASA prepares to send a crew of astronauts to Mars; a remote and hostile environment where no person has ever been before. A great design challenge is the matter of providing the crew with means to maintain good personal hygiene. As discussed in chapter 1.1.3, the importance of personal hygiene cannot be overstated; it affects the crewmembers' productivity, as well as physical and mental health. The challenge lies in the consideration of many and extreme conditions, which will be discussed in chapter 3.1.

One important aspect of personal hygiene is full-body washing. The direct purpose of full-body washing is to remove dead skin cells, hair, sweat, oil, bacteria and body odor from the skin. On all space station programs, there have been problems regarding the full-body washing systems, some astronauts have even refused to use the provided washing equipment, so there is no ready-for-use technology or procedure that is applicable for this kind of mission. Therefore, it is about time that someone designs a full-body washing system that can provide good personal hygiene on a Martian base.

When designing for extreme environments, one designs for extreme conditions, and the result is likely to be an *extreme design*. Although Mars is very different from any place on Earth, some of the Martian conditions can be found at certain places on Earth, albeit in milder forms. A design made for one extreme environment can be modified to be used in a less extreme environment. What is learned from this thesis can hopefully also be used in terrestrial extreme environments.

1.3 Objectives and limitations

The objective of the thesis is to design some aspects of a full-body washing system that has the capability of providing good personal hygiene on a Martian base. In this thesis, full-body washing systems are defined to consist of three principal parts: (1) a nozzle, (2) a water heater, and (3) the space where the washing is conducted with the aforementioned washing tools. The scope of the thesis is the design of a functioning prototype of the nozzle; conceptual, inspirational designs for a water heater; and the space itself is not to be designed, but great consideration is taken to it when the other parts are designed. Focus lies on the design of the nozzle.

2 Method

The following chapter presents and discusses the method, or rather methods, used within the analysis and design phases.

2.1 Background

John Chris Jones wrote in his pioneering book *Design Methods* "Methodology should not be a fixed track to a fixed destination, but a conversation about everything that could be made to happen. The language of the conversation must bridge the logical gap between past and future, but in doing so it should not limit the variety of possible futures that are discussed nor should it force the choice of a future that is unfree" [11, p. 73].

There are many methods out there, and many ways to implement them. This thesis used no method exclusively, instead several methods were combined; some were very conventional while some comprised seemingly bold elements.

2.2 Analysis phase

Jan Landqvist states that "if the result of our work does not live up to the set goals, the problem often lies in the ambition or the knowledge of how to conduct the analysis" [12, p. 17]. This statement shows how crucial a well executed analysis might be to a project. The analysis phase of this thesis combines the methods of Claus-Christian Eckhardt, Åke Axelsson, and the author himself.

2.2.1 The conditions for human exploration of Mars

As the challenges of this project are literally otherworldly, describing and analyzing the many and peculiar circumstances is essential to a scientific and fruitful design process as well as to ensure the readers' understanding of the process and the results. Most outsiders have no understanding of the problems related to space exploration. The methods of analyzing the conditions of a Martian full-body washing system were a visit to JSC, a literature study, and several discussions with Molly Anderson and Larry Toups from NASA.

The purpose of the JSC visit was to gather information from a wide array of experts in space exploration. Meetings with engineers, a psychologist, a lawyer, chemists, and an astronaut were conducted in addition to tours of the Habitat Demonstration Unit (HDU), the test chamber known as "the can", and a water processing lab. The visit and the lessons learned from it imbued the entire thesis. For the analysis of the conditions the meeting with NASA astronaut Andy Thomas was very instructive and inspirational. He spoke of his experiences and views based on his missions aboard Mir, the ISS, the Space Shuttles *Endeavour* and *Discovery*.

The literature study for analyzing the conditions for human exploration of Mars consisted of NASA publications and an in part NASA affiliated book. Through the literature study and the discussions with Molly Anderson and Larry Toups the physical conditions, reasonable assumptions, and design drivers were identified.

2.2.2 Benchmarking

Benchmarking is the activity of comparing competitors, however, in this case there are no real competitors. There are nevertheless historical washing artifacts and cultural washing procedures that can be instructive. The methods of benchmarking were a visit to JSC, a literature study and several discussions with Molly Anderson and Larry Toups from NASA.

The tour of "the can" with Frederick Smith, Advanced Life Support Systems Engineer, who not only did research on it but also participated in tests inside it, provided hard facts on NASA's simulated missions prior to the launch of the ISS. Also the meeting with Andy Thomas was fruitful in terms of benchmarking the washing systems on Mir and the ISS.

The literature study consisted of several university theses, articles, conference papers, two popular science books, and NASA astronaut Don Pettit's blog from his latest mission aboard the ISS.

In terms of drawing conclusions based on the vast information the benchmarking resulted in, and pretty much making sense of it all, the discussions with Molly Anderson and Larry Toups were vital. The illustrative documentation of the findings are inspired by Claus-Christian Eckhardt's diagrams from the compilation booklet *Design Methodology* [13] as well as traditional architectural diagrams.

2.2.3 Function dissection

This is the author's own method; it is rather bold and might to some not even make sense, but it was truly the most significant part of the analysis phase. The method can be described as rationalization to the extreme, applied to functions and procedures. The purpose is to push the limits of what is perceived as possible and to see beyond one's prejudices toward something so everyday as full-body washing. Implementation of the method is done by continuously during the analysis asking oneself: "What goes on? How? Why?" In other words, the functions are dissected.

2.2.4 Aesthetical analysis

Swedish furniture designer Åke Axelsson has stated that instead of making a mood board he lets his designs emanate from the room of where the design is to be placed [14]. Since the design of this thesis will be place-specific, this is a suitable technique to use. One problem is that the room in question, and its aesthetic qualities, does not yet exist. Analyzing desired and undesired aesthetical characteristics of various environments is essential to deciding a suitable environment and to make the design be a part of the chosen environment. Several environments, terrestrial as well as extraterrestrial, and their aesthetical qualities are compared with each other. The aesthetical analysis is finalized with a discussion on the decided environment.

2.2.5 Target group analysis

It is likely that the future users of the Mars full-body washing system currently are teenagers, and analyzing these unknown future space explorers is quite tricky. In the early days of space exploration, the astronauts were often fighter pilots, and now they tend to be scientists, so who knows what kind of background the astronauts will have two decades from now? Instead of speculating on this relatively inessential topic, it is assumed that the future space explorers, the target group, can be personified by Swedish astronaut Christer Fuglesang.

2.2.6 Function analysis

A function analysis is the analysis, categorization and classification of functions related to the design. A function is normally composed of one verb and one or more nouns, but for clarity the functions will in this thesis be described with a verb and a simple clause. Function analyses are a common step in design processes, but a disadvantage is that in the break down of functions into simple clauses, information might get lost in translation. In combination with the function dissection, however, it is a great method since most functions will already be broken down to their smallest components.

2.3 Design phase

The design phase starts out in the same way for both the nozzle and the heater, however, only the nozzle completes the design process. The implemented methods are conventional product development methods based on Karl T. Ulrich's and Steven D. Eppinger's book *Product Design and Development* [15].

2.3.1 Concept generation

Based on the previously conducted analysis, ideas are brainstormed and developed into full-body washing system concepts. The concepts are explained in text as well as images.

2.3.2 Concept selection

The selection between the nozzle concepts were made by a method called concept scoring. The generated concepts are compared to each other by rating the concepts regarding various criteria, which in turn are given a certain weight. The product of the rates and weights are summed, and the highest scored concept is to be further developed. All criteria are defined in the text, but the criteria weights and the concepts' rates are subject to the subjective judgment of the author, yet based on the research done in the analysis phase.

There is no selection between the heater concepts, they are merely evaluated in text.

2.3.3 Concept development

The highest scored concept is to be improved and developed into several new concepts. This is done by expanding upon the advantages of the concept while working against the disadvantages. Also the new concepts are explained in text as well as in sketches. The concept development is followed by yet another round of concept scoring.

2.3.4 Design development

The highest ranked concept among the improved and developed ones will be further developed. This is done by using an iterative design process of prototyping, testing, evaluating, and designing as seen in figure 2.1.

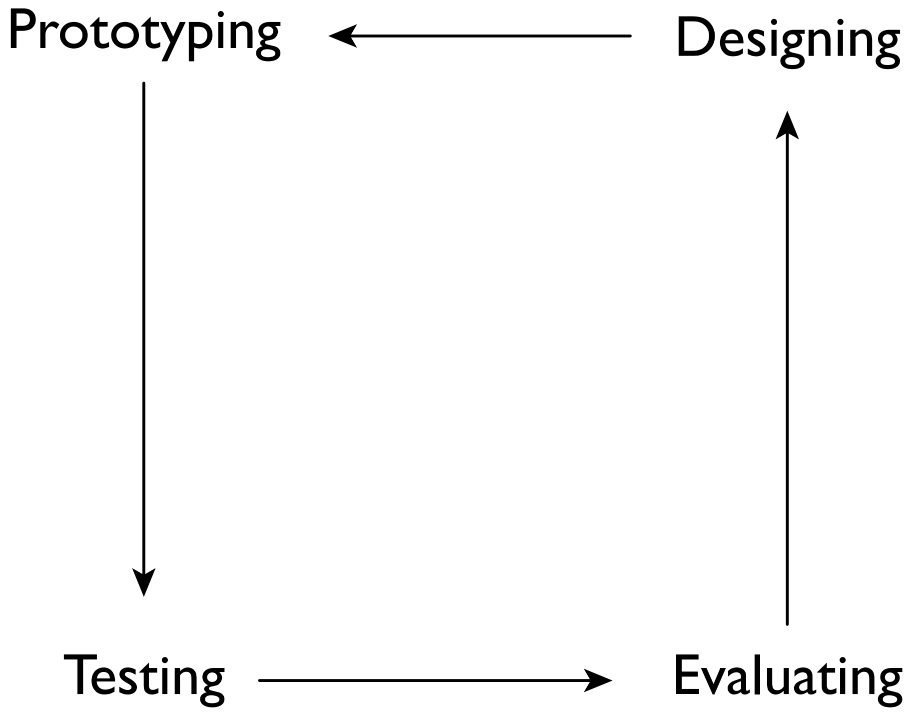


Figure 2.1 Illustration of the iterative design process and its four steps: prototyping, testing, evaluating and designing.

Ideas and thoughts throughout the iterative design process are described in both text and simple illustrations in order to promote the reader's understanding. Also, there are a couple of photos for each prototype; showing form and functions, while highlighting disadvantages and improvements from previous versions.

3 Analysis

This chapter examines the conditions, objects, processes, aesthetics, target group, and functions of the full-body washing system. The analysis lays the foundation for the design phase.

3.1 The conditions for human exploration of Mars

Mars might truly be as hostile as its namesake; the Roman god of war. There are many and extreme conditions that need to be considered when designing for human exploration of Mars. Fortunately, some of these extreme conditions do not directly affect the design of a full-body washing object or procedure. The relevant conditions and assumptions will be discussed in this subchapter.

3.1.1 General conditions

The Mars exploration mission will most likely be of a type called "conjunction-class". This means that circa 500 days will be spent on the Mars surface and that the travel time from Earth to Mars will be around 180 to 210 days. Prior to the arrival of the astronauts, the habitat will have been deployed and "captured into a high-Mars orbit". When the astronauts arrive, the habitat will have been orbiting Mars in a semi-dormant mode for two years [16, p. 3].

A consequence of the long travel time is that when the astronauts arrive at Mars, they will have spent around half a year in micro-gravity and have therefore suffered a great deal of bone loss and muscle weakening. NASA currently makes the assumption that an adaptation time of a few weeks will be necessary when arriving on Mars after such a long stay in micro-gravity. During this time the astronauts might experience some balance difficulties, and it is desirable that the full-body washing system could offer some balance support during usage [17]. Furthermore, the gravity of Mars is 3.71 m/s^2, or 38 % of the gravity on Earth. This means that water behaves differently on the two planets, it will basically fall slower; thus spending a longer time on the body. As a consequence, the water will also travel further horizontally before gravity pulls it down to the floor.

The mixed-gender crew is likely to consist of six astronauts from the United States, Canada, Russia, Japan and Europe. Today's astronauts are scientists in various fields. In preparation of the mission the crewmembers will have conducted years of training. For current missions, there is no training to specifically prepare the astronauts for full-body washing aboard the ISS. Astronaut Andy Thomas says, "we were simply taken to a room where the washing equipment laid on a table, we figured out how to use them just by looking at them. For the toilet, on the other hand, we spent around 2 weeks training on how to use and repair the system" [18]. In the future, to prepare for the usage of a somewhat more complicated full-body washing system on a longer mission, the toilet might be a better model in terms of training.

Vehicular activities will be conducted on the Martian surface, and these excursions might last for multiple days. As the general conditions and the hygiene requirements will be different aboard a space exploration vehicle in comparison to that of at the habitat, it was recommended by Larry Toups that the habitat system is designed in such a way that it can be modified for usage in an exploration vehicle [17]. Were the two full-body washing systems to share similarities, the mission would benefit regarding e.g. shorter astronaut training time and less unique spare parts.

Full-body washing will be performed on a regular basis, mostly after exercising. It could also be done in preparation for medical activities and after exposure to harmful chemicals. To simplify housekeeping, water and the cleaning agents should not easily escape their dedicated space. Also, the habitat must not contaminate the Martian environment, and vice versa.

The architecture of the habitat greatly affects the design of the full-body washing system. As the Mars habitat most likely will have a circular floor plan [17], unlike most terrestrial dwellings, the design needs to take this into consideration. Furthermore, as every kilogram and every liter has a cost - monetary and as a trade-off between other space and weight consuming objects - space and weight efficiency is a design driver. An estimate from Wiley J. Larson's book *Human Spaceflight: Mission Analysis and Design* is that the total mass, volume and power consumption would be 13,814.8 kg, 72.16 m^3 and 29,619 kWh, respectively. Of this the "shower" was estimated to weigh 75 kg, take up 1.41 m^3 and use 960 kWh. The shower's mass, volume and power consumption is a fraction of the total, but it is definitely not insignificant [19, p. 582-583]. A more recent assumption made by the Human space flight Architecture Team (HAT) is that the total weight for the entire full-body washing system will be 14 kg [17].

Andy Thomas identified stowage as an improvable element, with a significant "human factor" [18]. Consumables as well as spare parts need to be easily retrieved, while not taking up much space. The longer mission, the more critical is the stowage. For the full-body washing system on the Mars habitat, smart stowage is a design driver.

Due to the great distance between Earth and Mars, some highly relevant concerns do arise, for example the infeasibility of an emergency or quick-return home. There will be communication time delays spanning from three to twenty-two minutes. The shipping time and cost will be vast. Put together, these concerns require that Mars habitat designers pursue high reliability, repairability, autonomy, efficient use of consumable items, minimal logistical needs, self-sufficiency, reduced mass of for example spares and maintenance equipment [20, p. 2]. Overall, there must be great efficiency when it comes to the use of space and vital resources, such as oxygen, water and power. As for the full-body washing system, water is the most critical resource. A recent HAT assumption is that the water consumption for the full-body washing system will be 3.45 kg/person/day [17]. This is very little in comparison to showers and baths, which depending on the user and the equipment, can consume around 30-120 liters/person/use and 80-200 liters/person/use, respectively.

3.1.2 Anthropometry

As previously stated, the Mars exploration crew will most likely consist of people from the United States, Canada, Russia, Japan and Europe. An ergonomical guideline for designing for these international missions is to base the body measurements on the 5th to the 95th percentile of Japanese women and American men, respectively. This guideline leads to a great range of body measurements, enabling close to 95% of the global population to find themselves within its range. The following illustration, figure 3.1, is based on anthropometric data from NASA's *Man-Systems Information Standards* [21]. The measurements took place in the year 2000 and all subjects were 40 years of age. Furthermore, the effects of partial gravity on the anatomy are neglected.

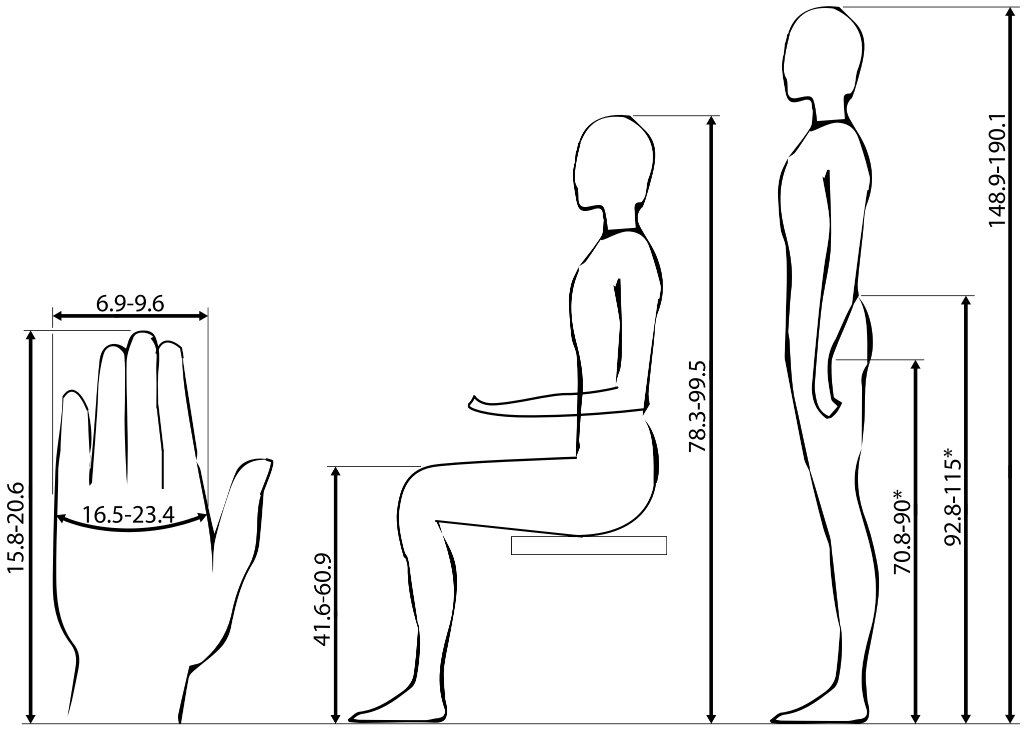


Figure 3.1 Illustration of the anthropometric range for an international crew of space explorers. There are great disparities between the two categories of people in for example height and hand width difference. The asterisk means that no data was available, so these numbers are estimations based on own measurements and assumptions.

3.1.3 Assumptions

As the Mars habitat is merely in a planning stage, many issues that are relevant to this thesis are still uncertain. Therefore, some assumptions regarding the overall conditions of the mission and the habitat need to be made. The first assumption is that there will be a laundry system. As this will require water and power, the use of resources that need to be washed regularly need to be minimized. The second assumption is that there will be a good system of storing energy so that power always will be available. In reality, the electricity production will be uneven at times, since it will depend on the sun. The third assumption is that the habitat has a water recovery system, and that it can handle the processing of some surfactants. Molly Anderson has stated that a decent guideline is that the surfactants should be gentle and environmentally friendly [22]. The fourth assumption is that the resources for the full-body washing system are integrated with the main supply lines. The fifth assumption is that the use of *j-wear*, a self-cleaning textile developed by JAXA [10, p. 199], will be negligible.

Lastly, some external conditions can be assumed to not affect the design of the full-body washing system. For clarity, a few examples of these conditions will be discussed in brevity. There will be very high levels of radiation at the Martian surface. The atmosphere mainly consists of carbon dioxide and the atmospheric pressure is around 0.6% of Earth's mean sea level pressure. The surface temperatures measured by the Viking landers ranges from -17^{o}C to -107^{o}C.

3.2 Benchmarking

In this subchapter the personal hygiene processes, tools and spaces of various environments are benchmarked.

3.2.1 Terrestrial environments

Personal hygiene procedures, practices and objects change during the course of time. In ancient Rome regular visits to bath houses were commonplace, while Elizabeth I much later wrote, "I bathe once a month, whether I need it or not." Bathing was perceived to be dangerous, as it removed the skin's protective layer of sebum, oil and dead skin cells [10, p. 199]. And there lies some truth in that statement. From a strictly medical perspective, we might today be over-washing our bodies, but as Scott et al. discusses, there is a difference between being clean and feeling clean [23, p. 7]. Being clean is a matter of health. Feeling clean, on the other hand, deals with the rituals of full-body washing and will on a Mars mission be, as Mary Roach puts it in her book *Packing for Mars*, "more an issue of morale than of health" [10, p. 202]. As a result, with some training it might be possible to alter the perceived cleanness. This could be accomplished by for example using the Martian full-body washing procedures prior to the departure from Earth. As mentioned in chapter 3.1.1, Andy Thomas did not implement any training in the use of the washing equipment in preparation of his ISS mission.

The rituals of full-body washing are culture-specific, and there is undoubtedly an interdependent relationship between design and cultural procedures. The relationship might also extend to technological advances, for example the highly resource intensive way of body washing in the Western world is made possible with access to a seemingly infinite amount of clean water and electricity. Bluntly, extreme wastefulness is an option in some societies, and in the daily life there will be no consequence for being wasteful or not. In other times and other cultures where the procedures are different, so are the designs.

A study from Delft University of Technology compares full-body washing methods in the Netherlands, India and Japan. The study identified three principal methods of full-body washing: to shower, to bathe and to use a reservoir [24, p. 4]. A shower is normally conducted in an upright position, with water being applied to the body from above; but the user has the possibility to choose the direction of the water flow by for example grabbing the nozzle, which enables partial-body washing. Bathing is when the user's body is soaked in a water reservoir. Reservoir washing is defined as when the user sits by a reservoir while splashing and pouring water onto the body. It resembles but should not be fully equated to sponge bathing, which is not discussed in the Delft study.

The Indian participants preferred to use a reservoir, while the Dutch participants tended to either shower or bathe. The Japanese participants, on the other hand, combined the methods: showering and bathing, showering with a reservoir, bathing and showering with a reservoir. The latter combination required the most water, but the other combinations turned out to be more efficient than only showering or only bathing [24, p. 4]. The study showed that a combination of procedures do not lengthen the total duration of the washing [25, p. 4]. The least water intensive procedure was reservoir washing, however, Matsuhashi adds that "the combination of using a water reservoir and a standing posture came to the surface as a possible new bathing style with lower resource consumption" [25, p. 4]. This technique could be equated to sponge bathing, and it is an area that could be further explored. To once and for all define the concept of sponge bathing; the water is applied on the body one area at a time, together with the friction and surfactants. This terminology and the basis for the it will be explained in chapter 3.3.

In many cultures, temperature plays a key part in the full-body washing procedure. It can be with steam, as in the saunas of Finland or the banyas of Russia. It can also be with very warm water, as in Japan, where the water temperature is at least above $40^{o}C$ [25, p. 4]. In the hamams of Turkey warm air, steam and water are provided in different parts of the washing ritual.

3.2.2 Simulated NASA missions

At Johnson Space Center there is a three storey test chamber referred to as "the can", see figure 3.2, where during the 1990's several tests researching advanced life support systems were executed. The tests went through three main phases, and were conducted under different circumstances. For the early test, called *Early Human Testing Initiative*, the only method of body washing was to use wet wipes. During the second phase tests, called *International Space Station Life Support Test Phase II* and *International Space Station Life Support Test Phase IIA*, the chamber was equipped with a shower. Frederick Smith, a Life Support engineer who participated in the IIA test, stated that the average amount of water consumed by the shower was 3.8 kg/person/day. The *Lunar-Mars Life Support Test*, the third phase test, was conducted with both a shower and a laundry system. The average water consumption by the shower was 6.36 kg/person/day. This represented circa 25% of the total water consumption, while the laundry system represented 50%. The duration of the tests were 15, 30, 60 and 91 days, respectively [26].

Figure 3.2 "The can" at Johnson Space Center where the advanced life support tests were conducted.

Note that the objectives of the tests were not to research how full-body washing could be accomplished on Mars, but to research the more vital parts of the life support system, for example the air and water revitalization systems.

3.2.3 Apollo

The Apollo spacecrafts provided full-body washing only aboard the Command Module, while the Lunar Module could not even provide hot water. Regarding the departure from the stay on the lunar surface up to the Command Module, Apollo 17 crewmember Eugene Cernan said: "When we got back in there [the Command Module], we took our suits off, and stripped naked and got hot water and a hot washrag and gave ourselves a [sponge] bath. I cannot tell you how good that feels" [27, p. 133].

When sponge bathing, the distance between the water and the friction is almost negligible, which limits the water usage. A significant problem with the sponge baths aboard the Command Module, however, was that there was no privacy in regards of space, which affects the physical and mental comfort of all crewmembers [27, p. 132-133]. One reason for only providing sponge baths could be the brevity of the missions. The average Apollo mission duration was 9.5 days, and the longest of the missions was Apollo 17, which had a total duration of 12.5 days out of which only 22 hours were spent on the lunar surface. On a longer mission, such as a Mars exploration mission, conventional sponge baths alone will not suffice. Firstly, it is a procedure that uses a lot of consumables, in this case referred to as "washrags". Secondly, the comfort level of sponge baths are relatively low.

3.2.4 Salyut

Except for on the first two Salyut space stations, a shower was provided. It was located in the Work Compartment; and the curtain walls were transparent polyethylene, so privacy was not provided. To minimize space, it was deployable from the *ceiling* and then connected to the *floor*. Out of a nozzle, hot and cold water was sprayed on the cosmonaut. Air flow drove the water *downwards*, where the shower was connected to the waste water container. However, much of the water stuck on the walls, on the user and - as always in microgravity - floated around inside the shower compartment. Therefore, although a successful full-body washing lasted only around 15 minutes, the crewmember had to spend several hours preparing the shower and then cleaning it afterwards. Showers were understandably not a daily routine, but a monthly one, and some cosmonauts simply chose to not shower at all. Valery Ruymin of Salyut 6 said that "the desire to take a shower diminishes" as he thought of all the work that was required. Salyut 7 cosmonaut Aleksandrov Lyakhov emphasized the need for "a special shower which is always assembled and ready for use" [27, p.140-143].

3.2.5 Skylab

Like the showers on Salyut, Skylab also had a deployable shower. Its cylindrical shower curtain was pulled from the floor, and connected to a ring *above* the head of the astronaut. To this ring one handheld device for spraying and one for suction were connected. These devices were not as flexible as the astronauts desired, which made the direction of the water flow arduous to control. Foot restraints gave the astronauts the ability to maintain a traditional terrestrial shower position with the feet on the floor and water sprayed from the ceiling [27, p. 148-151].

The shower was located in the experiment and work area of the Orbital Workshop. The beta-cloth curtain afforded some degree of privacy due to its non-transparency [27, p. 190]. Only 2.8 liters of water were provided for every shower [8, p. 501]. Among the three Skylab crews there is no consensus on the quality of the shower. Some were very satisfied saying that "the shower worked really well and we felt good after showering". Others showered rarely and one astronaut did not shower at all [27, p. 151].

3.2.6 Mir

Mir, which was manned almost consecutively from 1986 to 2000, provided full-body washing with three methods: sponge baths, showering and steam-bathing. For the first three years, sponge baths was the only method of cleaning; it was executed by the cosmonauts squirting drops of soap on their bodies, spreading it evenly with cloths and scrubbing their bodies with wet towels [18].

The shower, which was introduced in 1989, was the first rigid shower on a space station. The metal compartment was easier to clean and to dry in comparison to the deployable showers of Salyut and Skylab [27, p. 164-167]. One estimate of the shower time is 45 minutes, which includes all pre and post shower operations [28, p. 9]. Equipped with a small window above the door, the shower compartment did offer a good deal of privacy. It provided 10 liters of water, which was in part used to produce oxygen and in part recycled for later reuse. Just like the other space station showers, air flow carried the water downwards [8, p. 502].

This was the last shower used in outer space. Eventually, the shower was converted to a steam bath with steam being sprayed from a nozzle. After just a few years with the steam bath, it was put out of use in order to make room for other instruments. During the last five years of manned missions onboard Mir, sponge baths was once again the sole method of full-body washing [27, p. 166].

3.2.7 ISS

On the International Space Station full-body washing is a daily routine. The astronauts can either do sponge baths or clean themselves with cloths soaked in no-rinse soap and shampoo. Astronaut Ed Lu said about the no-rinse soap: "It works really well. That being said I am looking forward to a long hot shower when I get home!" In other words, the procedures do work, but they might not be as comfortable as a terrestrial shower. These procedures might require more towels and washcloths than is suitable for a long-term mission beyond *low earth orbit* (LEO). The water consumption on the other hand, is very low with sponge bathing, but since the ISS has water recovery systems, other full-body washing procedures would be feasible [27, p. 172-173]. Some remarks that Andy Thomas did regarding his full-body washing experience aboard the ISS can be found in chapter 3.1.1.

3.2.8 Benchmarking conclusions

One must assume that all methods eventually reach the same level of cleanliness. Notable differences between the methods are the levels of comfort, the water consumption, the washing time, and the time required for operations before and after washing. All illustrations and their valuation are results of the author's subjective judgment, which is based on the research presented in chapters 3.2.1-3.2.7.

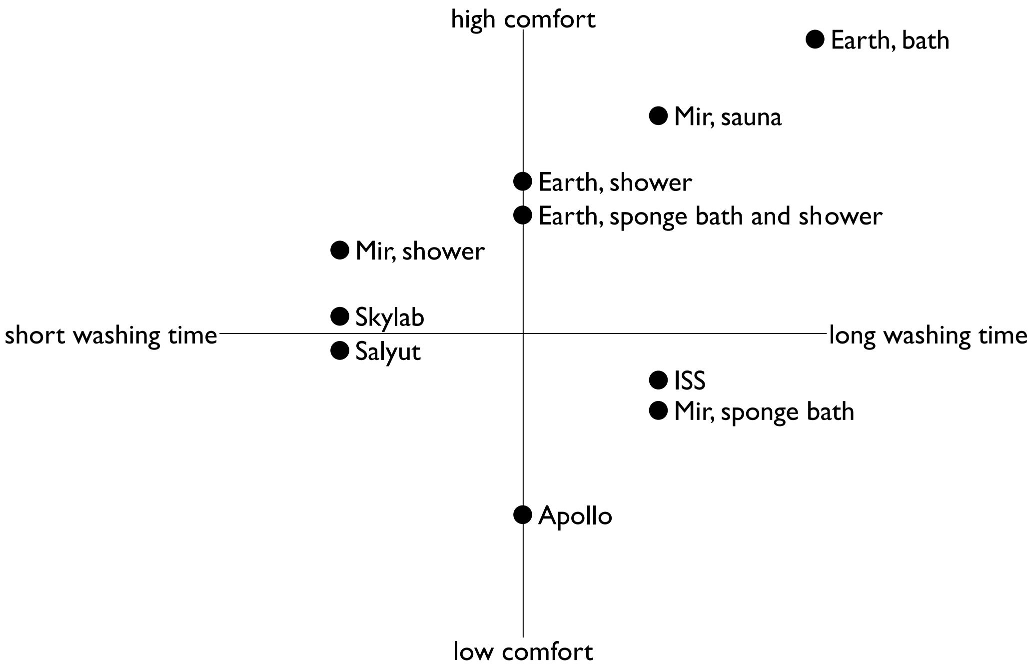


Figure 3.3 The diagram compares washing comfort with washing time for terrestrial and extraterrestrial full-body washing systems. The area of most interest is the first quadrant.

The above diagram, figure 3.3, compares washing time with washing comfort. Washing time is defined as the time required for the actual body washing. Washing comfort is here defined as physical and mental well-being during the washing, thus excluding the comfort before and after the washing procedure. Factors that affect the comfort are mental and physical effort, somatic stimuli and the perceived cleanliness.

The first quadrant, combining short washing time and high comfort, would be optimal. However, the two washing systems located within this area are the Mir and Skylab showers, which had their drawbacks. Firstly, the amount of water that Mir consumed per shower was 10 liters, which is too high for a longer mission beyond LEO. Secondly, the users' views on the comfort of the Skylab shower was not consistent, and this margin of error can actually put it anywhere from high in the first quadrant or low in the fourth. Most importantly, though, the total preparation and clean-up time required for a shower on Mir or Skylab was too high in relation to the actual washing time.

As in all design processes, trade-offs need to be made. Although other benchmarked designs border to the first quadrant, there is nothing that distinctly states that the full-body washing system designed for this thesis must be located in this area, or even that it is the pursued location. In fact, also short washing time with low comfort would be acceptable. During a discussion with Larry Toups and Molly Anderson it was stated that a full-body washing system that provides comfort on the expense of time is not desirable [17]. A very comfortable washing procedure, such as a bath, takes a long time to use simply because the user wants it to last for a long time. The expenditure of time is important to consider. Astronaut Don Pettit wrote in his blog during his mission on ISS with Expedition 31: "I have a 5-, 15-, and 30-minute plan in my pocket, so when there is a pause in the mission work, I know exactly how to use the moment productively" [29]. Even though it would be rewarding to take a well deserved bath or get a relaxing massage after a full days of work on Mars, there might just not be time for it. Do not misinterpret, comfort does indeed matter, however, it is not a key design driver.

In the above diagram, the definition of comfort excluded the comfort before and after washing, which does not offer a full picture of the situation. Comfort during usage might be followed by discomfort after washing, or before washing, thus making the overall comfort neutral. For example, could a nice, relaxing 30 minute bath be considered to be comfortable if the clean up would be tough, painful and last 60 minutes? Probably not, so this kind of comfort matters too. However, comfort as such is not easily measurable. A factor with great weight regarding the comfort before and after usage is the time required for activities before and after washing, from here on called *pre/post washing operations*. In the next diagram, figure 3.4, pre/post washing operations time is compared to washing time.

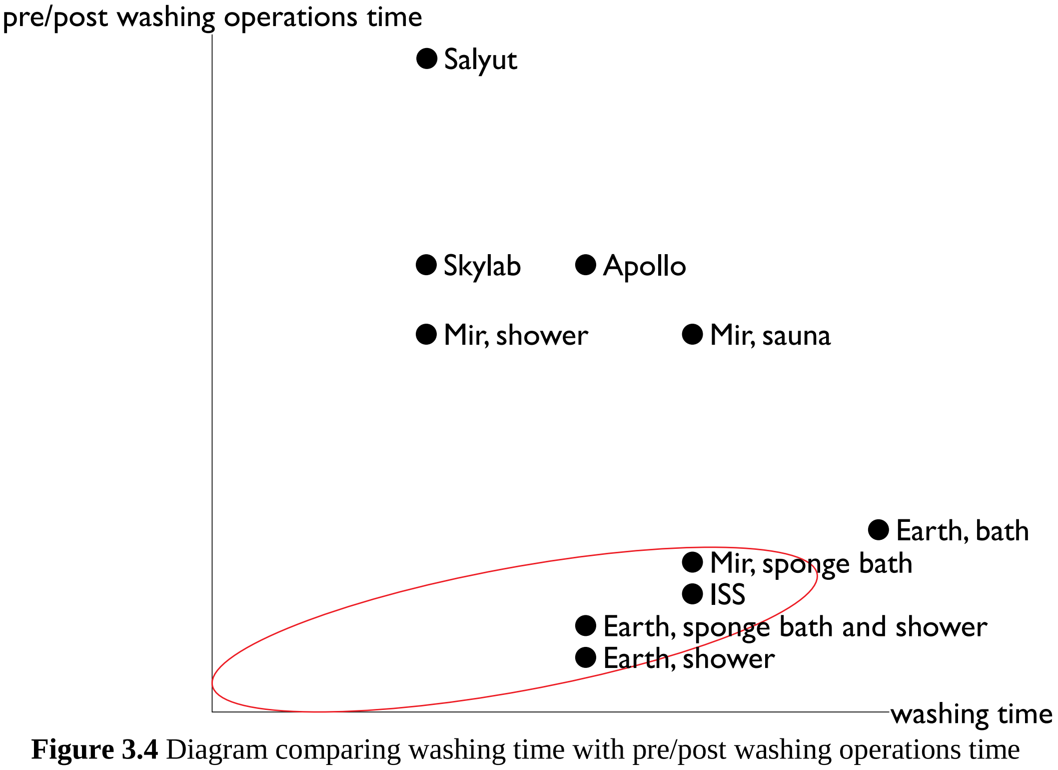


Figure 3.4 Diagram comparing washing time with pre/post washing operations time for space and terrestrial full-body washing systems. The area of interest is encircled by the red ellipse.

Short washing time and much shorter time for pre/post washing operations is truly an efficient combination. The red ellipse encircles an area with great potential. The four procedures in this area all have some shortcomings; showering on Earth consumes great amounts of water, while sponge bathing on Mir and the ISS require a lot of consumables. When it comes to the procedure of combining sponge baths with showering, there is no design that can offer this, at least not yet. Also, the combination procedure would have to avoid the water usage related to showering and the usage of consumables related to sponge bathing.

There are a few things to be learned from the cultural study, for example, reservoir washing and showering is more water efficient than only showering. Also, such a combination of methods do not lengthen the total washing time. To combine methods might serve as a good compromise between getting clean and feeling clean.

3.3 The ingredients of full-body washing

The primary and secondary purpose of full-body washing is to get clean and to feel clean, respectively. This is accomplished by removing dead skin cells, hair, sweat, oils, bacteria and body odor from the skin. On a Mars habitat, this will neither be done in a re-designed shower nor a re-designed bath tub. The extreme conditions require an extreme design. Researching cultural and historical aspects, as in the previous chapter, will be helpful, but it will in this scenario be far from a sufficient analysis. To fully break away from conventional solutions, the procedures of full-body washing need to be dissected and the actual physical constituents, or *ingredients* if you will, analyzed separately. Figure 3.5 shows a graphic representation of these constituents and, in a schematic manner, how they work.

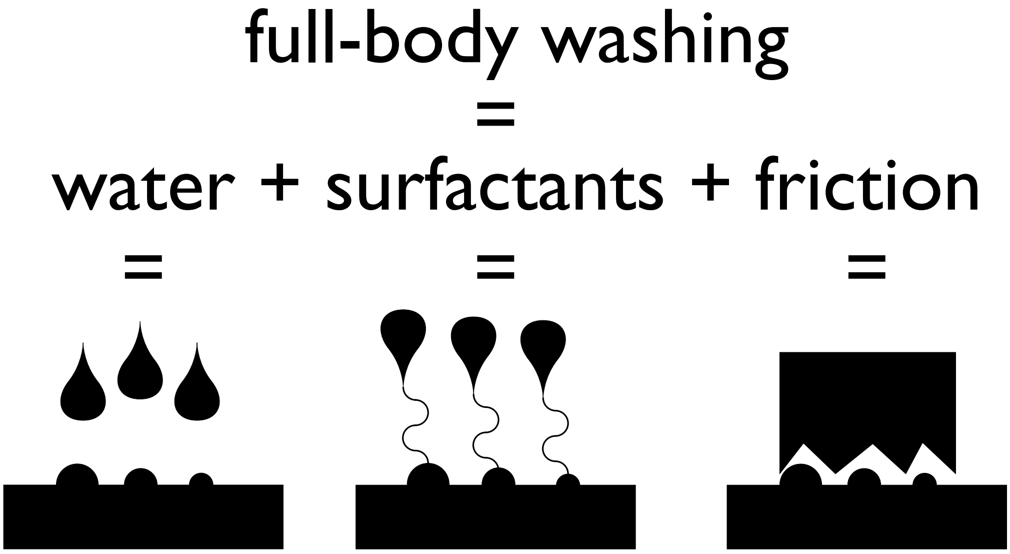


Figure 3.5 Illustration of how water, surfactants and friction interact to provide full-body washing. These are the constituents of full-body washing.

Essentially, full-body washing is hereby assumed to be accomplished by applying water, surfactants and friction on the skin. This assumption is the consequence of function dissection.

3.3.1 Water

The use of water is not necessary, however, moisture in some form is. On Earth, on spacecrafts and even in our bodies, water is the most prominent liquid, whereas the assumption is made that the full-body washing system will provide moisture exclusively in the form of water. Since a recent HAT assumption was that the water consumption for the Martian full-body washing system would be 3.45 kg/person/day [17], a goal for this thesis will be to trump this.

Water serves five functions in regards of full-body washing, all of which are involved in performing the main tasks: to get and to feel clean. In no particular order, the first function is that water softens the skin. Secondly, it reacts with the surfactants. The third function is that the water causes friction as it splashes, sprays and flows on the skin. The fourth function is that the water rinses the dead skin cells, hair, sweat, oils, bacteria and surfactants off the body. Lastly, water keeps the user warm, or cold.

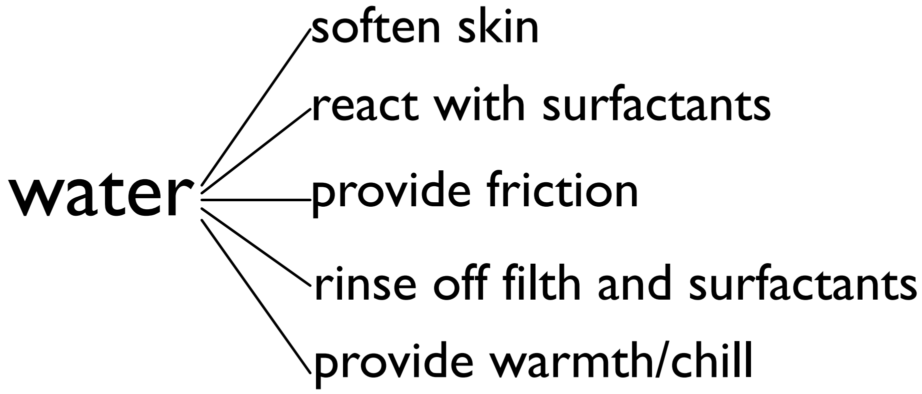


Figure 3.6 Illustration of the functions of water for full-body washing.

As the five functions are performed simultaneously and with such routine it is difficult to conclude how long time or how much effort is required per function. However, it is possible to determine how the functions relate to each other as well as to other phenomena: water flow and water pressure. The flow, or how much water is being dispensed, is measured in kg/s, while the pressure, or the force per area that the water give rise to, is measured in kPa or bar. In terrestrial showers the pressure tends to be around 2-6 bar, while on the ISS the water pressure is 1.4 bar [22]. There is no standard water flow level, since the user normally has full control of it. Some people might even vary the water flow during various stages of the washing procedure.

The first and fourth functions, skin softening and rinsing, relate to the water flow, but there is a reversed dependency between the two functions; the skin softening depends on water to stay on the skin, while the rinsing requires that the water is moved away from the skin. In a conventional shower, as water is flowing downwards, less water is softening the skin, which results in the user adding more water. Moreover, the fourth function is not only dependant on the flow; rinsing off filth and surfactants can also be accomplished by applying water with either high pressure or flow.

The fifth function, to provide warmth or chill, does neither relate to the water flow nor pressure. The same goes for the second function; reacting with the surfactants. These two functions will be further analyzed below and in chapter 3.3.2, respectively.

The third function, to provide friction, depend on the water flow as well as the water pressure, which even if the friction can increase by increasing either the flow or the pressure, there are much better ways to give rise to friction than with water, these will be discussed in chapter 3.3.3. Therefore, the third function is irrelevant in regards of water functions.

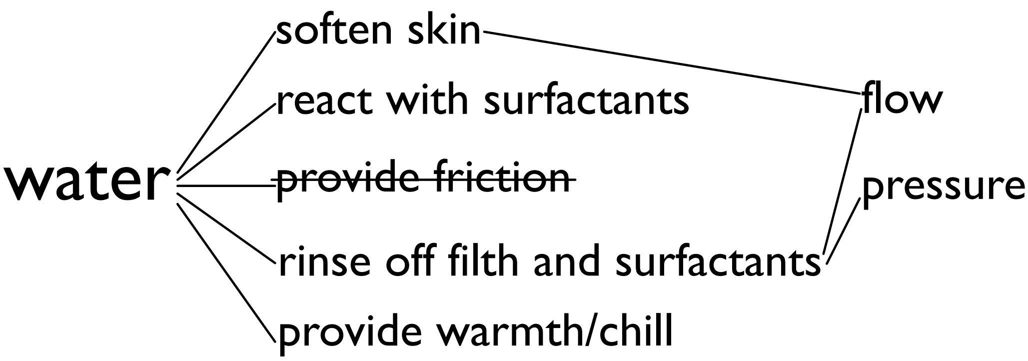


Figure 3.7 Illustration of the functions of water for full-body washing, and how they relate to each other as well as flow and pressure.

All things considered, a full-body washing system that is designed with great concern on water pressure is not essential. Sufficient water flow, however, is essential and cannot be regarded as a possible trade-off. There are patented technologies for shower nozzles that uses the Venturi effect to mix air with the water beam, which drastically decreases the water flow, but not the user's perception of it. One example is Oxjijet™ by New Zealand company Felton Products Ltd, which is connected to the tube [30]. Other technologies are located within the nozzle. These inventions might be added to the design, but as they are already invented and commercialized no further research on them will be conducted within the scope of this thesis. A design driver is, however, to design the system in such a way that the water is used to the fullest, which could be accomplished by for example keeping the water in a "pocket", by using materials that get wet, or by physically re-using the water in a loop.

In regards of the fifth function, to provide warmth or chill, NASA astronaut Andy Thomas stressed that for comfort purposes, the temperature of the water should be easily manipulated [18]. The astronaut might want different water temperatures depending on the situation. If one is to wash after exercising, it is likely that the user will want the water to have a cooling effect. At other times, one might want to warm up. During the third phase of NASA's advanced life support tests, issues regarding the shower water temperature were reported. There was a delay in the temperature adjustment, and sometimes the water would even be scalding. It was not only water but also time consuming to get the desired temperature. The shower water restrictions made this unnecessary water consumption even more irritating than it would under normal Swedish or American conditions, when one can afford to let the water run for minutes. Furthermore, the design of the shower head as well as the shower knob were reportedly unacceptable [31, p. 92-99]. Based on the criticism from the Phase III tests, it seems to be preferred that the chosen temperature is shown with fast and readily visible feedback.

It is likely that the water supply on the Mars habitat will be through one tube, just like on the ISS [22]. Therefore, a water mixer will not work in the design. Instead the water needs to be heated "locally", in other words within the washing system. There is no required position of the heater; it could be in the wall, inside the nozzle or somewhere in between. The water temperature when it enters the full-body washing system is currently assumed to be around 22^{o}C [22], while conventional bathing and showering temperatures can be up to 40-45^{o}C. This means that the system must be able to heat the water around 20 ^{o}C.

3.3.2 Surfactants

Surfactants have one water soluble end and one oil soluble end. Adhered to both kinds of substances, it adsorbs at the interface of the body's oily layer and the water that is running along the skin. The surfactant is more readily adhered to the water than to the oil, it will consequently follow the water flow. In the scenario of a sponge bath, there is not much water flow, and it is therefore required that the sponge or cloth is moist, wet or has the ability to contain water in some way.

On some parts of the body, surfactants are less desired than on others. The internal parts of both males' and females' genitals should not be washed with any kind of surfactant. Hair and body washing normally require different chemical solutions. Shampoo and body wash solutions tend to contain the same surfactants, although the latter one is often in smaller doses. There are some solutions that are used as both shampoo and body wash. Normally, the surfactant solutions are applied not as part of the design, but by the hands of the user. However, if the surfactants are to be applied as part of the design, the user must be able to manipulate the surfactant feed.

Some surfactants can cause problems with the water revitalization system. Molly Anderson stated that a good guideline is to use a surfactant that is "gentle and environmentally friendly" [22].

3.3.3 Friction

The primary purpose of friction is to separate the dead skin cells, hair, sweat, oils and bacteria from the body. Secondary functions are applying the surfactants as well as providing warmth and comfort. In this context, friction can be effectuated in several ways and with numerous tools.

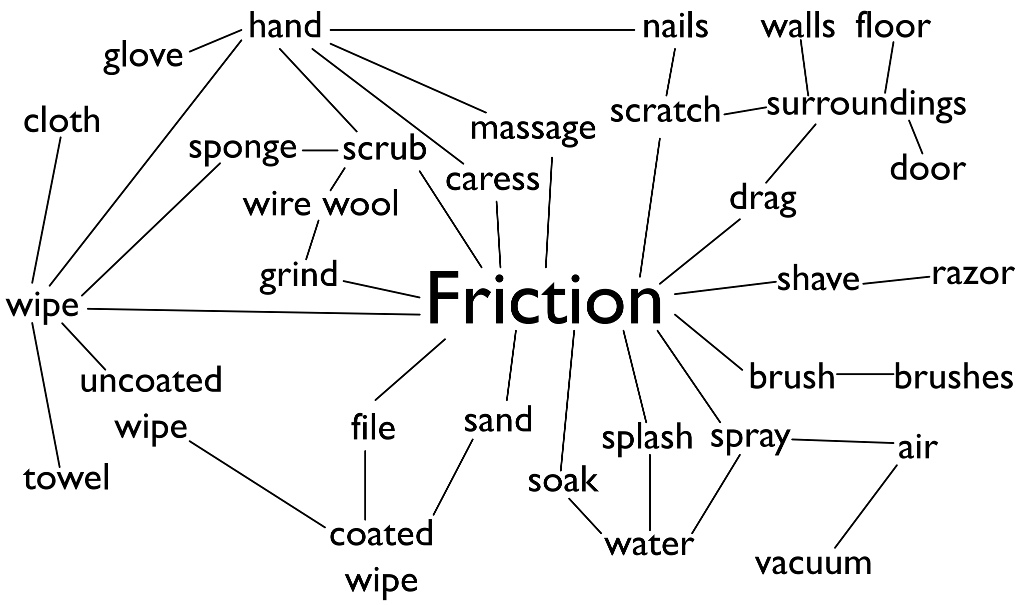


Figure 3.8 Illustration of various ways to accomplish friction. This was a result of two brainstorming sessions; first to find the acts that provide friction, and then to find the objects that are used to implement the acts.

Most of these tools are not typically used for full-body washing; and the most common tool in this context is of course the hands of the user. The hands can reach most parts of the body and can be used together with other objects. Furthermore, the hands are easily manipulated and can therefore provide friction for the body's different shapes, different levels of sensitivity and dirtiness. These qualities are requirements for the design, if it is to work as a substitute or a complement to the hand.

3.3.4 Concluding remarks

One important difference between water, surfactants and friction is that friction as such is not a resource. However, friction might depend on resources, for example on electricity and various consumables. Also, the way friction is used is exceedingly important for the overall efficiency of the washing. A conclusion drawn from subjective empirical studies is that limiting the distance between the friction and the water source will not only decrease the water usage, but also the required space of the washing compartment. This is based on the previously stated principle of full-body washing being accomplished by applying water, surfactants and friction. As the distance between the friction and water source increases, the area of impact of the water on the user's body will also increase, eventually encompassing a greater area than where the friction can be applied. The water that does not hit this area will therefore not serve its full potential of being an ingredient for washing. Furthermore, the space saving argument is based on the fact that partial gravity will make the trajectory of the falling water greater than it would on Earth. Limiting the friction to water source distance will decrease the possible trajectory, thus decreasing the impact area of the water. Assuming the washing compartment will, like terrestrial showers, not be completely enclosed, the required washing compartment space would also decrease.

Surfactants will be brought along from Earth, and is therefore a finite resource. Compared to water, though, it will be used in a very small amount. It is necessary that the system allows surfactants to be applied by the user, rather than making the washing system itself provide surfactants on the user. This is similar to most conventional showering procedures, where the user applies the surfactants after extracting it from a container.

3.4 Aesthetics

3.4.1 Background

A mood board is a tool used by designers to illustrate the pursued design style. This is usually done visually as a collage of images and text, but it can also include physical objects. Swedish furniture designer Åke Axelsson has stated that he uses a different technique, in which he lets the design emanate from the room of where it is to be placed [14]. Since the design of this thesis will be place-specific, this is a suitable technique to use. One problem is that the room in question, and its aesthetic qualities, does not yet exist. However, space station aesthetics do indeed exist, and by identifying an environment with the desired aesthetical characteristics, Åke's method can be used. The chosen environment could either be a space station or a terrestrial environment, or maybe a combination. It might even be a hypothetical environment that combines the desired aesthetical characteristics.

This chapter is a discussion on the aesthetical characteristics of the exemplified environments, but to understand the purpose of the aesthetics, the discussion will also be on the environments in general.

3.4.2 Space stations and terrestrial habitats

Space station aesthetics differ vastly from reality to that of science fiction. As does the aesthetics of different kinds of terrestrial habitats. As a basis of analysis of these environments' aesthetical characteristics, examples of these will be discussed and compared to each other.

Many walls of the International Space Station, see figure 3.9, are full of gages and chords; it is a highly mechanical environment. To some extent, it resembles a combination of a lab, storage and machine room. Metals and plastics make up the interior. While the most common *wall* colors are different shades of grey and beige, many objects have more clear colors, often consisting of the primary ones. The hygiene facilities are sets of robust machines. The ISS is a highly impersonal, functional, modular, fairly symmetrical and temporary residence. Also, if it were not for micro-gravity, the environment would have been very uncomfortable. The habitants are monitored from far away while they are located very far from their homes.

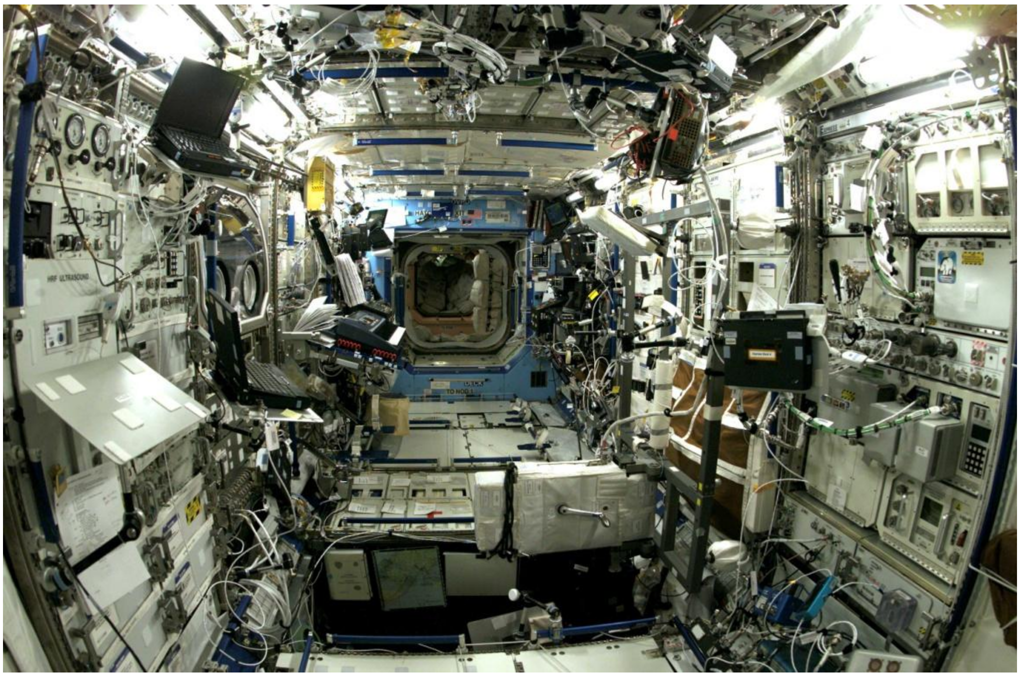


Figure 3.9 Inside the International Space Station; with these heavily occupied walls, this would not have been a livable environment were it not for the micro-gravity. Although the nodes have names such as Harmony and Tranquility, they are no feast for the eyes. Credit: ESA.

A home on the other hand, is a welcoming residence where one feels a sense of belonging, familiarity, affection and comfort. The habitants hold the ultimate power, or at the very least a say, over the environment's colors and materials, and the environment is therefore extremely personal. Decoration and functionality work together. Although being artificial, through its commonly used materials; concrete, textiles, wood and brick; homes can convey a sense of naturalness, whereas the ISS ooze of artificialness. A home is an actual terrestrial place where one can retreat and act on one's own terms. A home tends to relate to a particular place with clearly defined borders, but through these borders are openings where, when available, sunlight keeps the environment bright. Some objects are mechanical but the environment itself is definitely not. Unlike the ISS whose habitants are a team, the habitants in homes tend to be family or friends. A typical home and the ISS are opposites.

A typical hotel room is similar to a home, as it can have a great deal of comfort, however, the habitants are always short-term guests. It is impersonal and very functional, fits all the essentials in one room and has little left-over space. Most objects have determined positions and it is frowned upon, or even impossible, to re-decorate. A sign of the objects' determined positions is that hardly any objects are hanging, with the common exception of the window curtains. Two common materials compared to other environments are textiles, sometimes with kitschy floral motifs, and wood. Normally, there is one window per room, which is more than many rooms in the *Death Star* from Star Wars.

The Death Star is portrayed as a quite dystopian, sterile and dark place of serious work. In fact, the interior as well as the spherical exterior resemble some Lebbeus Woods sketches. The structural elements are visible, yet between them are patterns of ellipses or rectangles, which also serve as light sources. The environment is quite mechanical; some rooms have visible pipes and occasionally fog and dimmed light. It is an artificial habitat and its habitants are battalions of men, always in uniform. Although being spacious, the Death Star does not house many objects; the comfort and sense of affection ought to be very low. There is no particular color used in hotel rooms, unlike the grayscales used in the Star Wars' Death Star - these environments are opposites. Some hotel room characteristics are consistent with those of homes, implying that these environments are more similar to each other. The same goes for the ISS and the Death Star [32].

The USS *Enterprise* from Star Trek is partly a place of work, but mostly a long-term residence and to some of the crewmembers it seems to be perceived as a home. The most recent version of the spacecraft is the re-designed version from the 2009 *Star Trek* film, which will serve as the next subject for this aesthetical analysis. The spacecraft is so futuristic, bright, comfortable and welcoming that the hostile surroundings are easily forgotten. The environments and the objects within them are unadorned yet consists of non-elementary smooth shapes. To some extent, the shapes are streamlined. The USS Enterprise is remarkably shiny and reflecting; some parts are even transparent. Furthermore, several objects seem to be collapsible, for example the desk lamps and computers [33].

A typical terrestrial base is a temporary residence where one is provided with shelter, equipment and company. Bases can be modular, temporary, impenetrable and even disguised. Be it on Mars or on Earth, a base can be a safe haven within or close to a hostile environment. Despite this, very few characteristics of bases differ from those of prisons. Both environments are minimal, unadorned, impersonal and usually equipped with the mere necessities. By and large, the structures are exposed, which emanates a sense of coldness, especially when the structural materials are for example concrete or corrugated steel. Out of all analyzed environments, bases must be the most angular and rough one. Furthermore, a base is not necessarily a workplace, but it is strongly related to work and it is definitely not a place for relaxation leisure.

The aesthetics of the USS Enterprise shares characteristics with a home and the Death Star. Bases, on the other hand, can be seen as a combination of the ISS and a hotel room. Finally, Star Trek's USS Enterprise and a base are opposites.

Figure 3.10 graphically presents some characteristics in relation to the six analyzed environments. The desired aesthetical characteristics are comfort and robustness. Also functionality and smoothness could be appropriate. Were the environment to be geometrical or mechanical would not necessarily matter; these two characteristics were added to help clarify connections between the environments and characteristics. For example, if comfort and robustness were proven to be positively dependent on mechanicalness, but not to each other; by making the environment more mechanical the robustness and comfort would be positively affected.

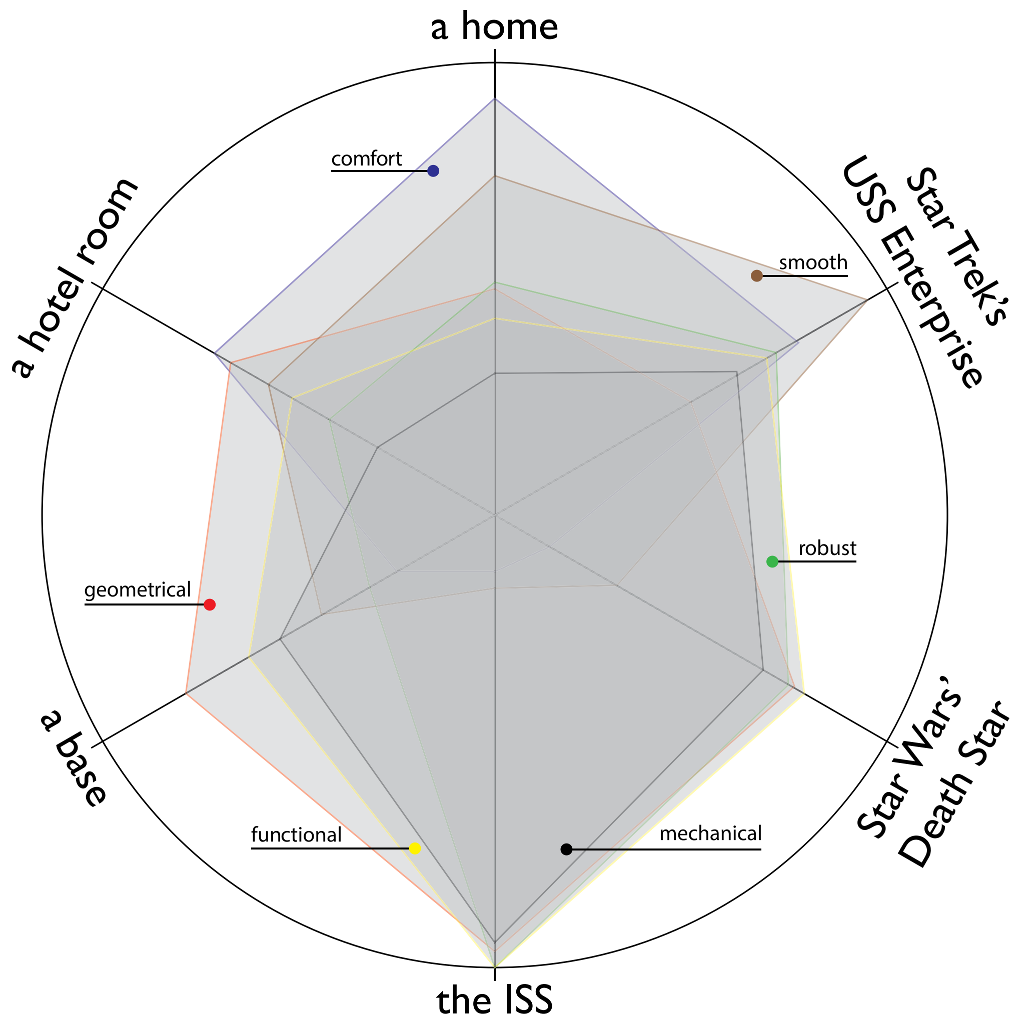


Figure 3.10 Graphical representation of the aesthetical characteristics of three terrestrial and three space environments

As seen in the above diagram there is absolutely no clear connection between the characteristics and the environments. To combine the aesthetics of a home and that of a space station should give the explorers a sense of belonging, familiarity and comfort while being in a very functionalistic, minimalistic, futuristic and sterile workplace. In regards of this balance, the three previously discussed space environments proved to be unsatisfactory. After further researching science fiction environments, the lunar habitat from the film *Moon* was chosen to illustrate the pursued design style. In chapter 3.4.3, the reasons behind this and an aesthetical analysis of *Moon* will be presented.

3.4.3 Moon film

The director Duncan Jones has described his film *Moon* as a homage to 1970's science-fiction films. In many ways it does resemble the classics, but compared to the three previously discussed space station environments, the lunar habitat in *Moon* is the one that most looks like a home. In fact, the lunar habitat serves more as a home than as a work place. As time goes, the habitat looks more gritty and more like a place that is actually inhabited, which is in stark contrast to other, constantly polished and clean, science-fiction environments. The collage below, figure 3.11, illustrates the aesthetics of the lunar habitat.

Figure 3.11 Collage of images of the lunar habitat in the film *Moon*. Credit: Duncan Jones and Gavin Rothery.

There are no visible structural elements. Mostly consisting of basic geometrical shapes, the habitat is a quite angular environment. The textures are, however, smooth and fairly shiny. The rooms are bright; the walls are white and hard except for some wall spaces that seem to be cushioned, gray and made of leather. Most objects are, however, either made out of metals or plastics, in white or beige colors. Although looking quite robust - definitely less than the ISS but more than a typical home - it does maintain some level of comfort. The environment does not ideally embrace the aesthetic qualities of that of a home, but it does indeed serve as a good compromise between a space station and a home. The design style of the lunar habitat in *Moon* could to some degree be classified as combination of functionalism and retro-futurism [34].

3.5 Target group analysis

The target group is personified by astronaut Christer Fuglesang. He has participated in two Space Shuttle missions and has made five spacewalks. This makes him ESA's most extra-vehicular activity (EVA) experienced astronaut. The photograph below, figure 3.12, shows Fuglesang returning from a spacewalk. Not only a cosmonaut, but also quite a cosmopolite, he has over the years lived in Sweden, Switzerland, Germany, Russia, the United States and he currently lives in the Netherlands where he is the Head of Science and Application Division within the Directorate of Human Spaceflight and Operations at ESTEC. He is a Fellow at CERN and holds a Docent degree in particle physics at Stockholm University [35].

Figure 3.12 Christer Fuglesang, Sweden's first astronaut, personifies the target group. Credit: ESA.

3.6 Function analysis

Presented in table 3.1 is the function analysis, where the functions of the design are presented and given a class of importance: MF (Main Function), N (Necessary functions) and D (Desirable functions). The functions and their class of importance are based on the research that was documented in chapter 3.1-3.5.

Table 3.1 The function analysis; it categorizes and classifies the functions of the design.

Function	Usage	Class	Comment
provide	full-body washing	MF	
provide	friction	N	
provide	water	N	
allow	surfactants application	N	
allow	daily usage	N	
allow	long term use	N	several missions
be	reliable	N	
be	repairable	N	parts and in entirety
be	resource efficient	N	power, space, consumables, renewables
be	water efficient	N	goal: 3.45 liters/washing/person
minimize	distance water-friction	N	
prevent	contamination of Mars	N	
prevent	leaks from designated area	N	water, filth, surfactants
provide	manipulation of feed	N	surfactants, water, friction
provide	manipulation of temperature	N	water
provide	smart stowage capabilties	N	
share	system similarities with rover	N	
use	WRS compatible surfactants	N	gentle and environmentally friendly
eliminate	the need for some consumables	D	e.g. towels and wipes
integrate	with clothes laundry system	D	

Function	Production	Class	Comment
allow	semi-dormant mode	N	
fit	circular floor plan	N	
integrate	with supply lines of resources	N	water, power
minimize	quantity of mainten, equipment	N	preferably 1 tool
use	in-situ resources	D	

use	standard parts	D	

	Ergonomics		
Function		**Class**	**Comment**
allow	mixed-gender crew	N	
be	comfortable	N	
enable	hands to be friction tool	N	or parts of the hands
fit	5th % Jap. ♀ to 95th % Amer. ♂	N	
integrate	with partial-body washing	N	
minimize	mass of spares	N	
minimize	post operations time	N	3 min
minimize	set up time	N	1 min
minimize	usage effort	N	
minimize	usage time	N	10 min
provide	feedback	N	of the water temp. and flow
provide	flexibility	N	dirtiness, sensitivity, body shape
provide	individuality	N	in usage, the object and its expression
provide	privacy	N	
provide	warmth or chill	N	
simplify	cleaning, sanitization, mainten.	N	
integrate	with hand and face washing	D	
offer	balance support	D	at least during first weeks

	Aesthetics		
Function		**Class**	**Comment**
appeal	to Christer Fugelsang	D	
express	hygiene	N	
have	space station aesthetic	N	
express	reliability	D	
express	repairability	D	
express	reward	D	
express	robustness	D	
express	smartness	D	

4 Design of the nozzle

This chapter deals with the design of the nozzle; from the first basic ideas to a functional mock-up of the final design.

4.1 Background

In traditional faucets, the nozzle, together with a water mixer, represents the design; sometimes they are both controlled with one and the same lever. As stated in chapter 3.3.1, the water needs to be heated within the washing system, but not necessarily as part of the same device as the nozzle. To reiterate what was defined in the very beginning of the thesis; the nozzle and the water heater are defined as two separate objects, albeit connected to and dependant on each other. Some important characteristics of the nozzle is different from that of the water: throughout the washing, the nozzle will continuously control the direction and magnitude of the flow, while the heater most likely will be set at a certain temperature before the actual washing begins.

The nozzle is a more critical element than the heater. In fact, providing warmth or chill is merely for the sake of comfort, while controlling the direction and magnitude of the water is essential in order to get clean without wasting water. Rather than designing both objects at the same time, the nozzle will be designed first, and the heater will be designed as its appendage. This chapter is about the design of the nozzle.

4.2 Concept generation

Based on the analysis, several nozzle concepts were generated. These are presented in order of simplicity, from the most simple to the most complex. To categorize the generated concepts: concept A provides a continuous flow sponge bath; concepts B, C and D combine sponge bathing with showering, and they are dependent on the user exerting forces on the mechanism; and concept E presents a concept in which all washing procedures are combined while also reusing water.

4.2.1 Concept A

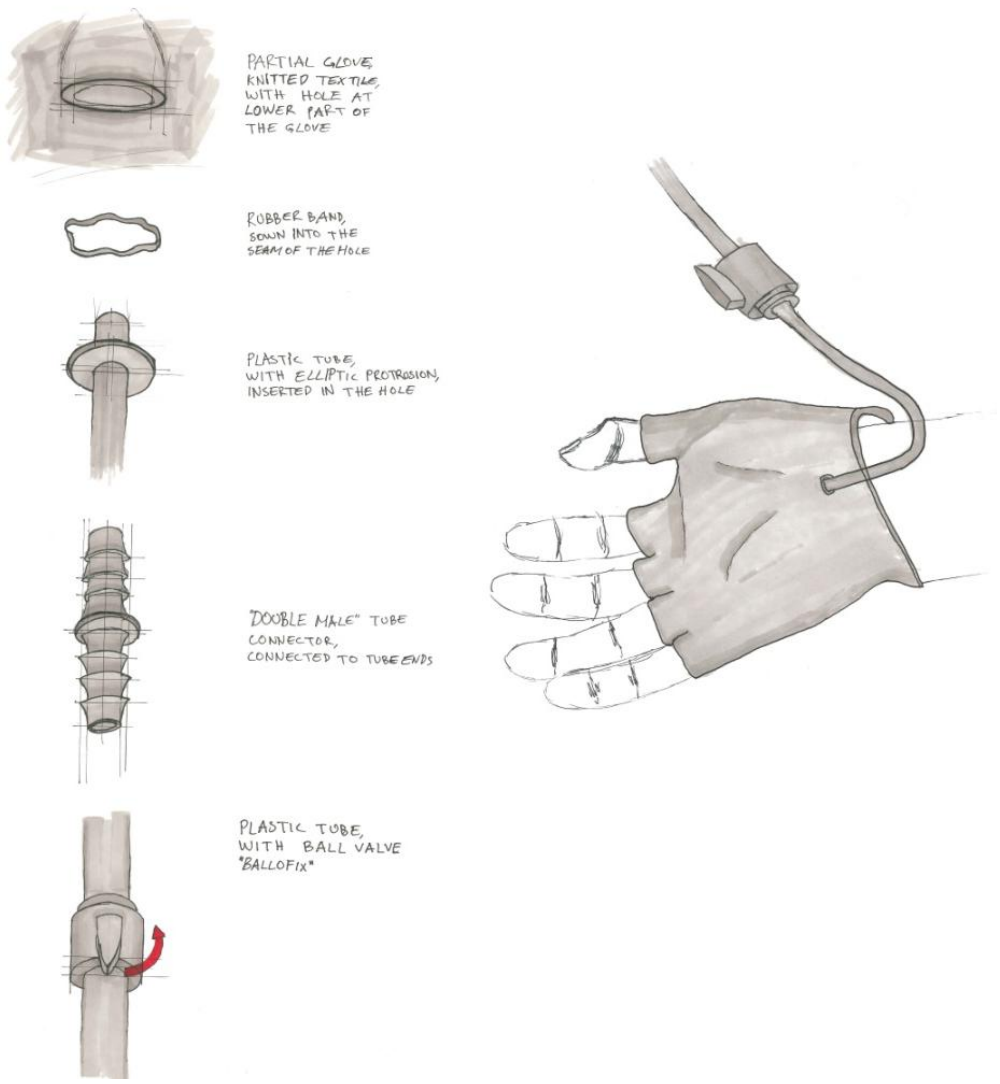


Figure 4.1 Exploded view (left) and sketch of concept A when worn (right).

Concept A, see figure 4.1, resembles an everyday exfoliating, knitted shower glove. It is, however, a partial glove, leaving much of the fingers exposed. That way the fingers can be used as a washing tool. At the lower part of the palm there is a small pocket, in which a rubber band is sown into the seam. Inserted in the glove's pocket is a water tube. The tube, made out of plastic, has an elliptic protrusion close to one of its ends. The rubber band and the tube's protrusion secures the joint between the glove and the tube. The tube is equipped with a small ball valve, whose purpose is to control the water flow. "Double male tube connectors" connect tube ends to each other.

The gloves are personal, while the tubes are all used mutually. The time and effort required to set up the washing system is quite minimal: one puts on the glove, inserts the tube in the glove's pocket and turns on the water flow by turning the lever on the ball valve. The textile gloves are easily compressed and packed. After several uses, the gloves will either be exchanged or laundered. To a large extent this design does provide a sponge bathing procedure, but like traditional showers it cannot provide instantaneous control over the water flow. To turn off the flow the user must turn the ball valve lever. It is likely that the user will want the water to run constantly, albeit with a low flow. Last but not least, each glove will be made for either the right or left hand.

4.2.2 Concept B

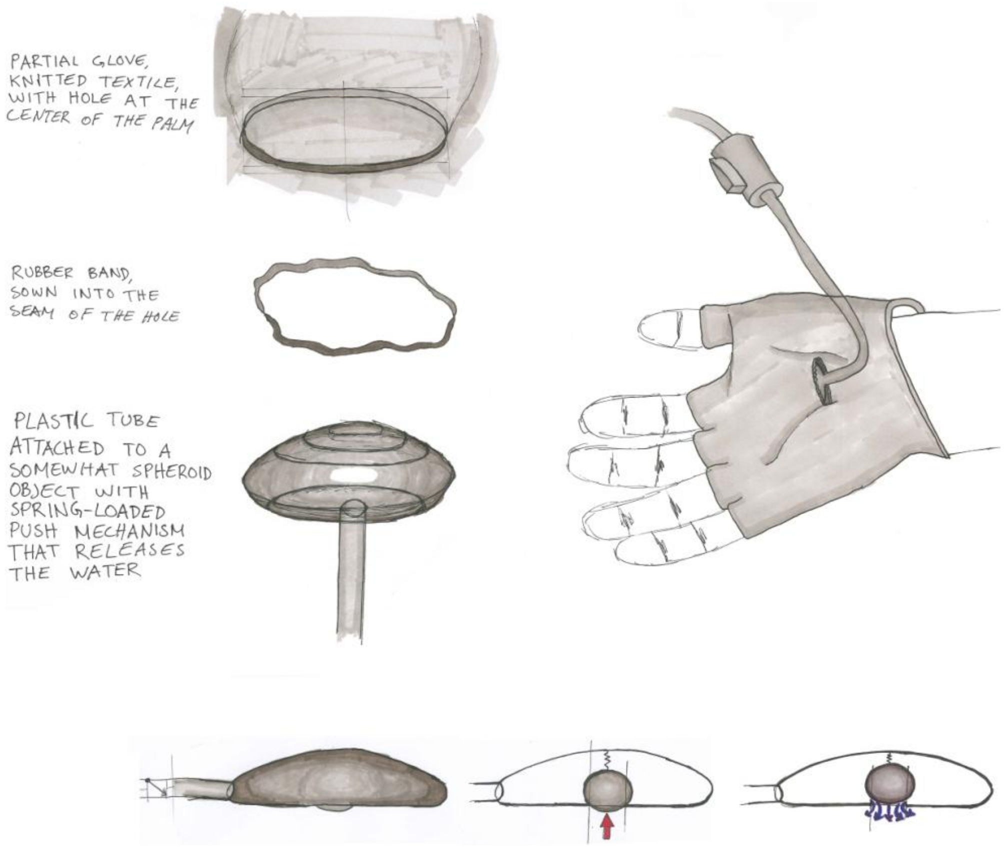


Figure 4.2 Sketches of concept B, exploded view (left), concept when worn (right), and an illustration of how the mechanism works. The red color symbolizes forces and the blue symbolizes water.

Concept B, see figure 4.2, is similar to concept A in that it also consists of a partial glove with a pocket. However, it does not use a ball valve to control the water flow. Inside the pocket is a somewhat spheroid object with a spring-loaded valve that will release the water when the glove is pushed onto the showering body. Similarities with

A include: fingers can be used as a washing tool, each glove is either made for a right or left hand, quick set up time, personal glove, mutual tubes and mechanics. However, concept B does not exclusively provide sponge bathing. By pressing the spheroid with the opposite hand, water will drip down from the glove, in turn also creating a drip shower. As mentioned in chapter 3.2.1, a combination of sponge bathing and showering does neither prolong the duration of the washing nor does it consume more water. The comfort level of a combined procedure is assumed to be close to that of the more comfortable one. It is, however, arguable how comfortable a dripping shower really is.

A ball valve is attached to the tube as a safety measure. The same goes for concepts C and D, which is expanded upon regarding the final design in chapter 6.3. Were the spheroid to start leaking, turning the lever of the ball valve would stop the flow to the spheroid. Furthermore, if the spheroid's spring-loaded mechanism would fail, it would be difficult to repair. The great advantage with this concept is that the flow will be very easily and rapidly controlled. Even the magnitude of the flow will be decided by the user; the harder the glove's valve presses against the body, the more water will flow out.

4.2.3 Concept C

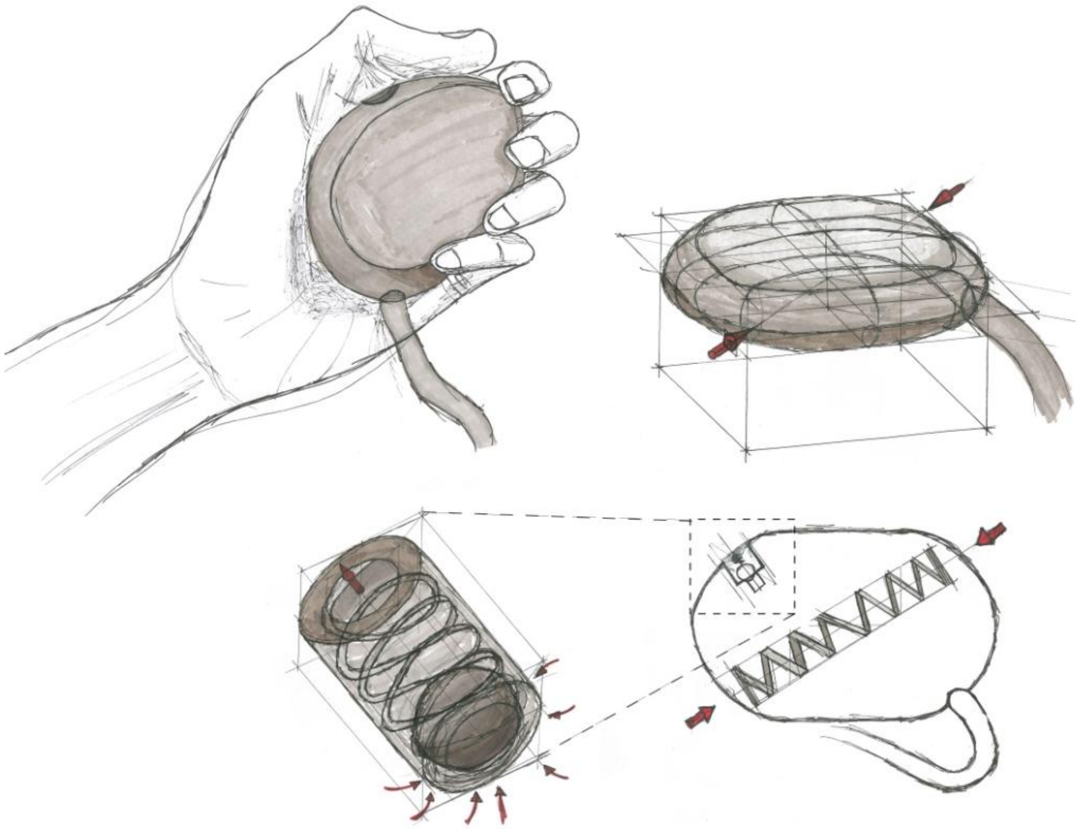


Figure 4.3 Sketches of concept C illustrating its parts and functions.

Concept C, see figure 4.3 above, is a handheld device in which the water is pumped out as the user's hand contracts the device. It has a somewhat ellipsoid shape and can, unlike the previously discussed concepts, fit in the grip of either hand, making it more versatile. During the washing procedure the user can freely change the device between the hands; there is no strap or suchlike. It is hollow; its interior shell is made out of rubber, and the exterior is coated with a textile with exfoliating qualities. There is a large spring that goes diagonally across the inside of the ellipsoid; its purpose is to make the ellipsoid inflate when the user no longer contracts it. A ball check valve between the ellipsoid's inside and outside is loaded with a spring force greater than the force produced by the normal pressure difference between its ends. Contracting the device results in the ball of the ball check valve experiencing so much force that it moves outwards and thus releases the water. Another ball check valve is located between the ellipsoid and the water tube; it prevents the water from travelling in the wrong direction. Depressing the ellipsoid will make it regain its former size while simultaneously filling it with water from the tube.

Unlike the previous concepts, this one is used completely personally; there would need to be one device per person. The only required assembling operation is to connect the device to the water source. To release low amounts of water, it will be sufficient to either push the device on the body or to contract it in any direction with one's hand. To empty the entire ellipsoid, it would have to be contracted along the spring. This concept also combines sponge bathing and showering, but unlike concept B it can offer more of a squirting effect than a dripping one. As the device consists of a large spring and tiny ball valves that hide within an object made by both rubber and textile it might, in its current shape, be relatively difficult to repair and to perform maintenance on. That the spring is in constant contact with water could compromise its reliability.

4.2.4 Concept D

Concept D, see figure 4.4 on the next page, is a plastic, flying saucer-shaped object that is strapped onto either hand. In function, but not shape, it is similar to concept B and C in that it enables a washing procedure that combines sponge bathing with showering. It provides more of a directed flow than its competition, which dripped and squirted, respectively. By pressing the bottom plate's coated surface on the skin or by pushing it with the fingers of either hand, the water flow is activated. As the force ceases, the water flow stops. The inner mechanism consists of two cylinders that are connected only through the tube. In the bigger, bottom cylinder there is an extrusion where the smaller, top cylinder is located. As a consequence of springs located on the bottom surface of the top cylinder, the tube is throttled in its resting position. Pressing the top cylinder downwards - or the bottom cylinder upwards - will diminish the throttling of the tube allowing for water to flow. It is possible that the tensions that occur on the tube might result in damages over time. If so, it is unfavorable that the tube is throttled at two different sections.

This concept requires longer assembly time than any other, circa 45 seconds. First, the inner mechanism is connected to the bottom plate through an annular snap-fit joint. The two identical top plates are then connected to each other when the bottom plate is locked in within it. The strap is attached to the two top parts and pulled around the hand.

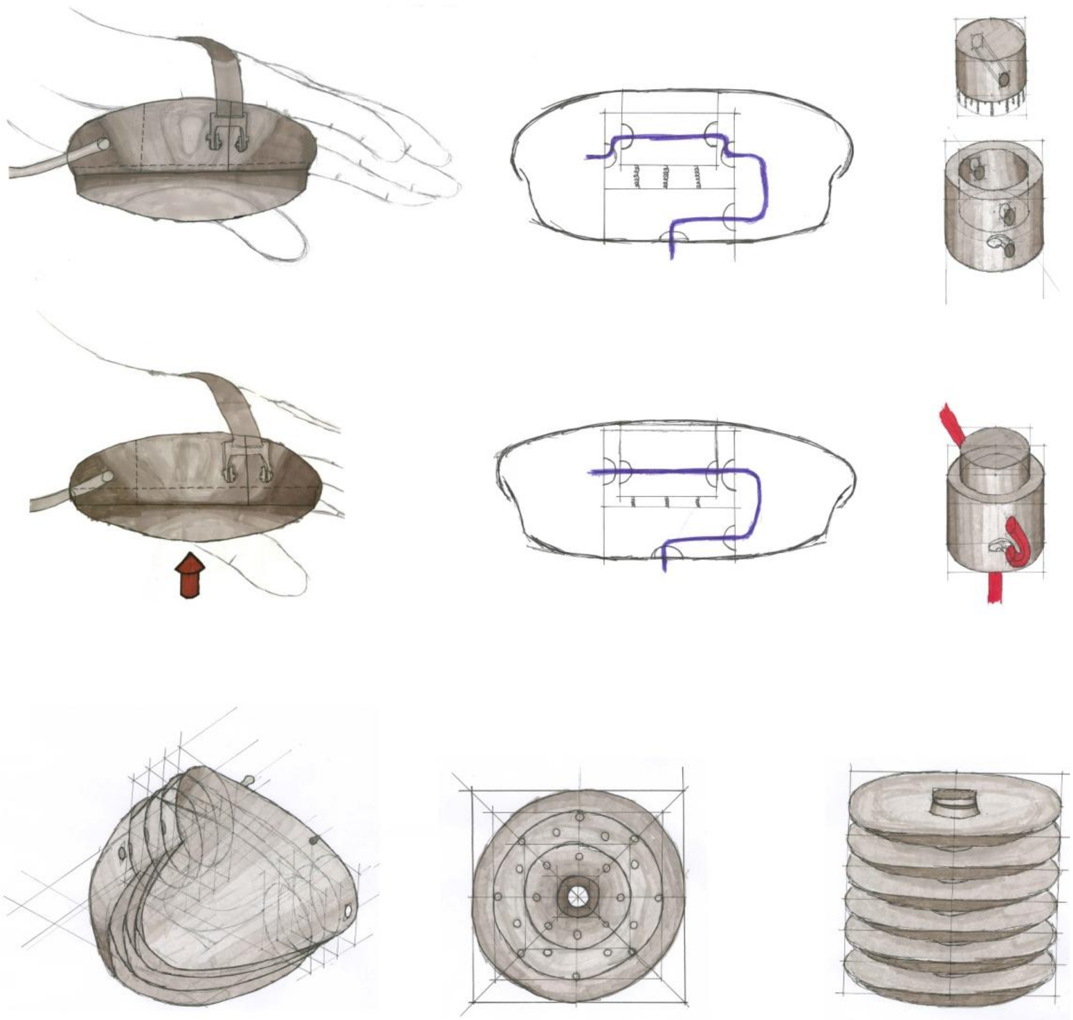


Figure 4.4 Sketches of concept D illustrating the functions, and showing the individual parts as well as the assembled device.

This design also consists of more parts than the others. However, all exterior parts are stackable, and no tool is required for assembling. No mechanism will be permanently enclosed within another. The teeth that connect the top plates are critical elements that might break. Furthermore, all parts have the potential to be mass-produced through injection molding, with the obvious exception of the springs, the tube and straps. The exterior parts are personal while the inner mechanism is mutual. A drawback is that it is possible that body hair can get stuck in the gap between the top and bottom plates.

4.2.5 Concept E

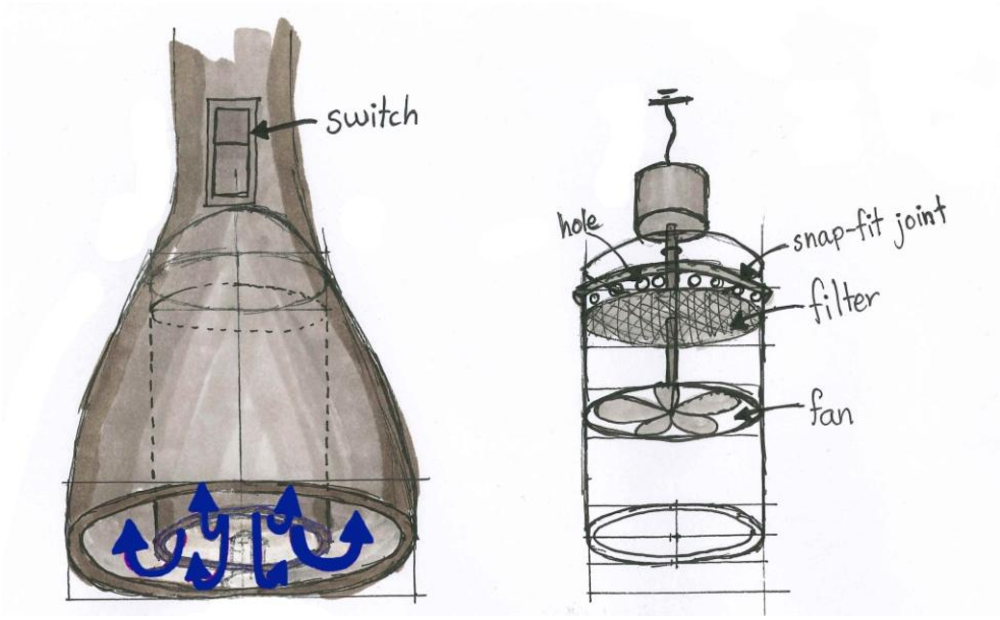


Figure 4.5 Sketch of concept E and its functions. The blue color symbolizes water.

The main thing about concept E, see figure 4.5, is that it can reuse the same water over and over again. It is quite robust, and consists of several parts. The inside of the inner tube holds a water revitalizing filter as well as a fan that makes the water spray out of the nozzle. As the water leaves the tube, it hits the body and travels outwards from the inner tube until it reaches the realm of the outer tube's suction. The suction in the outer tube is due to the fan blowing in the inner tube. Holes in the back of the tube let the water be transferred back from the outer to the inner tube. The friction is provided by the edges of the outer tube, by the air that is blown, but also by the water that repeatedly splashes on the skin.

The device will not be connected to an external power or water source; a rechargeable battery will be sufficient to power the fan, and the water will be added by pouring it in. Therefore, a water source of some kind, for example a faucet, will be needed somewhere within the system. Water will continuously be lost and the device would therefore need a few refills per washing. It should, however, require much less water than the other concepts. Filters and batteries will need to be changed regularly. The inner tube and all its contents will be used mutually, but the outer tube will be personal. The outer tube, which moreover is stackable, will connect to the inner one through a snap-fit joint. The estimated assembly time is 30 seconds, and it requires relatively low effort.

4.3 Concept selection

Based on the discussion in chapter 4.3, the five concepts are now to be compared to each other, and the best concept is to be further developed. This is done with a method called concept scoring, see table 4.1, which was discussed in chapter 2.3.2. The concepts are all rated regarding various selection criteria, which in turn are given a certain weight. The criteria, weights, and scores are the result of the author's informed judgment, but as previously mentioned, based on the information given in chapter 4.3.

In this round of concept scoring there are twelve selection criteria; some of which are used in quite general terms. Therefore, all criteria will be concisely defined:

- Ease of operation: how the flow direction and magnitude is modified and controlled.
- Repairability: how the device and its parts can be repaired, and how many tools are required.
- Comfort: how comfortable the usage is for the hands and body; sensitive areas of the body are given extra consideration.
- Durability: how the device and parts wear over time; moving parts and joints are examined in depth.
- Reliability: the likelihood of failure and its consequences; how it would affect the user in short and long term.
- Efficient storage capabilities: how the device and spare parts can be stored in a low space consuming and easily retrievable way.
- Low usage of consumables: the quantity and kind of consumable items that are being used, and in which way.
- Assembly time and effort: the time, physical and cognitive effort required for pre- and post-washing operations.
- Ease of maintenance: how often and in which way the device is serviced and sanitized.
- Hygienic expression: how the design expresses hygiene; during usage and in general.
- Integration with face and hand washing: how the device could, with or without some modification, integrate partial body washing in its repertoire of possible washing processes.
- *Moon* expression: how the design correlates to that of its environment, namely the film *Moon*.

The five generated concepts are to be compared with each other and a reference concept, which is a washing system equipped with a faucet and a washcloth. In the most recent HAT study the assumed full-body washing system was indeed a faucet and washcloth [17].

Table 4.1 Concept scoring between concept A-E with a faucet and a washcloth as a reference. D is by far the highest ranked concept.

		Concept											
		Reference		A		B		C		D		E	
Selection criteria	Weight	Rating	Weighted score	Rating	Weighted score	Rating	Weighted score	Rating	Weighted score	Rating	Weighted score	Rating	Weighted score
Ease of operation	15%	**3**	0.45	1	0.15	5	0.75	5	0.75	5	0.75	3	0.45
Repairability	15%	**3**	0.45	2	0.3	2	0.3	1	0.15	5	0.75	2	0.3
Comfort	10%	**3**	0.3	4	0.4	4	0.4	4	0.4	2	0.2	3	0.3
Durability	10%	**3**	0.3	2	0.2	2	0.2	4	0.4	4	0.4	3	0.3
Reliability	10%	**3**	0.3	3	0.3	3	0.3	3	0.3	3	0.3	3	0.3
Efficient storage capabilities	7.5%	**3**	0.225	5	0.375	5	0.375	4	0.3	5	0.375	5	0.375
Low usage of consumables	7.5%	**3**	0.225	3	0.225	3	0.225	4	0.3	5	0.375	4	0.3
Assembly time and effort	5%	4	0.2	4	0.2	4	0.2	4	0.2	**3**	0.15	4	0.2
Ease of maintenance	5%	**3**	0.15	2	0.1	2	0.1	1	0.05	4	0.2	2	0.1
Hygienic expression	5%	**3**	0.15	2	0.1	2	0.1	3	0.15	4	0.2	4	0.2
Integration with face/hand washing	5%	4	0.2	1	0.05	1	0.05	2	0.1	**3**	0.15	1	0.05
Moon expression	5%	**3**	0.15	3	0.15	3	0.15	4	0.2	5	0.25	5	0.25
	Total score	3.1		2.55		3.15		3.3		4.1		3.125	
	Rank	5		6		3		2		1		4	
	Continue?	-		No		No		No		Yes		No	

4.4 Concept development

The previously generated concepts were not finished designs, but more like themes or general kinds of solutions. Therefore, the winning concept D was to be developed and improved into several other concepts.

There were several flaws regarding concept D, it had the most parts and the longest estimated assembly time. The teeth that connect the top plates are especially weak elements. The bottom plate extrusion, that made room for the tube to travel downwards, weakens the snap-fit joint. That the tube is throttled at two sections might over time be damaging. It is possible for hair to get stuck in the gap between the top and bottom plates, which would negatively affect the comfort. However, there are some benefits too, which will be further studied in the developed concepts. No tools are required to assembly the device and all its parts. While the inner mechanism is always connected and used mutually between the crewmembers, the device has a personal exterior. Some parts of D are stackable, and all parts are easily stored.

4.4.1 Concept D1

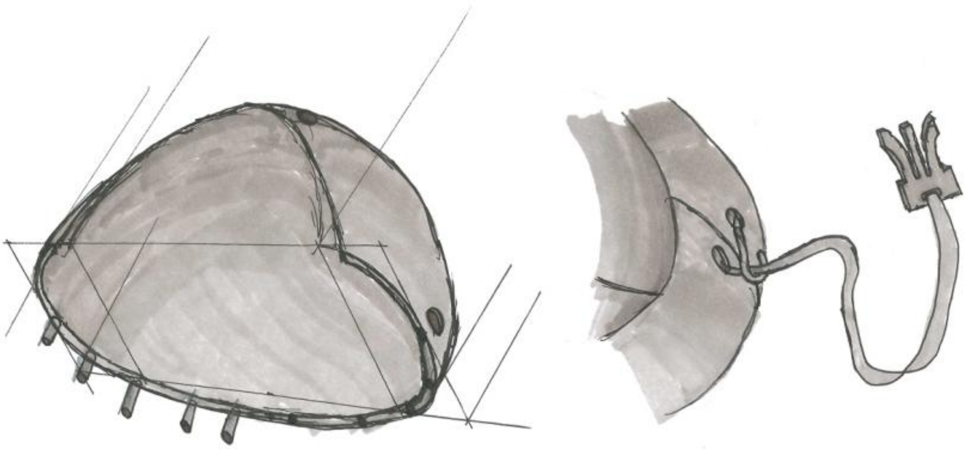


Figure 4.6 Sketch of concept D1 showing its extrusions and how the strap could connect the upper parts.

This is the original concept D, albeit with a few improvements. As illustrated above in figure 4.6, the top plates are now connected with five extrusions located along one of its edges, and along the other edge are holes that match the extrusions. The strap is connected to the top parts by a hook. The total number of parts are six: the strap including the hook, the inner mechanism's two cylinders, the bottom part and the two identical top parts.

The extrusions are less likely to break for the improved version, since there are now a total of ten extrusions that share the stresses instead of merely two. Given the thickness of the plates, the extrusions must be quite small and might therefore be a bit vulnerable. The hook solution is much less complex than the previous alternative, which was to clip it on.

4.4.2 Concept D2

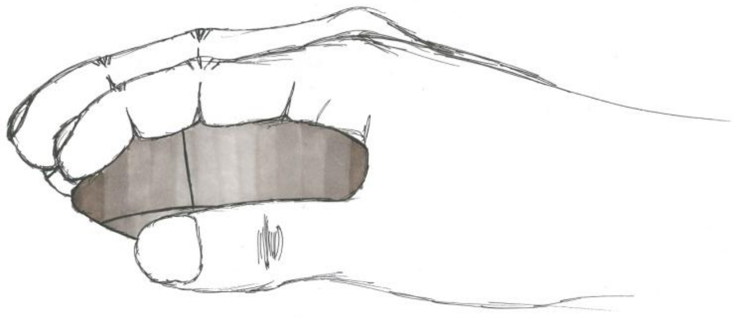


Figure 4.7 Sketch of concept D2 showing how it is held in the user's hand.

Concept D2, see figure 4.7, is not located in the palm and strapped around the hand, but located in the upper part of the hand and held with the fingers. A difference is that the water flow cannot be turned on by pressing the four fingers at the bottom plate, since they are now holding the device. Instead, with a bit more difficulty, the thumb can press the plate. A firm grip around the sides of the top plates is not necessary, since the extrusions will hold them at place. D2 consists of five parts, compared to the six of the D1. Furthermore, the top plates do not have holes by its edges.

4.4.3 Concept D3

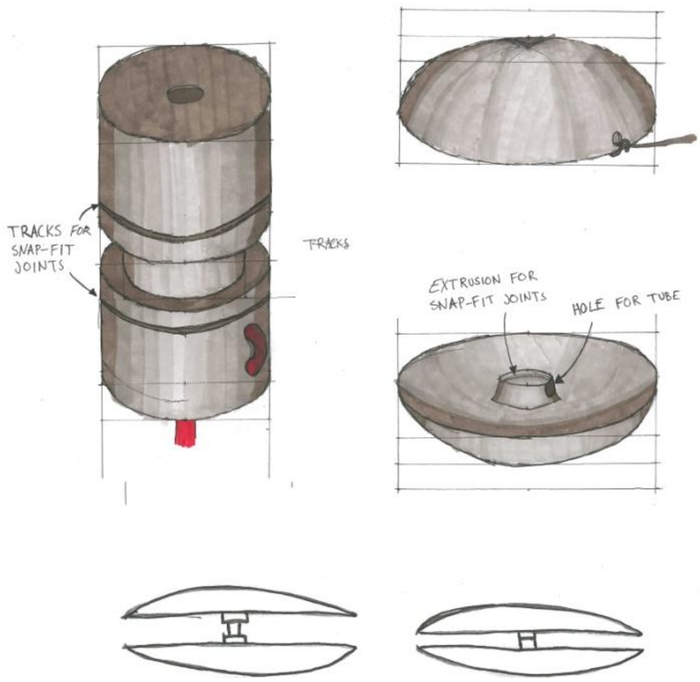


Figure 4.8 Sketches of concept D8 showing how its inner mechanism differs from the previous ones, and how the doublet plate attaches to it.

Concept D3 has a modified inner mechanism; except for the excision on its bottom part, it has horizontal symmetry. The top and bottom plates are identical, making the total number of parts five: the two plates, the modified inner mechanism's two parts and the strap. There is still a gap between the parts, however, the gap will never be completely closed. So, unlike concept D1 and D2, there is no risk of hair getting stuck. The concept is sketched on previous page, see figure 4.8.

The inner mechanism has snap-fit joints at both cylinders to attach to the plates. In an attempt to increase the stability for this concept the snap-fit joints are inverted. The connection will instead be on the inside of the plate's indentation, so that the stresses will be distributed on a bigger diameter. To make room for the tube, there is a small excision in the indentation.

One possible problem with this concept is that the plates are connected only through the inner mechanism. As the upper plate is strapped to the hand, and the lower plate yield the friction on the skin, there will be bending and torsion moment on the inner mechanism. Damages on it, the most critical part of the device, is not desirable.

4.4.4 Concept D4

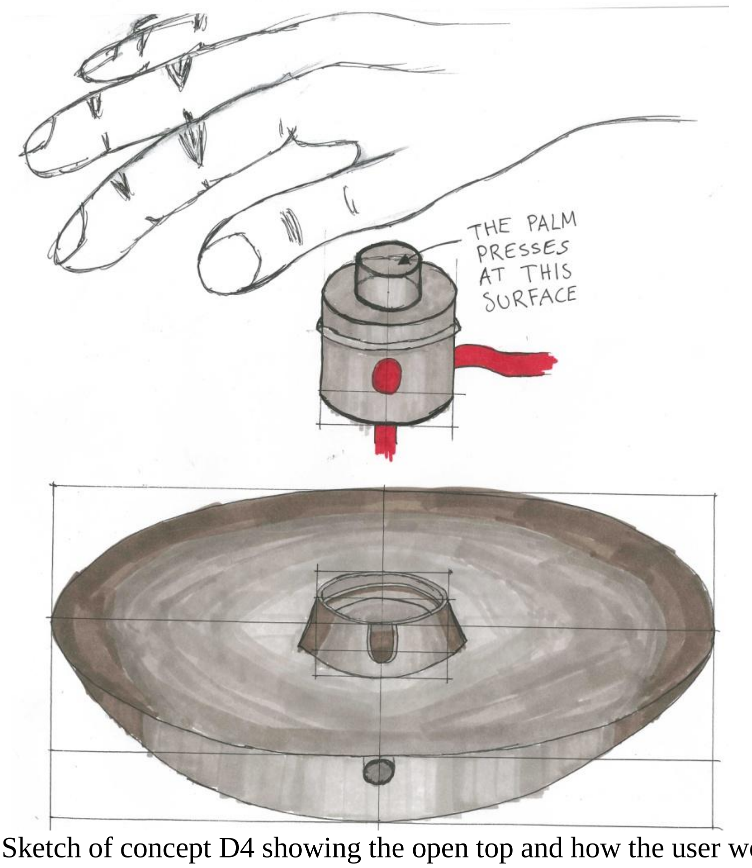


Figure 4.9 Sketch of concept D4 showing the open top and how the user would press directly at the cylinder to activate the water flow.

Concept D4, see figure 4.9, is much like its predecessor, the original concept D. It does, however, not hold a top plate and the hand is therefore strapped directly to the bottom plate. It consists of only four parts: the bottom plate, the strap and the inner mechanism's two parts. The snap-fit joint is inside the plate's indentation, just like for D3. The top of the cylinder and the edges of the plate will press at the palm. Unlike for previous concepts, the edges will be rounded to not discomfort the palm. The bareness will provide the user with a good conceptual model of how the mechanics work without requiring to disassemble the device. The fact that it consists of few parts makes this concept faster and easier to assemble than the previous ones presented.

Besides enabling the water flow by pressing the plate with the fingers, the flow might be possible to activate by elevating the fingers. This is because as the fingers elevate, the indentation in the palm decreases, hence the palm depresses the top cylinder.

4.4.5 Concept D5

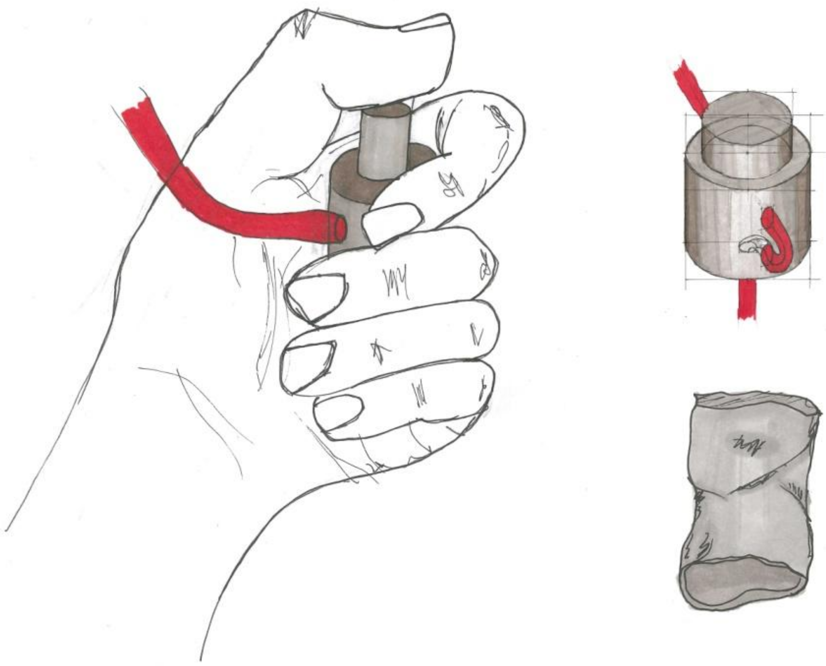


Figure 4.10 Sketch of concept D5 showing how it is held in the user's hand and how the user would activate the water flow.

This last concept, sketched above in figure 4.10, is as stripped as possible, it consists of an enlarged version of what-used-to-be the inner mechanism and a textile bag. The thumb depresses the top cylinder to turn on the water flow. The bottom of the cylinder wears the textile bag, which is the only personal element of the design. The bag will be laundered regularly. It is much like a terrestrial handheld shower nozzle, just more easily controlled, repairable and able to provide friction.

4.5 Concept selection

In this round of concept scoring, see table 4.2, the improved and developed concepts will be reviewed, although more in depth as these concepts are more similar to each other than the previous group were. There are some new selection criteria which will be defined in brief:

- Ease of friction manipulation: how the friction is controlled, and to what extent the fingers can provide friction.
- Stability: how the parts relate to each other; the failure of one part ought not to result in failure of another part.
- Ease of production: how the device would be produced.
- Flexibility in usage: to what extent the user holds power over the washing procedure.

Quantity and weight of parts: the quantity and weight of the device and all its spare parts.

Table 4.2 The second round of concept scoring, this time between concepts D1-D5. Concept D4 is ranked the highest and will therefore be further developed.

		Concept									
		D1 (Reference)		D2		D3		D4		D5	
Selection criteria	Weight	Rating	Weighted score	Rating	Weighted score	Rating	Weighted score	Rating	Weighted score	Rating	Weighted score
Ease of water manipulation	12.5%	**3**	0.375	3	0.375	3	0.375	4	0.5	1	0.125
Assemble time and effort	10%	2	0.2	**3**	0.3	**3**	0.3	4	0.4	5	0.5
Comfort	10%	**3**	0.3	4	0.4	3	0.3	4	0.4	2	0.2
Ease of maintenance	10%	**3**	0.3	3	0.3	3	0.3	4	0.4	4	0.4
Reliability	10%	**3**	0.3	3	0.3	3	0.3	4	0.4	4	0.4
Ease of friction manipulation	7.5%	**3**	0.225	2	0.15	3	0.225	3	0.225	1	0.075
Efficient storage capabilities	7.5%	**3**	0.225	3	0.225	4	0.3	5	0.375	4	0.3
Stability	7.5%	**3**	0.225	4	0.3	1	0.075	4	0.3	4	0.3
Ease of production	5%	**3**	0.15	3	0.15	4	0.2	4	0.2	4	0.2
Flexibility in usage	5%	**3**	0.15	4	0.2	3	0.15	4	0.2	5	0.25
Moon expression	5%	**3**	0.15	3	0.15	3	0.15	3	0.15	2	0.1
Quantity and weight of design	5%	**3**	0.15	3	0.15	3	0.15	4	0.2	4	0.2
Usage of consumables	5%	**3**	0.15	3	0.15	3	0.15	3	0.15	1	0.05
	Total score	2.9		3.15		2.975		3.9		3.1	
	Rank	5		2		4		1		3	
	Continue?	No		No		No		Yes		No	

4.6 Design development

The process of developing the design started out by creating handmade models out of clay, foam, and cibatool in order to study how the objects behaved in the hand. Conclusions of these shape studies were that a less pronounced curve is preferred, and that the indentation on the plate needs to balance the way the top and bottom cylinders press the palm and body, respectively. Figure 4.18 illustrates how the cylinders could be balanced.

CAD models of the design were 3D printed in the plastics ABS and PLA, and when assembled the entire mechanism was tested in its entirety. In total, three full prototypes were successively created and evaluated; a process that will be described on the next pages. The prototypes all had a diameter of 69 mm, which is the width of the hand of the 5th percentile Japanese women and in other words the smallest diameter for the design, when designed according to NASA's anthropometric guidelines. The prototypes were nonetheless tested on several hand sizes within the desired anthropometric scope - from 69 mm to 96 mm - because the objective was to create a design that could be used by all hands, as illustrated below in figure 4.11. A hand with a width of 96 mm represents the 95th percentile American men.

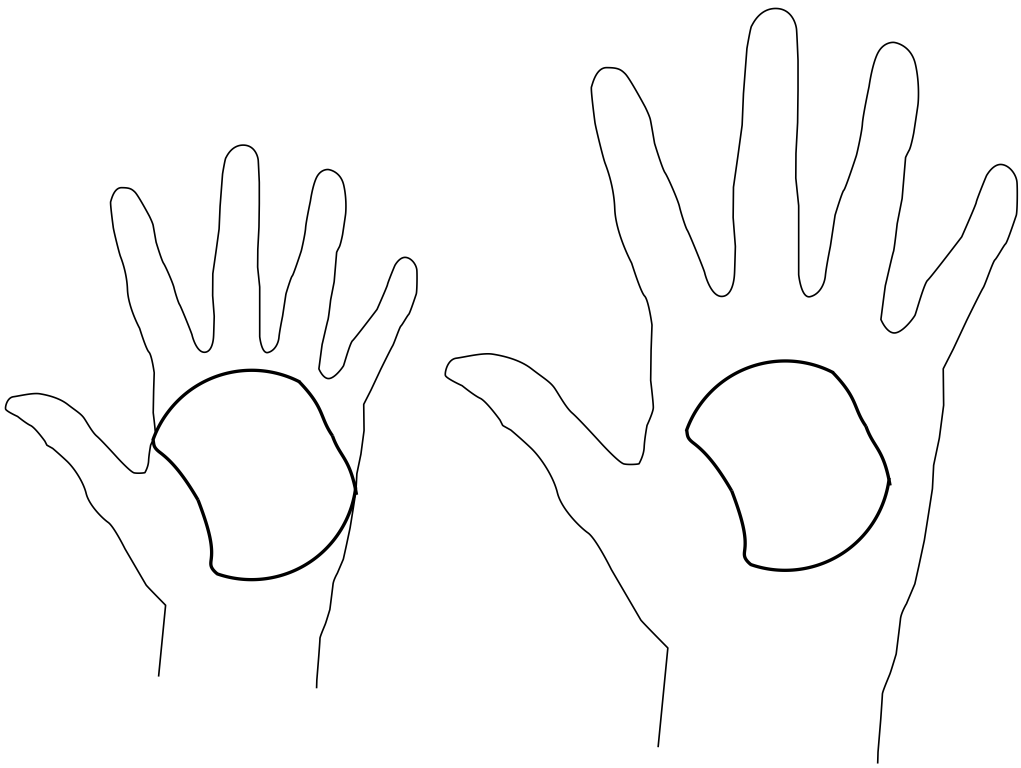


Figure 4.11 Illustration of how a plate with a diameter of 69 mm fits in a hand with a width of 69 mm (left) and of 96 mm (right). Note that the shape is that of the final design.

4.6.1 Prototype #1

Figure 4.12-13 Photos of the first prototype, showing the actual device without straps (left) and a close-up of the inner mechanism (right).

4.6.2 Evaluation #1

The shape of the plate was designed in a way so that its indentation can hold as much water as possible. It has a soft curvature and is rotational symmetric so that the forces are not concentrated at one area. This rotational symmetry, however, makes the device neither comfortable nor securely positioned in the hand. When studying hands it is easily discerned that there is no universal hand shape, that the palm is not symmetrical, and that the hand shape depends on the position of the fingers. As illustrated below, in figure 4.14, a plate designed to fit the hand's curvature can have both of the two upper shapes, depending on which section of the hand one refers to. A hypothetical cross section of the design might therefore look like the third shape. Rotational asymmetry is beneficial also because when stacked, the plates are more unfaltering since they only can be stacked in one way.

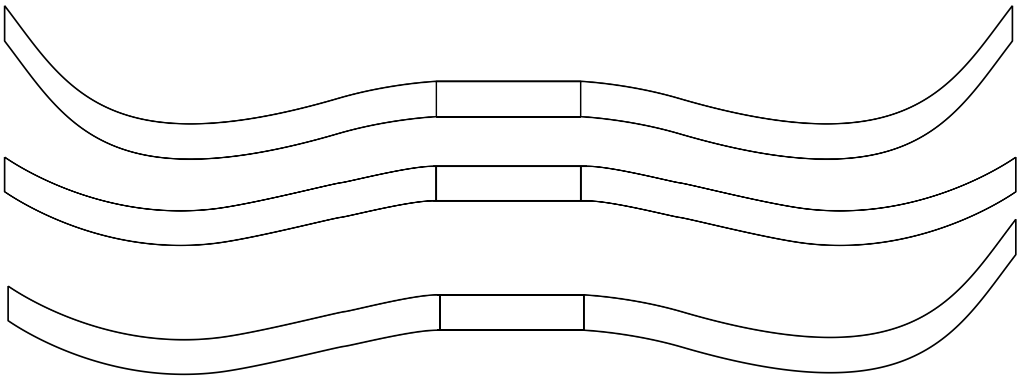


Figure 4.14 Illustration of how a hypothetical cross section could look like if the plate had a rotational asymmetric shape adapted to the curvature of the palm (bottom). The middle and top plates have rotational symmetry.

It is desirable that one plate can be used by both the right and left hand, that changing between the hands can be fast and easily accomplished, and that one size can fit all hands. The first prototype, see figure 4.12, does not deliver this as it does not consider that the position of the thumb vastly affects the shape of part of the palm.

The purpose of the springs is to push the cylinders away from each other, which will throttle the tube. The springs are glued to the bottom of the top cylinder, and the tube is located within it. Using three small springs, as discerned from figure 4.13, made the inner mechanism quite large in relation to the rest of the device. Moreover, the snap-fit joint was insufficient; an in depth analysis of the various tested snap-fit joints will take place in the second evaluation.

4.6.3 Prototype #2

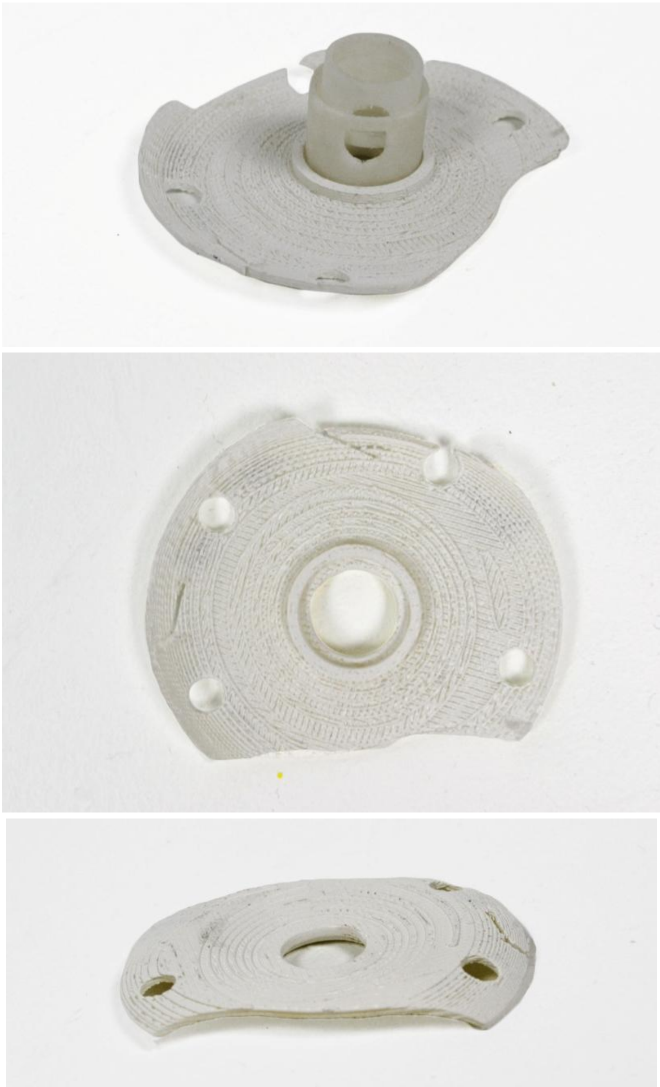


Figure 4.15-17 Photos of the second prototype, showing the entire device (top) and just the plate (middle and bottom). At this time the straps had not yet been designed.

4.6.4 Evaluation #2

To enable unhindered motion of the thumb some material around the thumb's bottom phalange was removed, as discerned in figure 4.15-17 on the previous page, but the grip still proved unsatisfactory. The curvature of the second prototype follows the shape of the palm, but it is way too low and fails to balance the cylinders' pressure on the palm and body. This is illustrated in figure 4.18 below.

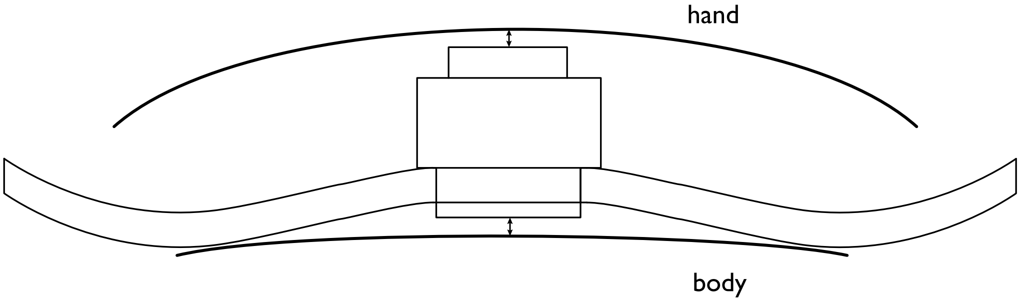


Figure 4.18 Illustration of how the top of the inner mechanism presses on the palm and how the bottom presses on the body.

The bottom cylinder attaches to the plate through a snap-fit joint. For the second prototype four new snap-fit joints were created and tested together with the one from the first prototype. They are all illustrated below in figure 4.19.

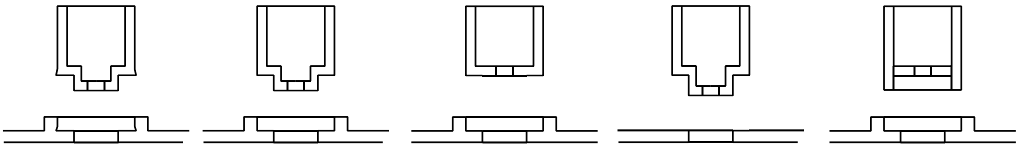


Figure 4.19 The five snap-fit joints that was created and tested.

The second from right turned out to be the most stable and the easiest to attach. Other advantages are that since there is no protrusion the plate is easier to stack, and that the fairly deep pit in the cylinder leaves a lot of room for the spring.

Close to the edges are small circular extrusions that can hold strings or thin straps, but these did not offer enough support for the hand.

4.6.5 Prototype #3

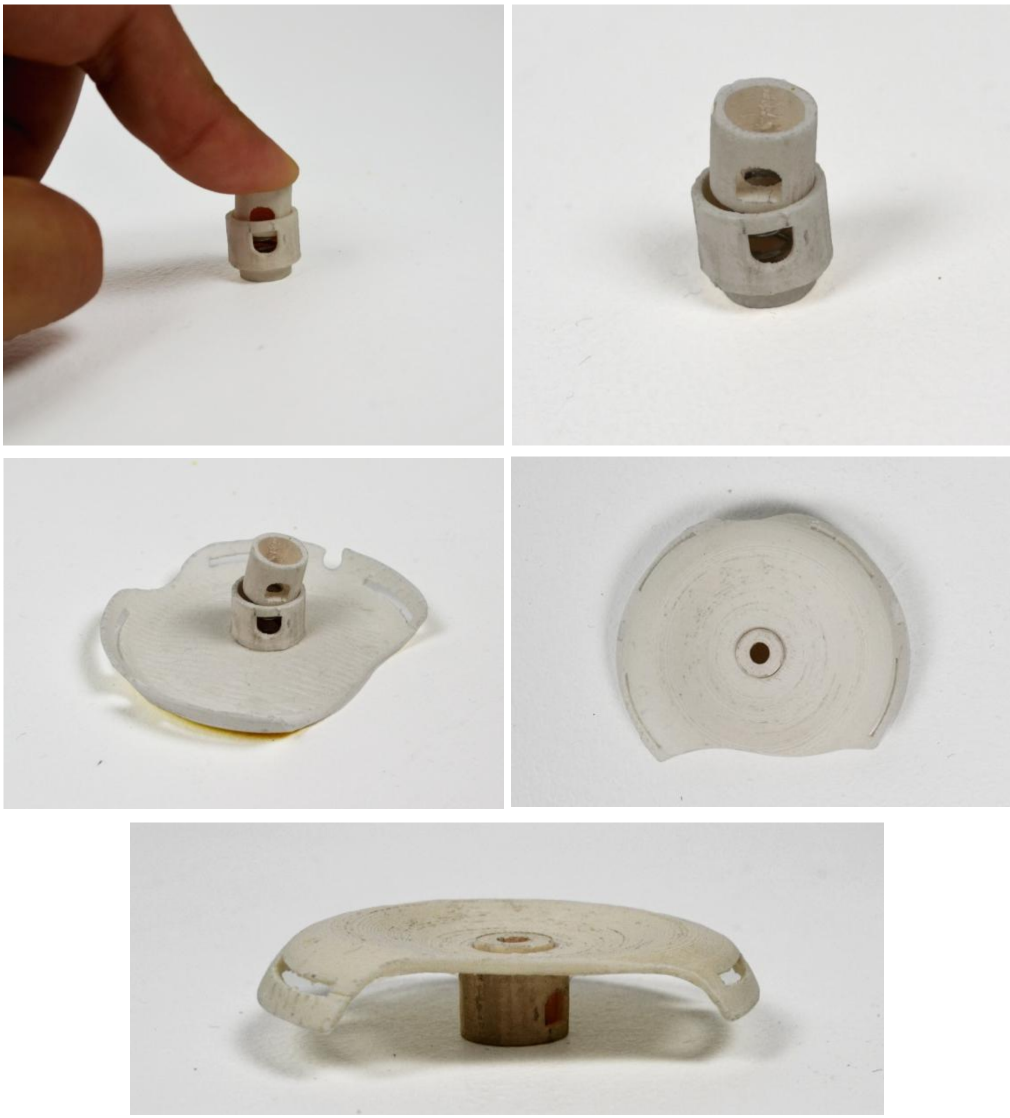


Figure 4.20-24 Photos of the third prototype showing the device, the inner mechanism and the compression of it. Note the broken edge by the extrusion in the bottom photo. The straps were not included in the photos.

4.6.6 Evaluation #3

The photos above, figure 4.20-24, show the third prototype. In order to enhance the grip, slight material was removed around the little finger. This was done in an almost symmetric way so that one plate can be used by both right and left hand. This is illustrated in figure 4.25. The left illustration shows a plate that can only be used by the left hand, while the right illustration shows a plate with almost symmetric material removal that therefore can be used by either hand. The reason for not having a completely symmetric extrusion is purely aesthetical; from a functional perspective it seems to work equally well with a symmetric extrusion.

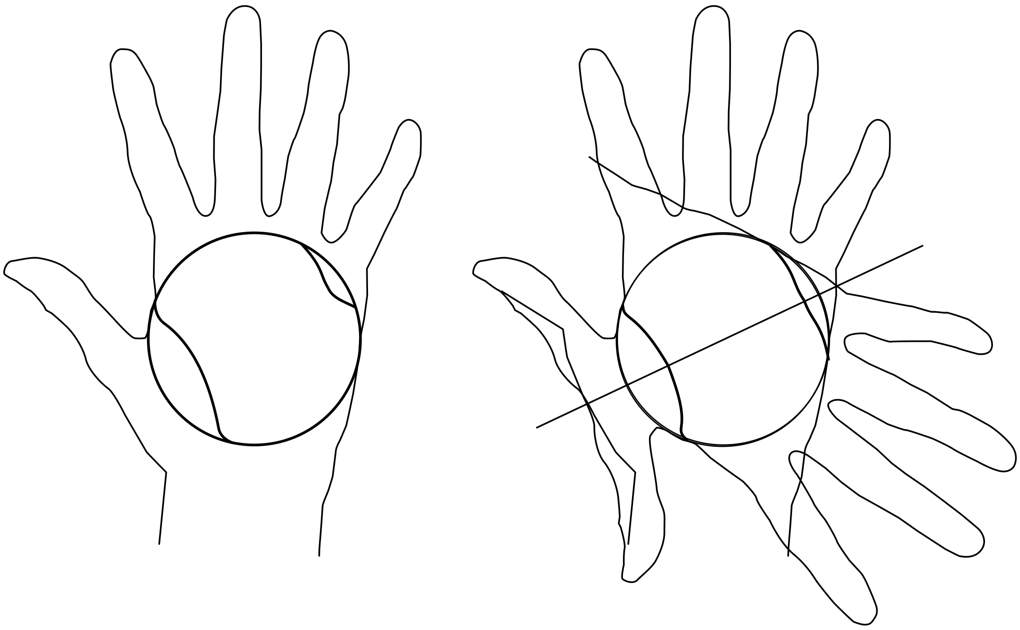


Figure 4.25 Illustration of how the extrusions would be designed if the plate was to fit in only one hand (left) and how a close to symmetric extrusion would make the device able to fit both hands (right).

The device is strapped around the hand with nylon straps. In preparation of the very first usage the straps are pulled through holes of the plate and then attached to a snap buckle. Detachment is accomplished by removing the snap buckles and pulling the straps through the holes. Depending on which pair of the plate's four extrusions the straps are attached to, the plate will either be for a left or a right hand. Because of the thumb and little finger extrusions, the angle between opposite strap extrusions is 155^{o}, which offers better support when the palm is bent.

One of the walls of a strap extrusion actually broke, see figure 4.24, because the width of the plate decreased proportionally to the radius and in part because it was too close to the thumb extrusion. On the final mock-up, however, the size of the thumb extrusion decreased by 10% and was slightly rotated.

The wall thickness of the final mock-up was made near constant on behalf of stackability; it was a trade-off between stackability and reliability. With a thicker plate it is possible to have tracks on the surface; several kinds are possible and a form study on tracks was conducted, see figure 4.26. The second from right was assumed to be superior in terms of comfort and reliability, and these tracks can be found on the final mock-up.

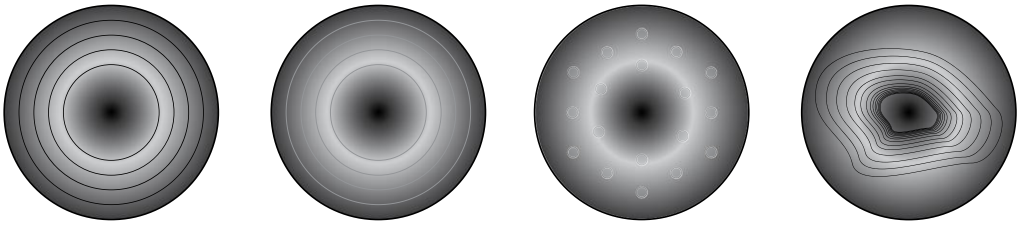


Figure 4.26 Illustration of four possible tracks for the plate's bottom surface.

The tube enters the device through extrusions in the side of the plate. These work like joints as they lock the tube's position without throttling the flow.

Lastly, the cylinder-to-plate snap-fit joint works great - as the bottom cylinder attaches to the plate it emits a "click!"

4.7 The final mock-up

The final mock-up weighs 22 grams, out of which the plate is accountable for 8 grams, the straps 5 grams, the buckle 5 grams, and the inner mechanism 4 grams. The plate and inner mechanism is made out of PLA, the spring is steel, the tube is silicone, the straps are nylon, and the buckle is POM. It is robust, comfortable, and could fit in a *Moon* environment.

The estimated set up and post operations time for just the nozzle is estimated to 20 and 15 seconds, respectively. The maximum thickness of each plate is 2 mm, and the maximum gap between stacked plates is 1.7 mm, making it very easily stackable.

The mock-up might require too high forces to control the flow, which will be further discussed in chapter 6.3. Chapter 6.2 discusses conclusions from the nozzle design. Photos of the final mock-up can be found on this and the following pages, see figure 4.27-39.

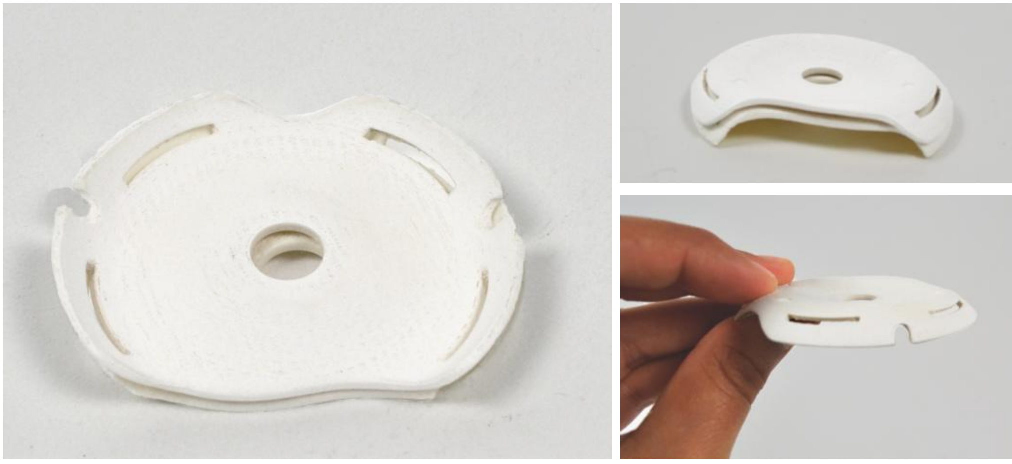


Figure 4.27-29 Photos of the final mock-up. Two plates stacked on each other (left and top) and a plate held in a hand (bottom).

Figure 4.30-34 Photos of the final mock-up. The assembled inner mechanism with the tube (top left), the small cylinder with its spring (top right). The bottom three photos show the assembled device held, open (bottom), closed (center left) and worn (center right).

Figure 4.35-39 Photos of the final mock-up.

5 Design of the water heater

The design of the water heater is the subject of this chapter. The design process is not as far-reaching as the previous; it will cease at a conceptual stage.

5.1 Background

Based on the headline, this part of the thesis might at first sight resemble the previous chapter, and it was truly intended to. As a result of a combination of overly ambitious goals, poor planning and eventually reasonably set priorities, this part of the thesis will not result in a finished design with a functional prototype. Instead, this chapter will serve as an inspirational discussion on how the water heater might work. It will provide some conceptual designs that will highlight design possibilities as well as areas of interest for future research.

The extensive product development process used in the previous chapter will not be repeated. From here on forward, concepts will be generated, explained and evaluated, but they will not evolve past a conceptual level. To some extent the evaluations contain recommendations for future research.

5.2 Concept generation

The two generated concepts, F and G, both work on the process of Joule heating. They have no specific location within the full-body washing system, they could be in the wall, by the nozzle or anywhere in between. Some details are presented in different ways between the concept just to distinguish and to illustrate the diverse opportunities. Note that this discussion is based on hypothetical designs that are in no way finalized.

5.2.1 Concept F

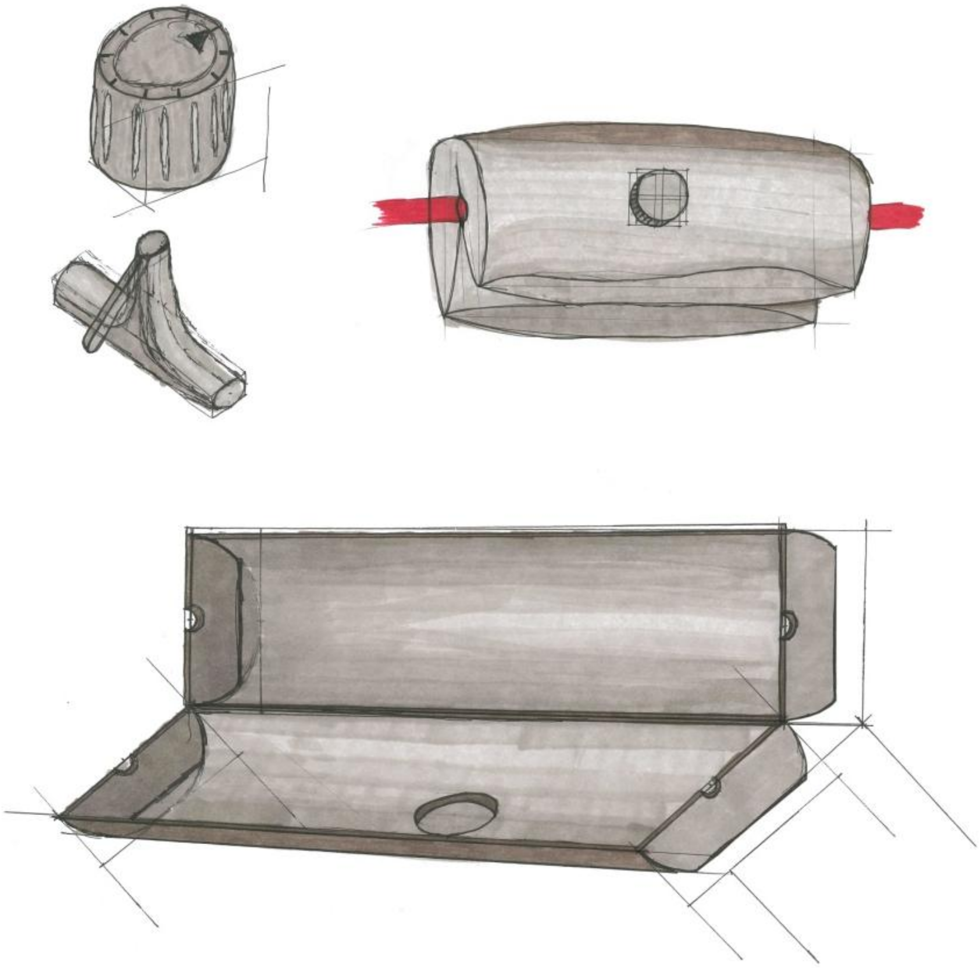


Figure 5.1 Sketch of concept F, the details from top are: the cap and temperature control; the folded, plastic bag with a tube through it; the resistive element heater; and the case with a hole for the temperature control.

This concept, see figure 5.1 above, consists of four parts, which will not be assembled or disassembled before or after usage, but only in connection to repairs or maintenance. The first part is a resistive element heater equipped with a temperature sensor. This attaches to a screw cap, the second part, which together with the resistive element heater makes up a thermostat. The top of the cap also serves as the temperature control and beneath it is a rechargeable battery. The third part is a plastic bag with an opening, which the cap is screwed to. The bag is filled with water that will be heated by the immersed resistive element heater to the set temperature. The fourth part is an insulated box where the plastic bag is placed. The box has a hole for the thermostat so that the temperature can be controlled without opening the box. The tube is placed in the center of the bag, which is then folded over the tube.

The water inside the bag is only used as a medium of transporting heat from the resistive element heater to the bag walls. From the bag walls the heat travels to the tube, which heats the water that it holds. The area of impact multiplies if the tube is folded, which increases the likelihood of the washing water reaching the desired temperature.

This concept takes a lot of consideration to the repairability, which includes e.g. how the device is repaired, how the parts are exchanged, and how the spare parts are stored. Therefore, no tools are needed to assemble the device, and all parts are able to take up very little space when stored, especially the plastic bag which can be flattened and folded.

5.2.2 Concept G

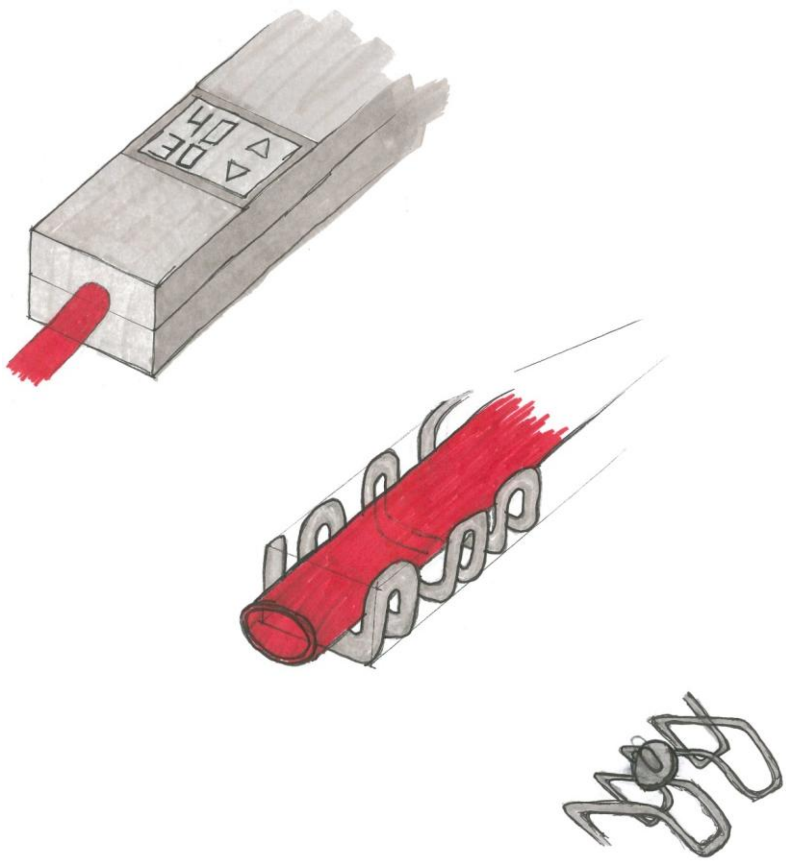


Figure 5.2 Sketch of concept G: the case with a digital temperature control; the coil and tube; and the coil turned upside-down to show its socket.

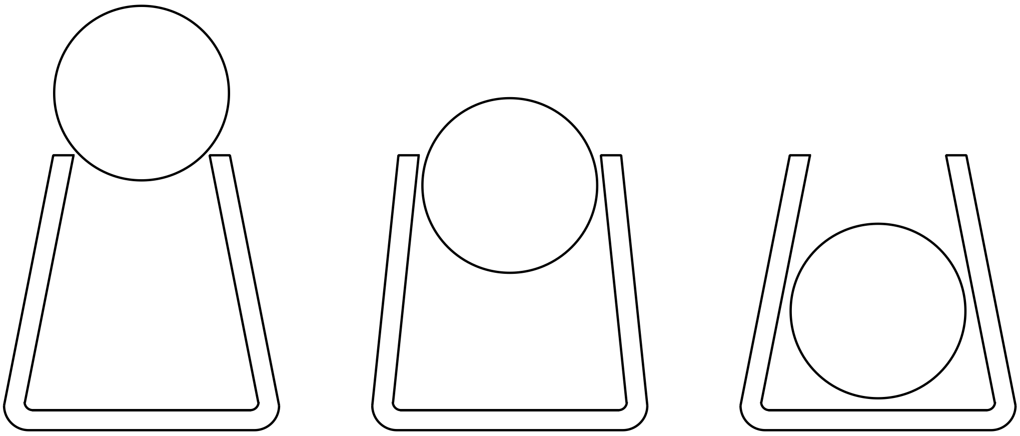


Figure 5.3 Illustration of how the coil would hold the tube in place as a snap-fit joint.

In this concept, see figure 5.2 on the previous page, there are less mediums between the heat source and the washing water; from the resistive element heater straight to the tube, which heat the washing water. An insulated rectangular box serves as the thermostat; it holds a digital temperature control on its top. The bottom of the heating element connects to an electric socket on the bottom of the box. This concept, unlike F, receives its power through a cord connected to the base's power grid.

The resistive element heater has the shape of a open trapezoid coil and the tube is simply pressed down in its cavity. The tubes are easily removable from the coils as they create a kind of snap-fit joint, as illustrated in figure 5.3. Nevertheless, disassembling the tubes does not need to be done frequently, but only in connection to repairs or maintenance.

This principle would work just as well with several coils, and in any kind of formation: beside each other, stacked, or completely separated. Furthermore, the coils' open side make them easily stacked.

5.3 Evaluation

There are three ways of transferring heat: conduction, convection and radiation. Both concepts combined conduction and convection, and there are several other ways that these combinations could be implemented. Of course they could also be implemented separately. The same applies to radiation.

The biggest challenges for heating the water is to design a reliable and efficient system, which concept F and G could have paid more attention to. Related to efficiency, it is important that leaks of heat and water is prevented. Designing easily repaired systems is preferable, but in some situations and with some objects the user might not mind a more difficult repairing. It might depend on how often the tasks will be done. When it comes to the reparation of the full-body washing system's water heater, it might be reasonable to assume that it will not take place frequently, but of course that would depend on the design.

5.3.1 Evaluation of concept F

This process of heating water is inefficient as the heat travels from heater to water, from water to bag walls, from bag walls to tube, and from tube to water. Before the washing water reaches the desired temperature, all these mediums also need to reach the desired, or a higher, temperature. However, as the temperature sensor is located in the bag the displayed temperature does not reflect the temperature of the washing water. The purpose of heating the water in such an intricate way is that immersed heaters - which commonly are used to locally heat water - result in the formation of scale. Scale could damage the washing equipment, however, this could be solved with a filter that collects the scale before it reaches any equipment or the user.

As this concept will not be further developed, it would be more constructive to focus on the advantages of this concept. The user can easily obtain a good conceptual model of the device and its functioning. All parts take little space and if a part were to break, that specific part could easily be exchanged.

5.3.2 Evaluation of concept G

Concept G heats the water in a more efficient way than the previous concept; the heat travels from the coils to the tube to the water. A similarity between the concepts is that the temperature sensor is still not located within the tube, but on part of the coil. This has its advantages, since it is likely that it would make the design more complex. The temperature sensor is part of the thermostat, and placing it inside or in relation to the tube would impair the parts' autonomy; if one part were to break, only that part should be repaired or exchanged. In the case of a sensor inside a tube, if the tube breaks, also the sensor might be exchanged with it, and vice versa. The position of the temperature sensor is a trade-off between temperature control and design complexity, which affects the repairability of the device. Both concepts could have the temperature sensor in the tube, but in both cases repairability was preferred.

There is no absolute dimension regarding how several coils could be placed in relation to each other; it could be a long string, a wide plate, or a cube. The digital display thermostat is not at all necessary, its inclusion was merely intended to exemplify design possibilities.

A broken coil is not easily fixed, but spare coils are easily stored and assembled to the rest of the device. Overall, this concept might have more potential as it not only considers repairability and stowage, but also efficiency.

6 Conclusions and recommendations

This chapter concludes the thesis with concluding remarks, recommendations for future research and a brief discussion on failure.

6.1 Background

Most time and effort was put into the creation of the nozzle, and as a consequence the water heater was not fully developed. Recommendations for future research of the heaters were included in their evaluations. For these reasons, this chapter focuses on the design of the nozzle.

NASA uses a measure called Technology Readiness Level (TRL) to classify the readiness of emerging technologies. There are nine levels where the highest level, TRL 9, requires that the actual system has been proven successful through a mission. To accomplish TRL 1 the "basic principles [must be] observed and reported". I believe that the nozzle design has only reached TRL 2, which is defined as: "Technology concept and/or application formulated: Applied research. Theory and scientific principles are focused on specific application area to define the concept. Characteristics of the application are described. Analytical tools are developed for simulation or analysis of the application" [36].

6.2 Conclusions

Focusing on the nozzle on the expense of the water heater is a reasonable decision. The nozzle allows for the actual washing to take place, whereas the heater simply heats up the water that is to be used when washing. The heater could also be more dependent on other systems than just the full-body washing system. Heating the water can be regarded as a sub-function of washing. The situation is similar for the actual space. The nozzle is the main tool used for washing within a washing space, which is greatly affected by the nozzle, and vice versa. The nozzle design is not postulated on a certain space, so the designed space can completely be designed in regards of the nozzle. For example, with this nozzle design the washing space could be enclosed by a curtain and be equipped with a simple drain.

Focusing on reliability, repairability and efficiency as design drivers was very instructive. It led to a design that might actually work under the given conditions. Although being labeled as a functioning prototype, because of time constraints, the design has not yet been tested with water. The only thing that the mock-up has tested has been the throttling of the tube when air is blown through it, which has been successful.

The "simple" technology behind the nozzle design, namely to throttle the water tube, proved to be a highly provocative design solution. Some of my peers were of the opinion that the simplistic nature of pressing and de-pressing a tube is not complicated enough to actually be used on Mars. Extreme environments and extreme conditions do require extreme design, but not at all does this mean imply extremely complex designs. These are not superior to extremely simple designs, or to designs that work extremely well regardless of the manner of its usage.

6.3 Recommendations for future research

The final mock-up had a few unexpected flaws that, when it comes to future research, would be necessary to look into. As a result of the tube's wall thickness the required spring force was quite high, which means that the user will have to press the device rather hard against the body. This results in a higher pressure on the palm from the top cylinder's sharp, upper edges. Were the edges less sharp, it might not be as uncomfortable. And if the tube's walls were thinner, it would pose a greater risk of throttling itself.

In the benchmarking analysis it was declared that a combination of washing procedures is beneficial. This statement inspired the generation of the concept that became the final design. Very late in the thesis process it was realized that this statement did not differentiate between various body parts. To clarify: perhaps bathing is the most efficient washing method for washing the feet, or is a combination of showering and sponge bathing a superior method for washing the chest, or sponge bathing for the face?

A material study is necessary. The only retrieved document on material guidelines focused on metals and manufacturing processes. One of the next steps in the design process would be a material study and optimize it as part of the design.

Another possible area for future research is to investigate the commercialization of the design. The product might especially be implemented in terrestrial areas with low access to clean water.

6.4 Discussion on failures

Designing while considering that failure is an option is a quite difficult task. In this particular situation, the user's concern would not ease even with the most generous money-back guarantee. Therefore, in this stage of concluding recommendations, it is important to look into the critical elements and the possible consequences of their failure. Acknowledging these and solving the problems related to them is key to the design of a reliable product.

The most critical element is the tube. Unlike most full-body washing systems this one has weak, thin walls. This characteristic is unambiguously an important part of the design that cannot be discarded. Tube failure can be caused by wear from the repeated throttling, by wear from the plate extrusions, by being wrongly assembled, by twisting or by pulling the device. If the tube failure occur between the throttled section and its exit, the consequences would be impaired flow manipulation and leaks during usage. Leaks can also occur if failure happens between the throttled section and the water source. The water flow to leaks can be stopped by turning a lever on simple ball valves that would be connected to the tube close to critical areas; for example near the connection to the water source, before and after the heater. The tube can also be throttled manually. Turning the ball valve lever between usage would also limit the amount of water that can be leaked.

Another possible failure is that the spring could break after excessive wear, water damage or due to being wrongly assembled. Were it to fall off, it is possible to reuse the cylinder by gluing a new spring to it, that is, assuming that the specific glue is brought along.

All of the mock-up's hard parts are quite robust and are not likely to fail; except for one part of the device. The third prototype broke in the edge of a strap extrusion. This kind of failure might lead to discomfort when the straps are stretched around the hand or even to the straps falling off. The straps are however not essential to the main functions of the design; the washing process could just as well be carried through without them. Were the plate to break, there would be nothing to do besides replacing it. Luckily, neither the plate nor any other parts take up much space or weight.

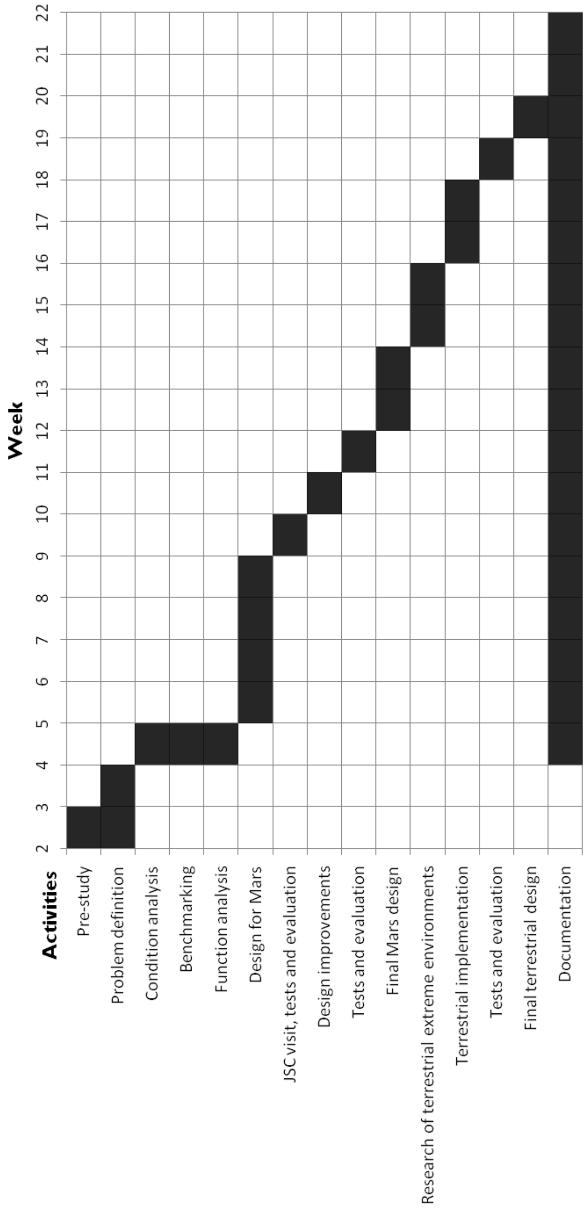
References

[1] About NASA (Electronic). http://www.nasa.gov/about/, 2013-06-04.
[2] NASA Spinoff Homepage (Electronic). http://spinoff.nasa.gov/, 2013-06-04.
[3] ESA: Technology Transfer Programme (Electronic). http://www.esa.int/Our_Activities/Technology/TTP2, 2013-06-04.
[4] Edenhall, Ylva. (2012). Rymdindustrin gynnar svenska företagare. Svenska Dagbladet. 2012-12-20.
[5] NASA - What Does NASA Do? (Electronic). http://www.nasa.gov/about/highlights/what_does_nasa_do.html, 2013-06-04.
[6] Wikipedia: Exploration of Mars (Electronic). http://en.wikipedia.org/wiki/Exploration_of_Mars, 2013-06-04.
[7] NASA: Mars Exploration Program (Electronic). http://mars.jpl.nasa.gov/, 2013-06-04.
[8] Human Integration Design Handbook (2010). Washington, DC, NASA Handbook.
[9] Feighery, J.E., Meyers, K., Dillon, P., Edeen, M. (2001). Waste and Hygiene Compartment for the International Space Station, NASA Johnson Space Center, Lockheed Martin, GB Tech.
[10] Roach, Mary (2010). Packing for Mars: The Curious Science of Life in the Void, W. W. Norton & Company, NYC, NY, USA.
[11] Jones, J.C. (1970). Design Methods. John Wiley & Sons, NYC, NY, USA.
[12] Landqvist, Jan (2001). Vilda idéer och djuplodande analys: Om designmetodikens grunder. Carlssons Bokförlag, Lund, Sweden.
[13] Eckhardt, C.C. (2010). Design Methodology. Lund University Industrial Design, Lund, Sweden.
[14] Harrysson, Mats (2011). Åke och hans värld av formgivning (Film). SVT2 2012-05-16.
[15] Ulrich, K., Eppinger, S. (2011). Product Design and Development. McGraw-Hill Higher Education, NYC, NY, USA.
[16] Drake, B.G. (2009). Human Exploration of Mars: Design Reference Architecture 5.0. NASA Johnson Space Center, Houston, TX, USA.
[17] Toups, Larry, Habitation Lead, Exploration Missions & Systems Office, Johnson Space Center, NASA.
[18] Thomas, Andy, Astronaut and Aerospace Engineer, NASA.
[19] Larson, W.J.(2007). Human Spaceflight: Mission Analysis and Design. McGraw-Hill Higher Education, NYC, NY, USA.

[20] Hurlbert, K. (2010). DRAFT Human Health, Life Support and Habitation Systems: Technology Area 06. NASA Headquarters, Washington, DC.
[21] NASA General Anthropometrics & Biomechanics Related Design Considerations (Electronic). http://msis.jsc.nasa.gov/sections/section03.htm#_3.2_GENERAL_ANTHROPOMETRICS, 2013-06-04.
[22] Anderson, Molly, Advanced Life Support Systems Engineer, Habitation Systems, Johnson Space Center, NASA.
[23] Scott, K., Quist, J., Bakker, C. (2009). Co-design, social practices and sustainable innovation: involving users in a living lab exploratory study on bathing. Joint actions on climate change, 8-10 June, Aalborg, Denmark.
[24] Kuijer, L., De Jong, A. (2011). Practice theory and human-centered design: a sustainable bathing example. Nordic Design Research Conference, Helsinki, Finland.
[25] Matsuhashi, N., Kuijer, L., De Jong, A. (2009). A Culture-Inspired Approach to Gaining Insights for Designing Sustainable Practices. Japan Society of Mechanical Engineers.
[26] Smith, Frederick, Advanced Life Support Systems Engineer, Habitation Systems, Johnson Space Center, NASA.
[27] Häuplik-Meusberger, Sandra (2011). Architecture for Astronauts. Springer Praxis Books, Berlin, Germany.
[28] Mohanty, Susmita (2001). Design Concepts for Zero-G Whole Body Cleansing on ISS Alpha. International Space University, Strasbourg, France.
[29] Letters to Earth: Astronaut Don Pettit's blog (Electronic). http://blogs.nasa.gov/cm/blog/letters/posts/post_1340397309756.html, 2013-06-04.
[30] Felton Products Ltd. (Electronic). http://www.felton.co.nz/, 2013-06-04.
[31] Lane, H.W., Sauer, R.L., Feeback, D.L. (year). Isolation: NASA Experiments in Closed-Environment Living. American Astronautical Society.
[32] Lucas, George (1977). Star Wars IV (Film).
[33] Abrams, J.J. (2009). Star Trek (Film).
[34] Jones, Duncan (2009). Moon (Film).
[35] ESA Celsius Mission, Christer Fuglesang (Electronic). http://www.esa.int/Our_Activities/Human_Spaceflight/Celsius_Mission_-_English_version/Christer_Fuglesang, 2013-06-04.
[36] Definition of Tehnology Readiness Levels (Electronic). http://esto.nasa.gov/files/trl_definitions.pdf, 2013-06-04.

Appendix A: Time plan

A.1 Preliminary time plan



A.2 Actual time plan