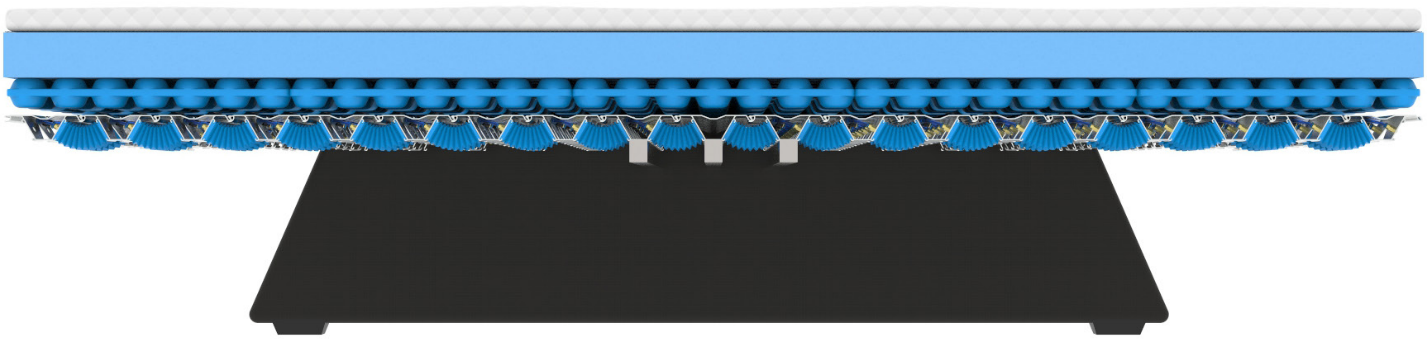
A DYNAMIC MODULAR SLEEP SYSTEM

A graduation report by Paul Bosch



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PREFACE

This report is the result of my graduation project. During this project I was allowed the opportunity to start my own project, which was not part of any running research program or requested by an existing company.

I want to thank Peter Vink for granting me this opportunity, and for the willingness to supervise and support this adventure. Thanks for the enthusiasm, enjoyable coaching sessions and endless supply of knowledge on ergonomics.

Also thanks to Wim Poelman, who supported me during my project as my day to day mentor. He was always prepared to answer my questions and I could reach out to him whenever needed. Thanks for the criticism, countless ideas and thoughts on technical principles and design.

EXECUTIVE SUMMARY

Project context

Currently, beds are static objects. This makes it difficult when purchasing a bed, as people do not know what bed is best for them. Sleeping on the wrong bed can result in bad sleep quality and even medical conditions, such as low back pain. Also, people take different sleep positions during the night, meaning that a static bed is never capable of supporting all those positions.

Some researchers have therefore suggested to design a dynamic bed, capable of adjusting during the night to support any sleep position. As a result, some improved dynamic and intelligent beds are under development or have made it to the market recently. This may be the start of a paradigm shift towards a new type of bed.

While these beds are an improvement compared to static beds, they still have limits to the support and adjustability they can offer. They can only change the firmness, and only in a few zones, which means that the number of positions is still limited and not all body types are perfectly supported.

For that reason, this graduation project was focused on designing an even more dynamic bed, which can adjust in shape and not only in firmness and can adjust to almost any type of body.

Sleep system design

The scope was to design the system of the bed that would allow for the change in shape of the bed's surface. This system was called the sleep system and consists of the bed base, mattress and pillow integrated in one. The technical principle underlying the shape changing behaviour had to be designed and prototyped to obtain a proof of concept.

A section cut of the final design is shown in figure 1 and shows that the system consists of multiple modules. This modularity allows to resize the bed to the user's needs and improves ease of maintenance and sustainability. It also allows for the system to be used in other ergonomic applications, such as seating. The modules are aluminium extruded profiles connected through an integrated hinge and a TPU bellow that functions as actuator. The used dimensions are based on a parametric computer model and cover a wide range of body types.

Technical principle

By increasing the pressure in a bellow, it extends and pushes the modules apart, increasing the angle between them. As multiple modules are connected in a row and the system consists of multiple rows, by independently controlling the pressure inside each bellow, different shapes can be created. Top layers will smoothen the surface and the result will be a shape-controlled double-curved sleep surface.
Using a folding bellow as a pressurised actuator is a new application for this old folding principle. The principle was proven to be achievable due to an extensive iterative process of 3d printing. The final prototype does not work under pressure but can demonstrate the principle.

Conclusion

The project started with the problems found in existing beds, and after an analysis phase led to the design vision of solving these problems with the design of a modular dynamic sleep system. This project concludes with the design of such a system, which can effectively solve the problem of shape restrictions and uses an innovative technical principle to do so.
This project is the first step in the design of an intelligent versatile bed that can solve numerous existing problems around sleep and beds. This project still leaves much to be researched but offers a good starting point to take this project forwards.

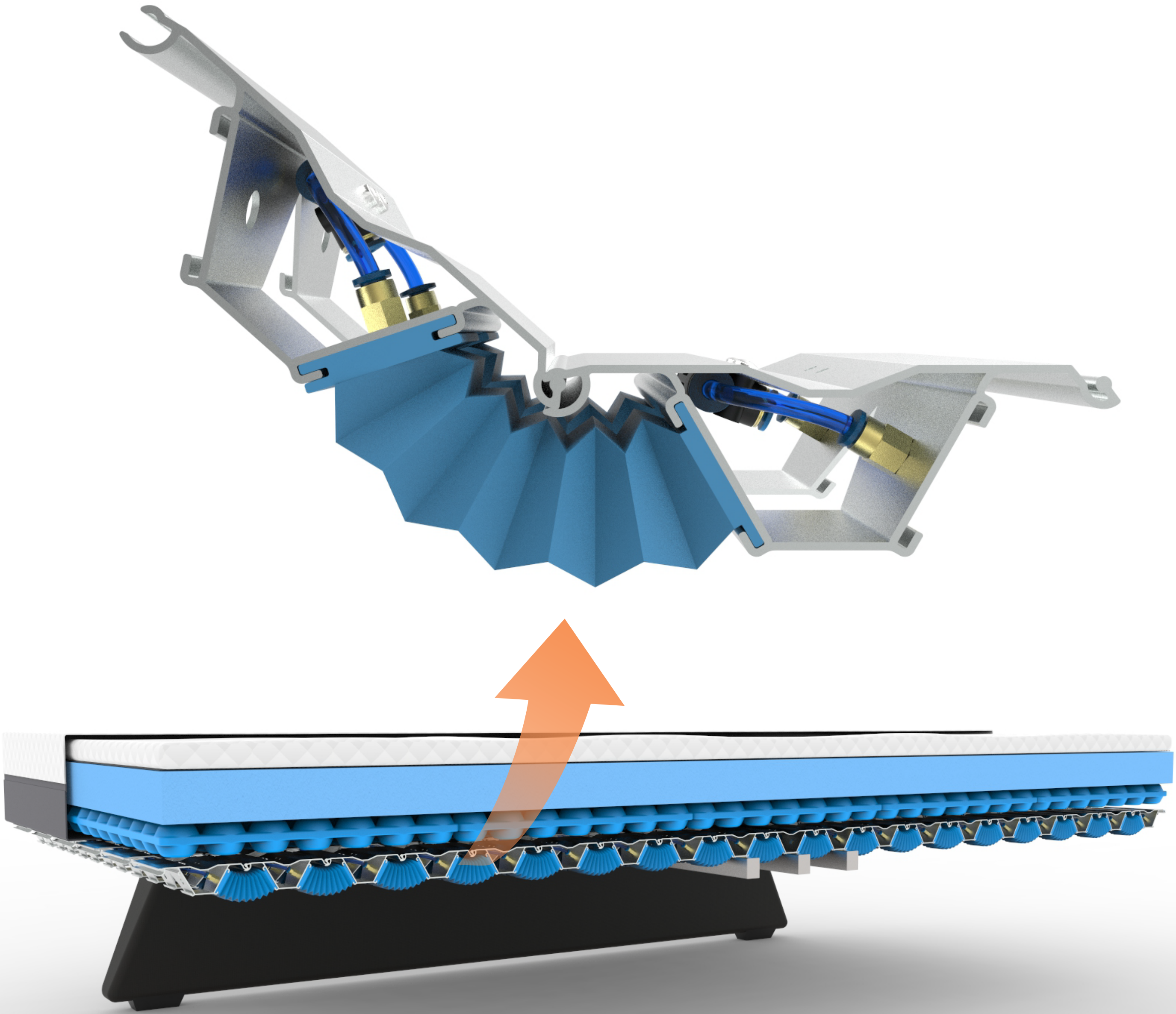

Figure 1 *Section cut of final design, with module (by author)*

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Appendices

1. INTRODUCTION

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Billions of mattresses, office chairs and driver's seats are fundamental to people as they are used for hours daily by billions of people. Especially beds, as people sleep approximately one-third of their lifetimes. Using the wrong bed can result in sleep deprivation, which is dangerous and can result in long term health problems, such as back pain-related conditions see appendices B.1, B3 and B.4).

Using the right bed may prevent or even cure these problems. The difficulty is that people have different anthropometric measurements, sleep differently and have different personal preferences. And during the night, people change sleep positions and each position requires different support.

These facts led to believe that the ultimate bed is not something passive, as is the case with most existing beds, but something dynamic that adjusts its shape and firmness where needed to provide ultimate body support and optimal sleep.

Recently, developments of more dynamic and smarter beds started, and some were already introduced to the market (see chapter 4.2). These beds allow the user more control over firmness settings and have some form of measuring and adjusting firmness during sleep.

While these smarter beds already improve the comfort experienced compared to regular beds, they are still limited to a small range of different sleep positions and only support a limited number of body types.

A more versatile solution would be adjusting the shape of the sleep surface to the ultimate position for a wide range of body types and needs. With such a system, comfort-, sleep- and even therapeutic needs could be provided.

The design for such a system was made within this graduation project.

To create one system that can be extended as needed, and to take a sustainable design approach, a modular system was chosen. The challenge was to find an innovative technological solution using Soft Robotics, as this is an upcoming technology well suited for interacting with human beings.

The scope of this graduation was to design one such module fully functioning and get a proof of concept.

This report describes the process of getting from a broad assignment to the design of a modular sleep system. The first phase is an analysis of the context and challenge. This section concludes in a purpose design (i.e. design brief), which is the starting point of the second phase. The second phase covers the design process of the module and shows the final design.

Finally, the design is evaluated and recommendations for further research and developments are given.

2. PROBLEMS DEFINED

It's time to solve world problems. Time to get to the core. This chapter will describe the challenge, scope and limitations that are part of this graduation project.

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2.1. CHALLENGE & SCOPE

To understand what inspired this project, the bigger picture is briefly explained here. Based on the problems identified, an initial challenge was formulated that was used as the starting point for the project.

Unfortunately, good health and well-being do not come naturally to everyone. As such, these are recognised as existing problems by over 150 world leaders when they adopted the 2030 Agenda for Sustainable Development, including the Sustainable Development Goals (United Nations, 2015).

Designers can try to improve people's health and well-being by introducing artefacts as described by Roozenburg and Eekels (1998) (see appendix A.3). Ergonomics is the scientific discipline concerned with understanding and optimising the interaction between these artefacts and their users and determining where the design could be improved.

Ergonomic research may lead to innovation and ways to solve problems. For example, firm mattresses causing insomnia may have been reason for ergonomically improved sleep products in the past (see appendix B.5), such as memory foam mattresses. And while this innovation may have solved problems for some people, symptoms of insomnia are still prevalent widely among populations worldwide (Leger, Poursain, Neubauer, & Uchiyama, 2008; Kerkhof, 2017; Ohayon & Smirne, 2002).

Although the cause of insomnia symptoms differs per case, it was proven that the right bed can help in prevention or treatment of some symptoms (Jacobson, Gemmell, Hayes, & Altena, 2002; Jacobson, Boolani, Dunklee, Shepardson, & Acharya, 2010; Kovacs et al., 2003; Jacobson, Wallace, Smith, & Kolb, 2008). When considering that sleep problems are globally still a big issue and that the right bed may improve this situation, the challenge for ergonomic innovation can be detected.

Figure 2 *Sustainable Development Goal 3 (United Nations, 2015)*

Similar needs for ergonomic innovations were found in other products, such as office chairs. For example, Complaints of Arm, Neck and/or Shoulder (CANS, or formerly known as Repetitive Strain Injury, RSI) are also prevalent worldwide, with different causes and symptoms (Yassi, 1997; Newman, 2017). A study conducted in the Netherlands shows that yearly 8% of Dutch citizens take time off due to CANS symptoms (Bongers, de Vet, & Blatter, 2002). Attempts have been made to improve the problems by introducing more ergonomic work environments.

Initial challenge

The identification of the above mentioned problems led to further research into what may be the cause of these problems. It led to believe that the passive state of these products maybe be interfering with the need for movement and changing positions. That led to the following initial challenge (also see appendix A.1):

> *The main problem is that ergonomic systems currently used in bedding- and seating applications are static and do not sufficiently adjust to users and use, sometimes causing them to feel discomfort or in extreme situations decubitus.*

Solution

As a solution for this problem, an adjustable system was suggested which would be dynamic and smart, meaning it would automatically adjust to the optimal position for the user. This system had to become modular to use it for different applications, for allowing modification of the product's size and for sustainability purposes.

Scope

To make the challenge achievable within the limits of a graduation project, a scope (see appendix A.2) was determined:

While the challenge exists for all bedding- and seating applications, the scope was set to just beds, as these are most frequently used per person.

Also, only the interaction of 'sleep' was focused on as this is the primary use of a bed (see chapter 3.3).

Besides that, it was determined that only the most challenging part of the total system would be designed; the modules that create the adjusted shape of the surface.

2.2. APPROACH

The approach to design the solution proposed in the previous chapter is explained here.

For this project, an iterative approach was used. That means that research or simulation were conducted, the outcomes were brought together in synthesis and evaluated which led to a decision and this process repeated itself all over again (see figure 3).

Overall, the structure can be divided in phases with each a conclusion. The first phase of exploration was partially done before and partially during the graduation project and resulted in the initial challenge and scope.

The second phase of analysis was conducted during the project and resulted in criteria and a design vision.

The third phase of ideation, prototyping and conceptualization resulted in the final design.

The final design was finally evaluated and recommendations were given.

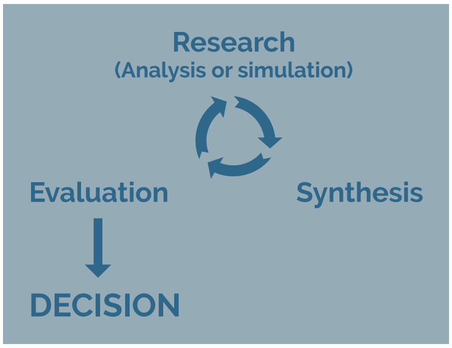


Figure 3 *Iterative process (by author)*

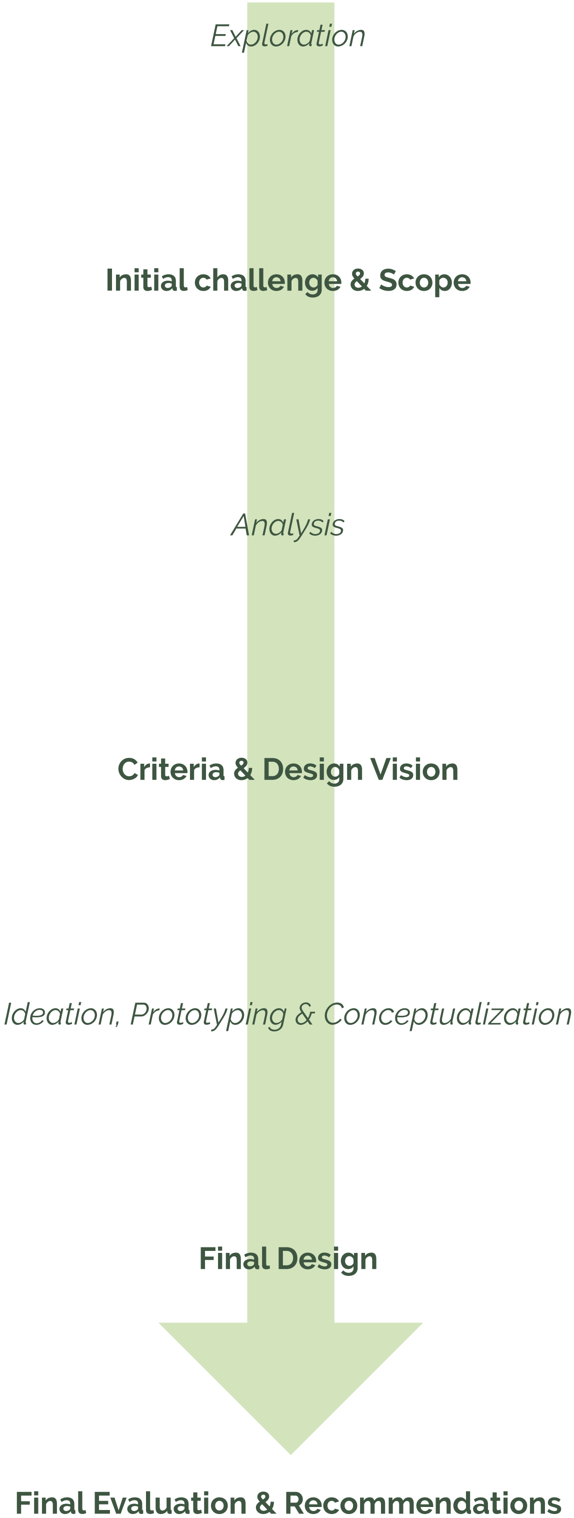
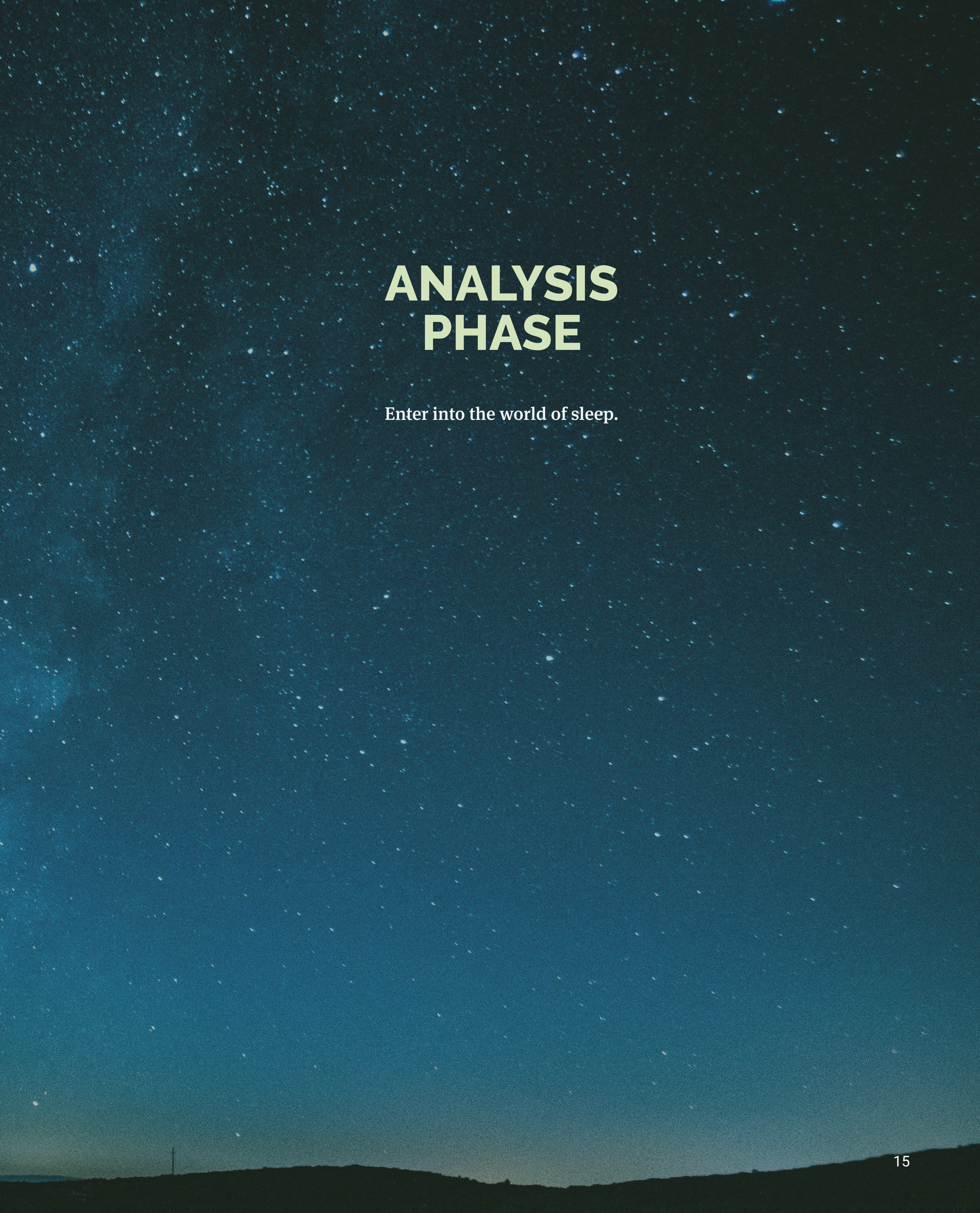


Figure 4 *Project structure (by author)*


Photo by Juan from Pexels.com



ANALYSIS PHASE

Enter into the world of sleep.

3. USE CONTEXT

This chapter describes what a bed entails, what the influences of the bedroom environment are and how people use a bed.

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3.1. SLEEP SYSTEM

In the challenge, it becomes clear that this project aims to introduce a new type of bed. This chapter will explain what a bed consists of and will introduce the term 'sleep system'.

Although the bed seems to be a very straight-forward product, it can consist of many different parts as visualised in figure 5.

Figure 5 shows how complicated it can get. Not all beds look like that as most people us simpler setups. Hotels usually have most layers to extend the lifespan of their beds and to offer maximum comfort and ambiance.

In figure 7, the possible different parts of a bed - from bottom to top - are listed with their primary functions and the user needs they attend to.

Some of the mentioned parts are optional, and many people do not include those in their beds. Sometimes, even basic parts are not present as many people around the world cannot afford a bed and sleep on the floor instead. Also, in some cultures people use alternative bed bases, such as Japan, where people sometimes sleep on a floor that consists of Tatami mats (traditionally rush grass woven around a rice straw core).

And depending on the context, other types of beds are thinkable (e.g. sleeping on an air mattress with a sleeping bag in a tent). However, in this project, the

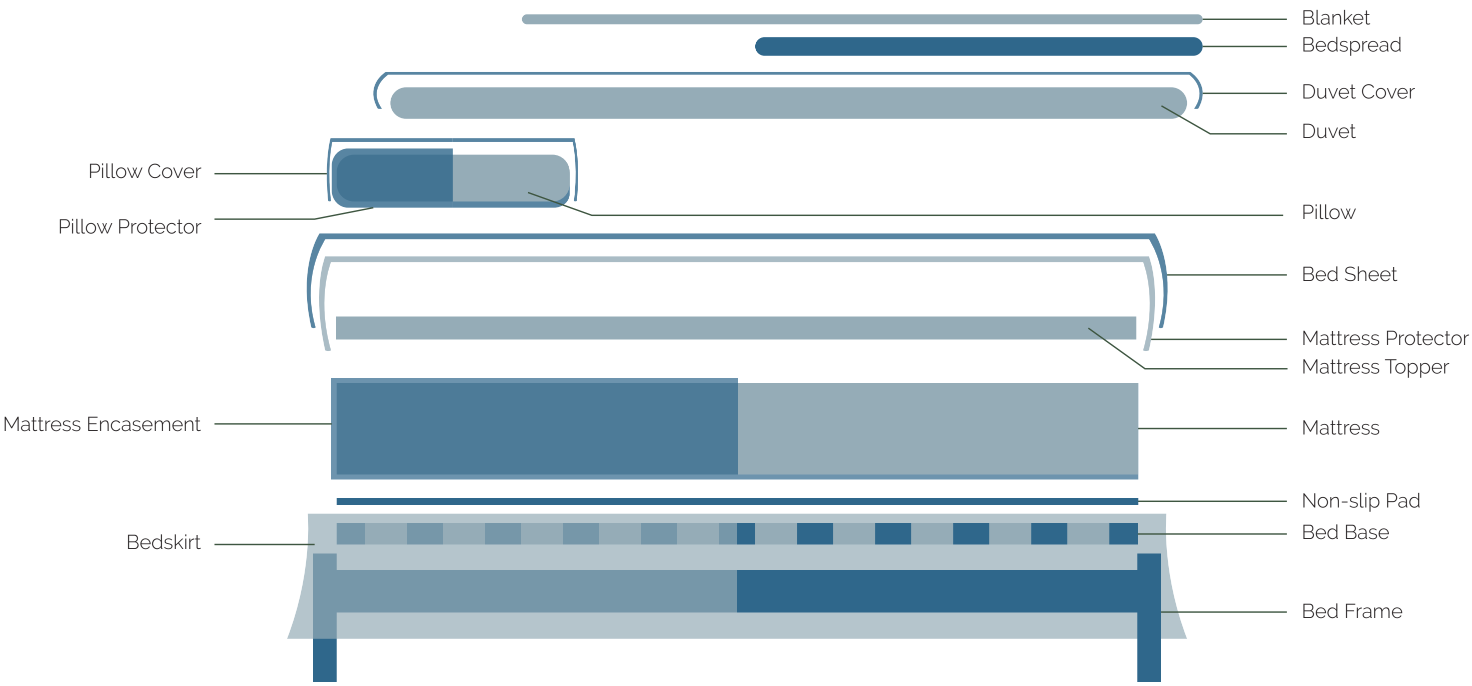


Figure 5 *Parts of an extensive sleep system (by author)*

focus is on Western cultures and the “standard” bed as visualised in figure 5, which is a piece of furniture in common households.

Within Western households, there are also different types of beds to be found, but these still consist more or less of the mentioned parts. For example, a common bed used in the United States is the box spring bed which is essentially a bed base integrated with a bed frame.

As this project is mainly focussed on designing a system for improved comfort, pressure distribution and spinal alignment, not all parts will be considered. The parts that are relevant for this project will be integrated in one system and are shown in figure 8. This will be regarded as the “**sleep system**” from here onwards.

The bed frame is also briefly considered in this project, but mainly to propose a way to carry the integrated sleep system. Aesthetics are mainly influenced by the bed frame, therefore it is recommended that the design proposed in this project is tested with potential users and adjusted to their needs.

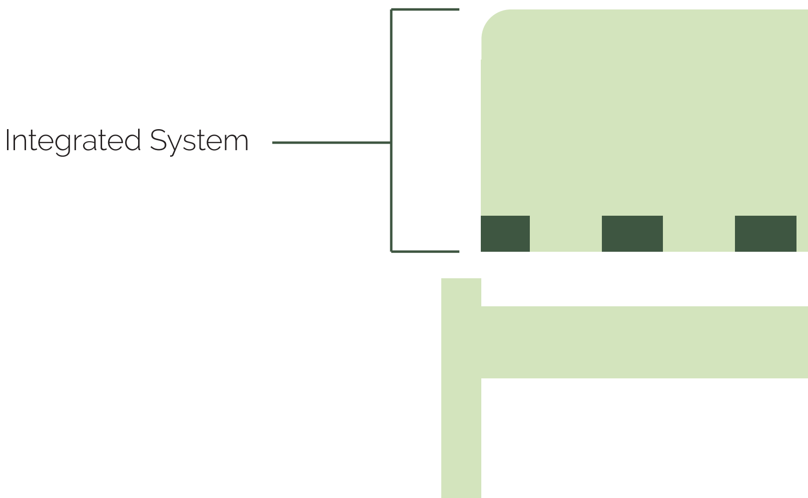
It is also good to consider the top layer, as this influences humidity regulation, insulation and shear forces. The material is mainly responsible for these qualities (see figure 6). There should be some stretch in the top layer to minimise shear forces and the top layer can also be treated to protect against bacteria and mildew formation. The ability to wash the top layer at 60°C helps against house dust mites, but requires the top layer to be taken off (Haex, 2004).

	Elastic Properties	Fluid Absorption/ Permeability	Heat Insulation	Antibacterial
Wool	+	+	+	−
Silk	+	+	−	+
Cotton	−	+	−	−
Linen	−	+	−	+
Acrylic	+	−	−	+
Polyester	+	−	−	+
Rayon	+	+	−	+
Nylon	+	−	−	+

Note: “−”=bad; “+”=good.

Figure 6 *Top layer material qualities*

image obtained from Haex (2004)



Parts in a sleep system

Part	Core function	Need
Bed frame	Lift bed	Improve ventilation
(Adjustable) Bed base	Distribute weight, Spine correction, Position change	Comfort and health
Optional: Bedskirt	*Aesthetics*	*Personalised/cosy room*
Optional: Non-slip pad	*Prevent mattress movement*	*Stable mattress*
Mattress	Pressure distribution, Spine correction	Comfort and health
Optional: Mattress encasement	*Bug barrier*	*Hygiene*
Optional: Mattress Topper	*Extend lifespan of mattress, Pressure distribution*	*Durability, comfort*
Optional: Mattress protector	*Extend lifespan of mattress, Prevent moist mattress*	*Durability, hygiene*
Bed sheet (fitted or flat)	Protect mattress from dirt and dust	Hygiene
Pillow	Support sleep posture	Comfort and health
Optional: Pillow protector	*Extend lifespan of pillow*	*Durability*
Pillow cover (Pillowcase or sham)	Aesthetics, Protect pillow from dirt and dust	Personalised/cosy room, hygiene
Duvet	Heat insulation	Warmth
Duvet cover	Aesthetics, Protect duvet from dirt and dust	Personalised/cosy room, hygiene
Optional: Bedspread	*Aesthetics, Heat insulation*	*Personalised/cosy room, warmth*
Optional: Blanket	*Heat insulation*	*Warmth*

Figure 7 *Parts of a sleep system and their functions (by author)*

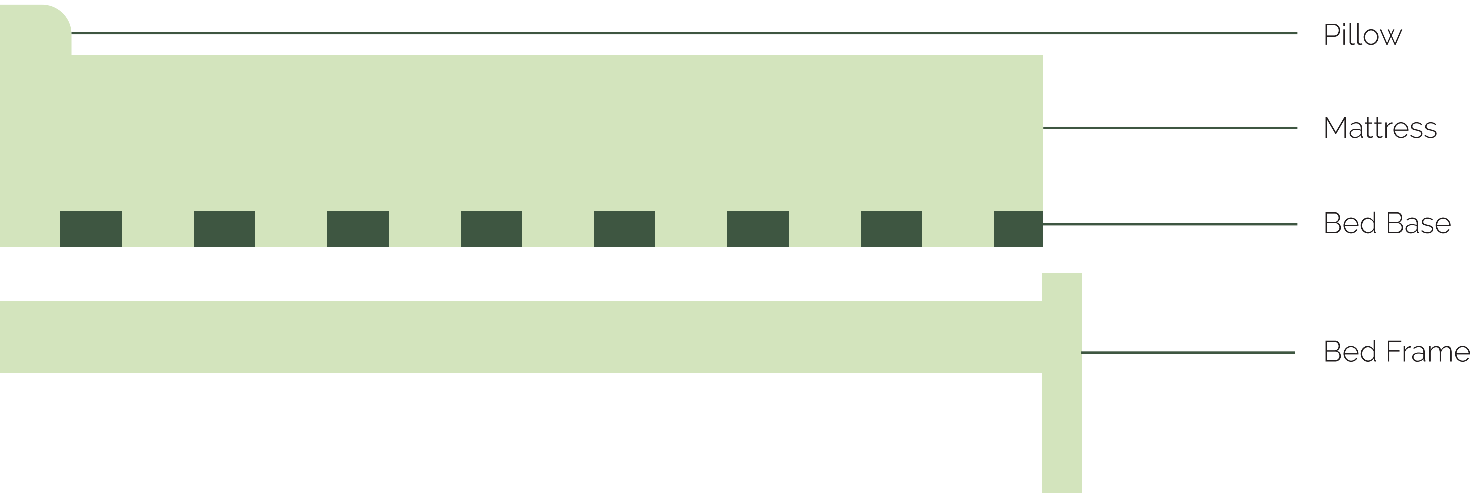


Figure 8 *The new integrated sleep system will encompass the pillow, mattress and bed base (by author)*

3.2. BEDROOM ENVIRONMENT

Different functions of the bed are now clear. But the bed is placed in a certain environment which also affects user experience and influences the demands of the bed. Therefore, this environment was examined, to find which factors are most important, what opportunities these create and which factors can be influenced by the sleep system itself.

The previous chapter shows the wide range of varieties in types and compositions of sleep systems. But there is also a wide range of use contexts of beds. Some people prefer simple beds that they can 'build' every night to preserve valuable space, while others have a king size bed that shifts positions to watch a big tv screen in a room larger than some people's entire house. Sleep systems are also used in other contexts, for example in hotels and hospitals. However, because the first target market is set to consumers (see chapter 8), the use context will be the home of people.

Specifically, the bedroom is considered as the environment where people keep their beds. In some situations, people do not have bedrooms, but in Western cultures, most sleeping takes place in the bedroom. Environmental factors that influence the use of a sleep system are sound, light, smell, colours,

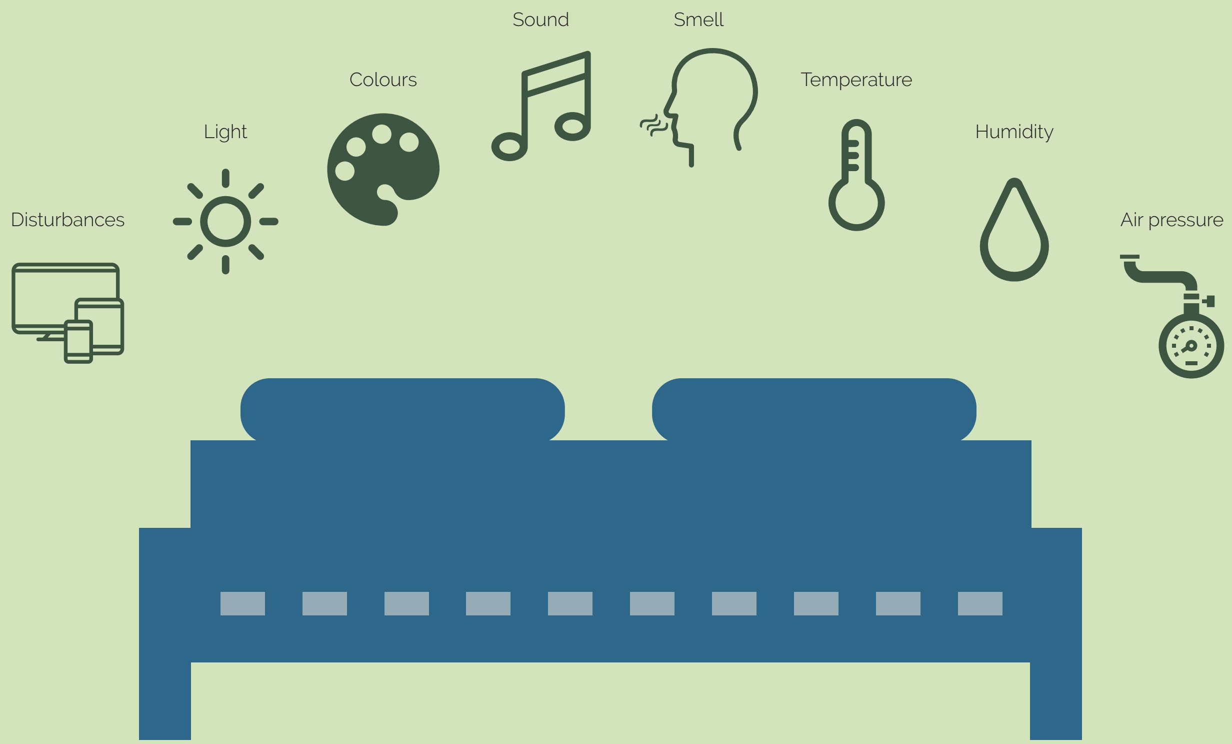


Figure 9 *Environmental factors that influence user experience (by author)*

temperature, humidity, air pressure, and disturbing devices, such as televisions (see figure 9).

Disturbances

Electronic devices in the bedroom are common. Most people take their mobile phones with them everywhere they go and televisions are part of many bedrooms. This is also true for children (about 40% of 12-year-old European children have a TV in the bedroom), although having a TV in the bedroom is associated with watching more television and obesity (Cameron et al., 2013).

For adolescents it is common to use music, television or computer games to doze off to sleep. However, adolescents using these media slept fewer hours and were significantly more tired (Eggermont & Van der Bulck, 2006). Also, using a mobile phone after the lights are out, is related to increased tiredness (Van den Bulck, 2007).

Research conducted by Gradisar et al. (2013) shows that using interactive media (computers/laptops, cell phone, video gaming) in the hour before going to bed significantly contribute to difficulty falling asleep. And 10% of the people was interrupted during their sleep at least a few nights a week by their mobile phones.

According to the National Sleep Foundation (2017), the main reason for these negative consequences is that mental activity and light exposure promote wakefulness.

Another potential problem with electronic disturbances are the electromagnetic fields (EMF). There is a great mix of research with different conclusions concerning the effects of EMFs on humans. However, the European Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR, 2015) shows that there is no conclusive evidence of any dangers from EMF if the levels fall within numbers recommended by EU legislation. Despite this lack of evidence, some people still have these fears and minimising all frequencies of radiation is therefore advised.

Light

Humans are sensitive to light. Their circadian rhythm (see appendix B.2) approximates but is not precisely 24 hours. Therefore, their rhythms should synchronise to the external environmental time to match the periods associated with the earth's rotation. For this synchronisation, light and darkness are the most important cues (Duffy & Czeisler, 2009).

The effect of light is relevant because this circadian rhythm programs the biological sleep period for people. Exposure to light has a significant phase-shifting and melatonin-suppressing effect. In other words; by using artificial light, even dim light (e.g. room light or even candle light), the body is tricked into believing it is not time to sleep yet. Also, a short light stimulus has effect, as within 5 minutes after the stimulus the melatonin will be suppressed and after 10 minutes when the light stimulus ended, the melatonin levels will begin to increase again. Not only can disturbing the circadian rhythm increase difficulty to fall asleep, but research by Anisimov et al. (2012) has shown that it can accelerate aging and increases the chance for cancer (Duffy & Czeisler, 2009).

It is also important to know that short-wavelength (460 nm) has a significantly greater effect than longer wavelength (555 nm) light on attenuating sleepiness, alertness and performance (Lockley et al., 2006). This knowledge is used for example in certain phone applications that reduce the short-wavelength light (blue light) emitted by the screen in the evening.

Requiring media (e.g. smartphones) to control the sleep system should be avoided, as it attenuates sleepiness. The same is true for interfaces that use short wavelength light (in the blue spectrum). Therefore, using longer wavelengths (in the red spectrum) is advisable in case light-emitting usecues are required.

Colours

Colours are associated with different meanings in different cultures. Some colours are therefore more appropriate in the bedroom than others. Madden, Hewett & Roth (2000) examined multiple cultures and concluded that the colours white, green and blue are considered to be calming. Using primarily these colours in the bedroom could reduce stress.

Sound

When sounds or noise leads to annoyance it can disturb sleep. As shown in figure 10, there are different noises that can cause this disturbance. Interestingly, this was a study done to determine the disturbance caused by wind mills, but people who benefited economically from the wind mills were significantly less annoyed by the sound than people who did not benefit. The figure shows only the respondents who did not benefit economically (Bakker et al., 2012).

Sound can also work positively on sleep. Lai and Good (2005) found that elderly listening to slow soft sedative music during sleep onset improves their sleep quality. They scored better on perceived sleep quality, sleep latency, sleep efficiency and less daytime dysfunction.

Smell

Humans do react to olfactory stimuli (smell) during sleep (Badia et al., 1990). However, according to research conducted by Carskadon and Herz (2004), it is not reliably capable of alerting a sleeper. Therefore, alarms that use smell to wake people are not reliable.

On the other hand, smells can be used to consolidate memories if used in a certain way (Rasch, Büchel, Gais, & Born, 2007) and can be used for aromatherapy to promote deep sleep in young men and women as well as certain gender specific sleep effects (Goel, Kim, & Lao, 2005).

According to Arzi et al. (2009), smells do not increase the frequency of arousals or wake, but do influence respiration. They suspect it can be used to treat sleep apnea.

Temperature

Temperature is extremely important for sleep. Therefore, the environment in which sleep is attempted must fulfil certain requirements to facilitate sleep onset. It is known that a mild increase of ambient temperature may promote sleep propensity, while too cold environments could even be dangerous and lead to hypothermia (Chokroverty, 2017).

Sound source of sleep disturbance	Rural		Urban		Total	
	n	%	n	%	n	%
Not disturbed	196	69.8	288	64.9	484	66.8
Disturbed by people/ animals	33	11.7	64	14.4	97	13.4
Disturbed by traffic/ mechanical sounds	35	12.5	75	16.9	110	15.2
Disturbed by wind turbines	17	6.0	17	3.8	34	4.7
Total	281	100	444	100	725	100

Figure 10 *Different sources of sound disturbances (Bakker et al., 2012)*

It is impossible to give a precise number as to the ideal bedroom temperature, as this differs per person. Also, other factors such as blankets, mattress materials, sleeping naked or clothed, influence heat dissipation and can disturb the sleep propensity. However, some helpful guidelines can be given. Extreme low (-9°C) and extremely high room temperatures (+25°C) must be avoided because they affect the duration of the REM sleep (see appendix B.2 for more information on the physiological process of sleep). A hypothesis is that thermal regulation of the body during REM sleep is suppressed, making the body more vulnerable to environmental temperatures. In general, lower temperatures are preferred by people. But these require better ventilation to prevent mildew (a fungus) formation (Haex, 2004).

Humidity

Humidity is important for a comfortable sleep environment as well as hygiene. The mattress needs a certain ventilation to allow for the transportation of body fluids to the environment. This is necessary to prevent the clammy feeling of the mattress, prevent mildew (a form of fungus) on the bottom of the mattress, and to prevent decubitus, since a moist skin is more sensitive to shear forces. But also, the room itself needs to have proper ventilation. Opening a room window can improve the room ventilation in dry weather. Furthermore, warm humid air should be avoided to enter a colder bedroom, where it might condense and form an ideal climate for house dust mites (Haex, 2004).

Air Pressure

The atmospheric pressure also affects sleep. With a decrease of atmospheric pressure, the total obstructive apneas per hour of sleep increases in a lineair fashion (Doherty, Youn, Haltiner, & Watson, 2010). Although this information is relevant for airplanes and to explain certain medical or psychological symptoms as a result of the weather, it is less relevant for the bedroom and sleep system because it is almost impossible to regulate the air pressure of the environment.

Using the colours white, green and blue are preferred as these are considered calming.

Noise from the sleep system during sleep or sleep onset should be avoided as this can disturb sleep.

Opportunity: Slow sedative music can improve sleep onset and sound can even be used to consolidate certain memories.

Opportunity: Smell can be used to consolidate memories and to influence respiration. Scientists expect that it can be used to treat apnea.

The temperature is important for sleep, but the bedroom temperature cannot be influenced by the sleep system. However, the sleep system's temperature can be influenced.

Humidity is also important, and while the air humidity cannot be influenced by the sleep system, the ventilation of the sleep system itself has a lot of influence on transportation of bodily fluids and moist creation.

Although the atmospheric pressure influences sleep, it is not influenceable by the sleep system.

3.3. USES FOR A SLEEP SYSTEM

A sleep system has many uses besides sleeping. An overview of most uses is introduced here, and the most important uses are briefly discussed.

Primary use

Most time in bed is spent sleeping, leaving aside exceptions such as hospitalised people. Adults typically spend between 6 and 9 hours sleeping per day, with averages depending on culture and age (National Sleep Foundation, 2012). That means that the main function of a bed and mattress is to support sleep. However, supporting sleep also means support the activity of trying to fall asleep, which is an active movement of finding the right position and getting comfortable. The new sleep system can be used to test what degree of interfering in this 'position-finding' is desired. The question is whether the user should find a position and the system should react to that, or whether the system should facilitate the user in changing to a certain position (also see chapter 3.4). This could be an interesting future research question if a sleep system capable of doing both options has been designed.

Other uses

People do a lot of different things besides sleeping. To come up with as many uses as possible, a mind map, shown in figure 11, was made with input from four different persons, complemented with online research. Note that overlap between categories exists, as for example all mentioned categories include some degree of movements and reading can be done sitting and

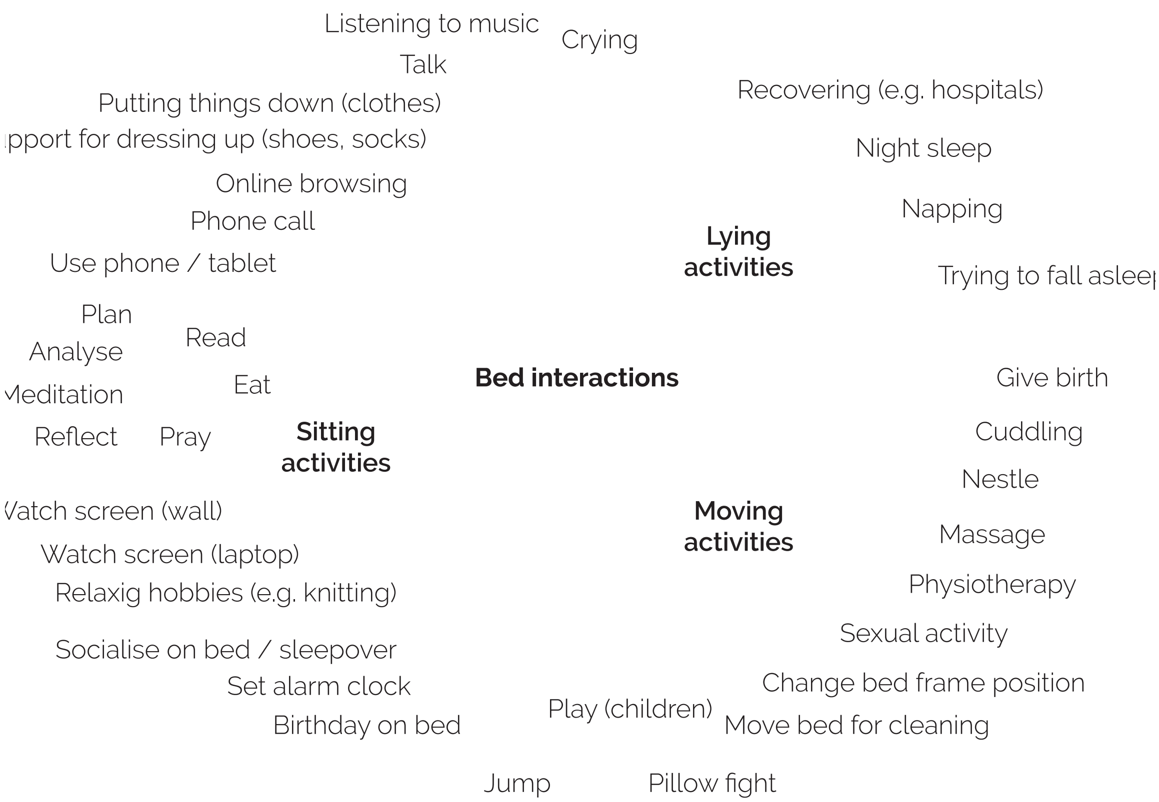


Figure 11 *Different uses for a sleep system (by author)*

lying down. These categories should not be considered as hard boundaries, but merely to summarise all activities by their main characteristics.

Although this is likely not everything that people use a bed for, it gives a good impression. As shown in figure 11, the interactions are divided into three categories: sitting activities, lying activities, and moving activities. Ideally, a sleep system supports all three of these interaction categories. However, existing sleep systems are not always capable of doing so. For example: memory foam mattresses make it difficult to move around and many slat-based sleep systems do not allow for sitting up in bed.

Most sleep systems are not dynamic, so do not adapt to change of movements or use. This is a good opportunity for the new sleep system. The two other uses, besides sleep, that will be kept in mind when designing are sexual activities and meditation, as together with sleeping, they form a good representation of the three interaction categories mentioned.

Sexual activities

Besides supporting sleep, supporting sexual activities is one of the most important secondary functions of the bed. How well a bed supports sexual activity is mainly determined by the mattress. The importance of this property shows through the number of websites that are dedicated to figuring out which mattress is ideal to perform sexual activity on. One of these websites, Sleeplikethedead (2017), claims to have collected data from over 640 mattress owners and made a matrix which compares different mattress types on suitability to support sexual activity (see appendix B.8). These results are averages and individuals' experiences may differ from these findings (Sleeplikethedead, 2017).

Meditation

Meditation has been around for thousands of years. People in the past went to sleep with sunset and got up at first light. This means that in many places, during certain seasons, nights would be too long for humans to sleep all the time. This causes humans to wake up after approximately 4 hours and spend some time (1~3 hours) awake before going back for a second 4-hour sleep. The time between sleeps was used for various things, also meditation (Ekirch, 2001; Oomen, 2003).

Suggested by psychologist Gregg Jacobs is that this time in between sleeps, could have played an important part in the human capacity to regulate stress naturally (Hegarty, 2012). For example, mindfulness is proven to be effective against anxiety and depression (Khoury et al., 2013). But also, other effects can be observed, such as an improved immune system (Davidson et al., 2003).

Today, people take less time for meditation, but because of the proven effects, it would be good to stimulate meditation. The bed could play a role in this. Many people have bedtime rituals that serve as "cue" for the body that it is time to sleep such as reading, bathing, and listening to music. But also meditation can serve as cue. There are several meditative positions, some a form of lying down, but more common is to sit up straight. A bed that sinks in too much can make it difficult to remain seated, while a bed that is too firm could cause painful pressure (Haex, 2004).

The focus of this project is facilitating the best sleep, which includes the dynamic process of falling asleep. While doing so, it is good to remember that the solution should allow for other interactions, such as sexual activity and meditation. The extent of different activities can be brought back to sitting-, lying- and moving activities, which are not hard boundaries but summarise the main characteristics of certain uses.

3.4. SLEEP POSITIONS

The primary use of a bed is sleeping, and this project aims to optimise that use. To do that, it must be understood in what positions people sleep and why. People also shift positions during sleep. This chapter focusses on how a sleep system controls the position of its user, the pros and cons of different sleep positions and how and why people move during sleep.

Forced position

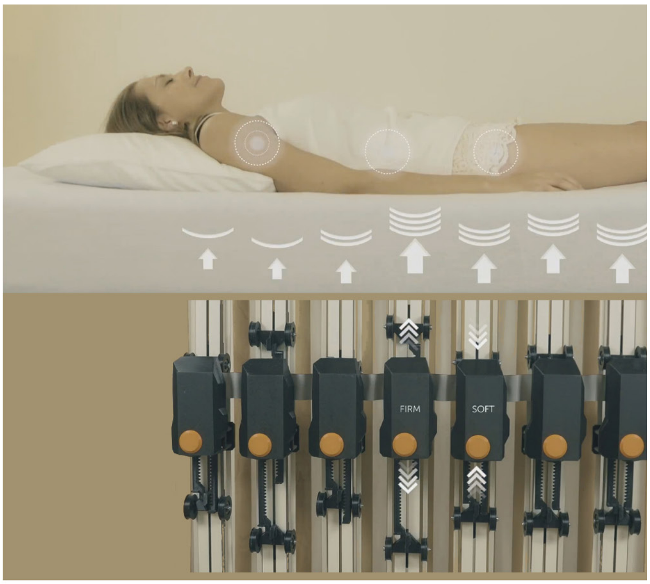
In his book, Haex (2004) writes that a sleep system (i.e., mattress, base and head cushion) should create perfect conditions (a state resembling weightlessness) and permit users to move freely to be able to optimise their body position unconsciously. But in reality, most sleep systems force their users in a certain position leaving few possibilities to minimise spinal deformations. Because of this, the sleep system plays a leading role in protecting the spine while the influence of the user's body posture is limited to an initial and conscious selected sleeping position and some minor unconscious optimisations during sleep. The challenge is to design a sleep system that has a less forceful impact or optimises the physical aspects of sleep quality (Haex, 2004). This requires control of the sleep surface.

Control

When examining existing sleep systems, three different types of control can be distinguished; some examples: With traditional beds **(1)**, the user has minimal control over his sleep position, as only his initial posture can

1. No control

2. Increased user control



3. Shared control

Figure 12 *Three types of control,*

images obtained from www.marktuckey.com.au/portfolio/simple-bed/, gethousedecor.com/adjustable-bedframe-for-your-room/adjustable-bed-frame-for-headboards and www.slimbed.be be chosen, while during sleep, the body unconsciously changes position. The bed on the other hand does not control anything, as it is a passive object, but sets limits to the available (comfortable) positions. Also, beds **(2)** exist that allow for more control by the user, such as adjustable bed frames or customised pressure zones. But control is still limited to an interface (e.g. a remote control or tablet) and adjustments while being awake. Recently, beds **(3)** have been developed hat allow the bed more control, such as the 'Slimbed' that responds to posture change and corrects sub-optimal body support (see chapter 4.2 for more examples). However, these types of beds are state of the art and some have not even been introduced to the market yet. Therefore, it is difficult to validate the claims made by the companies.

This last example is new territory within the industry as beds that are capable of dynamic and autonomous behaviour never existed and are just making its introduction to the market. The to-be designed sleep system in this graduation project takes it even further by not only adjusting pressure but also posture, which gives the sleep system even more control. These developments might be the start of a paradigm shift in the way sleep systems are designed.

An interesting dilemma accompanies this paradigm shift: *To what extent should the product have control over the user's sleep position?*

Poelman (2012) wrote about this dilemma and compared the interaction between a smart product and its user to the interaction between a horse and its rider. In this paper, he writes that the operation of a product has changed over time and that products can be controlled without any device or material interface at all. The operation by a user is shifting towards a cooperation between product and user. According to Poelman, this cooperation is very well illustrated by the cooperation between a horse and its user; The horse is susceptible to extreme subtle input but does not obey its user slavishly. The horse processes the information and makes an interpretation which determines the course of action. This could result in an action opposing the user's intention, for example to protect the user in a dangerous situation.

This cooperation is also important in this project because it is the user who unconsciously feels what is happening and whose sleep is influenced, while being unable to operate himself while asleep, whereas the product must sense what the user feels and how his sleep is influenced, while operating the controls. The bed could protect the user from harmful positions and optimise pressure and position to accommodate improved sleep. During sleep, operation is easier for the bed than for a horse because the user is unconscious and cannot interfere, but more difficult because the feedback will be more subtle and harder to read. While awake, the user can give clear feedback and the bed can learn about the user's preferences.

Learning about the user's preferences is expected to be a very important process, because the relationship between user and bed is based on trust. The user needs to trust the bed in knowing what is best for the user while asleep.

As beds in the past were never able to actively control a user's sleep position, it is unknown what the short- and long-term effects are of doing so. For example, it is possible that sleep does not improve with an improved spinal support, or that the amount of detail with which this system can provide spinal support is excessive. It could also be possible that continuous ideal spinal alignment is in fact bad for unknown reasons, such as the loss of spinal strength or capabilities to recuperate.

The question to what extent automated position control is desired can only be answered through extensive short- and long-term research. The bed as described in this project can provide for the tools required for this research.

Knowledge on sleep positions

Before thinking about controlling the sleep position of a user, it must first be known how people sleep and why. There are different sleep positions, and people have preferences how to fall asleep, but will change positions during sleep. Figure 13 shows some of the many possibilities, but available research limits itself in general to three main positions:

- Supine (lying on back)
- Prone (lying on stomach)
- Lateral (lying on side)

Of these, people spend most time on their sides (60-70%), second-most on their backs (20-30%) and least on their stomach (5-10%), as several studies have shown (De Koninck et al., 2992; Verhaert et al., 2013; Haex, 2004).

McCabe and Xue (2010) also linked sleep postures to gender differences as 73% of women seem to prefer lateral positions over 50% of the men. The study was done through a survey where the subjects were asked for their preference, which could mean that this is merely the preferred position when falling asleep, but it does not mean that females sleep more on their sides.

The trustworthiness of self-reported sleep positions is questionable. Gordon, Grimmer and Trott (2004) studied how accurate self-reported sleep positions are compared to the actual video recorded sleep positions. They found that the reliability of self-reports of ‘usual’ (92%) and ‘last night’ (83%) sleep positions was good. But another study, by Russo and Bianchi (2016), suggest that the self-reported body position may not reliably match objective position.

Figure 13 *Number of sleep positions,*
image obtained from bedtimesmagazine.com/2017/09/new-bsc-research-says-sleep-positions-may-reveal-think/

Supine position

De Koninck, Gagnon & Lallier (1983) compared sleep positions between 8 good sleepers and 8 bad sleepers. They found that bad sleepers spent more time in positions sleeping on their backs, with their heads straight. This could facilitate a degree of upper airway closure. Miyawaki et al. (2003) suggest that sleep bruxism (teeth grinding) is also associated with the supine position. For people with obstructive sleep apnea (OSA), a study by Penzel et al. (2001) found that the lateral position is better than the supine position. However, this depends on the type of OSA, as people with tongue-related obstruction do not have improved airflow in the lateral position, while people with other types of OSA did show small or great improvements (Marques et al., 2017). In general, most studies show that supine sleeping could have negative consequences for people with OSA.

On the other hand, the supine position distributes the body weight over a larger surface, which improves the pressure distribution and stability (Haex, 2004). Besides that, Khan and Uddit (2015) researched different sleeping positions for the best cardiac activity and concluded that the soldier (supine) position is the best while the freefall (prone) position is the worst. Also, for infants it is recommended to sleep in the supine position, at least the first six months of their life, to prevent Sudden Infant Death Syndrome (SIDS). But these infants should also get sufficient prone play time to prevent undesired side effects (Jones, 2004).

When sleeping in the supine position on too soft a mattress, the hips will sink in too deeply resulting in some relaxed muscles, but not a relaxed spine. The pelvis cants backwards resulting in an undesired kyphosis (see figure 14) in the lumbar area of the spine, where the intervertebral disks are compressed at the anterior side, while soft tissues are dilated on the posterior side (see figure 14).

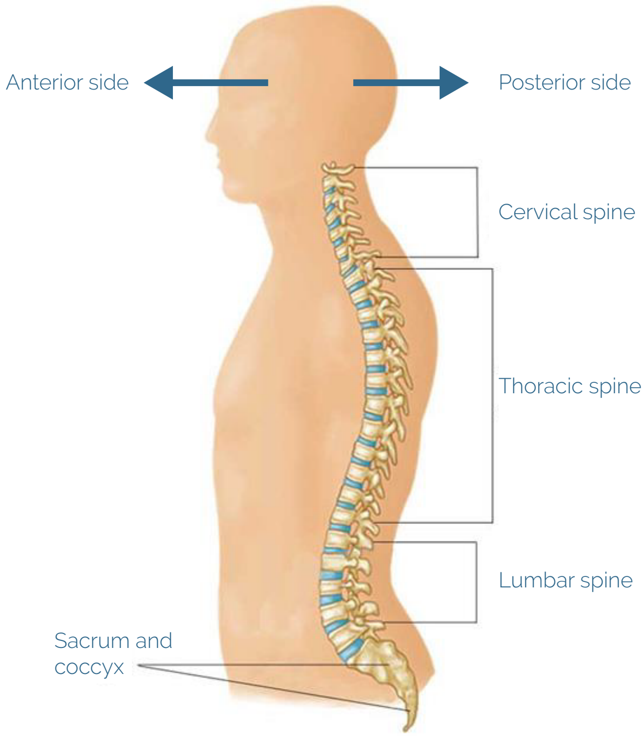


Figure 14 *Parts of the spine,*
image altered from https://orthoinfo.aaos.org/en/diseases--conditions/fractures-of-the-thoracic-and-lumbar-spine/

In case of too firm a mattress, the lumbar area will not make contact with the mattress when lying down. When the muscles relax (approximately 10-15 minutes after lying down), the pelvis cants backwards upon which the lumbar area makes contact with the mattress. This can lead to discomfort for some, when the legs stay in horizontal position. Haex (2004) mentions that the semi-Fowler's position may solve this problem, which is acknowledged as a common relaxed position.

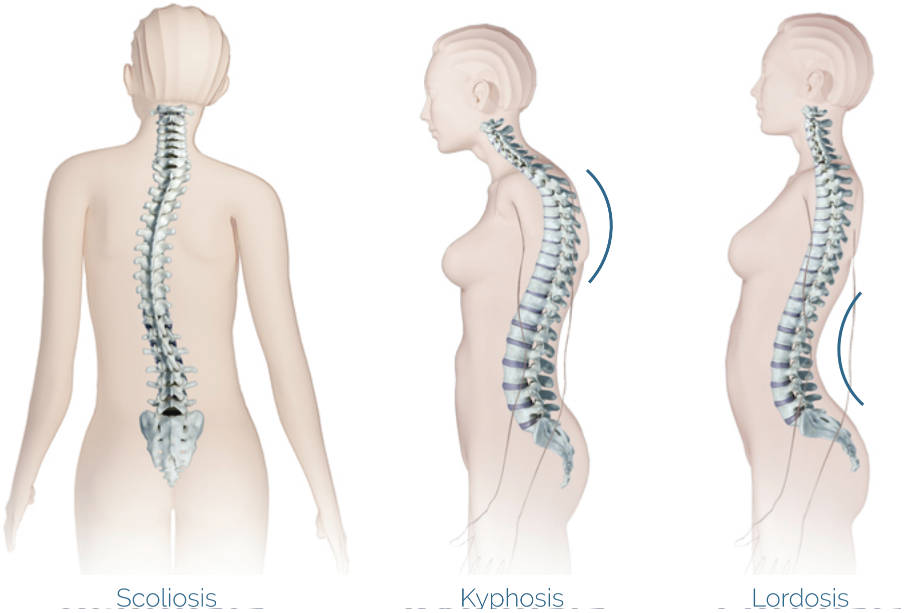


Figure 15 *Spinal deformations,*
image obtained from https://webcontent.temed.com/spine/disorders/symptoms/spinal-deformity

Prone position

According to Coenen (2011) the prone position is least favourite, because the body presses on vital organs such as the heart and the position of the head relative to the body is not ideal, which is also true for the supine position. Most pillows do make it worse as they are designed for the lateral position. Haex (2004) also considers prone to be the worst position, but because of missing back support. Gravity increases the lumbar lordosis significantly and causes pressure on the facet joints on the posterior side and dilates the soft tissue on the anterior side. In some soft sleep systems, this may result in hyperlordosis due to an increased indentation in the pelvic zone. Spinal loading is also increased because the head is usually twisted sideward to improve breathing. Respiratory problems may also be caused because of the body weight resting on the rib cage and the intestines pushing against the diaphragm, which both increases pressure on the lungs. Even blood vessels may be compressed, possibly resulting in headaches, dizziness or other disorders (Haex, 2004).

On the other hand, Defloor (2000) mentions that the prone position results in a lesser interface pressure than the lateral position. And some of the disadvantages caused by the prone position can be improved, for example removing the pillow reduces the neck rotation and adding a pillow under the belly restores the natural spinal curve. Also shifting slightly towards the lateral position towards the side the head is turned by elevating the knee and hip or lifting the arm on that side will take away quite a number of problems as well (Haex, 2004).

Lateral position

The lateral position is judged positively by many researchers. It is also the most taken sleep position among Western people. Coenen (2011) calls it the best sleep position and Haex (2004) explains that sleeping lateral makes it possible to flatten the lumbar lordosis (which also happens during unloading of the spine) by bending the knee and hip joint which may be the reason why many people prefer this position. Sleeping on the right or left side does not make a lot of difference, except when sleeping on the left side the weight of the liver acts on the stomach and lungs.

The disadvantage, according to Haex (2004), is that the lateral position is more unstable than the other positions. That is why people often use their arms and legs to increase the support area and improve stability. However, the pelvic and shoulder girdle should lie at the same angle to prevent torsion on the spine which may be harmful for the intervertebral disks. This can be prevented by putting something between the knees (e.g. a pillow or blanket), which also helps prevent scoliosis do to a more symmetric loading of the spine. For this reason, it is also important that the feet are positioned higher than the pelvis (see figure 16).

Defloor (2000) found that the lateral position in fact results in the highest interface pressure on the skin and that the semi-Fowler position and the prone position are both preferred over lateral in terms of pressure readings.

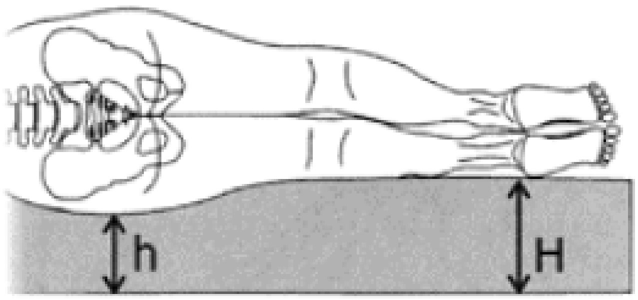


Figure 16 *Feet positioned higer than pelvis (Haex 2004)*

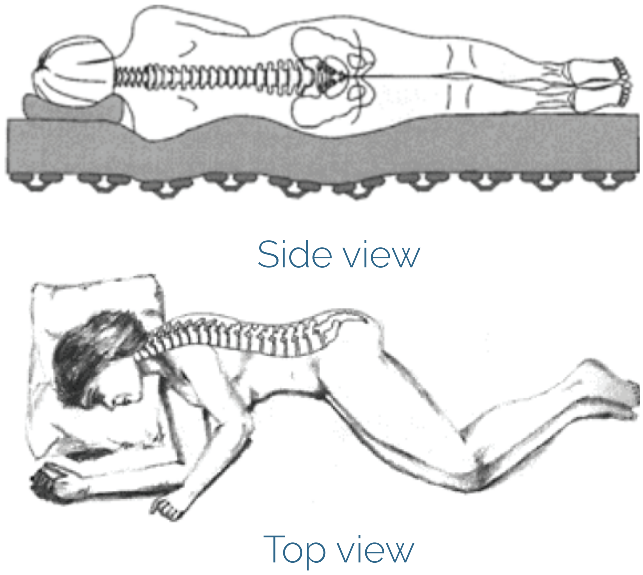


Figure 17 *Spinal alignment for lateral position, image altered from Haex (2004)*

When sleeping in the lateral position, the optimal spine support is obtained when the spine looks straight from a side view and adopts the natural curve from the top view (see figure 17).

Too soft a mattress causes too much sagging and prevents a relaxed spine (often the case with worn-out mattresses), while too firm mattress result in a wrong spinal alignment.

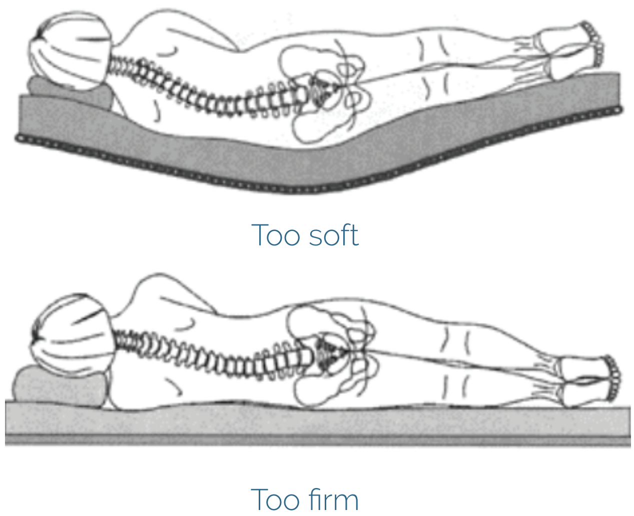


Figure 18 *Mattress firmness for lateral position, image altered from Haex (2004)*

The pillow

The pillow should also be contributing to proper spinal alignment. This is done by the shape of the pillow as well as the correct positioning done by the user. However, different positions require different pillows, which means one pillow could contribute to spinal alignment in one position and counteract in another position.

Differences according to body structure

Preferred sleep position is also different for people from different races. Asian people sleep more often in the supine position, while Caucasian people prefer the lateral position. That does however not mean that all Asian people sleep supine or all Caucasians lateral. Differences in anthropometric properties may play a role in this preference. There are theories and indications that Asians have some differences in their musculoskeletal system compared to Caucasians, which could clarify why they would experience less discomfort sleeping on hard surfaces (e.g. a futon). Also, Caucasians seem to profit from a lateral sleep position because they can smoothen the lumbar spine, which is needed to approximate the natural shape, as is the case in the semi-Fowler's position (see figure 22) (Haex, 2004).

Movement during sleep

People change their positions during sleep. According to Haex (2004) this is because body zones in contact with the sleep system will form local ischemia's (a shortage of blood, thus oxygen supply) which signal the body to change position before it gets painful. Also, lying still for too long could be bad for the health, and some form of movement may be imperative. Movement is required to prevent pressure sores, muscle stiffness and provide for proper blood flow (Defloor, 2000; Haex, 2004). A regular shift of position, about 20 times per night for adults according to De Koninck et al. (1992), should be sufficient. On some types of beds (e.g. waterbeds, pressure distributors, or too soft mattresses) the user sinks too deep into the mattress resulting in rolling back into the cavity when trying to move. The resulting extensive time spent without movement is

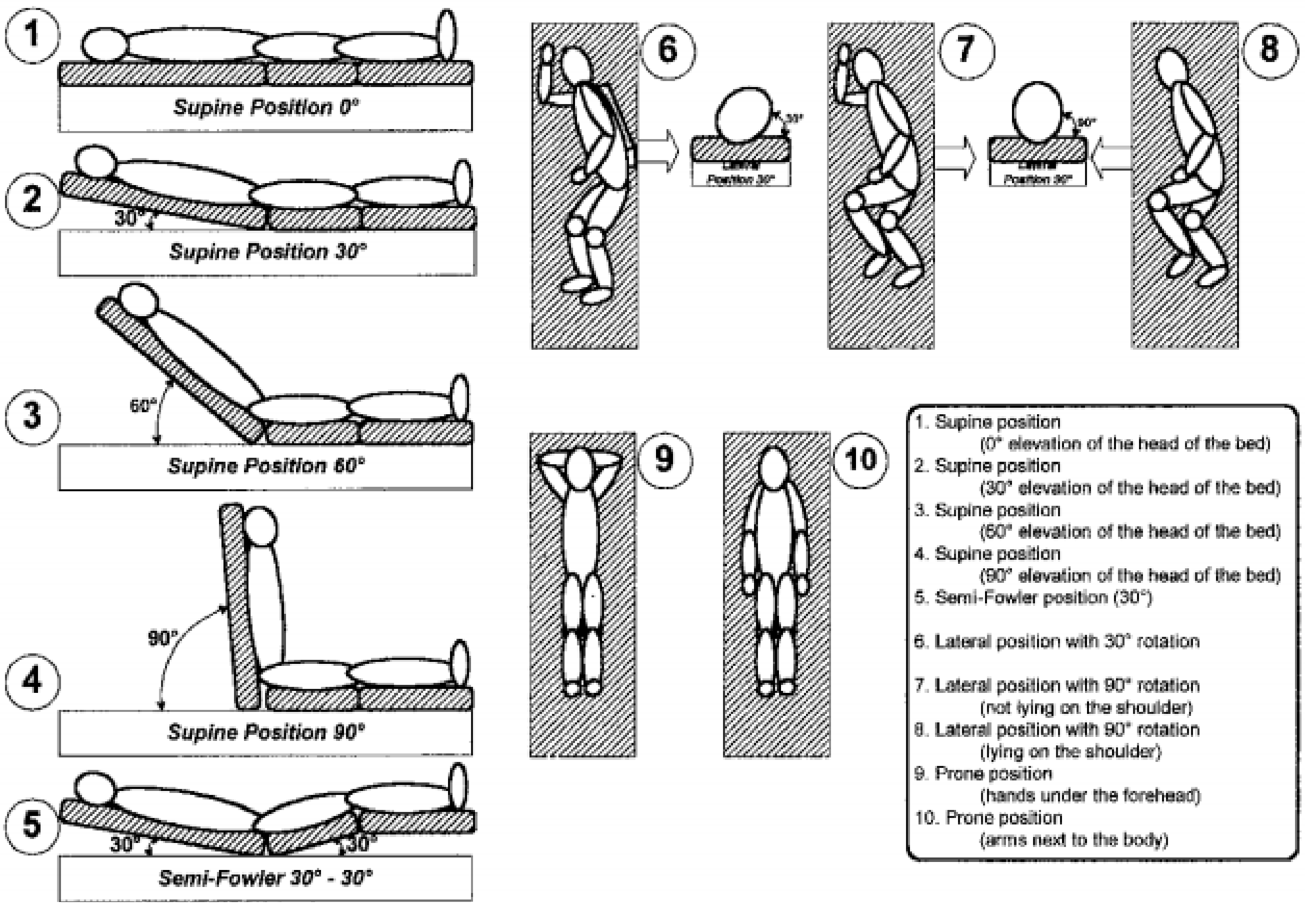


Figure 19 *Tested positions by Defloor (2000)*

harmful for the muscular system and possibly the respiratory system as well (Haex, 2004).

The negative effects for a lack of movement were also discovered in office work, where sedentary behaviour is associated with health issues, such as type II diabetes, cardiovascular disorders and even premature death (Groenesteijn, Commissaris, den Berg-Zwetsloot, & Mastrigt, 2006). Whether insufficient movement during sleep could also contribute to these health issues is unknown.

How often people move is related to several factors. One of these factors is how much interface pressure is applied by the mattress. Defloor (2000) tested ten different positions with two different mattresses and concluded that the 30° semi-Fowler position and the prone position generate the least pressure (see figure 19). Increasing the contact surface will also decrease the interface pressure.

A study conducted by De Koninck, Lorrain, & Gagnon (1992) shows that children change their positions about twice as often as elderly. In their study, pre-adolescents (8-12 years) changed positions most often (4.7 changes per hour on average), and elderly (65-80) the least often (2.1 changes per hour on average), see figure 20. Also, with age, people have an increase in the duration of their positions and an increase in the number of periods of postural immobility longer than 30 minutes. Children would spend equal amounts of time in the supine, prone or lateral positions, while with age, the prone position is less favoured and elderly prefer right-side positions.

Changing posture too often is also not a good thing. Too firm mattresses can sometimes cause this excessive movement, but it will increase restlessness and sweating during sleep. Also, it will prevent the muscles from relaxing sufficiently, preventing intervertebral disk rehydration, causing back pain indirectly. Changing positions can also interrupt sleep stages (especially SWS), which could have adverse effects on the fitness of a person the next day (Haex, 2004).

From a skype session with sleep researcher Rachel van Sluijs (ETH Zürich), it became clear that people take some time to consolidate a new sleep position. Any adjustable bed or mattress should therefore not respond too fast to position changes. On the other hand, people need to be able to change posture easily. Posture change is needed to avoid pressure overloading of soft tissues and to prevent muscle stiffness (Haex, 2004).

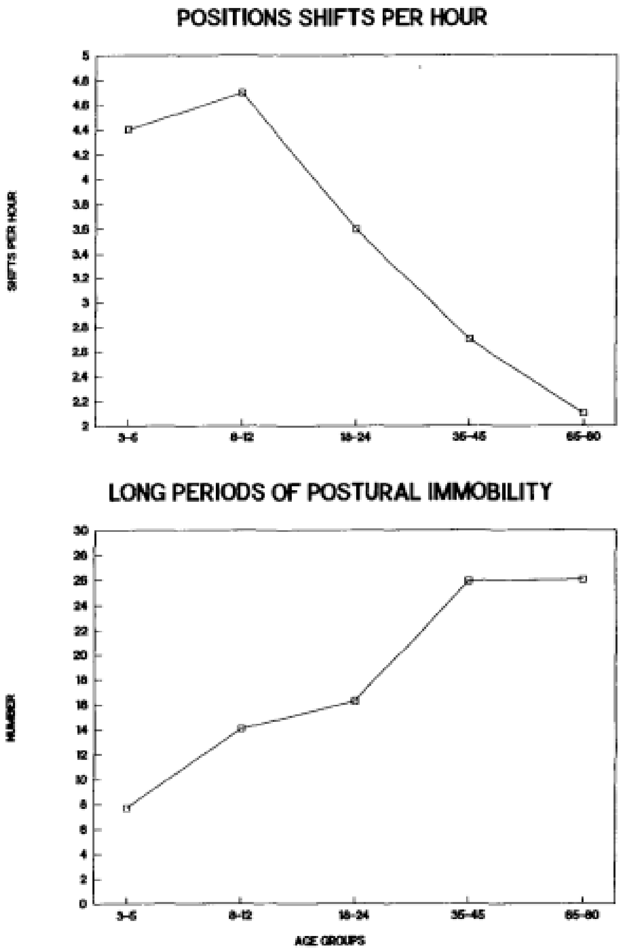


Figure 20 *Position shifts (De Koninck, Lorrain, & Gagnon, 1992)*

Decubitus ulcers

Body areas that are in contact with the sleep surface, especially on firm mattresses, can suffer from a restricted blood flow, called ischemia. This ischemia stops oxygen from reaching certain body tissues, which will eventually lead to cell death (see figure 21). Normally, the body can detect this change in metabolic activity in time, resulting in posture change. But in some cases, a person is unable to move, for example in a hospital situation, where this is a big problem. The critical duration that can cause pressure injury is different per person and lies somewhere between 30 and 240 minutes. And aside from external pressure, there is also an individual variable tolerance of tissue to ischemia (Anders et al., 2010).

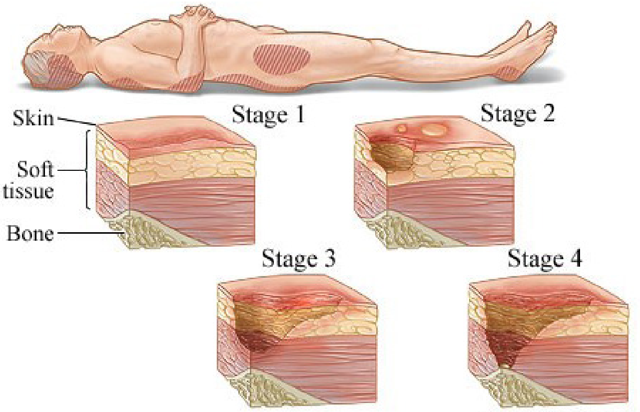


Figure 21 *Stages of decubitus, image obtained from decubitusulcervictims.com/wp-content/uploads/Peripheral-Vascular-Disease-and-Pressure-Ulcers.jpg*

Too soft mattresses can make it difficult or even impossible to change positions. It will cost more energy on a soft mattress to turn, than on a firm mattress. Especially for older people this can be problematic, as it becomes more difficult to move with age. Too firm mattresses on the other hand, can make it difficult to stabilise a position because of lack of support. Some mattresses have different zones with altering physical properties to deal with different weight distribution (Haex, 2004).

Fowler's positions

As several researchers mentioned, the Fowler's position has certain advantages. Dr. George Ryerson Fowler used the now famous "Fowler's position" as he found it could save people from diffuse septic peritonitis (a harmful and dangerous inflammatory reaction of the body to an infection in the peritoneal cavity, which is located in the abdomen) as it allowed septic fluids to flow from the abdomen to the pelvis (Volk, 2006; Kelleher, Swan, & Kelleher, 2011).

The original Fowler's position kept the trunk of the patient at an angle of 45 degrees from horizontal. Later, according to Kelleher et al. (2011), alternative Fowler's positions were added, such as the high Fowler's position where the head is raised almost upright, and the low semi-Fowler's position at 30 degrees from

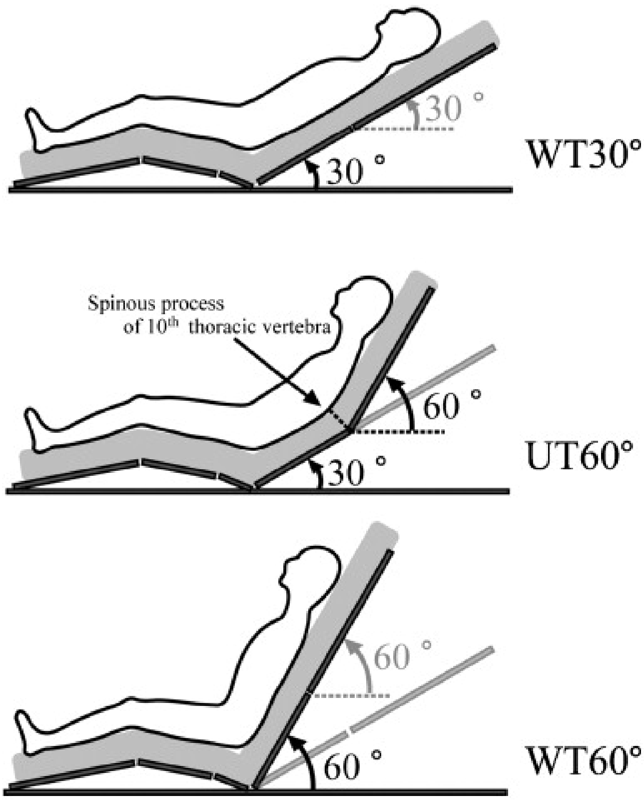


Figure 22 *Fowler's position alternatives (Kubota, Endo, Kubota, Ishizuka, & Furundate, 2015)*

horizontal. Other sources mention different angles and give different names, but in general, a lying supine position where the upper body is lifted under an angle between 15 and 90 degrees is considered a Fowler's position. The legs may be slightly bent and there are some other variations thinkable (see figure 22). But most authors that relate to Fowler's positions for an ideal sleeping position, refer to the 'semi-Fowler's' position, which Defloor (2000) specified was under a 30-degree angle.

Known advantages of this position are:
- Optimal pressure distribution.
- Spinal strain relief.
- Muscle relaxation.
- Contours the natural spinal curve.

Existing sleep systems limit the number of comfortable and physically healthy sleeping positions people can take as shape and firmness cannot be adjusted or only before going to sleep. Users as well as the sleep system have almost no control how users position themselves during sleep. Some beds are in development that improve this control, but a truly smart bed that makes decisions for the user is not yet on the market. This graduation project takes a step towards that direction.

In general, three sleep positions are distinguished: supine (back), prone (belly) and lateral (sides). There is not one ideal sleep position since all have their pros and cons, and people have different preferences and anthropometrics between age, gender and race. But in general, the 30-degree semi-Fowler's position is considered one of the best positions for pressure distribution, strain relief and relaxation.

People take different sleep positions during sleep, which is important. Insufficient movement can lead to pressure sores, stiff muscles or even health problems. To support the new positions, the mattress should take different physical properties and the pillow should change in height or even shape. The product designed in this graduation project incorporates this desired behaviour.

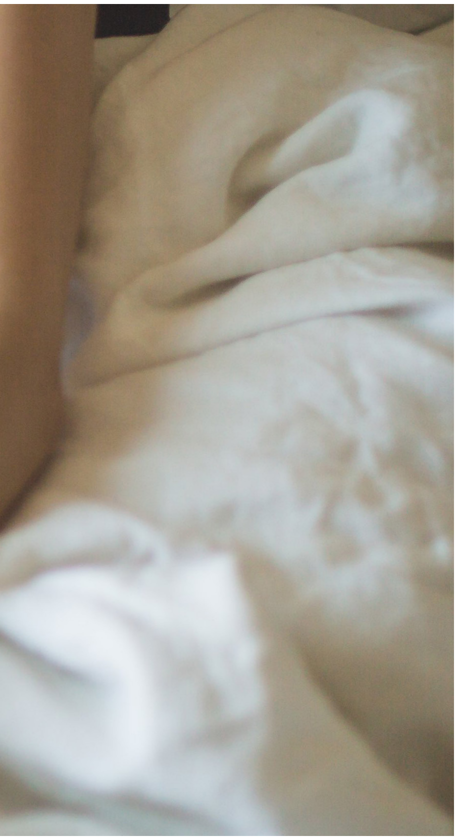
3.5. SLEEP PROXIMITY

Besides different uses for a sleep system, the bed can also be shared. How beds are shared depends on age, culture and preference.

Sleep context differed throughout time and differs between cultures. There is a big difference between how families sleep in Western cultures and other cultures. For example: In a study conducted in India by Bharti, Malhi and Kashyap (2005), 91% of children between 7 and 10 years old still shared the bed with their parents. In contrast, a study conducted in Kentucky by Montgomery-Downs and Gozal (2005) shows that only 10% of the children between 2 weeks and 2 years old co-slept with their parents in the same bed, with another 4.9% who slept part-time in the same room (not bed) as the parents and part-time in another room. Also, other setups are commonly found, for example where the father sleeps separate from mother and siblings.

Figure 23 *Sleeping with pets (image obtained from pexels.com)*

A common composition in Western families is that the parents sleep together and the children have their own rooms and beds. Research shows that when couples share a bed, there is a strong relationship between body movements during sleep, although declining with age. Subjective evidence suggests that men are more likely to affect their partner's sleep than are women. Men had a higher incidence of discrete movements. Interesting to note is that objectively, sleep is "poorer" when couples sleep together, yet they still prefer to sleep together rather than alone. Subjectively, they feel that they sleep better together, apparently unaware of the decrements in their sleep quality. For women, the main reason for this preference is because they feel secure with their partner, while for men, it is more through habit. Couples that prefer to sleep alone was mainly due to a partner snoring, taking up too much space or being restless. On average, people sleeping together sleep longer than people sleeping alone (Pankhurst & Horne, 1994).



Co-sleeping

A highly complex discussion is held concerning the question whether infants should co-sleep with their mothers or not. There is good reason to believe that infants should never sleep alone, as they benefit physically and mentally in several ways and because observations of Sudden Infant Death Syndrome (SIDS) are less among non-smoking mothers in many cultures where co-sleeping is normal (McKenna & McDade, 2005). On the other hand, it is argued that the baby should sleep alone because of risks for suffocation. Especially if the parents are smokers, risk of SIDS increases when sleeping in the same room (Fleming & Blair, 2007). The compromise is often that a crib is placed in the same room, which seems to be at least an acceptable solution, as according to McKenna and McDade, room sharing combined with an actively breast-feeding mother saves lives.

Sleeping with pets

Another thing that must be considered is people who sleep with their pets. Eckstein (2010) writes that nearly half of the dogs in America sleep in their owner's beds. And about 62% of cats sleep with their adult owners while 12% sleep with children.

This also offers challenges to mattresses in terms of hygiene, and of course for a smart mattress, to measure the pets and adjust to them as well.

Concluding from people's different sleeping proximities and co-sleeping behaviour is that a bed should be designed keeping specific use contexts in mind. A smart bed that optimises sleep for one or two persons might not be sufficient as more family members and even pets could be sharing the same bed.

Also, the co-sleeping dilemma offers an opportunity for a smart bed, as it could help in preventing SIDS, e.g. by measuring the breathing pattern of the infant and warning the parents.

4. USER, TRENDS & TECHNOLOGY

The previous chapters explained about sleep, the sleep system, the bedroom environment and problems related to sleep. This chapter describes the potential users and latest technological developments to find possible user needs and values.

Photo from pexels.com

4.1. POTENTIAL USERS

When thinking about a smart bed that can adjust shape and pressure to the preferences and personal profile of its user, it is possible to imagine that certain users would see different benefits for such a system:

1. Medical sector: Previously, it was defined that a sleep system could influence the prevention, symptom management or cure for back pain-related disorders. People suffering from these disorders could benefit from a sleep system that knows the user personally with their specific pain points and knows how to position them best. In that sense, a user becomes a patient of his own bed. This means that, depending on the severity of the medical disorders, the bed could be used for home care or in hospitals.
2. Hospitality sector: Another interested user would be the frequent visitor of hotels (e.g. business travellers). Imagine that the user would go to his hotel room and the bed would simply retrieve his data from the cloud and know exactly about the preferences and situation of the user. Therefore, hotels might be interested in delivering such a service to their customers.
3. Transport sector: Also, frequent flyers or truck drivers, people who use chairs for a longer period might benefit from more personalised systems. Of course, the focus of the project is on sleep, but the system could be applicable for seating appliances as well.
4. Mass consumer sector: And lastly, the largest group that would benefit from a sleep system that facilitates better sleep are the mass consumers, as insomnia symptoms are common among the general population (Leger, Poursain, Neubauer, & Uchiyama, 2008; Kerkhof, 2017; Ohayon & Smirne, 2002).

These potentially interested user groups also relate to potentially interested customer segments. But some of these end user groups would not be the customers, and a distinction between business to business (b2b) and business to consumer (b2c) market segments must be made. A short overview of business potential and market opportunities is described in chapter 8.

4.2. STATE OF THE ART

Besides looking at beds from the past and more recent times, it also important to look at the state of the art and realise what people buy today and current trends.

As history shows (appendix B.5), much of the technology that was developed over the last 150 years is still being used today and beds today look similar to beds 150 years ago: A bed frame, with a bed base and a mattress.

In general, four kinds of mattresses are used in the Western world: Foam mattresses, latex mattresses, spring mattresses and fluid-based beds. However, it looks like a paradigm shift might be coming, as the Internet of Things (IoT) trend has a hold on many industries and a lot of companies feel pressure to make their products smarter. Xia et al. (2012) explain IoT as follows: "Generally speaking, IoT refers to the networked interconnection of everyday objects, which are often equipped with ubiquitous intelligence." This is also visible in technological bedroom- and sleeping trends, sleep related start-up companies as well as some of the newest mattresses and bed related products that appeared or are appearing on the market.

Bedroom trends and developments

Trendwatcher Van Dijk (2016) who also writes for Elsevier Juist magazine, expects the bed to become centralised in the house. With growing attention for the bed, accompanied with other trends for health and smart technology, there is a rise in sleep promoting technology. The latest technological trends are sleep apps, sleep products and smarter mattresses and beds (see appendix B.7). The smart beds that could compete with the system designed in this graduation project are discussed here.

Mattresses and beds

Besides apps and smart bedroom products, also smart mattresses and beds are upcoming. Below is a summary of each of these mattresses. Some are already for sale while others are still under development.

Sleep number 360 (on market):
Price range: 1699 – 4499 $ (the price increases with thickness of the bedding and features, such as cooling)
Tracks sleep and posture and adjusts firmness accordingly by inflating air chambers. Can also detect snoring and can automatically raise the head slightly to stop snoring. There is also a heated foot zone.

Figure 24 *Sleep Number 360 (obtained from www.unwrapp.co.uk/home/sleep-number-360-smart-bed/)*

Balluga (discontinued):
This bed was very promising as it came closest to a dynamic bed with active adjustment throughout the night in both length and width dimensions in a grid of air-filled suspension cells. The bed ran a few successful crowdfunding campaigns but were unable to deliver to the customer. They now claim to be refunding the backers and the project is discontinued.

Figure 25 *Sleep Number 360 (obtained from www.indiegogo.com/projects/balluga-the-world-s-smartest-bed#/)*

DynaSleep Intelligent Bed System (under development):
(developed by Custom8, used in research institutes and retail environments)
This is the system that seems most dynamic compared to its competitors. It is a smart sleep system that measures posture and comfort related parameters (not specified which parameters) during sleep. They have developed two systems. The first is an adaptive spring unit, which consists of several pocket springs with a variable pre-tension that can be linearly adjusted using two motors. The DynaSleep system uses eight of these adaptive spring units, located around the torso and hip zone.

They also developed an adjustable bed base slat system. An actuator can adjust the stiffness of the slats to improve the body support.

The bed contains a sensor mat (IdoShape) that detects movement and measures deflection. Currently, the bed is used as a measurement tool in R&D centres and in retail environments.

Figure 26 *DynaSleep (obtained from www.custom8.be/intelligent-bed/)*

Figure 27 *ReST bed (obtained from thesleepemporium.com/product/rest-performance-smart-bed-king/)*

ReST (on market):

Price range: 2799 – 5598 $ (pay for size)

Has five zones for which firmness can be controlled manually or automatically by inflating air chambers. The bed measures the pressure of the user on each zone. It is also possible to set firmness for different positions beforehand; the bed will detect the positions during sleep. This is probably the best dynamic bed currently on the market.

Somnomat (under development):

A project under development at the ETH Zürich in which they try to create an autonomous robotic platform that can monitor and interact with the user to improve sleep quality. In this project, they have tested the effects of rocking movements on promoting relaxation. No conclusive effects were witnessed yet (Crivelli, Omlin, Rauter, Von Zitzewitz, Achtermann, & Riener, 2016).

Figure 28 *Somnomat project*

(obtained from www.sms.hest.ethz.ch/research/current-research-projects/somnomat.html)

Developments of smart beds

These beds are all attempts to improve problems caused by passive beds. However, they must be tested and compared to each other and non-dynamic beds before being able to conclude that they are indeed an improvement. No scientific studies have been conducted yet to verify any of the claims made by these companies.

Some things that these beds have in common is that they all rely on changing firmness. However, they cannot change their form to match the shape of the body or make a user sit or lie down in any desired position.

Also, these beds use predefined zones with set dimensions. This could cause problems for very tall or very short users. They also only allow for adjustments in firmness over the length of the bed, not over the width.

Vincent (2016), reporter for The Verge, writes:

“Dr Himender Makker, a sleep specialist at University College London Hospitals, told The Verge that in cases when a sleeper needs to change position to stop snoring, a significant adjustment is what’s required — having them sit upright by at least 35 degrees. The Balluga’s gentle tilting and shifting probably wouldn’t help here, and Katan [Balluga’s CEO] admits that this anti-snoring tech also wouldn’t be able to combat more serious problems like sleep apnea”

What is different?

The sleep system developed in this graduation assignment is focused on changing shape instead of firmness. This system is designed to closely approximate a large range of human body measurements, based on extremities (see chapter 6.2). This means that the system creates a double-curved surface which can optimally align the spine. Being able to change the shape in both the length and width direction allows for far greater control than only adjusting firmness of a few zones in the length direction.

The system is also unique because it can change the user’s position. This could be valuable for therapeutic purposes, for example to prevent decubitus in hospitals or to keep people with chronic back pain in comfortable positions.

This system also allows people to take a great variety of seated positions, which the other smart beds cannot do besides the slat system which can be used in a traditional adjustable bed frame.

4.3. CONSUMER NEEDS & VALUES

Needs and values are different per consumer. However, Bain and company (2016) identified 30 universal consumer needs that companies can target with their product or service (see figure 29). These are divided into four categories:

- Social impact
- Life changing
- Emotional
- Functional

To find overlap between these 30 needs and sleep-related needs that could be targeted in this project, a synthesis of all information collected in the previous chapters was made. This resulted in the needs highlighted with a blue circle in figure 29.

- Provides hope: This is mainly applicable to users who have trouble falling asleep.
- Design/aesthetics: In the past, people saw the bed as a status symbol, and now the bed and bedroom are becoming more important again, meaning that aesthetics play an increasingly large role.
- Wellness: A relevant need to all users is that the bed keeps the user healthy and prevents spinal injuries or pressure sores.
- Therapeutic value: Users suffering from back pain-related medical disorders or potentially other sleep-related disorders, have strong therapeutic needs.
- Fun/entertainment: With most recent innovations, it becomes clear that users enjoy gadgets and special functions such as smart alarms and massage options.
- Simplifies: Buying behaviour shows that people do not know what to buy because there are too many different types of beds and beds consist of too many different parts.
- Avoids hassles: Users need a bed that makes the difficult decisions of what is a good position, firmness and support instead of themselves having to set and decide everything manually.
- Quality: Users need a bed and especially mattresses that do not need to be replaced every 7 to 10 years and that not get worse over time.
- Variety: Although people do not like hassle, there must be variety in options to give a feeling of autonomy.
- Sensory appeal: When attempting sleep, sensory appeal is evident as smell, noise and discomfort could all ruin a good night's sleep.
- Informs: With all the sleep trackers available, there seems to be a clear need for information.

Not all of these are relevant to all potential users or equally important. But it does help to come up with desired functions for the design of the sleep system. To determine the underlying user values, similarities between these needs and the analysis from the previous chapters were sought. This resulted in the following values:

Comfort	Wellness, Therapeutic value, Simplifies, Avoids hassles, Sensory appeal
Confidence	Provides hope, Wellness, Therapeutic value, Quality
Curiosity	Fun/entertainment, Variety, Sensory appeal
Enjoyment	Design/aesthetics, Wellness, Fun/entertainment, Variety, Sensory appeal
Control	Variety, Informs

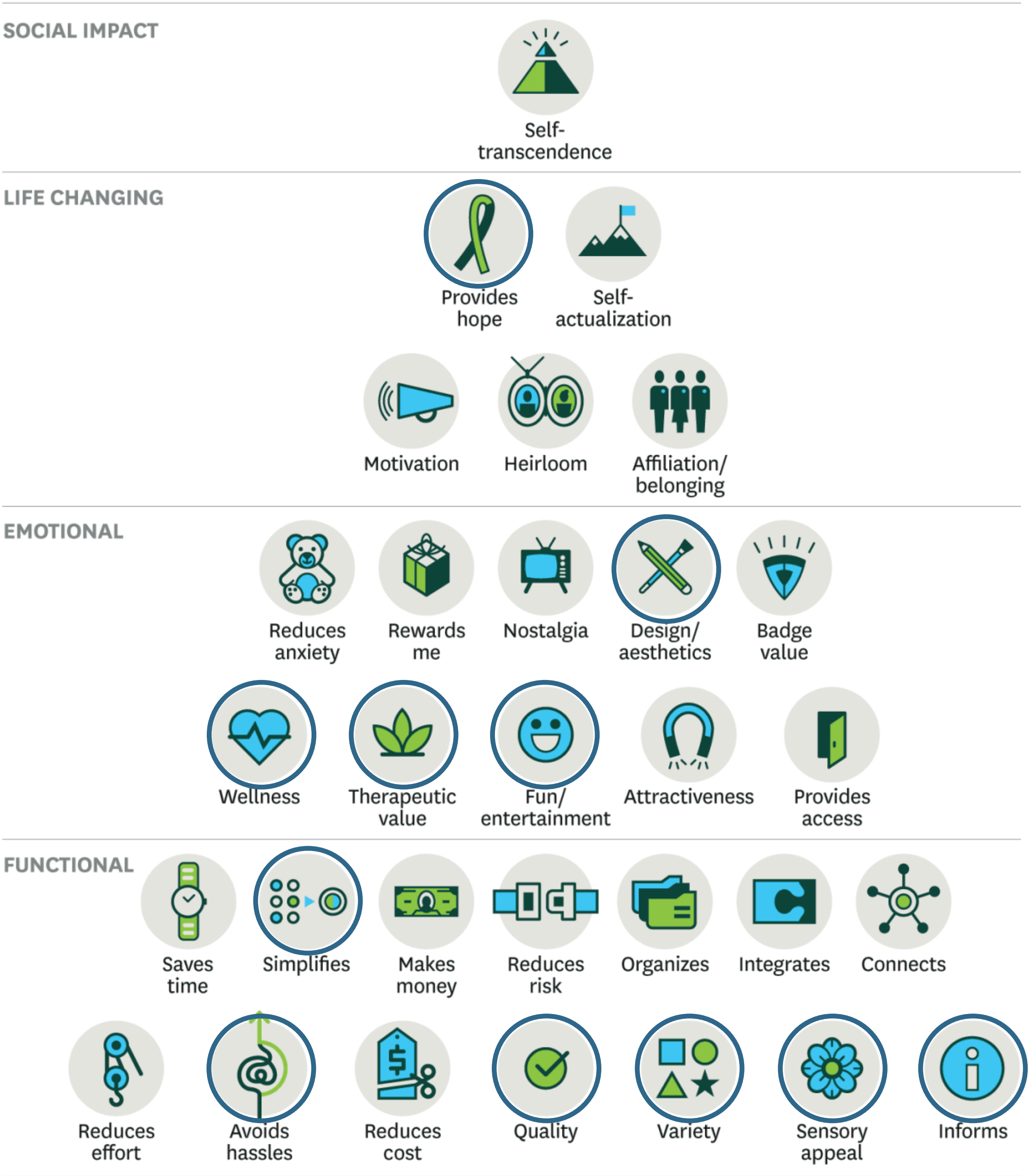


Figure 29 *Universal consumer needs (image by Bain and company, 2016)*

Photo by Burak Kebapci from Pexels.com

5. PURPOSE DESIGN

Roozenburg and Eekels (1998) created a model that explains the act of interfering in the existing state of reality (see appendix A.3). A designer does this by capturing his desired state of reality in a 'purpose design'. Based on this purpose design, the designer will come up with a means design (an artefact) that will be the 'interfering act' and result in a new state of reality.

This chapter will conclude the analysis phase with a purpose design. Following chapters will focus on the means design.

5.1. DESIGN VISION

As the initial challenge and problem statement are quite generic, they have been redefined in conclusion to an extensive literature review and several conversations with experts. This research is found in the following chapters.

The focus of the project is on facilitating the best sleep. Therefore, it is important to know which factors contribute to sleep and who would benefit most. In appendix B.2, it becomes clear that sleep is a highly complex process and that sleep quality is affected by physiological, psychological and psychical factors. From these factors, the following were selected to focus on as they have a relevant influence on the comfort perception and are influenceable by the sleep system:

- Spinal alignment
- Pressure distribution
- Temperature

By influencing these factors sleep quality can be improved. But for people who are already good sleepers, it is questionable whether their sleep can be improved even further. Especially because people who feel confident about their sleep are not likely to buy a new bed or wonder whether they could improve their sleep quality. Because of this, the focus of the project will be on people who surely benefit from an improved sleep as their current sleep quality is poor.

For that reason, sleep disorders were studied and the potential effects of an improved sleep system were estimated in appendix B.3 and B.4. This resulted in the focus on people suffering from insomnia. However, as it can be difficult to properly diagnose insomnia, it is also difficult to determine what role the sleep system plays in this situation. There is however a clear relation between pain, mood and insomnia. Reducing pain results in better sleep and in better mood which also improves sleep. As pain is a clear symptom that can be influenced by a sleep system, it was chosen to target people suffering from insomnia from a pain-related cause.

There are many disorders that cause pain, but three frequently occurring pain-causing disorders that can be influenced by changing spinal alignment or pressure distribution are: (acute or chronic) low back pain, rheumatologic disorders and decubitus. For each of these three an actively adjusting sleep system has beneficial effects on the patient's quality of life by reducing pain, improving comfort and improving sleep quality compared to a passive sleep system.

Therefore, the redefined problem statement is as follows:

> *Improving the quality of life for people suffering from low back pain by introducing a sleep system that relieves their pain, increases comfort and improves sleep quality through actively adjusting spinal alignment, pressure distribution and temperature to their personal needs.*

5.2. CRITERIA

All information gathered in the previous chapters is captured in a list of requirements. The most important criteria are summed up in this chapter. Also, some interesting opportunities found during the analysis but that are out of this project's scope are mentioned. The full list is shown in appendix B.9.

The criteria are divided into demands (D), which must be included into the design and wishes (W), which are desirable properties but optional.

All demands and wishes are divided into categories that were part of the analysis done during this project. This list is not definite as new criteria can be added later and existing criteria can be revised when new knowledge becomes available.

To get to the conceptual design of a smart and dynamic sleep system, the following criteria are most relevant:

Enhance health

1.1 Should prevent, manage or cure users' back pain-related disorders.
1.2 Should allow to painlessly move people suffering from back pain-related disorders.

Enhance sleep & comfort

2.1 Should optimise the contact surface to enhance sleep.
2.2 Should maximise contact area without restricting movement.
2.8 Should learn about the user's physical pain areas.
2.9 Should sense and judge the user's sleep quality.

Enhance ergonomics

3.1 Should support and facilitate a user's desired position.
3.2 Should enhance users' spinal alignment.
3.3 Should allow for precise control of the users' position.
3.9 Should sense and judge the user's body position and spinal alignment.

5.3. PURPOSE DESIGN

Based on the analyses and list of requirements, a purpose design is formulated. This purpose design answers to the design vision and defines what should be designed.

Concluding from a thorough analysis is that there are multiple problems that existing sleep-related artefacts cannot solve or even helped create. To take away a number of these problems, a purpose design is envisioned and presented here. This purpose design is presented explaining the problem, solution and desired result and visualised in figure 30.

Problem	Solution	Method	Result
Back pain-related sleep disorders	Spinal alignment	Calibrating the bed on its user, measuring current spinal alignment and adjusting the sleep surface to correct errors for optimal alignment	Prevention, curing or managing symptoms of back pain-related sleep disorders
Static bed built for one sleep position	Dynamic adjustable bed	Measuring current sleep position, adjusting the sleep surface to match the sleep position	Optimal support in all sleep positions
Low sleep quality	Increasing comfort	Measuring sleep quality (sleep duration, sleep onset latency, sleep efficiency, number of awakenings and movements) and adjusting temperature, firmness and sleep surface to learn the optimal settings	Optimal sleep quality in regard to the sleep system

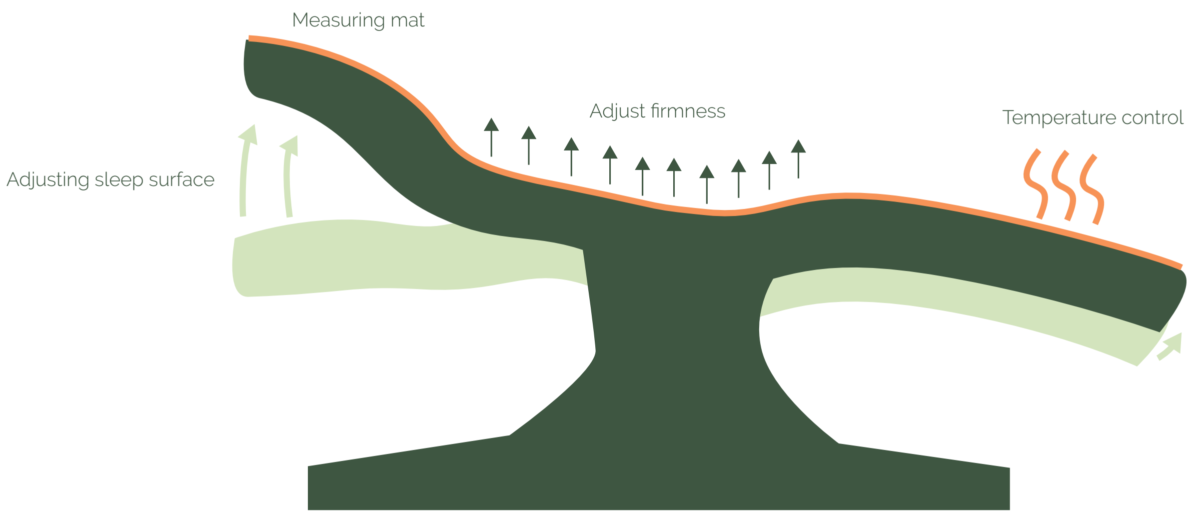


Figure 30 *Purpose design visualised (by author)*

5.4. SUSTAINABILITY

For designers, sustainability is no longer something that can be ignored. This poses a great challenge as it often interferes with commercial interests. However, design choices can be made to reduce the impact of products and work towards a circular system in which no materials are lost and energy is obtained from durable sources like the sun.

The effects of humans' interfering acts become visible on a global scale and are problematic as materials become scarce, eco-systems are disturbed and several life forms are threatened, including humanity itself. That is why the United Nations (2015) adopted 'responsible consumption and production' as one of their Sustainable Development Goals.

To fight the causes of these problems, environment can no longer be ignored by product designers, which means it naturally becomes part of this project as well.

With the redesign of a product, there is an opportunity to improve on sustainability. Therefore, existing mattresses and sleep systems were examined.

Mattress core

Most mattress cores consist of polyurethane foam or visco-elastic polyurethane foam, isoprene rubber or natural latex. Some cores also contain metal springs. Although some of these have a bio origin, all materials undergo energy intensive processing (e.g. vulcani-sation) and chemical additives are added in most

Type	Origin	Recyclability	Energy recovery (incineration)	Mechanical recycling	Chemical processing	Thermo chemical processing	Source
Polyutherane foam	petrochemical	Downcycling	excellent (same amount of energy as coal)	Rebonding, regrinding/powdering, adhesive pressing/particle bonding, compression molding	Glycolysis, hydrolysis, alcoholysis, aminolysis, phosphate ester method	Pyrolysis, Blast furnace, gasification, hydrogenation	Zia, Bhatti, & Bhatti, 2007
Polyurethane foam	bio + synthetic additives						Zia, Bhatti, & Bhatti, 2007
Visco-elastic (memory) polyurethane foam	petrochemical	Downcycling	excellent (same amount of energy as coal)	Rebonding, regrinding/powdering, adhesive pressing/particle bonding, compression molding	Glycolysis, hydrolysis, alcoholysis, aminolysis, phosphate ester method	Pyrolysis, Blast furnace, gasification, hydrogenation	Zia, Bhatti, & Bhatti, 2007
Visco-elastic (memory) polyurethane foam	bio + synthetic additives						Zia, Bhatti, & Bhatti, 2007
Isoprene rubber	petrochemical	Downcycling		Grounding, re-use in less demanding applications	Devulcanization, but with reduced grade, sometimes toxic process	Pyrolysis	
Natural latex	bio	Downcycling		Grounding, re-use in less demanding applications	Devulcanization, but with reduced grade, sometimes toxic process	Pyrolysis	

Figure 31 *Mattress core materials and end of life processing (by author)*

cases. Still, biomaterials used in mattresses emit fewer greenhouse gasses than petrochemical materials and should be the material of choice, according to Glew, Stringer, Acquaye, & McQueen-Mason (2012).

These materials can be processed in a mechanical, chemical or thermoschemical way but will always be of a lesser grade than the original product (see figure 31). Energy recovery through incineration is also possible and recovers a lot of energy for polyurethane foams. In this project, the top layer of the bed that will equalise the surface created by the sleep system consists of a foam-like material. Based on this short analysis, Latex seems to be the preferred material, but more research is recommended.

Sleep system

Most sleep systems consist of materials like wood, steel and textiles. Most of these have a bio origin and can be recycled or re-grown. That means that not the materials, but mainly the energy loss and emitted greenhouse gasses are a problem. A good method to reduce the impact is to design the sleep system according to Ellen MacArthur Foundation's (2017) principles of a circular economy. This can be done through design for resource conservation, design for slowing resource loops and whole systems design (Moreno, De los Rios, Rowe, & Charnley, 2016).

For this project, design for slowing resource loops is most applicable. Moreno et al. (2016) summarised ways to design for slowing resource loops from many different authors. The methods incorporated in this project are shown in figure 32. This figure also shows in which parts of the project the sustainable design methods are implemented. The overall design is considered meaningful and delivers a pleasurable experience. To make the sustainable design choices relevant, a product-service system is inevitable. If the product is designed for repair or remanufacturing, but there is no service to do so, the product will still end up in normal waste streams which is no improvement of the existing situation.

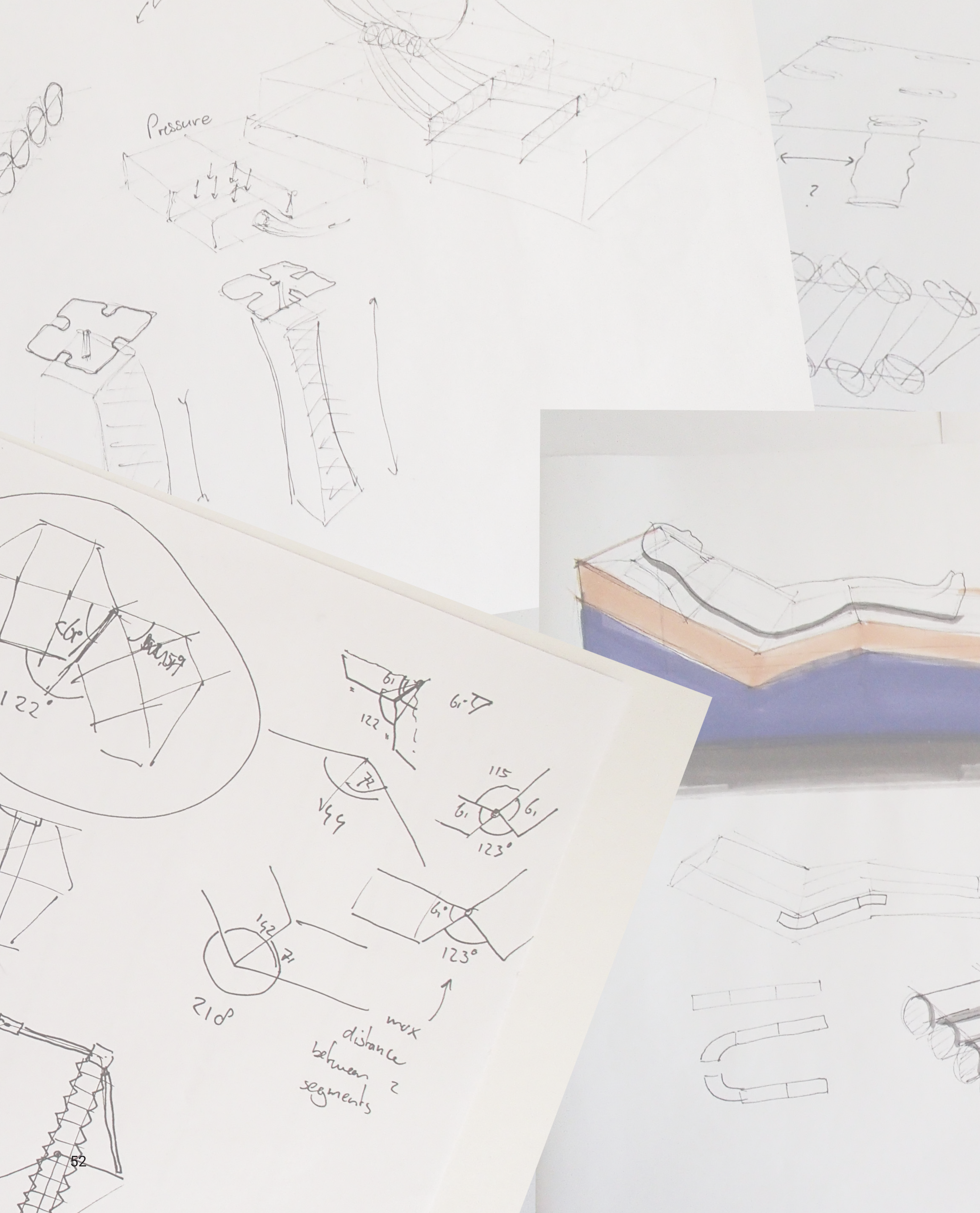
In the design of the sleep system, specific measures were incorporated to follow up on the methods mentioned in figure 32:

- The sleep system is designed as a modular system. This modularity makes it easy to maintain and repair and ensures a prolonged life span of the product.
- The connections are designed for dis- and re-assembly. That means that no adhesives or welds are used in the final product that make disassembly impossible.

Billions of mattresses are used worldwide but are often comprised of non-sustainable materials, contain toxic chemicals and are not recyclable, which means they end up being cascaded or ultimately incinerated for energy recovery.

Part of project	Design for slowing resource loops	Source
Overall design	Design for pleasurable experiences	Bocken et al. (2016)
Overall design	Meaningful design	Bocken et al. (2016)
Sleep system	Design for repair/refurbishment	Bakker et al. (2014); Bocken et al. (2016)
Sleep system	Design for easy maintenance, reuse and repair	Bakker et al. (2014); Bocken et al. (2016)
Business model	Design for product-service systems	Bakker et al. (2014)
Sleep system	Design for (re)manufacturing and dis- and re-assembly	Bakker et al. (2014); Bocken et al. (2016)

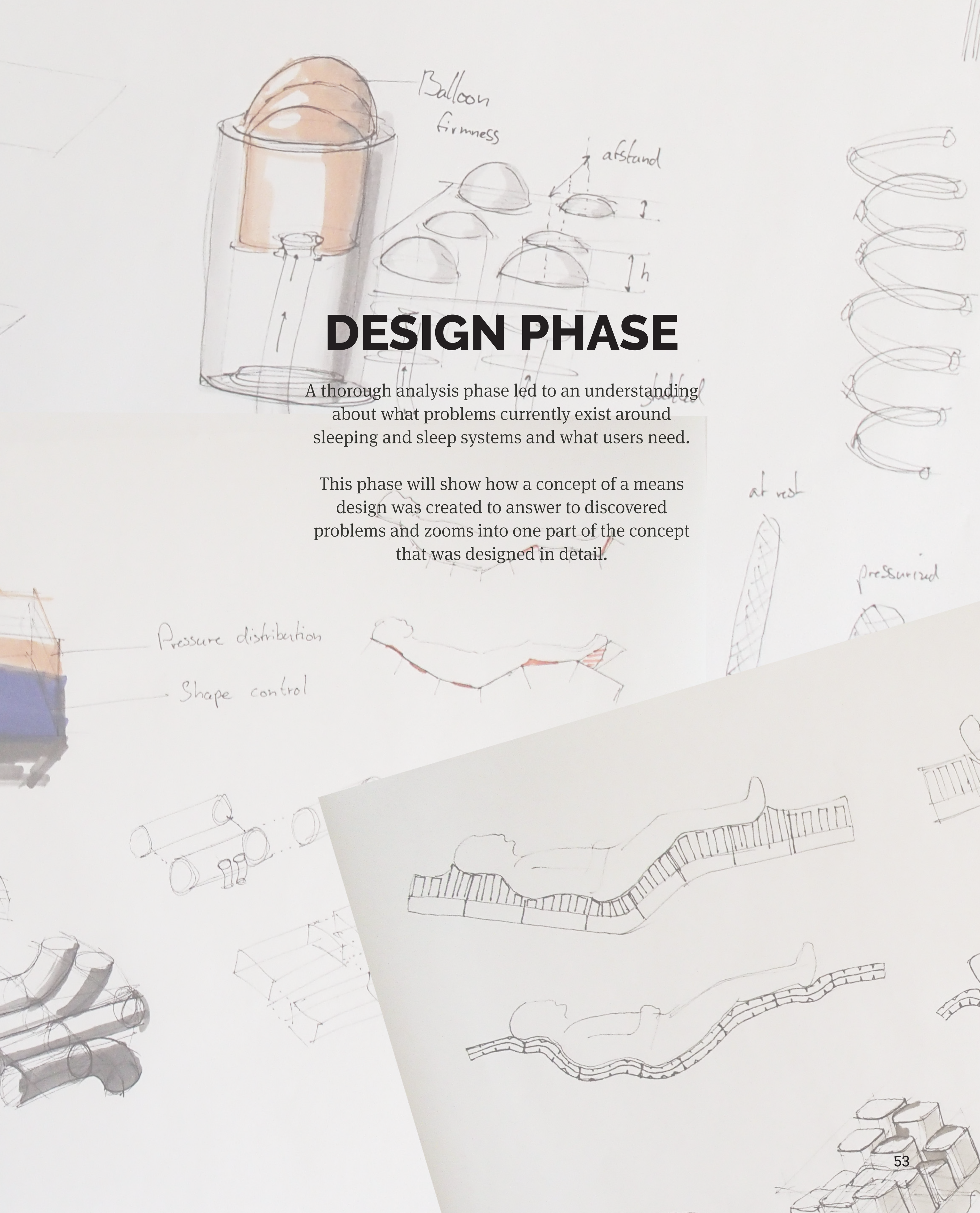
Figure 32 *Parts of the project that cover ways of slowing resource loops (by author, based on Moreno et al., 2016)*


Pressure
?
122°
115
123°
123°
max distance between 2 segments

DESIGN PHASE

A thorough analysis phase led to an understanding about what problems currently exist around sleeping and sleep systems and what users need.

This phase will show how a concept of a means design was created to answer to discovered problems and zooms into one part of the concept that was designed in detail.



6.CONCEPTUALIZATION

This chapter describes the process from ideation to a final concept.

Photo from rawpixel.com

6.1. IDEATION

With context, user and interaction known, the process of ideation was started. This process was an iterative process that consisted of diverging activities, focussed on gathering ideas, and converging activities, focussed on narrowing down the number of ideas.

Initial ideas were gathered by studying existing solutions and sketching different ideas. Also, Rob Scharff, researcher at the TU Delft, was consulted for his ideas and an inspirational event on inflatables, organised by Ton Hurkmans and Wim Poelman, was attended. By dividing the design problem into sub-problems and formulating these as questions, it was possible to come up with even more ideas. All ideas were combined, and the most promising ideas were filtered and included in a morphological chart, sorted per sub-problem as shown in figure 33.

Instead of creating multiple concepts based on different combinations from this morphological chart, for each row the best solution was determined separately to come up with one concept and develop it further. As designing the complete sleep system was too much for this project, it was chosen to focus on the most distinguishing part; an adjustable double curved surface.

In the morphological chart, this is divided in the two upper rows: 'How to create a double-curved surface shape?' and 'Which technological principle can be used to achieve this?'

To find an answer to both questions, the following processes were used:

Question 1: Setting up a parametric model that could determine design parameters based on anthropometric data. Besides determining which of the three options for creating a double-curved surface was most effective, this model also helped to define the limits and requirements of the system.

Question 2: Answering this question came down to tinkering with materials, trying to copy existing pneumatic and soft robotic actuators and getting an understanding for working with pneumatic systems. Doing these activities gave insights into the benefits and disadvantages of different technical principles.

The process of findings answers to these questions make up for the following two chapters.

Morphological chart

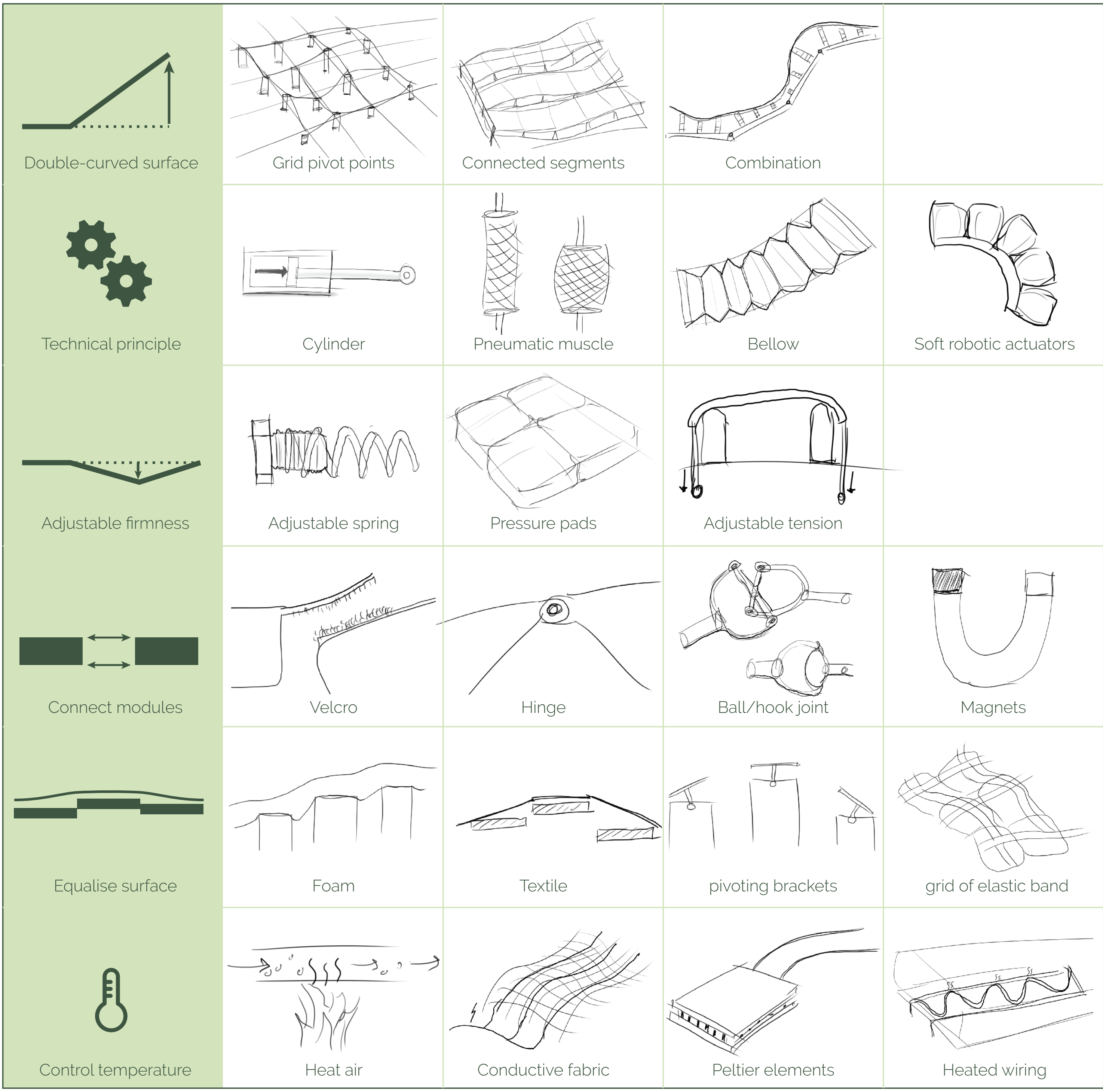
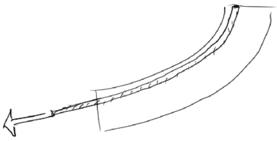
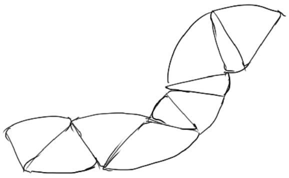


Figure 33 *Morphological chart (by author)*

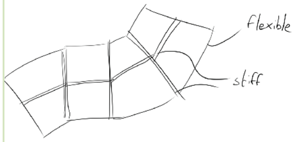


Steel cable



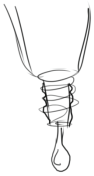
Pressure chambers

Tightening/relaxing chamber

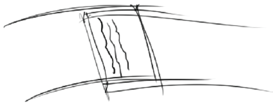


Material properties

Hooking/form-fitting



Adhesion



Stitches

6.2. ANTHROPOMETRICS

To answer the first question, a study was made of anthropometrics and a parametric model was built.

As the sleep system should adapt to the majority of people, a user range is determined between P5 (Dutch) adult 60+ females, who are the shortest adults according to the available data set from Dined (2017), and P95 Dutch adult 20-30 males, who are the tallest according to the same data set. Besides that, P95 Dutch adult 20-30 males, who are the heaviest, were chosen to determine the maximum mass exerted on the surface (see figure 34). Also, an extra female subject, modelled with a curvy body, was added to complement the data set.

All models (see figure 35) were modelled in the program MakeHuman (version 1.1.1) and their positions were created in Blender (version 2.77). Main dimensions such as stature and hip circumference were based on the Dined data set used, and other body dimensions and proportions were estimated to create diversity between models. Therefore, used proportions might differ from real proportions of human beings, but these differences can be neglected for the purpose of finding design parameters that can cover a whole variety of different bodies.

Each of the models has different traits, and together, this sample creates a good mixture of shapes and resembles approximately 90% of the Dutch adult population.

populations	Dutch adults 60+, female	Dutch adults 20–30, male
measures	P5	P95
Stature (mm)	1498	1980
Body mass (kg)	53	103
Hip circumference (mm)	918	1127

Figure 34 *Anthropometric data on P5 female and P95 male (Dined, 2016)*

Figure 35 *Range of computer modelled subjects (by author)*

Size of segments

The system will consist of multiple identical segments that are connected. The length and width of the segments are not necessarily similar. The dimensions of the segments determine the detail of the resulting surface. Smaller segments result in the most precise body support, but with an increased number of segments, also the system's complexity goes up, which increases chances of system failure, as well as the cost price. Therefore, the segment size should find a balance between these aspects (see figure 36).

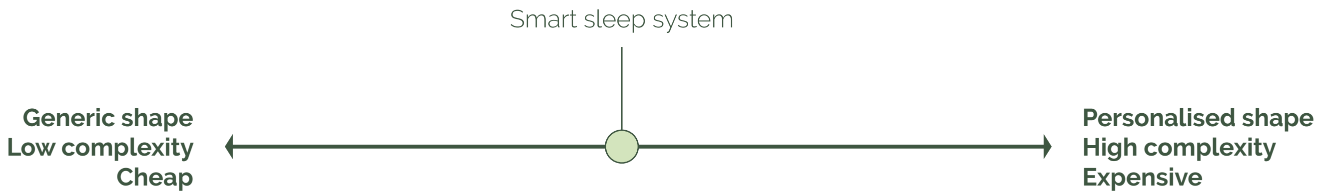


Figure 36 *Balance between shape, complexity and price (by author)*

In comparison to existing sleep systems, the smart sleep system must be better in delivering a personalised surface area. Complexity and price are expected to be higher as well but could be comparable to adjustable bed frame solutions (see figure 37.

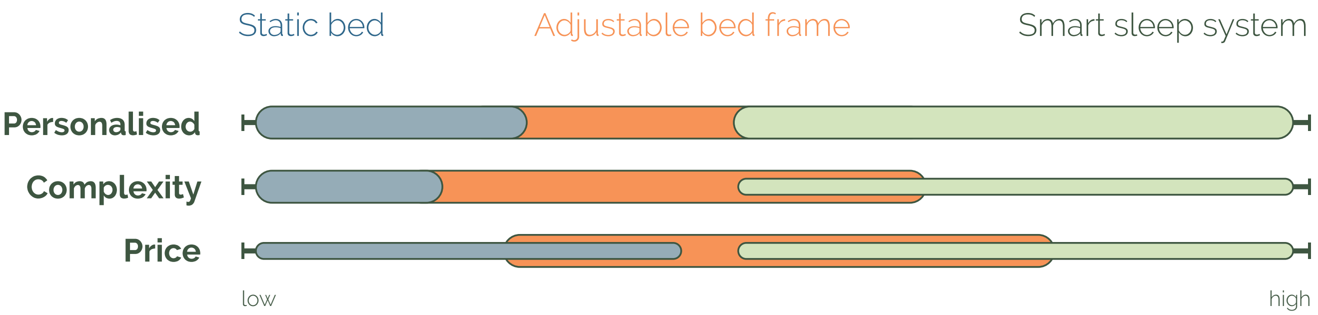


Figure 37 *Comparison between sleep systems (by author)*

Method

To decide which dimensions are right for the segments, four different human models (see figure 35) were used in various positions.

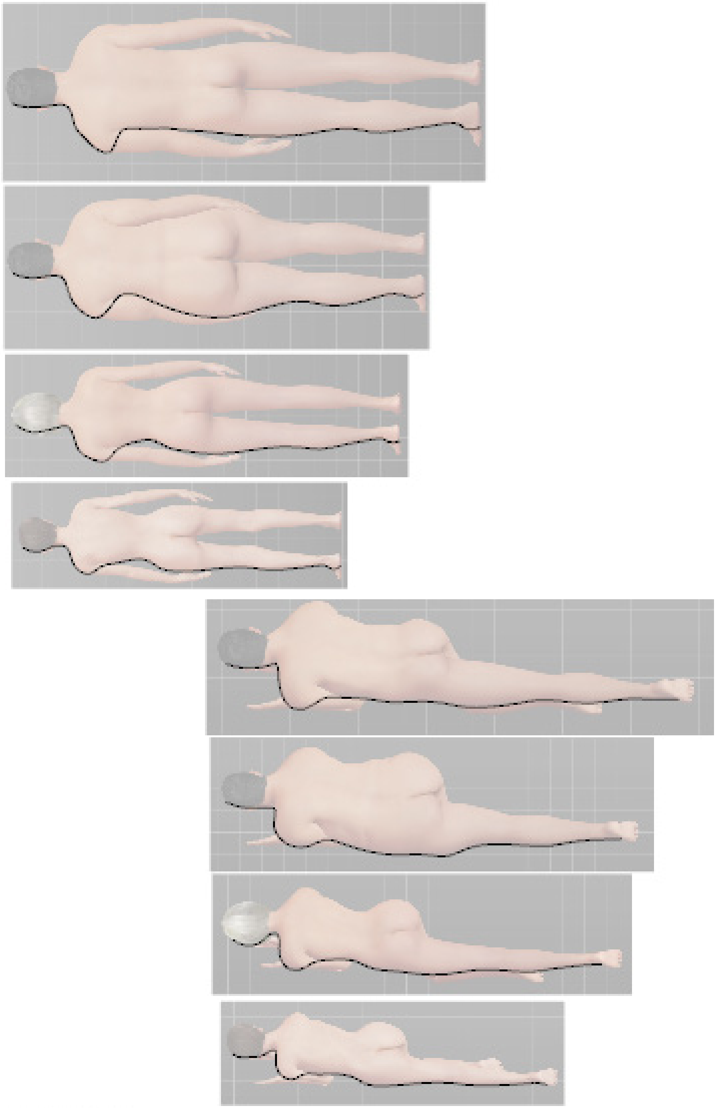
Length

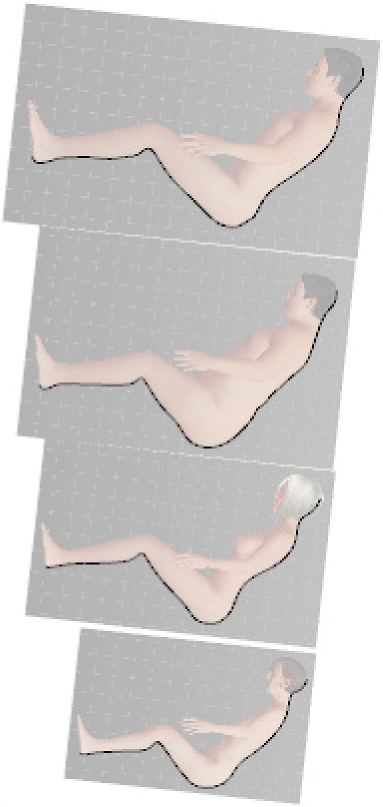
- Lateral position – A flat position like on a typical bed, i.e. with sagging.
- Lateral position – A flat position which approximates an optimal spinal alignment, obtained from rotating a person in standing position by 90 degrees.
- Supine position – A flat position which approximates an optimal spinal alignment, obtained from rotating a person in standing position by 90 degrees.
- Supine position – An upright position when watching a tv on the wall approximates the fowler's position and is therefore considered an optimal position for spinal alignment.

Width

- Supine position (A flat position which approximates an optimal spinal alignment, obtained from rotating a person in standing position by 90 degrees.)
- Measured at three intersections, around the shoulders, waist and feet.

Screenshots of the models in the correct positions were taken and imported in Rhinoceros (version 5). An ideal support curve was drawn to approximate their body curvature. A complex parametric model (see figure 39) was created using the Rhinoceros plugin Grasshopper (version 0.9.0076) in which segments were projected on the ideal support curve.





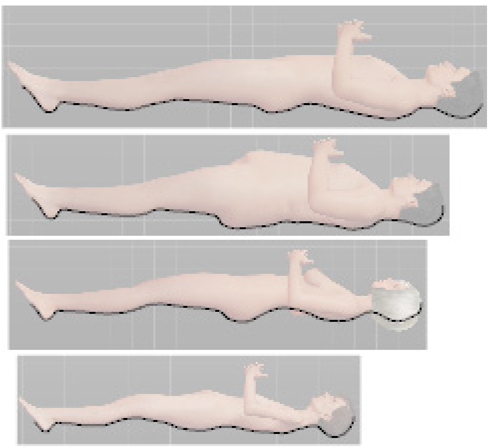


Figure 38 *Positions of models with their approximated body curvature (by author)*

By adjusting a slider (see figure 40), the length of the segments is adjusted and information on the following is returned (see figure 41):

- Number of segments
- Angles
- Maximum elongation
- Maximum displacement
- Average area between body and approximated curve
- The largest area
- Biggest mismatch between body and approximated curve

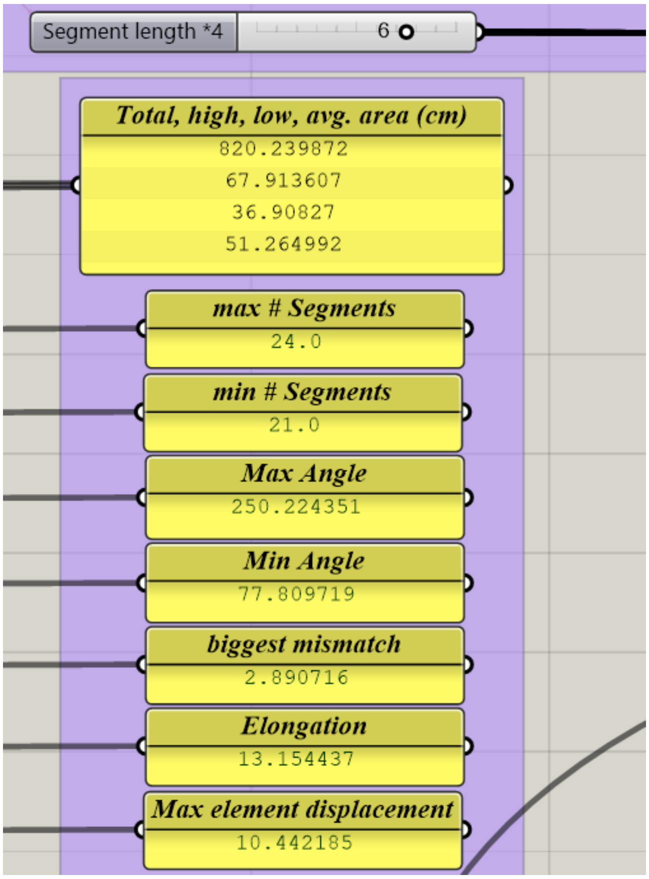


Figure 40 *Adjust slider to retrieve information (by author)*

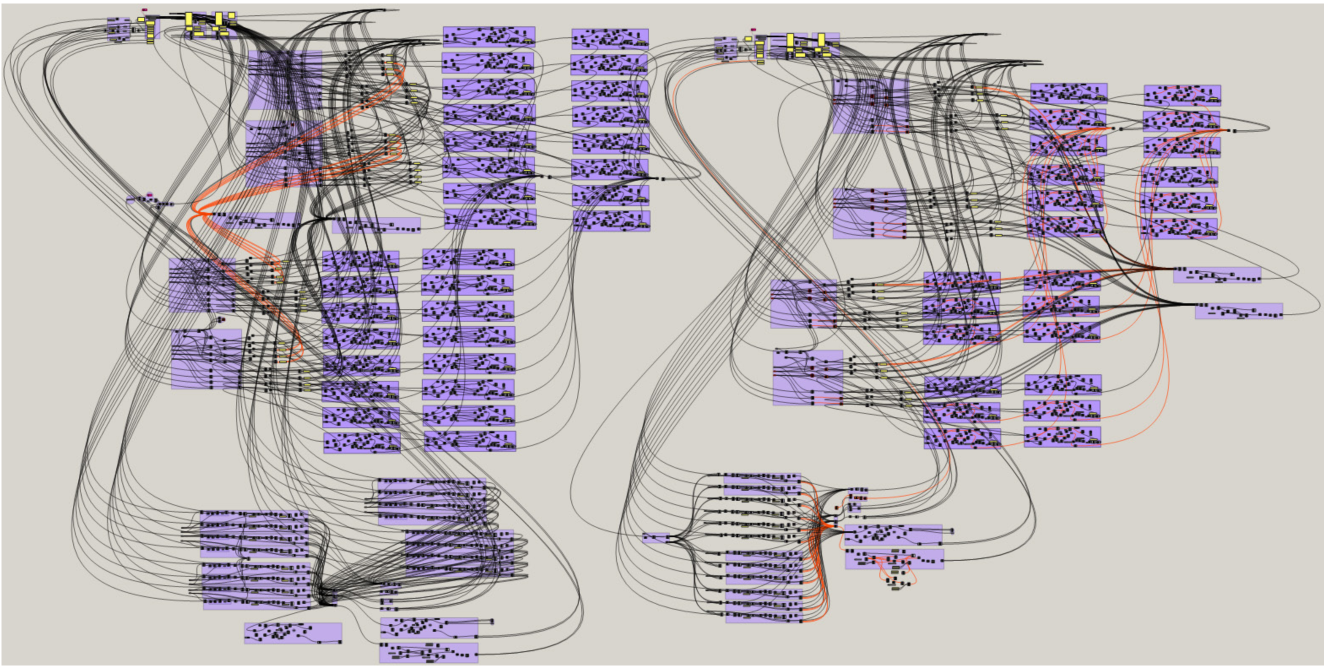


Figure 39 *Model used (made in Grasshopper, by author)*

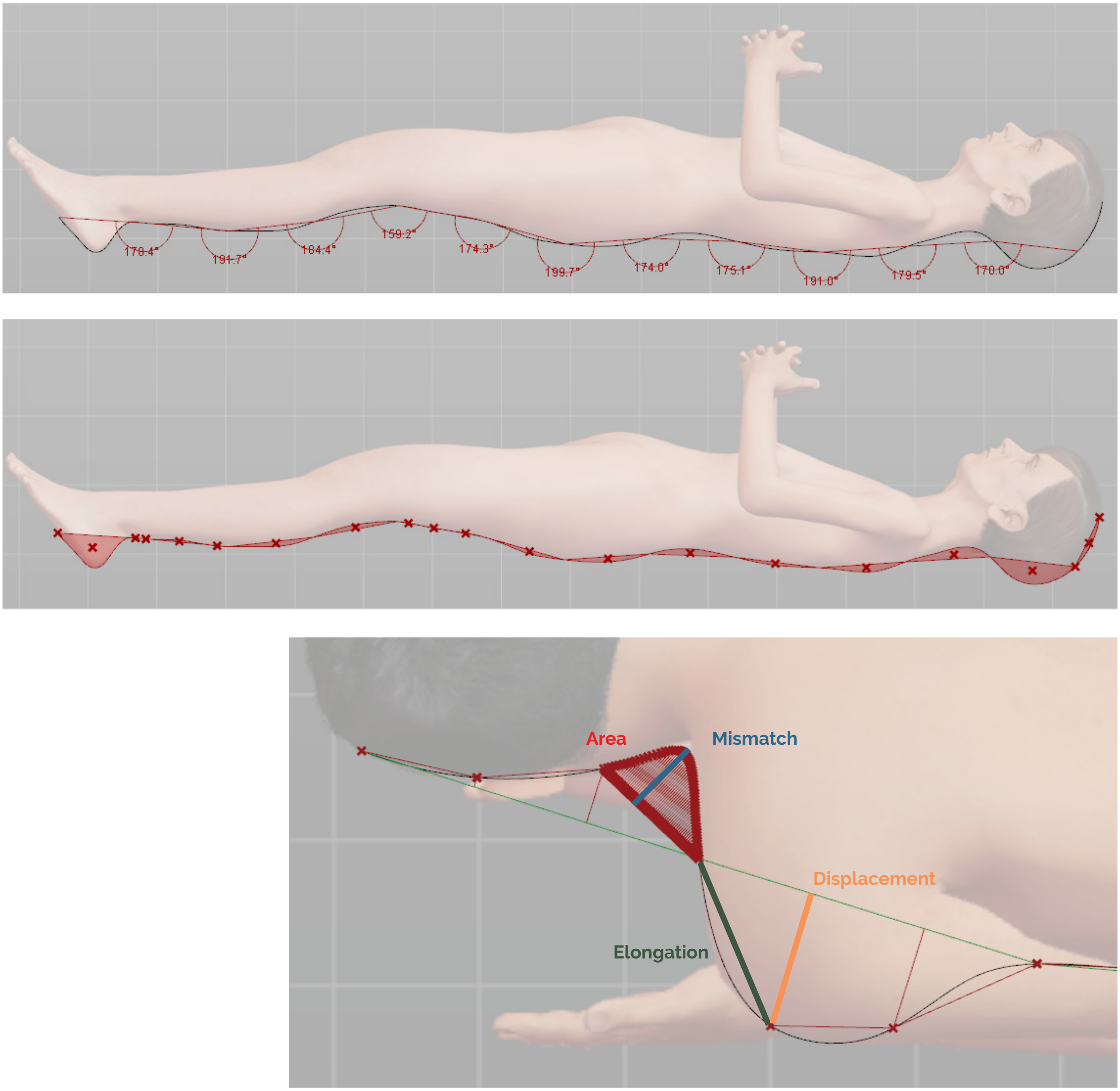


Figure 41 *Visualisation of obtained information by model (by author)*

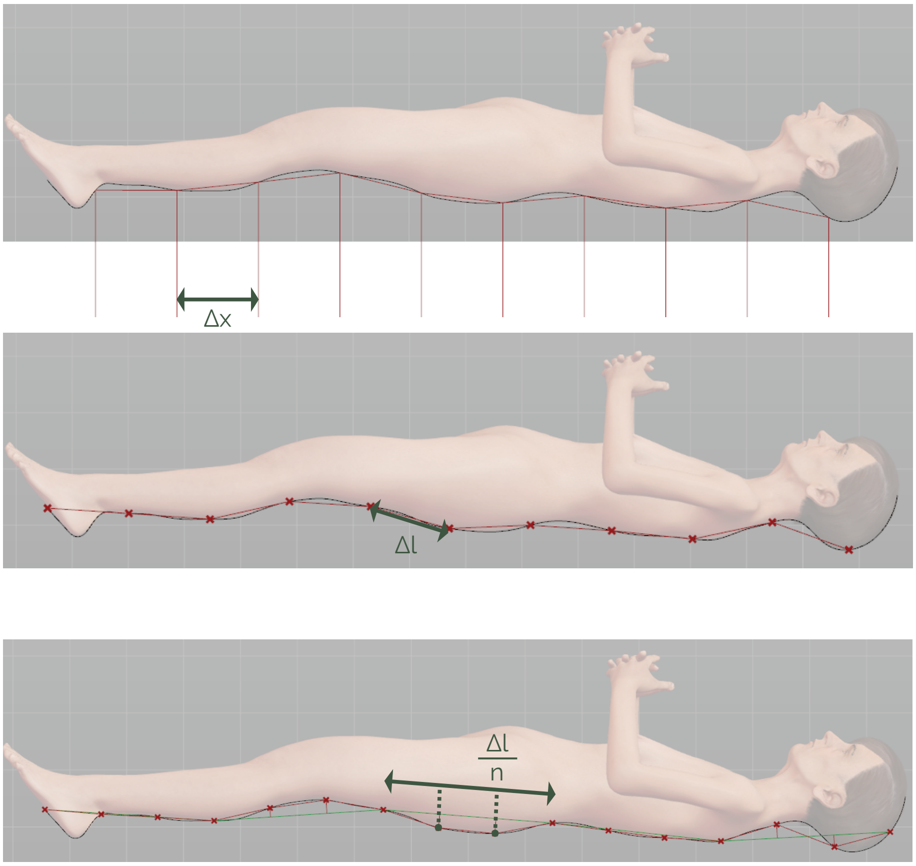
For this model, three different ways of connecting segments were considered (see figure 42):

Option 1: The distance between each segment's pivot points (dx) is the same, meaning that the absolute length and width of the sleep system stay the same, despite changing user positions. The design challenge that follows from this decision is to use materials that can stretch and cover the changing area that result from deformation.

Option 2: The length of each segment (dl) is the same. The consequence of this decision is that the absolute length and width of the sleep system will change depending on the position of the user. This does not have to be a problem if there are enough segments to cover the full area of the user.

Option 3: A combination of option 1 and option 2. Where option 2 (equal lengths of segments) is used for the bigger segments and option 1 to divide these segments in smaller segments with equal distances.

At first, results for option 1 and 2 were retrieved by manually going through the different outputs generated by adjusting the slider. To narrow down the options, the slider was first set to 40, 30, 20, 10 and 5 cm. By going through the results, some extra sizes were chosen to find a range of acceptable outcomes. Based on this method, segment lengths of 9, 6 and 5 cm would be acceptable and widths of 7, 6 and 5 cm for option 2. Also based on the results, using solely option 1 was ruled out, by looking at the extreme displacement required to create this construction. As shown in figure 43, a displacement larger than 64 cm is needed.



Option 1
Equal distance between segments

Option 2
Equal lengths of segments

Option 3
Equal lengths of segments with extra pivot points equally divided over the segment's lengths

Figure 42 *Three options of dividing segments (by author)*

Therefore, only option 2 and 3 were left. To determine the ideal combination of lengths for option 3, an extra slider was added to the model. One slider adjusted the module length which would behave like option 2 and the second slider adjusted the number by which to divide this length.

The ideal settings for these sliders were simulated. To do this, four out of the seven possible criteria (the information returned by the model) were chosen to use as parameters, namely:

- The maximum number segments required (increases segment length).
- Average area (decreases segment length).
- Biggest area (decreases segment length).
- Biggest mismatch (decreases segment length).

As only the first criterium increases the segment length, several simulations were done with assigning different weights (1-4) to this criterium to match the others, which consistently held a weight of 1. Each criterium was calibrated to 1 when the sliders were set to 20 cm long segments divided by 2, which was based on the interpretation of data previously found.

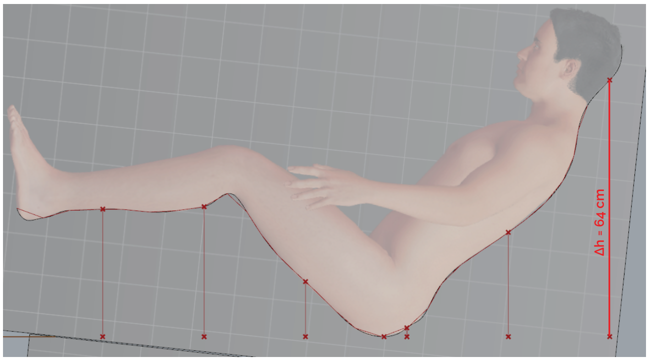


Figure 43 *Displacement larger than 64 cm (by author)*

From the outcomes of the simulations, it was decided that a length of 24 cm, divided by three (option 3) and a width of 12 cm, undivided (option 2), would be the best solution.

The maximum displacement for the divided length segments is 10.4 cm either up or down, but never more than 10.4 cm between the two. The maximum elongation for a connecting material is 65%. The maximum angle between two segments is 105 degrees when going up or 122 degrees when going down (as shown in figure 44).

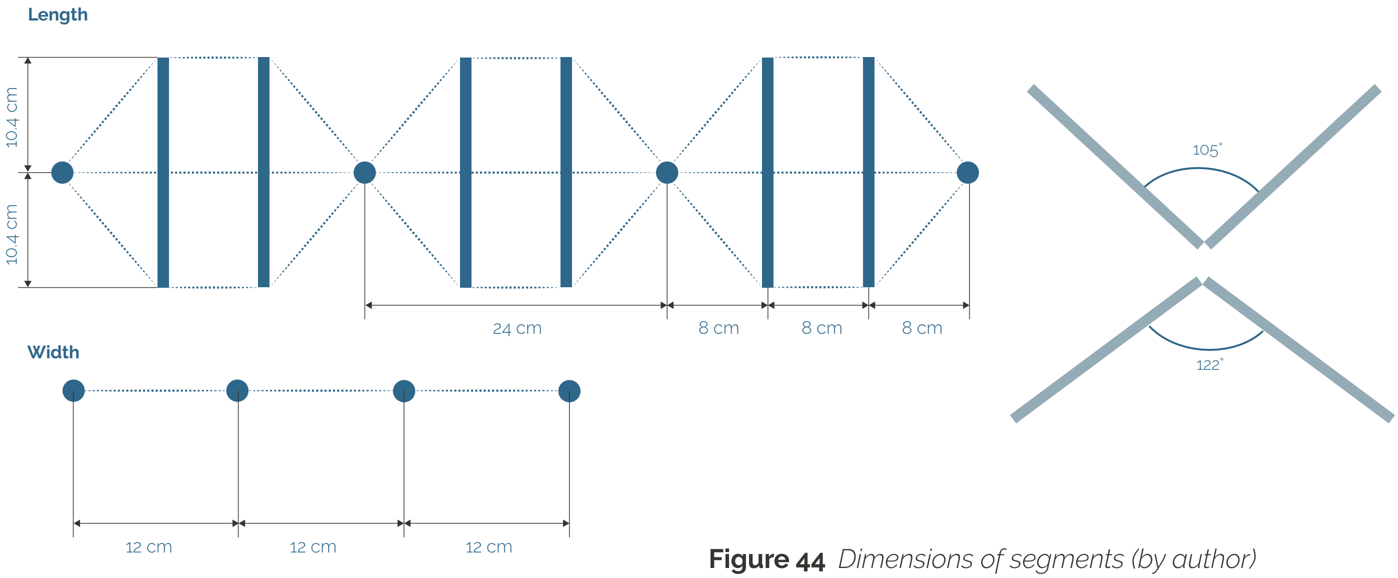


Figure 44 *Dimensions of segments (by author)*

6.3. TECHNICAL PRINCIPLE

As pneumatics and soft robotics are not included in the Delft Industrial Design Engineering curriculum, it was helpful to build several simple prototypes to test and understand different techniques and their limits.

To test and compare different technical principles, quick prototypes had to be made. This was done using different prototyping techniques:

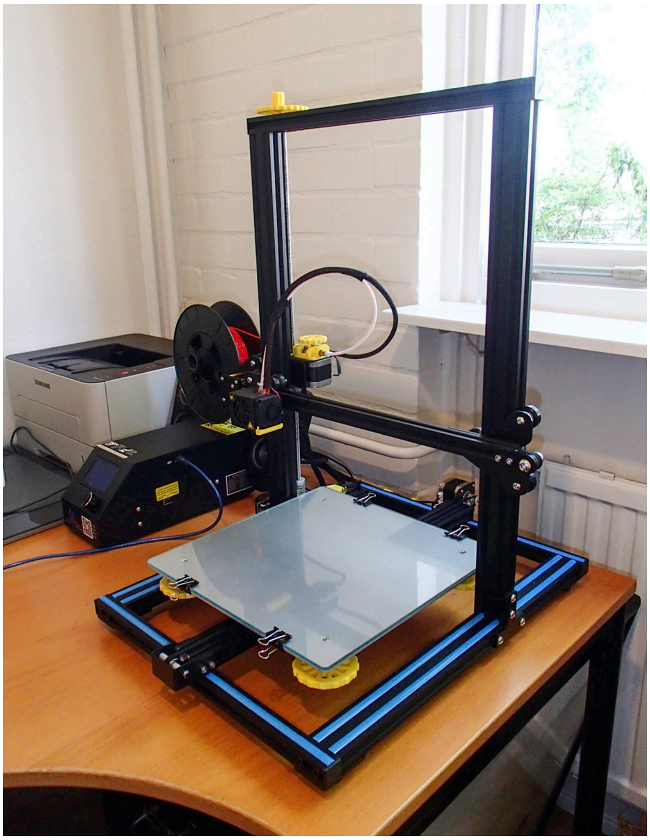


Figure 45 *Creality CR-10 3d printer (by author)*

3d printing

To speed up the process of developing prototypes, the Creality3D CR-10, a 3d printer that uses the Fused Deposition Modelling (FDM) printing method (see figure 45), was purchased. Using this printer, the following was tested:

- Airtight 3d printing: Using FDM, it is not possible to print fully airtight. Using certain flexible materials and print settings does decrease the permeability, but other 3d printing methods or post-processing is required to make a part airtight. In this case, peel-off paint was used to seal the holes. This does work but cannot withstand much pressure.
- Printing air connectors and inlets (figure 46): Printing air connectors is a cheap and effective way to connect hoses. However, the inlets are not useful because the used material (TPU-based flexible filament) cannot be glued.

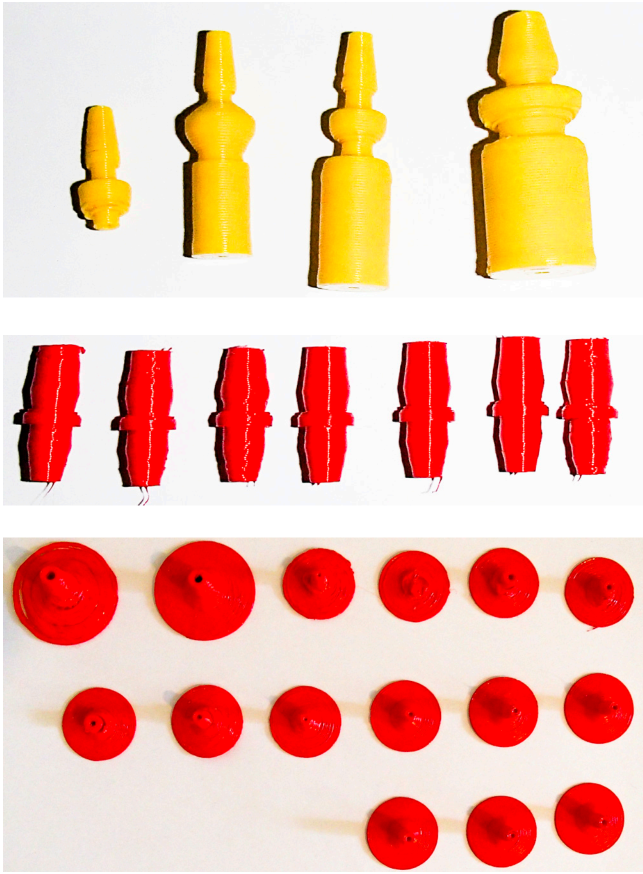
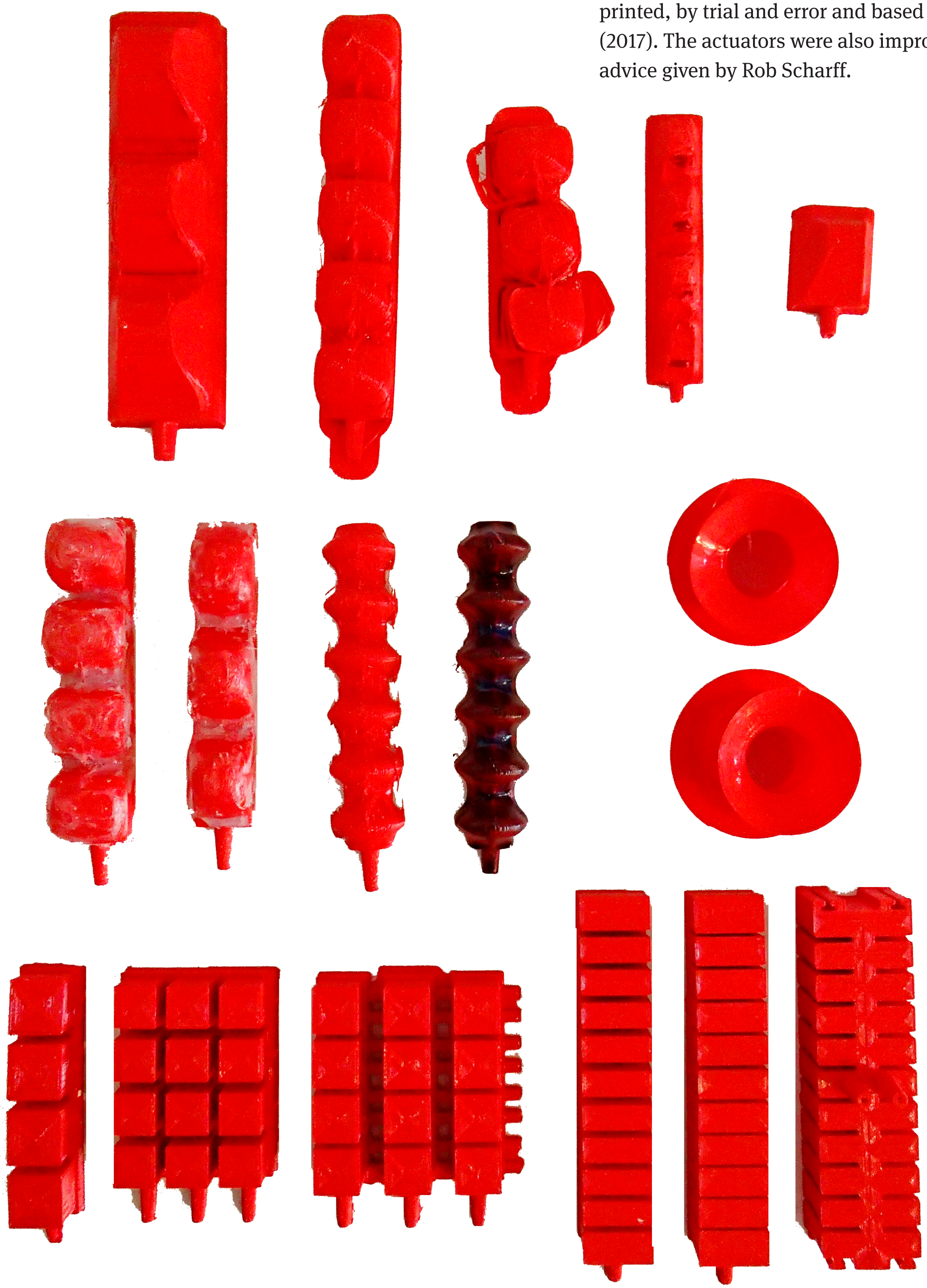


Figure 46 *Air connectors and inlets (by author)*

- Printing soft robotic actuators as shown below: Also, several soft robotic actuators were designed and printed, by trial and error and based on Scharff et al. (2017). The actuators were also improved based on advice given by Rob Scharff.



Inflatables

By welding together plastic sheets with a hot iron, inflatables could be created. At first, PE sheets recovered from plastic bags and table cloth were welded together. Although this worked (see figure 47), according to an employee from Bison (a brand of adhesives) there exists no adhesive for PE. Therefore, other materials were sought to produce inflatables with. This resulted in testing different types of PVC, which is a material also used for simple inflatable products, such as rubber swimming bands.

To make sure that it was possible to use adhesives for the new PVC material and to see if it was possible to combine these inflatables with 3d printed valves, a test was performed in which different combinations were glued to see which would stick and which would not (see figure 48). The glue used was the soft plastic adhesive from Bison, which their employee recommended to use as this adhesive was based on polyurethane while the red 3d printed material was based on thermoplastic polyurethane.

Three types of PVC with different thicknesses were tested: Material recovered from an existing inflatable, a table cover and pond foil. As these materials all felt different but should be PVC, a test was performed to see if they would weld together using a hot iron (see figure 49). Although all would weld together, the pond foil was much thicker and took longer to weld. The other two materials welded fine, but the table cover was much stiffer than the other materials. Therefore, the material from the existing inflatable was used for the prototype shown in chapter 6.4.

Figure 47 *Plastic bag inflatables (by author)*

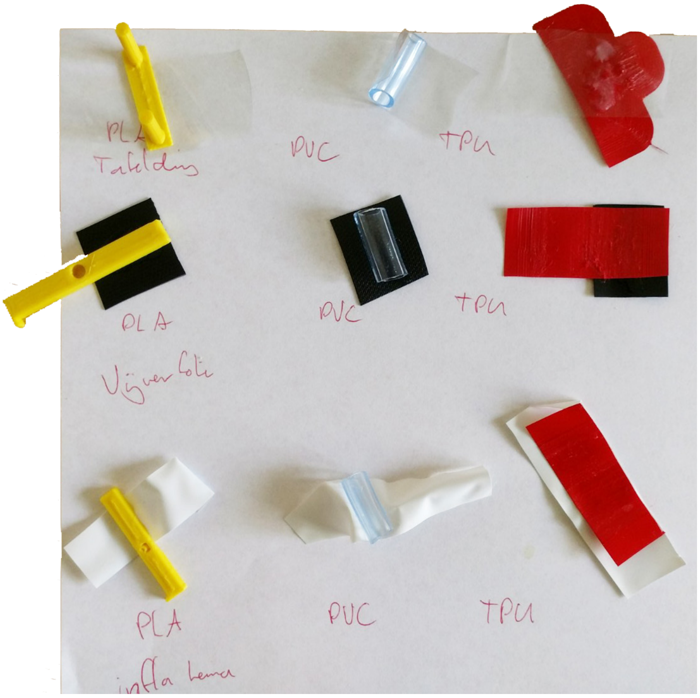


Figure 48 *Adhesion test (by author)*

Figure 49 *Ironing test (by author)*

Figure 50 *Three types of PVC (by author)*

Silicone moulding

Silicone moulding was also briefly considered as a means of producing soft robotics. In fact, existing soft robotic actuators are often produced this way. However, for this project it was decided not to use this process for ideation and concept development as the creation of such actuators takes too much time for fast iterations. A quick test using silicone glue and a starch-silicone combination (see figure 51) was done to see if the process could be simplified and accelerated with reduced curing time. The results of this test were not satisfying, and therefore this method of prototyping was not pursued any further.

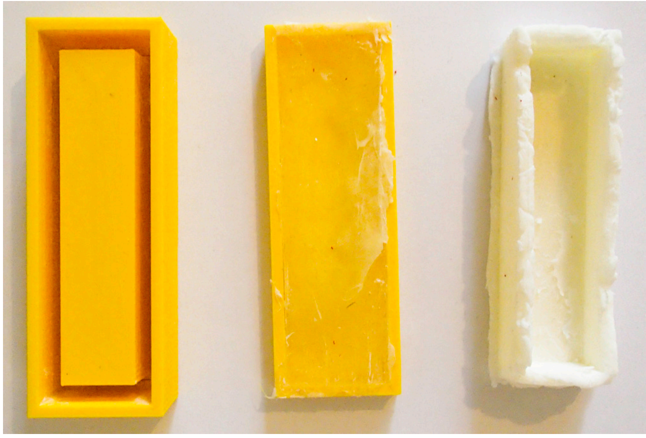


Figure 51 *Silicone moulding of soft robotic actuator (by author)*

Pneumatic muscles

Using cable protectors and balloons is a simple method of creating strong pneumatic muscles. Different sizes of cable protectors and balloons (see figure 52 and 53) were used to find working combinations.

Figure 52 *Different sizes cable protectors (by author)*

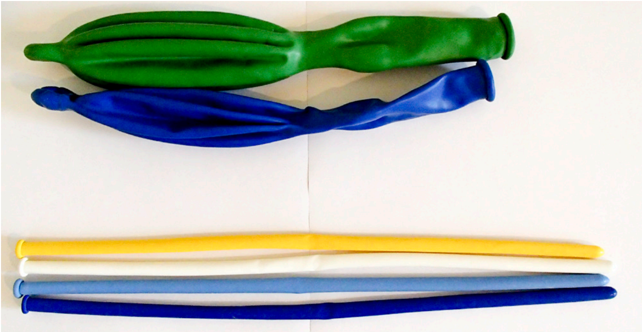


Figure 53 *Different sizes balloons (by author)*

Other techniques

Other quick tests performed were:
Connecting steel wire to a flexible plastic tubing and pulling to see how shortening the cable would affect the tubing.

Using chicken wire and a matrix of flexible plastic tubes to create double-curved surfaces to see how this would react to pressure and shape changes.

Calculations and materials

To be able to estimate how feasible ideas based on soft robotics and inflatables were, some calculations were made (see appendix C.2). Based on these initial calculations, required pressure could run up to approximately 5 bar over-pressure.

Also, a first material study was conducted to know whether it was feasible to create parts that could handle the desired amount of pressure combined with demands for sustainbility.

Although not all technical principles were tested, the gathered information was considered enough to estimate which techniques would likely fulfil the requirements that were set by the parametric model from the previous chapter.

The last three ideas from the second row in the morphological chart were considered too difficult to control and were therefore disregarded.

Using cylinders was also not tested, but they are considered as a last resort in case other actuators fail. Although cylinders do not create the required transmission to obtain the desired angles between segments, they are commonly used in many different applications and have proven to be an effective and reliable actuator.

Based on the tests with soft robotic actuators, bellows were also considered feasible.

6.4. CONCEPT DESIGN

The ideation gave valuable information which allowed to create a concept.

Based on the ideation process, a concept was formed from the morphological chart. The model showed that the most effective solution for creating a double-curved surface is a combination of larger displacements caused by bending the surface and smaller displacements through vertical motion.

Although several technical principles could work for creating the larger displacements, the bellow was chosen because of its originality and because it resulted in the largest angle without requiring a complex transmission mechanism to increase the range.

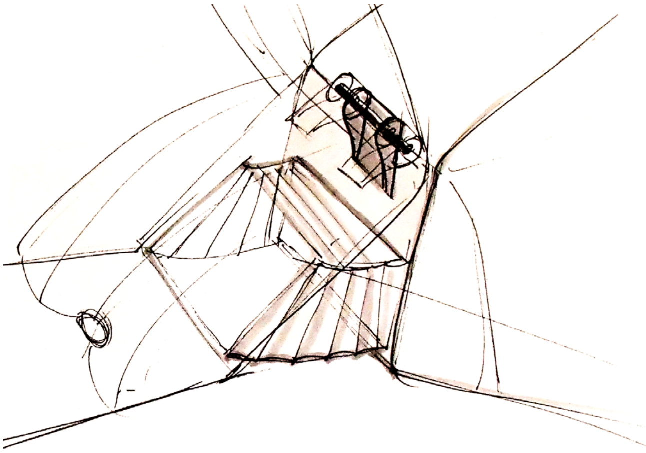


Figure 55 *Bellow principle (by author)*

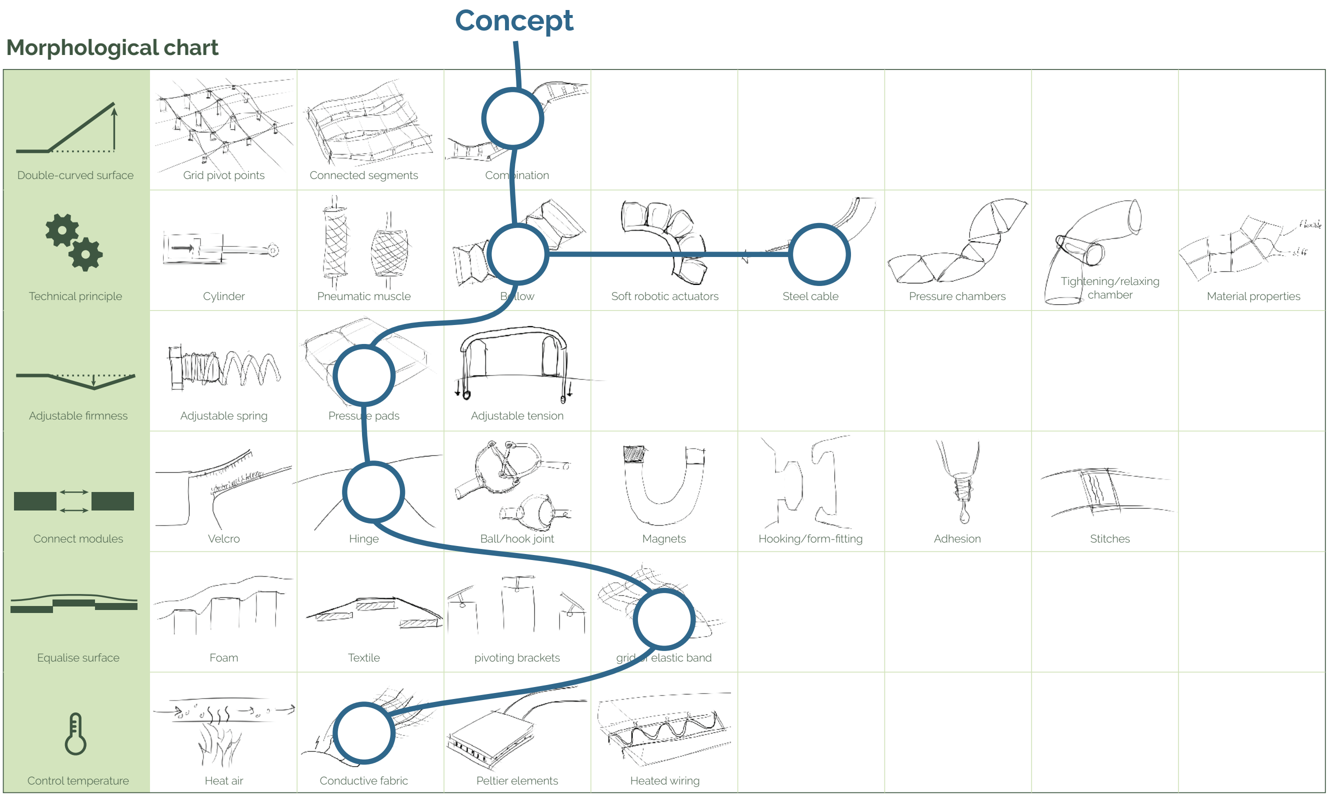


Figure 54 *Concept from morphological chart (by author)*

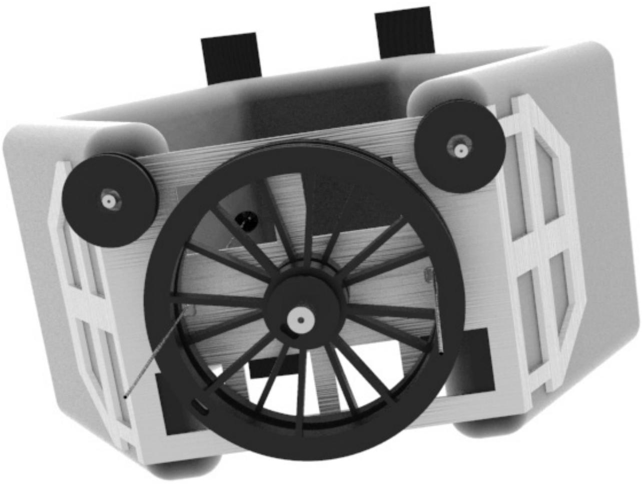


Figure 56 *Transmission wheels (by author)*

The steel cable was chosen for the smaller displacement, because a large elongation (20.4 cm) was required and a steel cable could do this with relatively few space. The disadvantage was that this steel cable did require transmission gears which resulted in a lot of different parts and high complexity (see figure 56).

The pressure pads were chosen to control firmness, because it was the simplest solution and a pneumatic control system was already in place for control of the double-curved surface.

The modules were connected using axes, which is a simple and reliable method and ensures that the modules only have freedom of movement in the desired direction.

To equalise the surface, it was chosen to connect the rows using elastic bands (see figure 57) that were connected to the pressure pads. In this way, the elastic bands would set the boundaries for how the pressure pads would expand.

Conductive fabric was chosen for temperature control. This was decided after consulting Prof. dr. ir. K.M.B. Jansen, experienced in smart materials. According to Jansen, using fabric infused with conductive resistance wiring is a cheap, simple and effective solution compared to other solutions. However, this temperature control functionality is not included in the concept as the focus is on creating a double-curved surface.

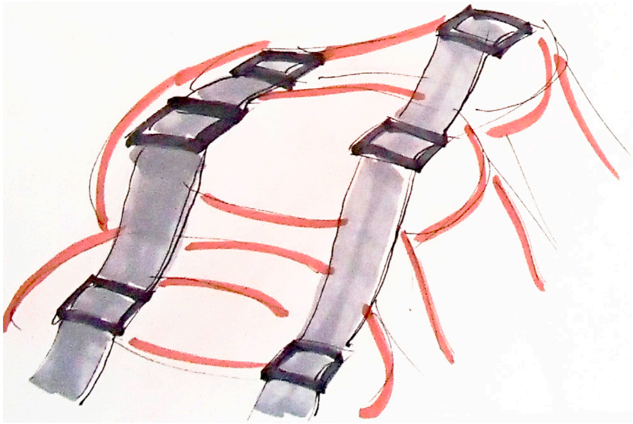


Figure 57 *Equalise surface using elastic bands (by author)*

Based on these decisions, a concept was created, shown in figure 58.

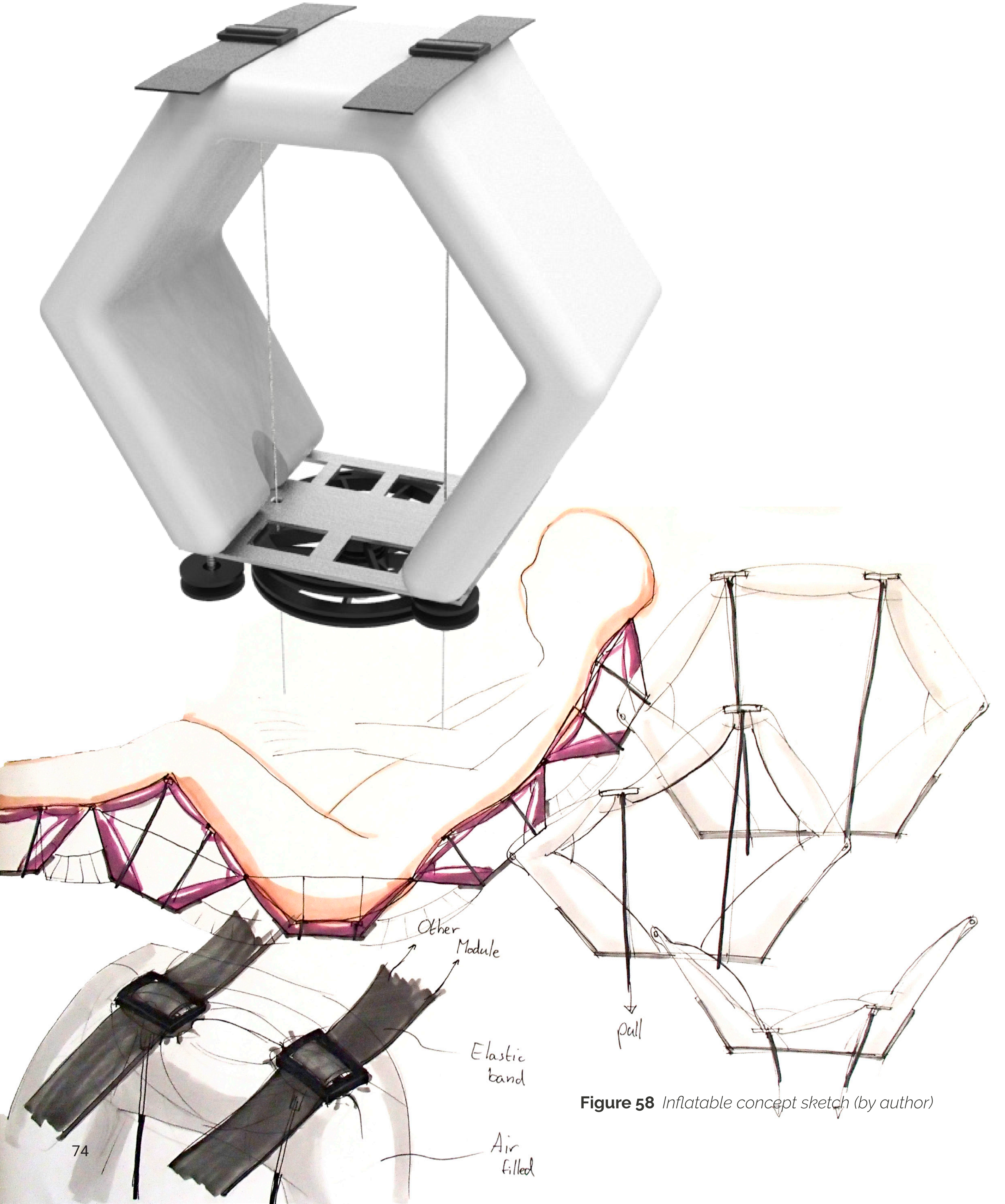


Figure 58 *Inflatable concept sketch (by author)*

Prototype and result

To verify whether this concept was feasible and would function as desired, a prototype was created (see figure 60.

Building of the inflatable was done by printing the template, cutting the PVC material in the right shape and ironing the pieces together (see figure 59). The clasps were 3d printed from PLA and inserted in the two holes of the inflatable. Next, elastic band was pulled through. Fishing thread was connected to both clasps from the bottom. Steel thread was also tested but was too thick for this application. A more flexible steel thread would be required.

The inflatable was connected to the frame with two bands that were also ironed to the inflatable. On the bottom of the inflatable, some wheels were connected on which the fishing thread could wind up. By winding up the thread, the inflatable would be pulled down on the corresponding side of the inflatable.

By connecting several modules together and control their relative positions with bellows in between (not prototyped for this concept), large displacements could be created. By pulling the threads per module, small displacements could be created. By having several rows of these connected modules, a double-curved surface could be created.

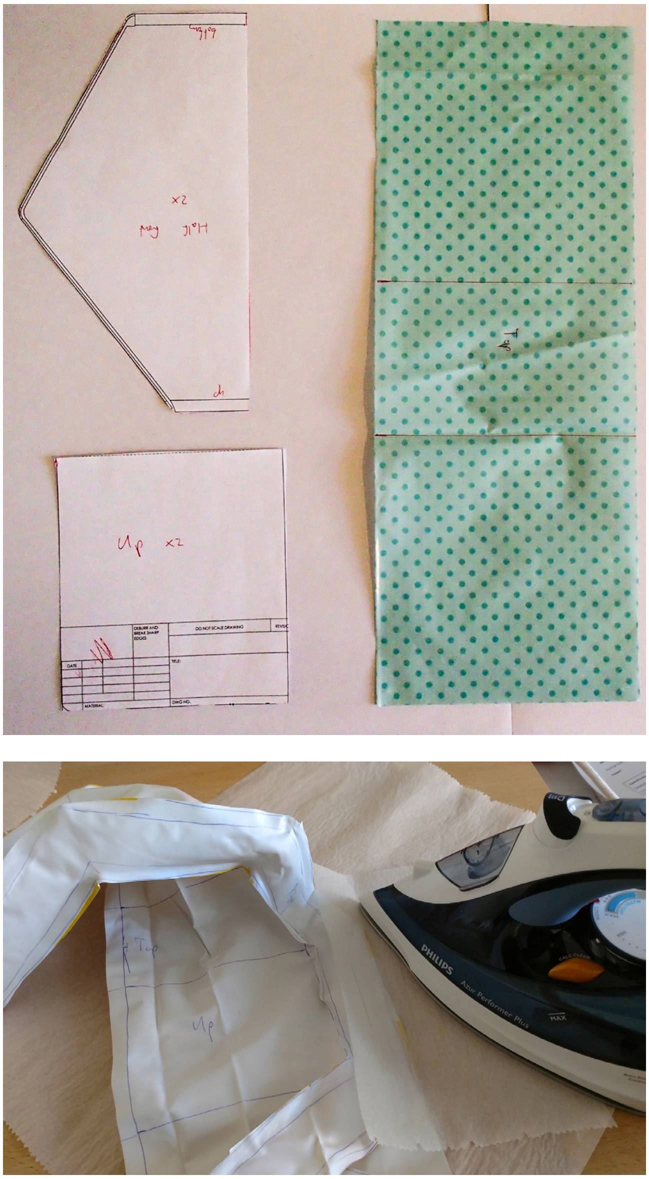


Figure 59 *Creating an inflatable (by author)*

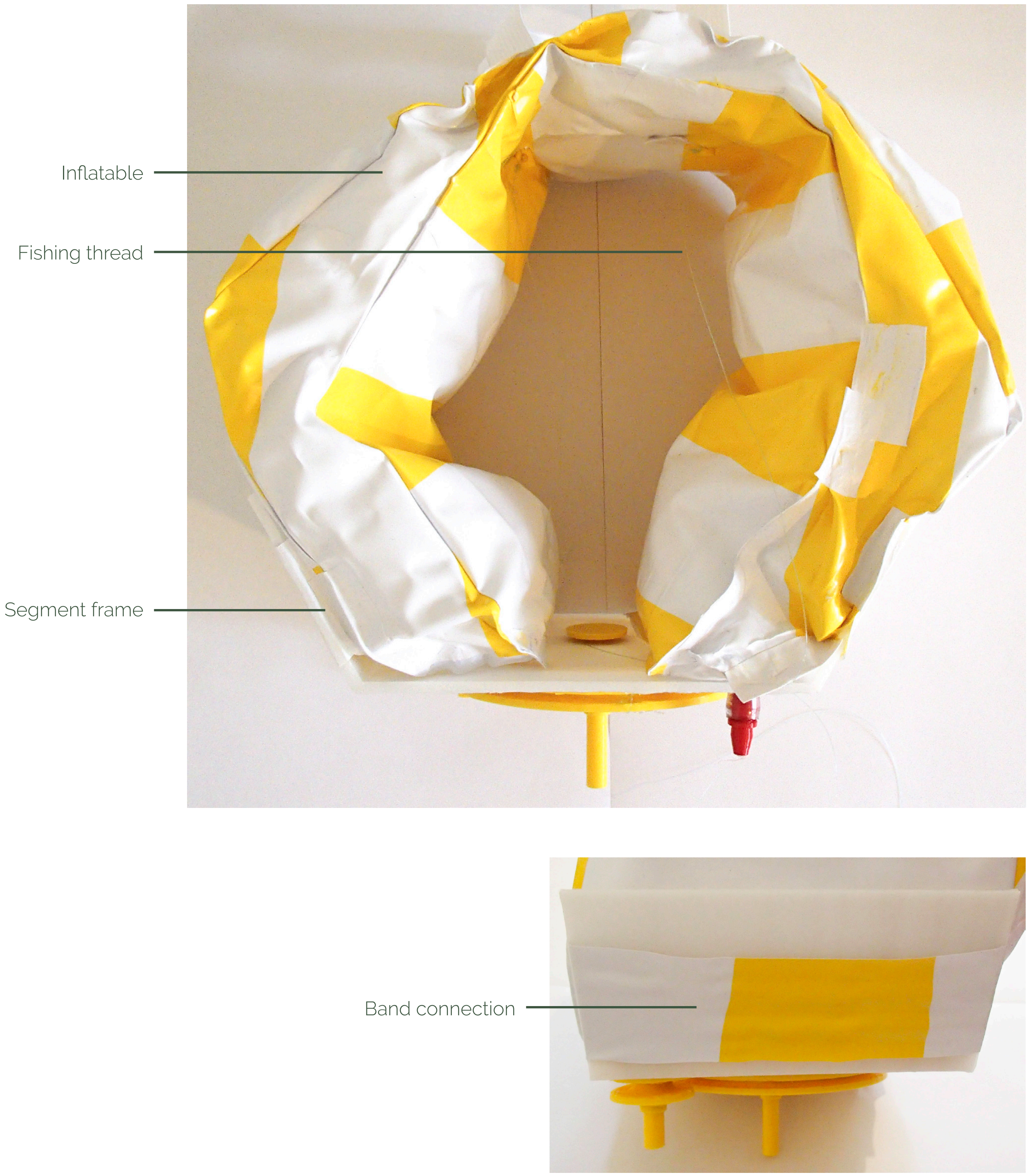


Figure 60 *Concept prototype (by author)*

Although the concept incorporates the demands created by the parametric model from chapter 6.2, by doing so the design becomes extremely complex. Building the prototype gave valuable insights into the feasibility of the concept and showed the following:

- Although theoretically ideal, combining two methods of creating displacement is not practical. It adds much complexity and it is questionable whether the benefits way up.
- Adding transmission gears or wheels is not ideal, as the segments are quite small and fitting everything on there is hard. Also, extra parts mean more chance of failure and increases the assembly time.
- Inflatables work well for adjusting firmness, but for controlling shape they are less suitable as the air flows wherever it can. If this functionality is still desired, a better way of controlling the inflatable's boundaries should be found than a complex network of elastic bands.

6.5. ITERATIONS

After assessing the first prototype it was decided to make some improvements and simplifications. This led to several design iterations.

Based on the concept evaluation and a discussion with both author's supervisors, important design decisions were made:

- A simplification was made for the principle to create a double-curved surface by going for the second option in the morphological chart; creating displacements solely with connected segments.
- By doing so, only the technical principle of using bellows would be required.
- Instead of a complicated elastic band network, a type of foam is used to equalise the surface.

These choices lead to the new pattern in the morphological chart as seen in figure 61.

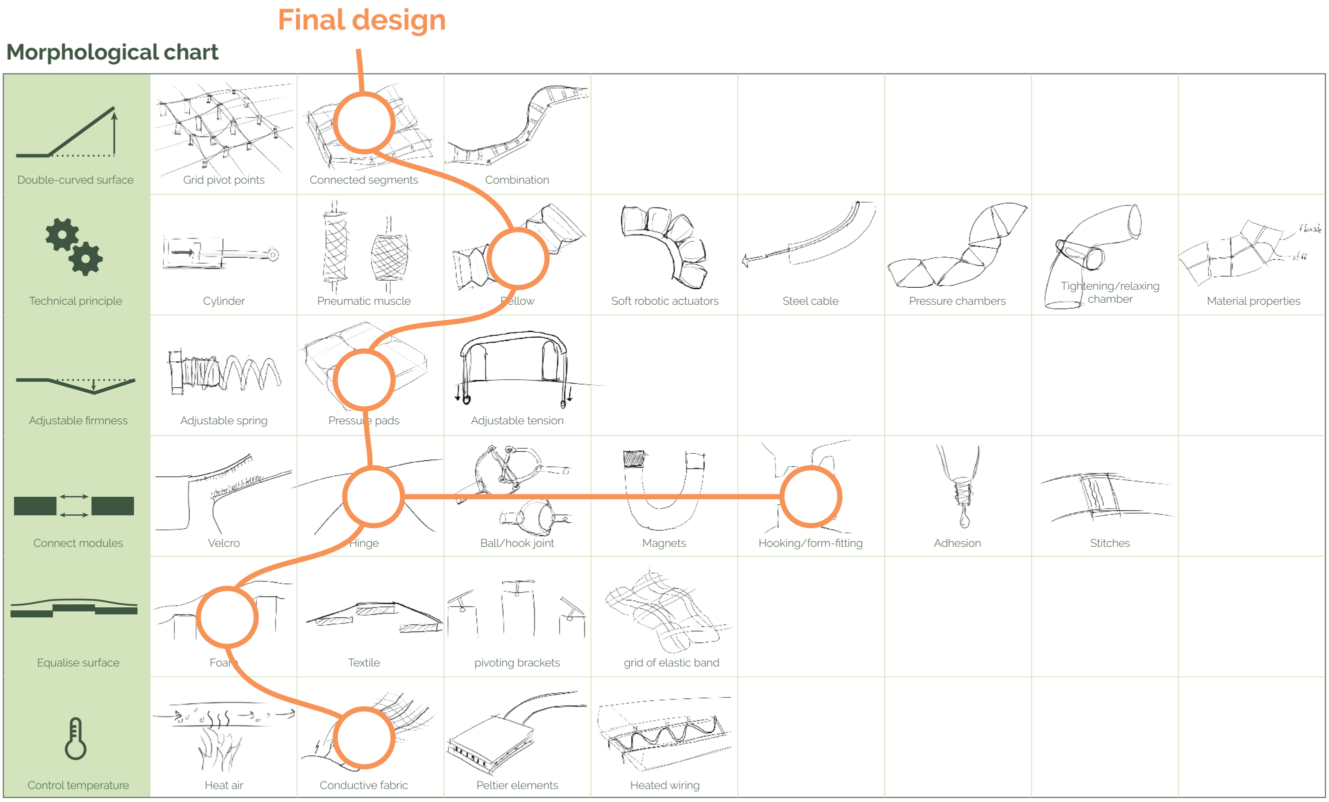


Figure 61 *Final design in morphological chart (by author)*

Prototyping the new concept

For the new concept, it was most important to create a bellow capable of extending under pressure. Although the bellow was already planned for the first concept, it was not prototyped and therefore uncertain whether the principle would actually work.

To prototype the pressure bellow, it was decided to use a folding mechanism for example found in old cameras (see figure 62). Other bellows without a folding mechanism were also tested, but did not work properly and were disregarded.

Different bellows were 3d printed with the same TPU-based flexible material used earlier to test soft robotic actuators. With each prototype, changes were made in dimensions, wall thickness, amount of folds and angle between folds to get the right bellow.

Figure 62 *Folding mechanism in old camera (obtained from www.alanwood.net/photography/olympus/auto-bellows.html)*

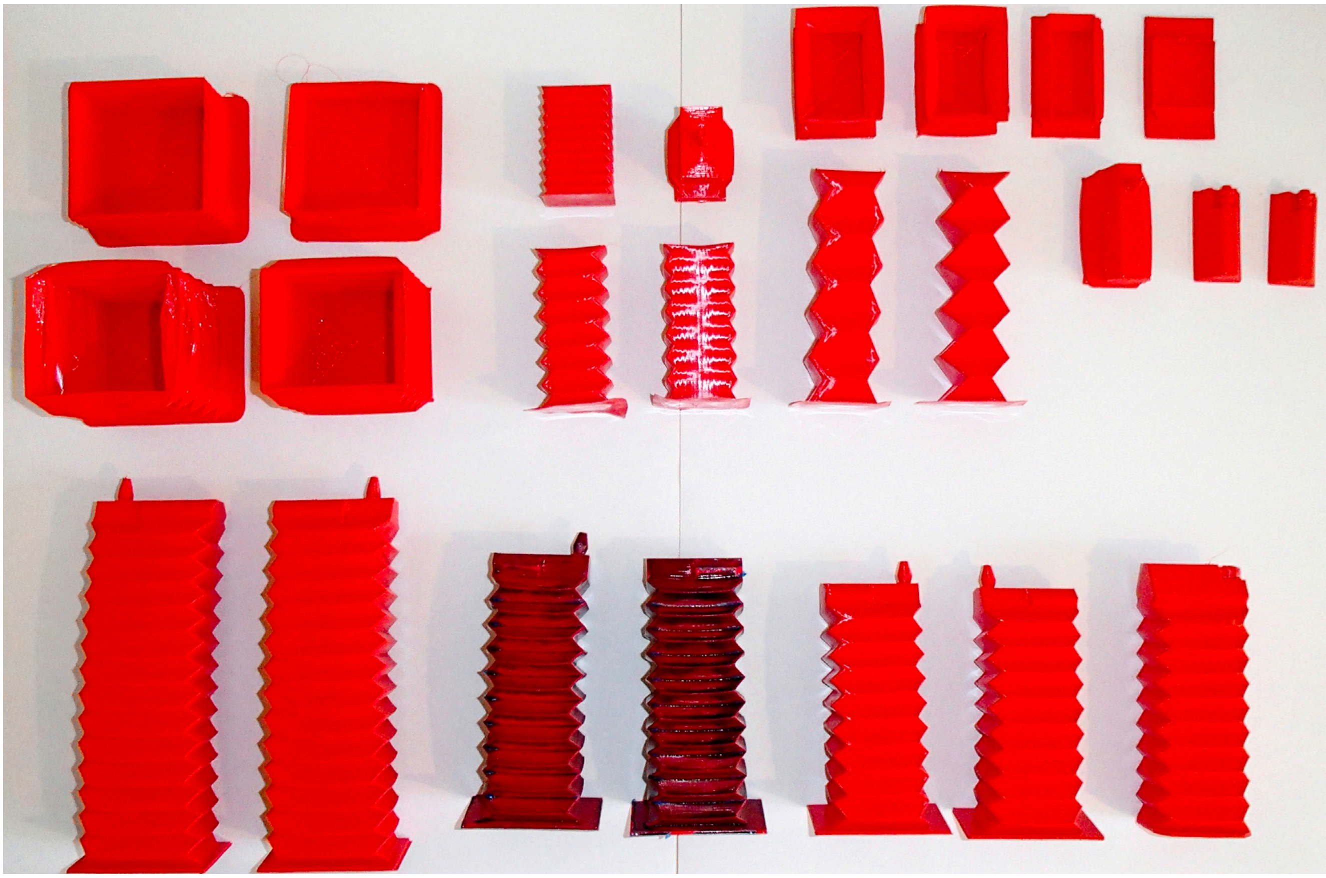


Figure 63 *Prototyping of bellows (by author)*

As the prototype was 3d printed with an FDM printer and had to be hollow, the top of the bellow was increased in size to enable an inner angle of 45 degrees, to make sure support material was not required on the inside. The segment bodies to which the bellows connect were also adjusted to match the shape of the bellows.

The prototype that resulted from these iterations is shown in figure 64. The prototype is capable of demonstrating the technical principle.

The darker bellows were painted with a peel-off spray paint to make them airtight. Although this method works, the adhesion of the different 3d printed layers makes the bellows very prone to tears, meaning that this method of prototyping does not deliver functioning prototyping besides demonstrating the principle or a visual prototype.

Evaluation

The prototype shows that the technical principle is feasible. The prototype demonstrates that the desired angles can be realised and that the folding mechanism works.

The prototype also shows that the material for the bellow will be critical for achieving the desired result. That means that the material must withstand all the forces and torque exerted when fully extended, but at the same time compress with minimal loading and pressure. Currently, the bellow does not compress as it is printed under an angle of 45 degrees between folds and the material's stiffness prevents it from compressing without enough load.

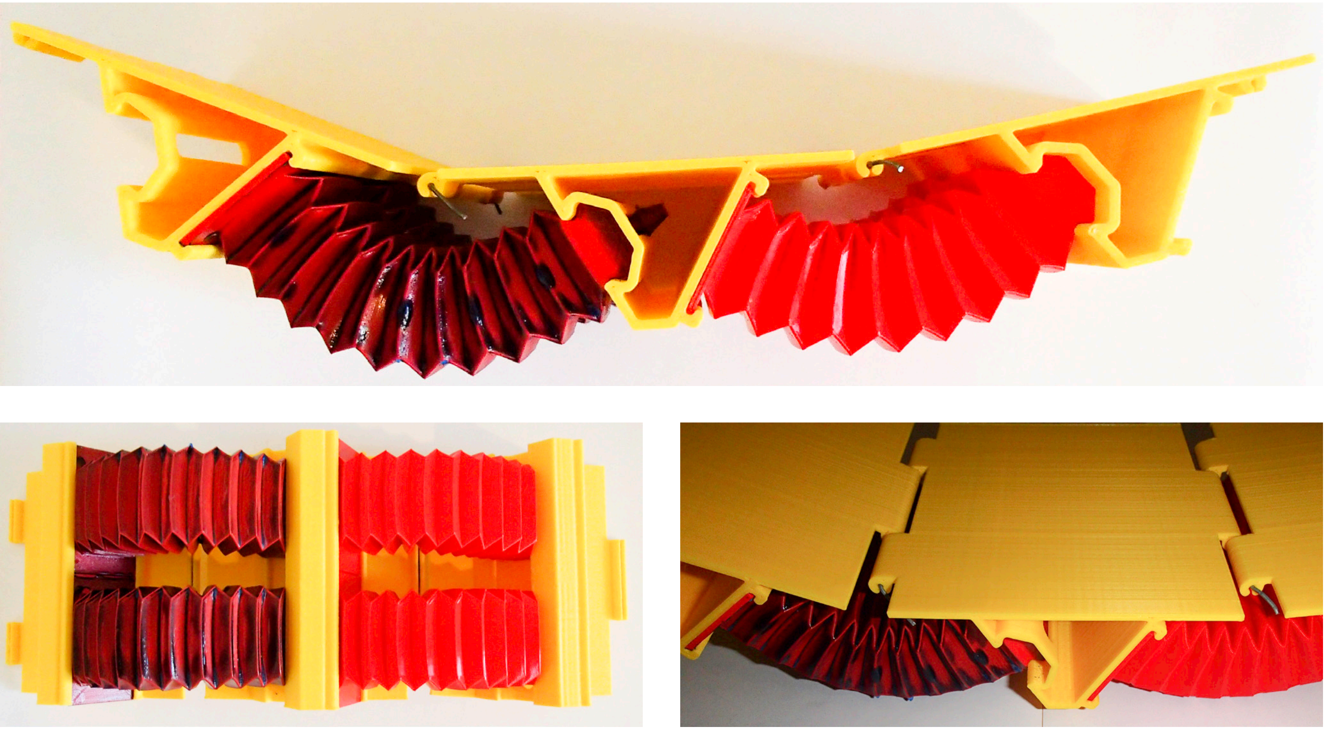


Figure 64 *Prototype of technical principle (by author)*

Imrovements

After the new concept was prototyped, a few points of improvements came up:

- The hinge could be integrated in the segment design in a form-fitting hinge joint without the need for a pin. This would reduce the number of parts and make assembly easier. The joint shown in figure 65 was chosen as it allows of a movement up to 180 degrees, which fulfils the demand for 133 degrees.
- The middle section to which the bellows attach had to increase in size to fit the air connectors.
- The top of the segment body got an indentation which will align the air connector underneath.
- To fit a larger middle section, the bellows should reduce in size from nine folds to eight folds.
- In the middle of the segments, a section is cut out to leave room for the air hoses. The area of the piece that is cut out was determined by summing up the area of all section cuts for the hoses, allowing enough space for al the hoses.
- In the first prototype, the bellows had a 'cap' for printability. In the new prototype, this is better integrated to make the bellows look more like the final product.
- Instead of printing the air valves directly onto the bellows, which did not work well because they easily broke, the bellows have a hole in the top where an air connector is screwed in.

These changes led to the prototype shown in figure 66.

Final prototype

The final prototype was made with 4 body segments connected with the integrated hinge mechanism. This mechanism was first tested and optimised as shown in figure 66.

Also air hoses and connectors were ordered but unfortunately were not the right size so they could not be installed on the modules. These parts took weeks to arrive, and unfortuantely there was not enough time left to order the right size. It does show that all dimensions

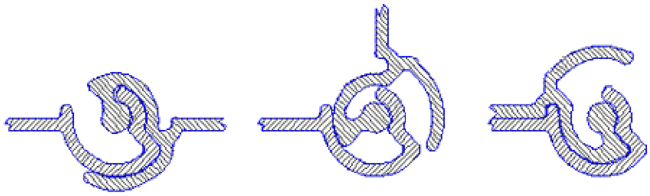


Figure 65 *Form-fitting hinge joint*

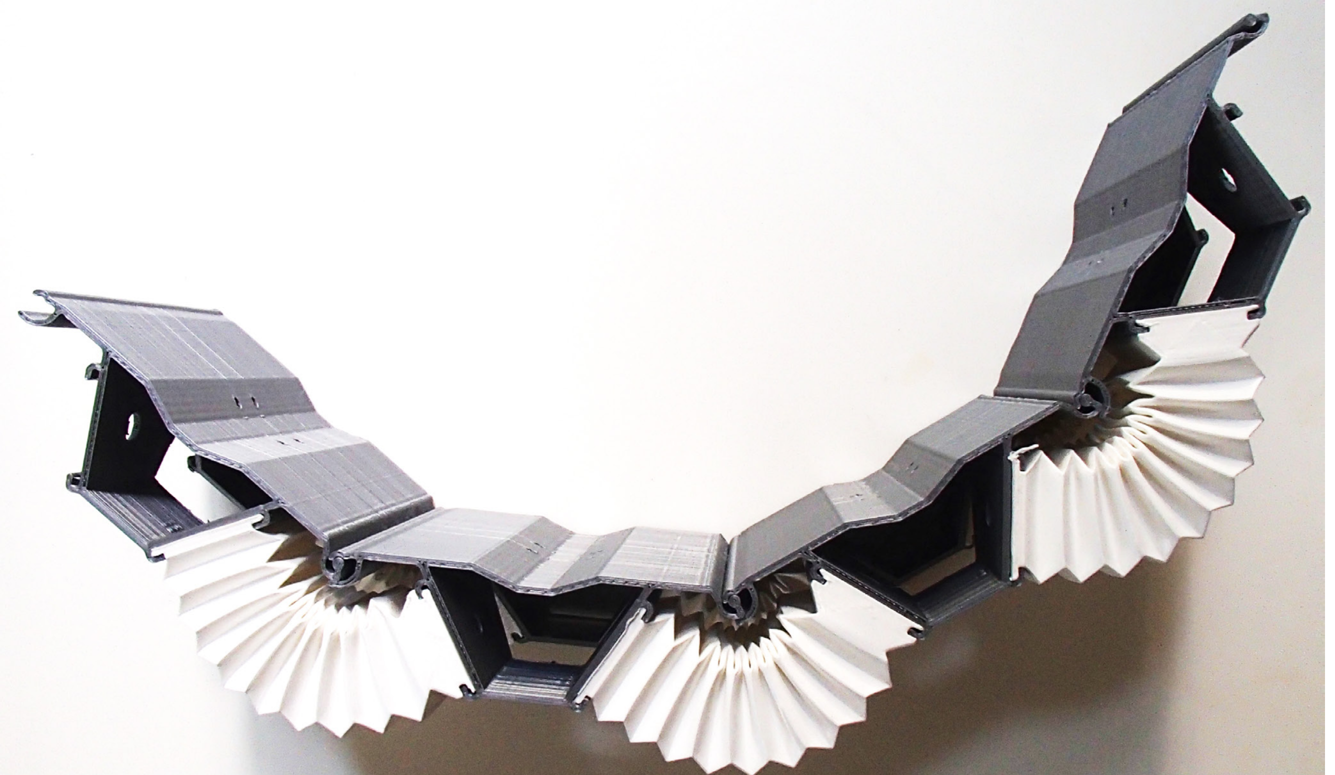
image and principle obtained from www.profilgruppen.se/construction/extrusiondesign/functions/hinge-joints/?lang=en

for the connectors differ with different hose diameters, and not just the part where the hose connects to. Therefore, the type-I connectors (see chapter 7.4) are too long and do not fit inside the segment body and the type-II connectors are too wide and do not align with the screw holes in the body segment.

Therefore, it is recommended to determine the right hose diameter for further design improvements and adjust the body segment design to the chosen diameter (see chapter 9).

Evaluation

Although not complete with connectors and air hoses, this prototype comes much closer to the final design. Visually, it is more attractive, and it allows for the other parts to be connected. This prototype is only one step away from a fully functioning prototype. The only thing that should be improved is the bellow, to get one fully airtight and to finally test it, the plastic body segments should be prototyped from metal.



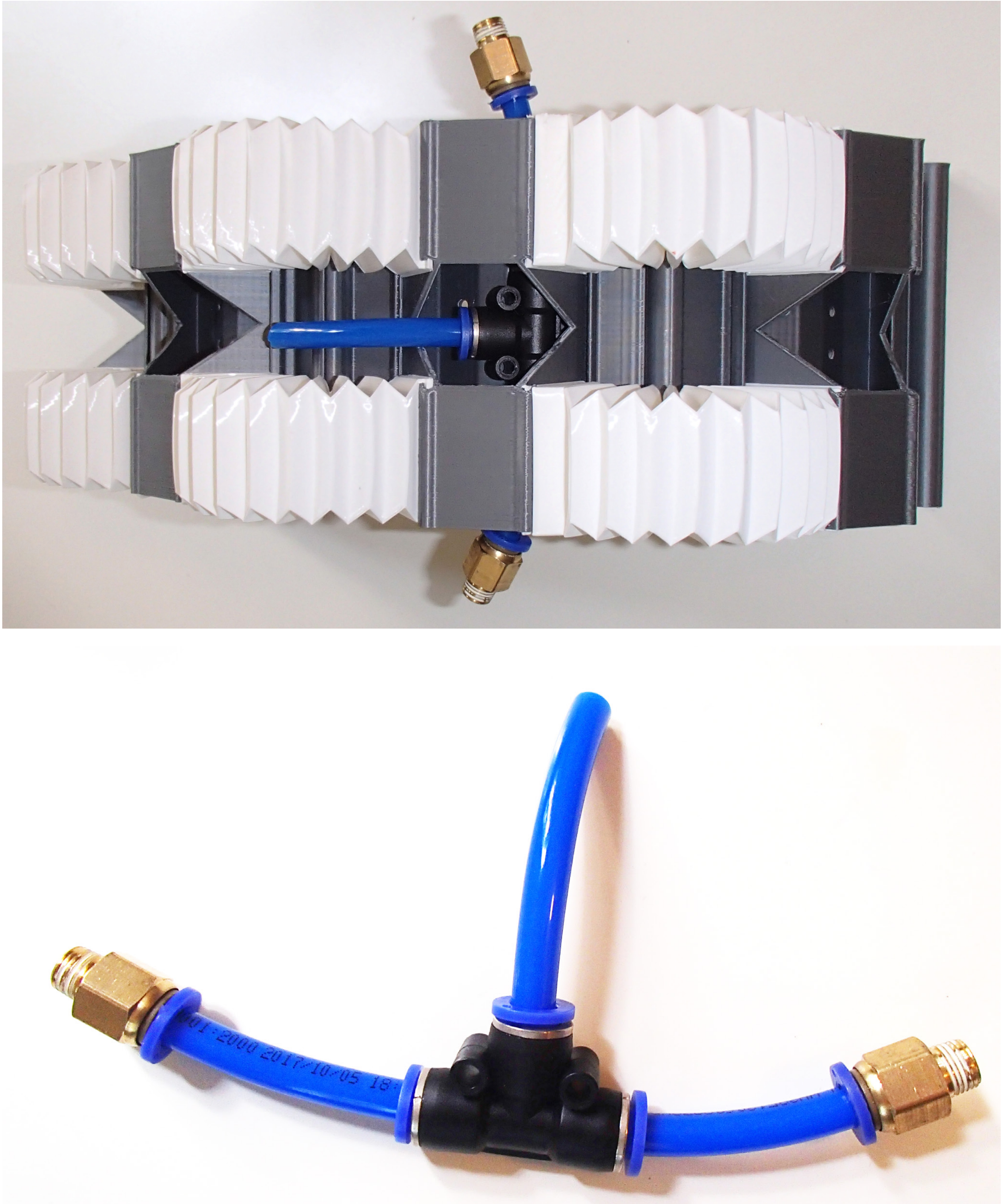


Figure 66 *Photos of final prototype (by author)*

7. FINAL SYSTEM DESIGN

With the valuable information gathered from prototyping the concept, choices could be made to get to a final design. This chapter will reveal the final design and specifics on parts and production.

Photo from rawpixel.com

7.1. DESIGN OVERVIEW

The design of the bed is built up of several subassemblies as shown in figure 67. In this project the Sleep System (1.3) was designed with a focus on the Modular System (1.3.2) which consists of many Modules (1.3.2.1). Also, to get a better picture of the final product and a feeling for the use context, a concept for the Overall Bed (1) was designed.

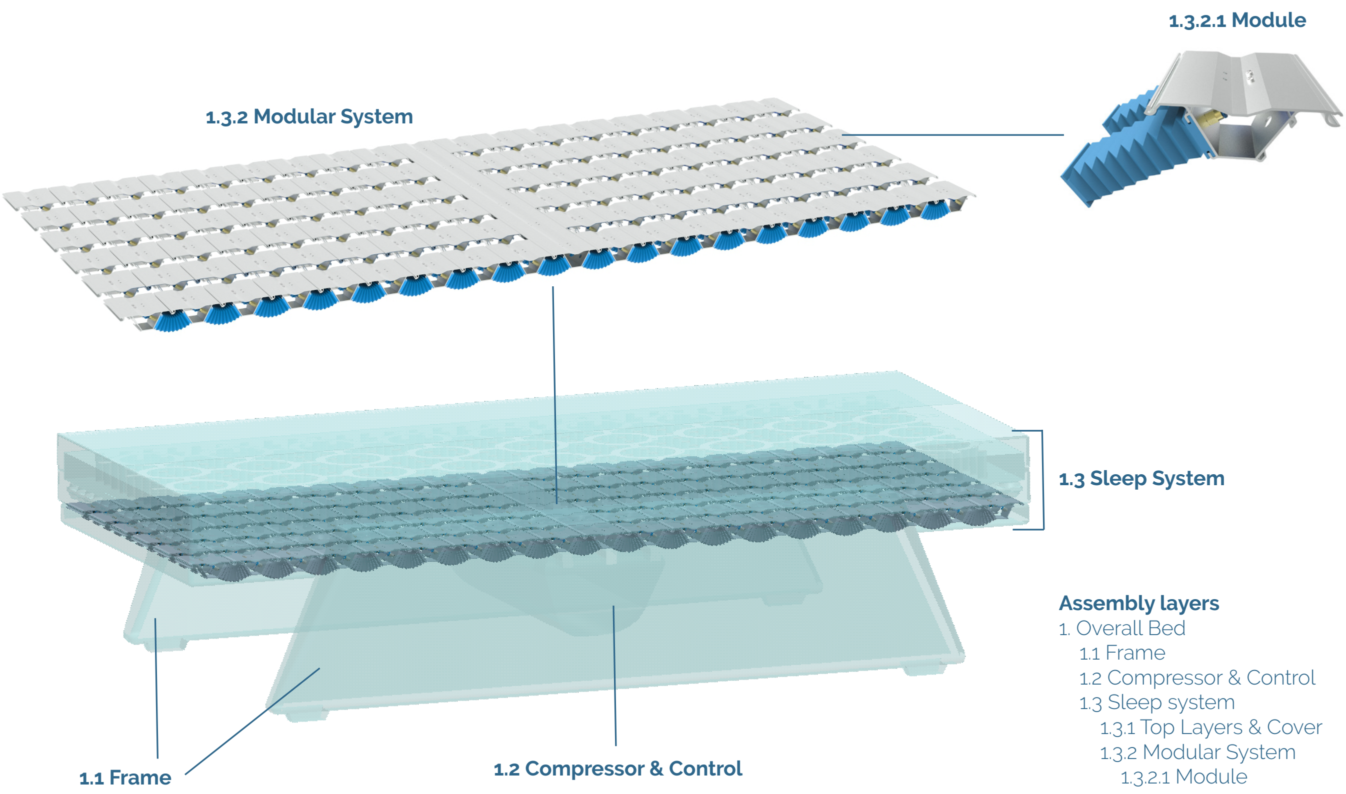
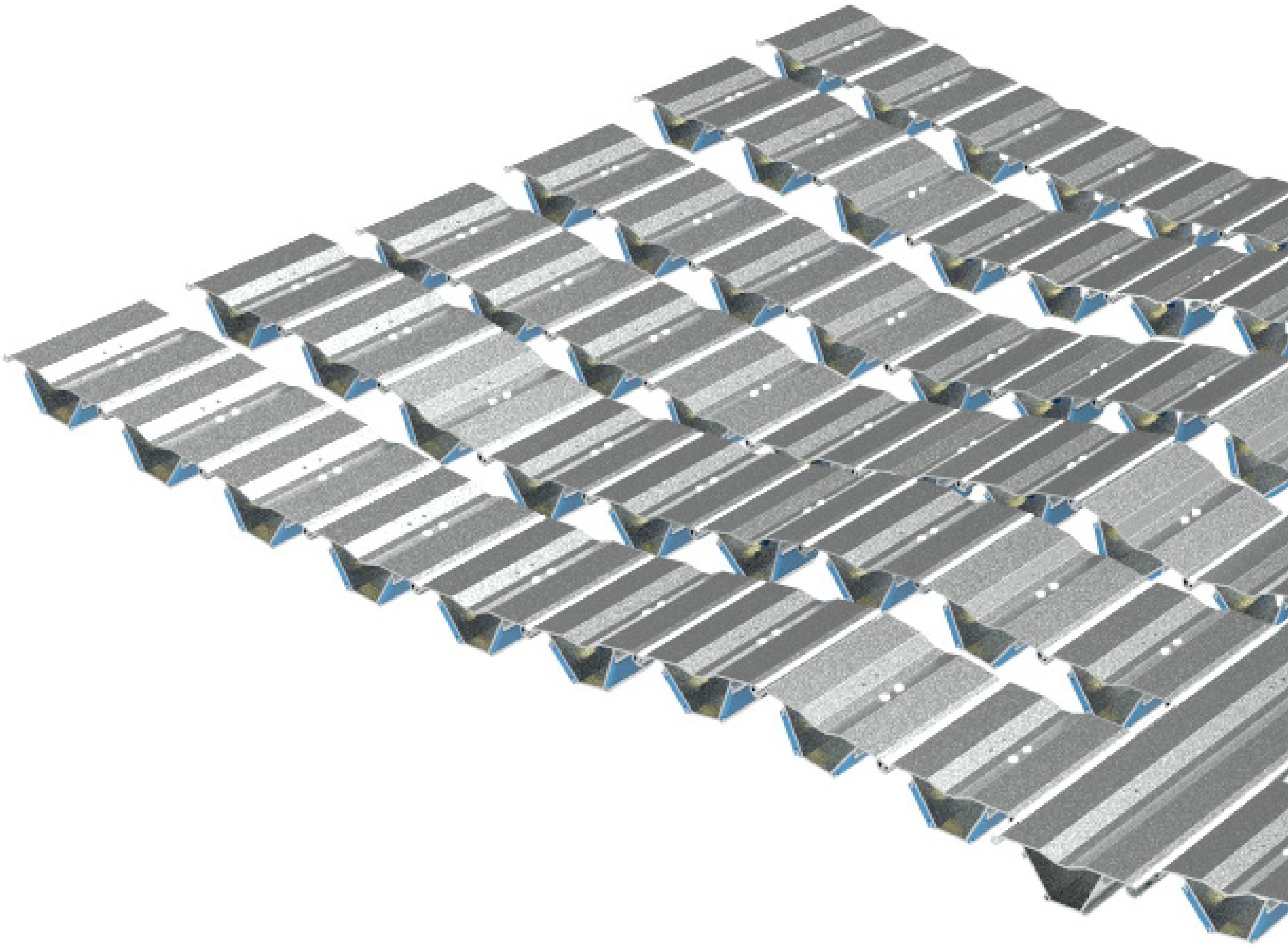


Figure 67 *Design overview with subassemblies (by author)*



7.2. MODULAR SYSTEM

The modular system supporting the rest of the sleep system consists of modules connected in rows as seen in figure 68. By controlling the angle between each of these modules different surface shapes can be created.

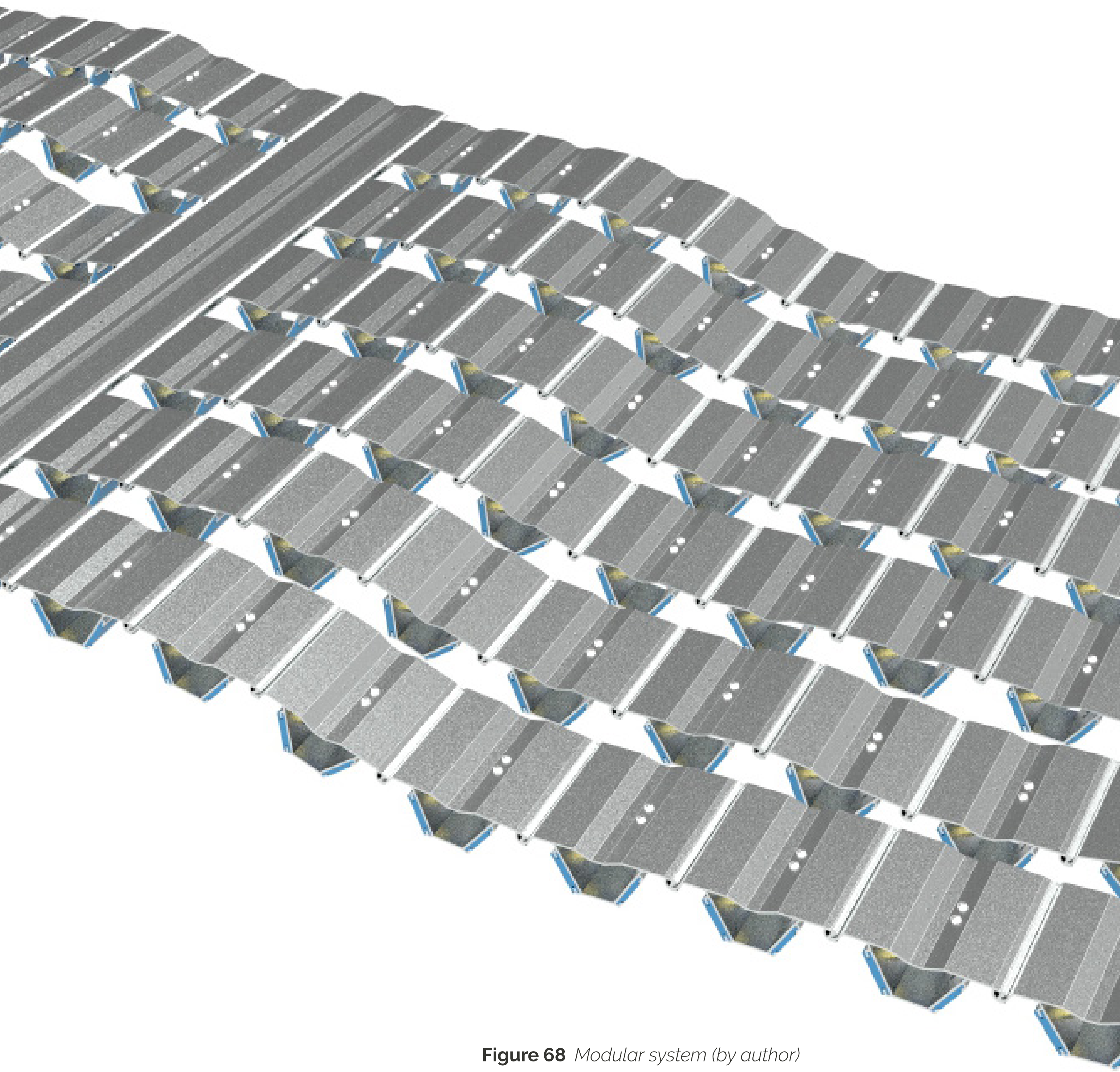


Figure 68 *Modular system (by author)*

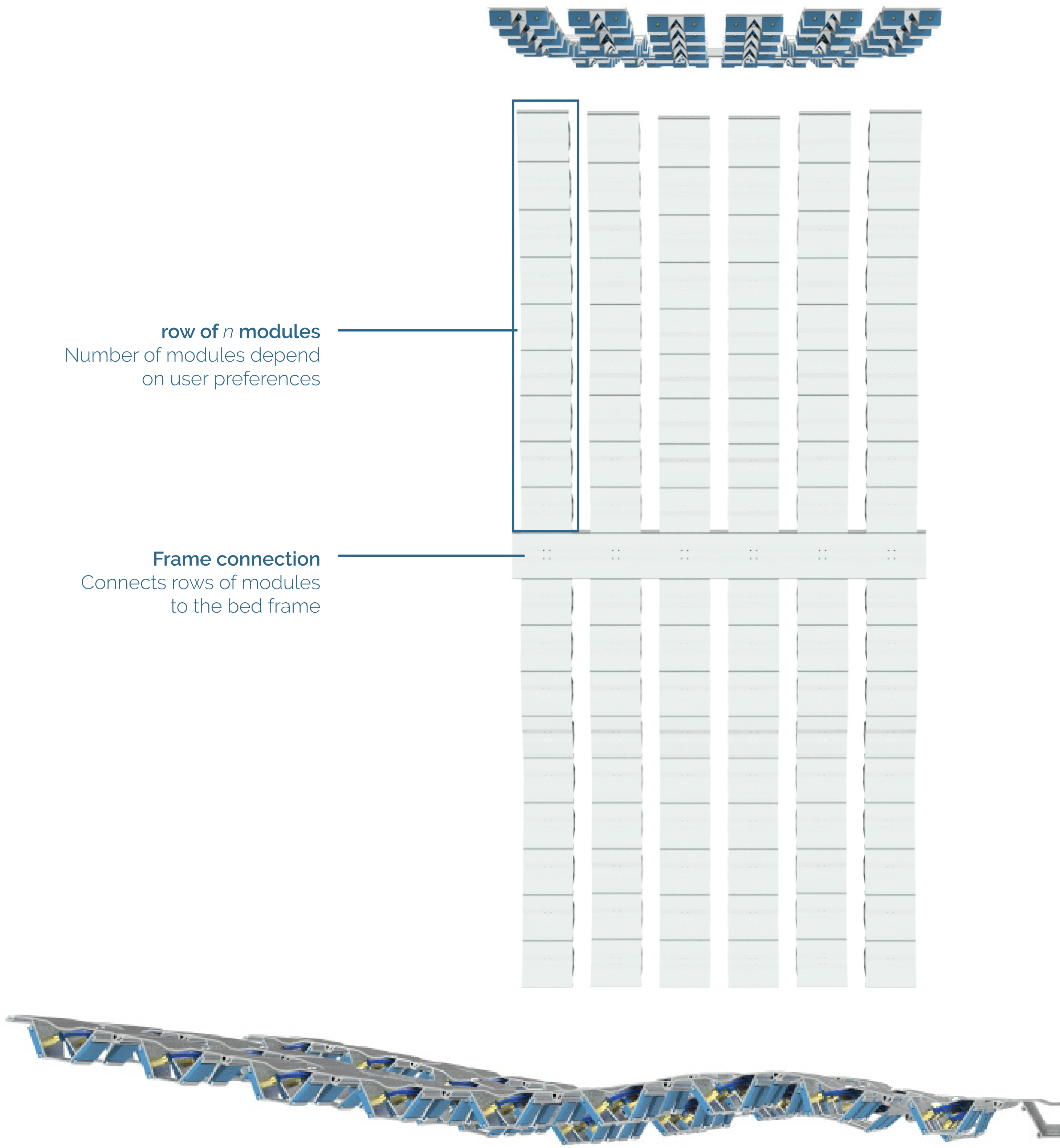


Figure 69 *Different views of modular system (by author)*

Modular System

The system consists of several rows of modules that connect to an extended profile in the middle, called the frame connection. The number of modules used depends on what is required by the user.

Each module has a length of 100 mm, meaning that a person of 1.65 m may find a length of 17 modules enough while a person of 2 m will require at least 21 modules. For the width the same principle applies, although a width of four modules seems to be the minimum to create enough variation in surfaces. This means that the bed can be turned into a two-person bed by adding extra rows of modules. In the images, a total of 108 modules is used, which means rows of 9 modules long on both sides of the frame connection.

Between the rows, a space of 40 mm ensures that the rows will not touch, even when the rows are pulled towards each other because of an extreme position or when sideward pressure is applied. This space also makes sure that the transition between rows is smoother. Besides that, it leaves room for air flow which creates ventilation.

The full modular system is covered with a protective textile layer that hides the mechanism from sight (see figure 96).

Examples of positions

The system is based on a parametric computer model (see chapter 6.2) and is capable of supporting all types of P5 - P95 bodies in the correct position. It can also support the head which makes the use of a pillow optional. Two examples of possibilities are shown here, with a male on his back and a female on her side. More related images are shown in appendix C.4.

The positions of the modules are estimated based of an image of the human model. The mattress in between is an approximation of the surface created by the modules. It is a difficult to get a more precise model as the human figure is made in MakeHuman 1.1.1 and edited in Blender 2.77, the modules are constructed in SolidWorks 2017 and the mattress and final assembly in Rhinoceros 5. Unfortunately none of these programs is capable of doing all these operations, which makes it a complicated process.

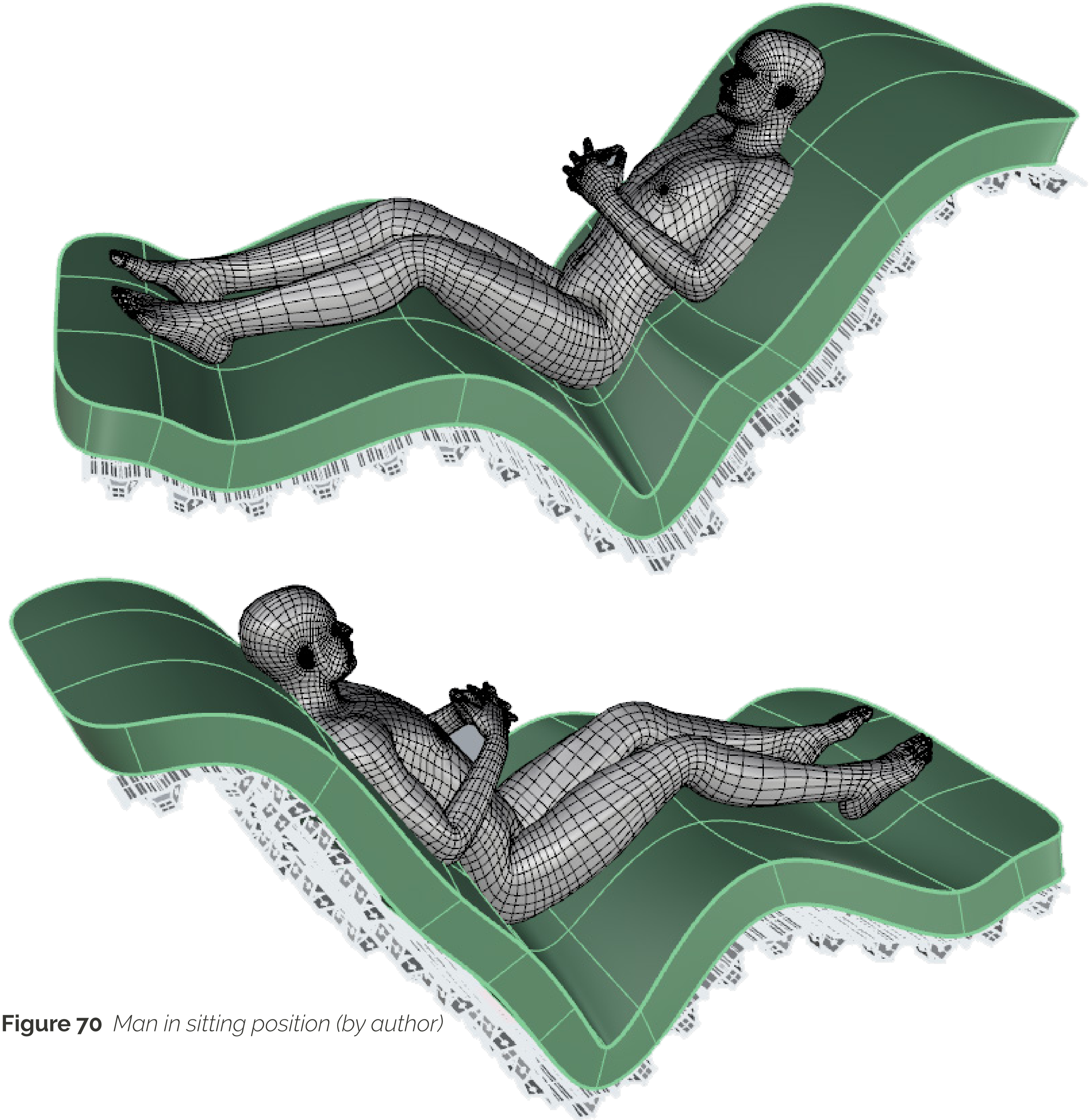


Figure 70 *Man in sitting position (by author)*

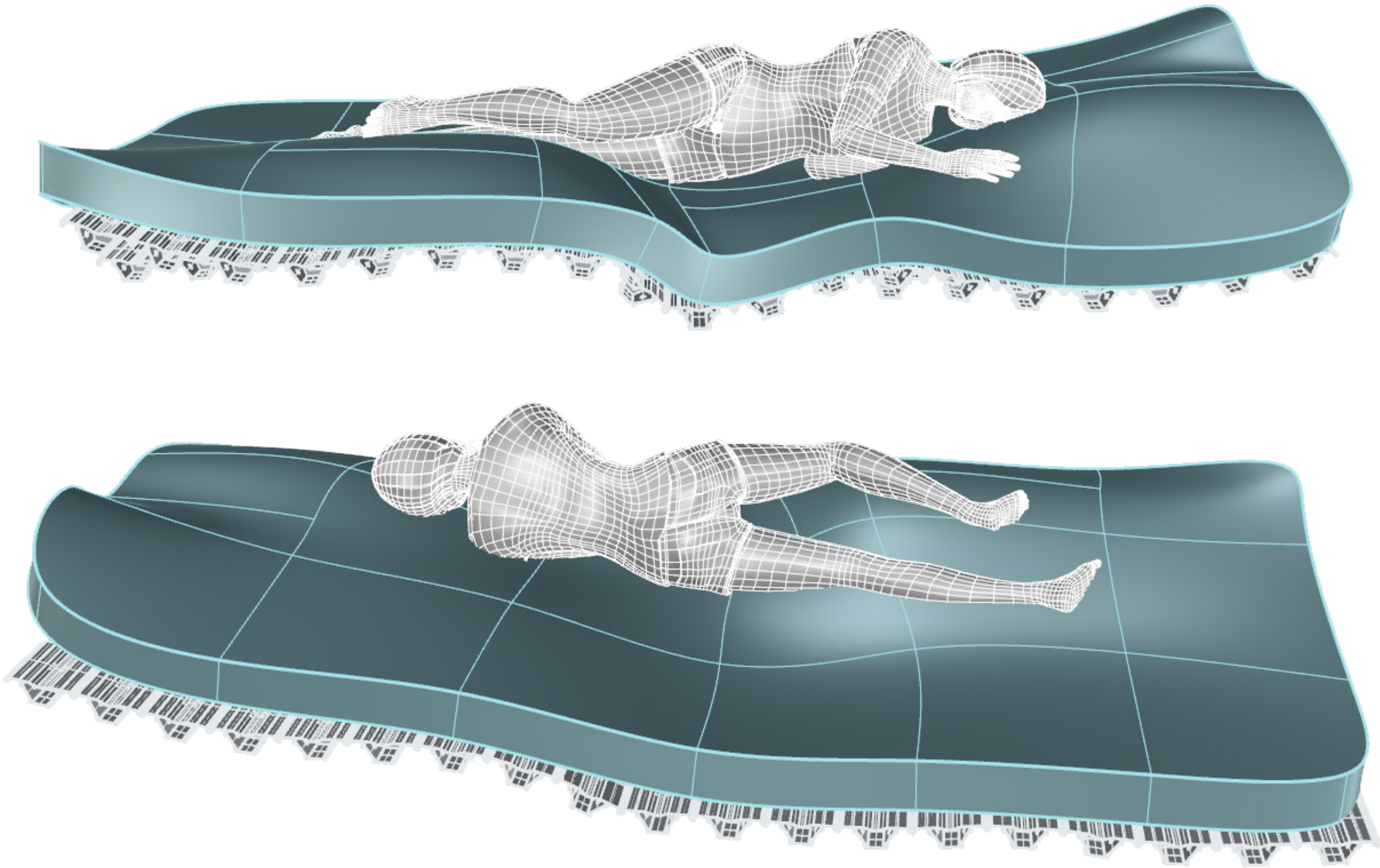


Figure 71 *Woman in side position (by author)*

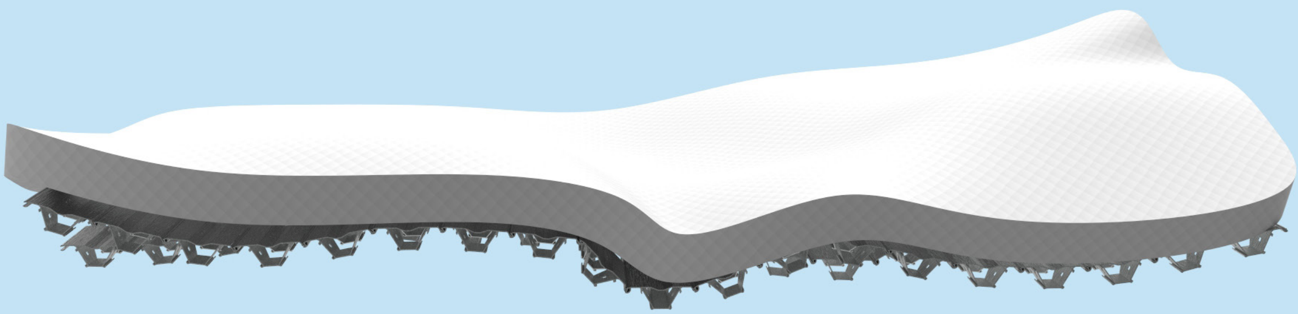


Figure 72 *Side position renderd (by author)*

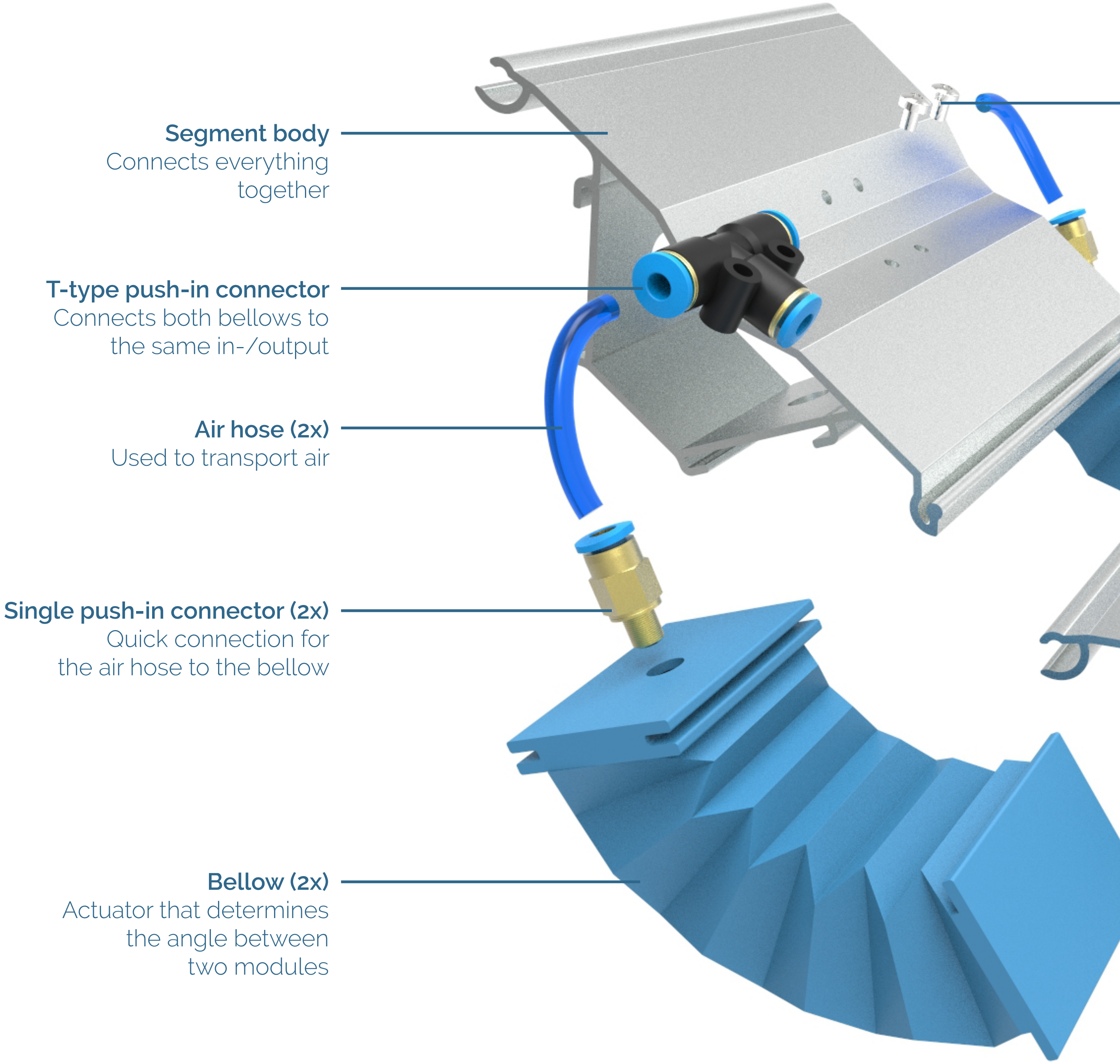
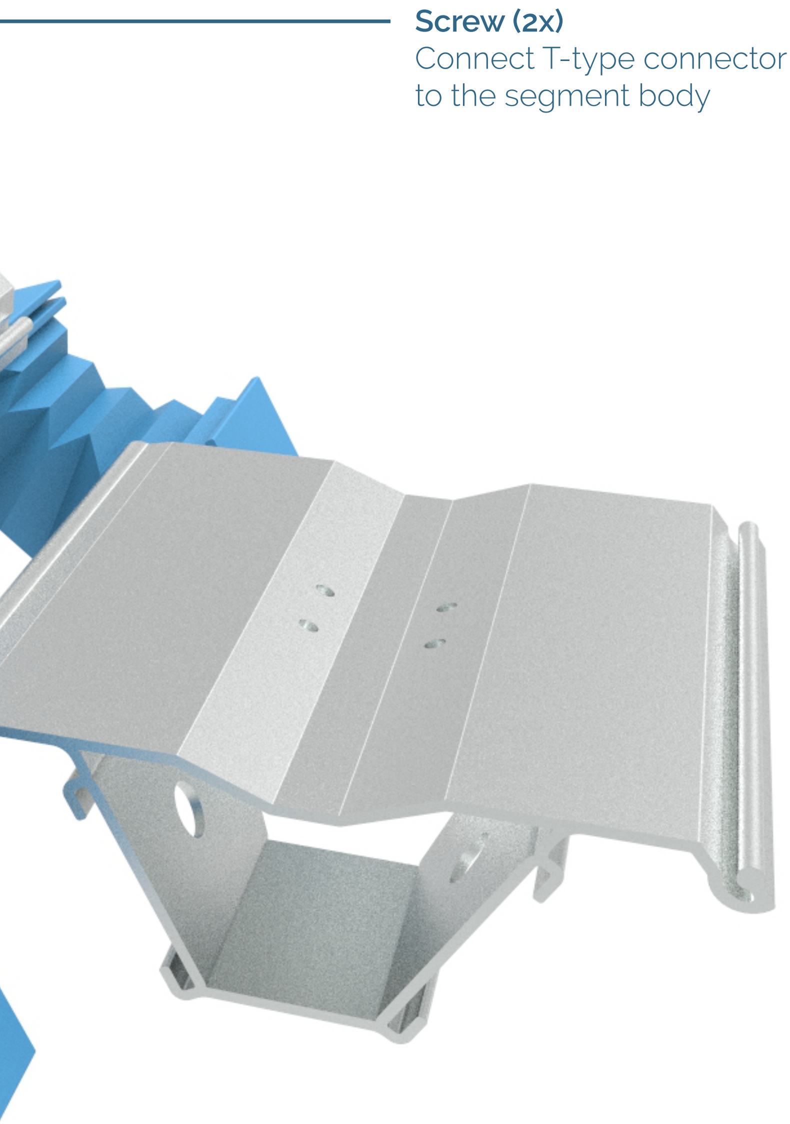


Figure 73 *Exploded view of Module (by author)*



7.3. MODULE DESIGN

The module has been the focus of this design project. The module is a subassembly of the overall design presented in the previous chapter. In figure 73, an exploded view of the module is shown to show of which components the module exists. In figure 74, some other views of the module are shown to give more insights in the functioning of the module.

The module consists of a segment body, which functions as the base component. Other parts are mounted on the body. Internally, pneumatic connects connect the bellows to a pneumatic system.

The bellows and segment body connect to another segment body. These bodies can rotate around an integrated hinge.

In the following chapters, each component is explained in more detail.

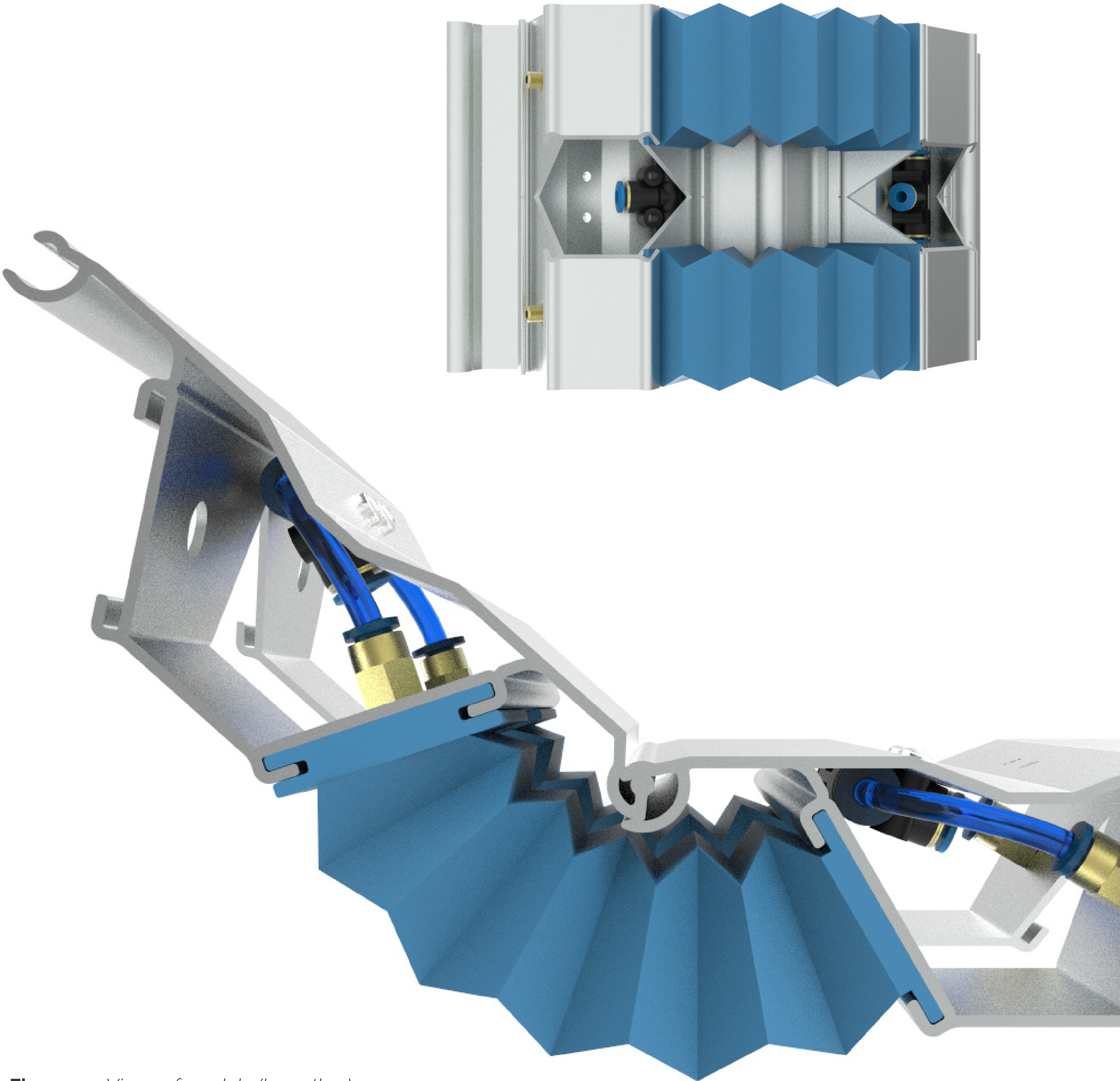
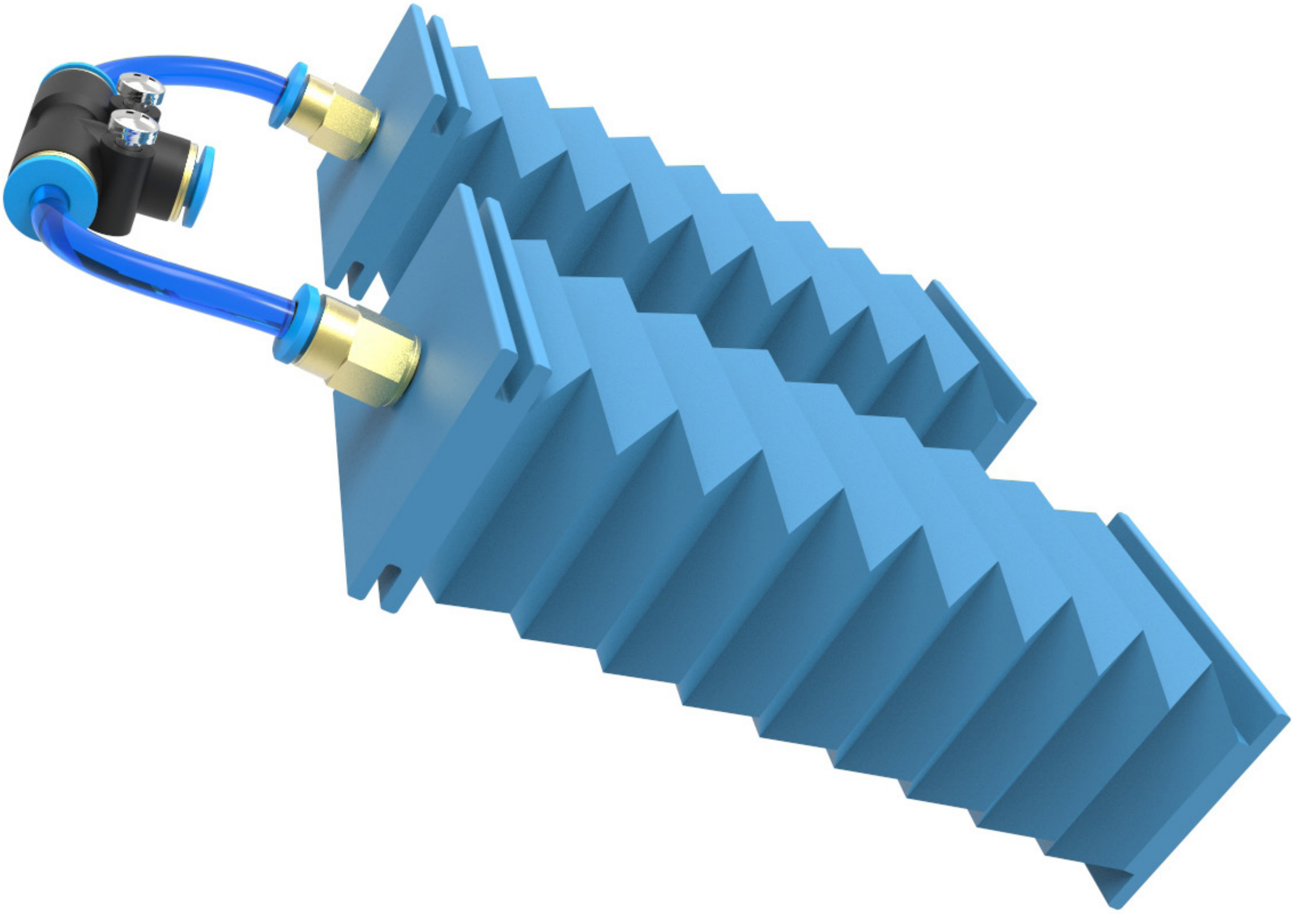
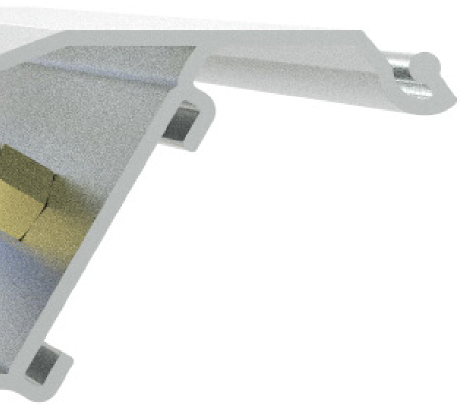
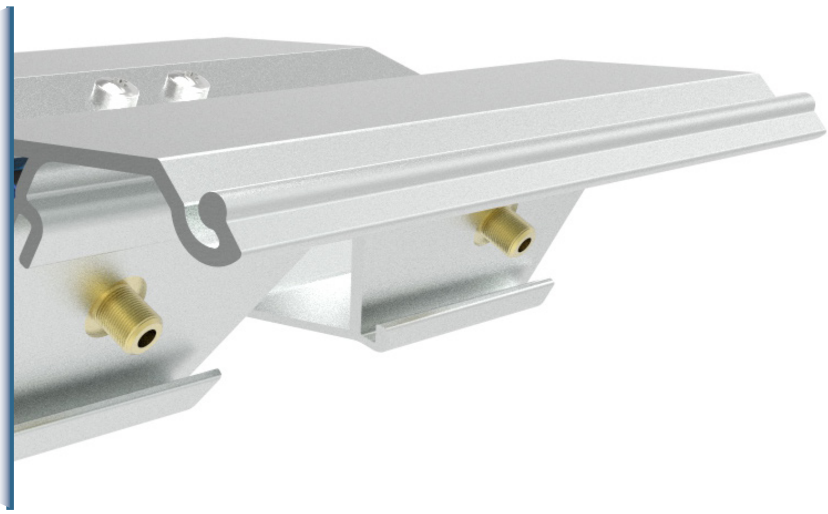


Figure 74 *Views of module (by author)*







Segment body

The segment body forms the base of the module. All other parts of the module connect to the segment body and the segment body functions as hinge and connection between two modules.

Main dimensions

The segment body is 100 mm long instead of the ideal 80 mm (according to the parametric model from chapter 6.2) because the bellow needs the extra space to enable a larger angle between segments.

The width is 110 mm instead of the 120 mm calculated in the model (see chapter 6.2). However, this 120 mm was the ideal distance between points varying in height if connected with a straight line. In other words, the elements should be able to rotate over the width as they do over the length. However, this design does not allow for that, and therefore it was chosen to make the segments slightly less wide and use the top layers to smoothen the surface.

The attachment for the bellow is positioned under an angle of 120 degrees to make sure the bellow only bends in one direction and can make all the desired angles.

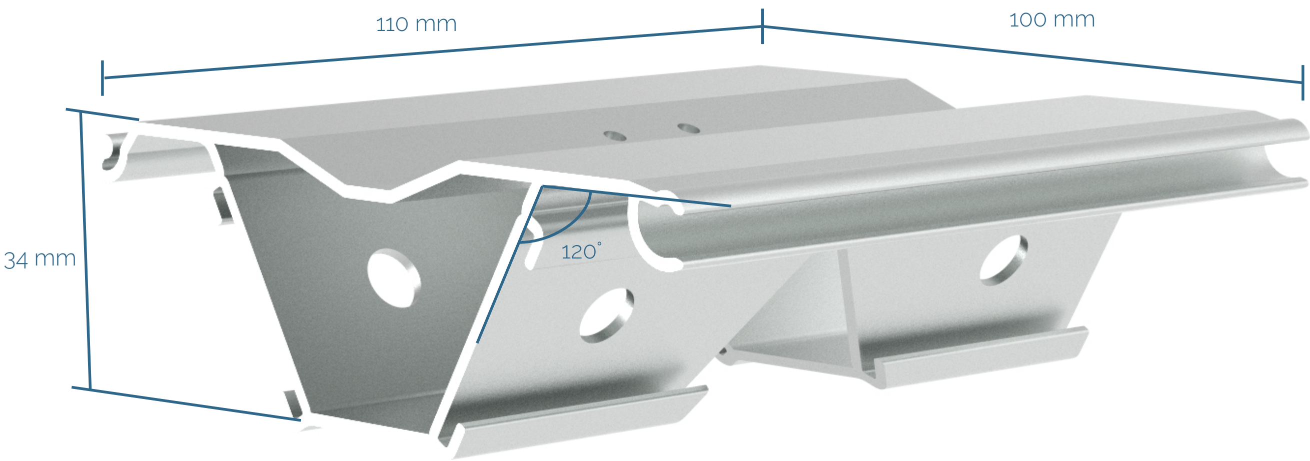


Figure 75 *Main dimensions segment body (by author)*

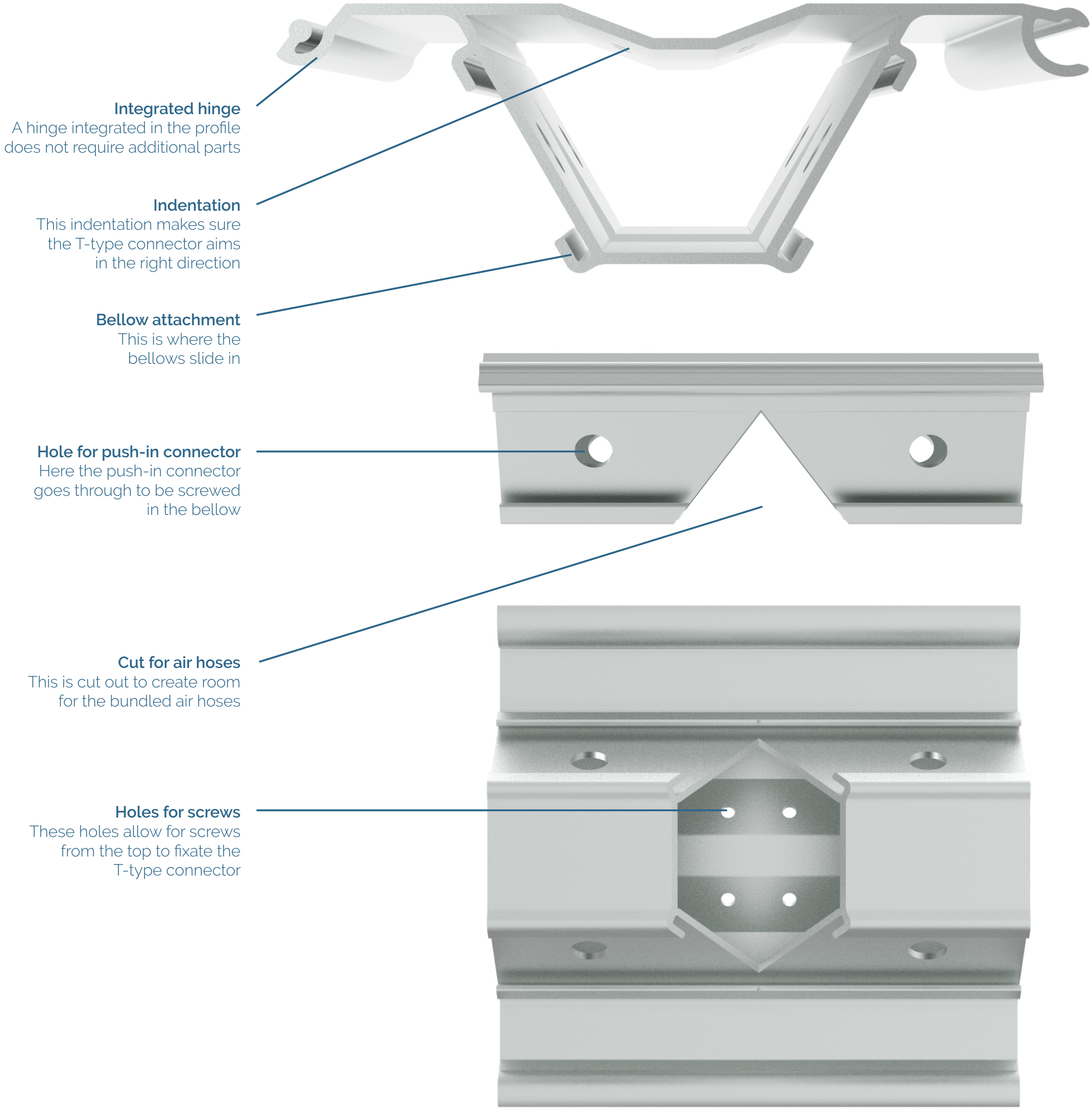


Figure 76 *Segment body overview (by author)*

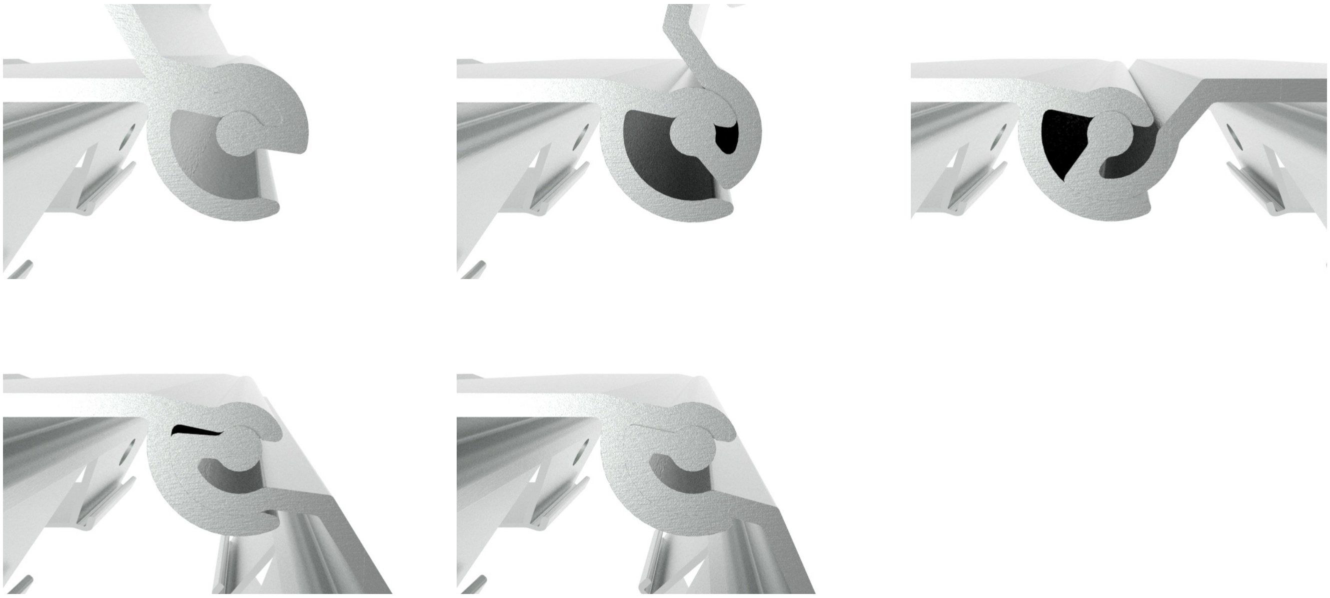


Figure 77 *Integrated hinge design (by author, principle obtained from www.profilgruppen.se/construction/extrusiondesign/functions/hinge-joints/?lang=en)*

Integrated Hinge Mechanism

The mechanism that connects different segments is integrated in the extrusion profile. This mechanism is based on the mechanism shown in figure 65, but slightly adapted to match the design and to create the angles in the right direction. The design was made in such a way that the mechanism is positioned on the bottom of the segments. In this way, it does not stick out like the original mechanism would.

Material

The segment body is made from wrought aluminium in the 6000 series, as these are optimised for extrusion. That means that it is an aluminium alloy wich consists of about 95-99% of aluminium with some magnesium (Mg) and silion (Si) mixed in.

The advantages of aluminium are the combination of light-weight, strength and high corrosion resistance. It is also perfectly recyclable.

Production

To make the segment body, it was chosen to use aluminium extrusion. The advantages of extrusion are that it is a cheap process with cheap dies which can also be used for small series, which is a likely scenario as it will be an expensive final product and may first be introduced to hospitals for example.

The production steps are as follows:
1. Aluminium extrusion of profile.
2. Punching of different holes in sides and top.
3. The cut in the bottom is sawn out.
4. The extrusion profile is cut to length.

Strength analysis

To verify that the segment body or the integrated hinge will not fail under extreme conditions, Solidworks simulations were run. The scenario tested was a person of 200 kg dividing his weight over four modules (for example when sitting on the edge), meaning that each module had to carry approximately 500 N.

Several simulations were run, fixating the part at the bellow or at the bellow and the hinges. The maximum displacement was approximately 0.3 mm (see figure 78), which is acceptable. And the maximum stress applied was about 103 MPa (see figure 78). Although the material applied in Solidworks had a yield strength of 41 MPa and failed, there are many alloys in the 6000 series with yield strengths much higher than 103 MPa, so this should not be a problem if the right alloy is used.

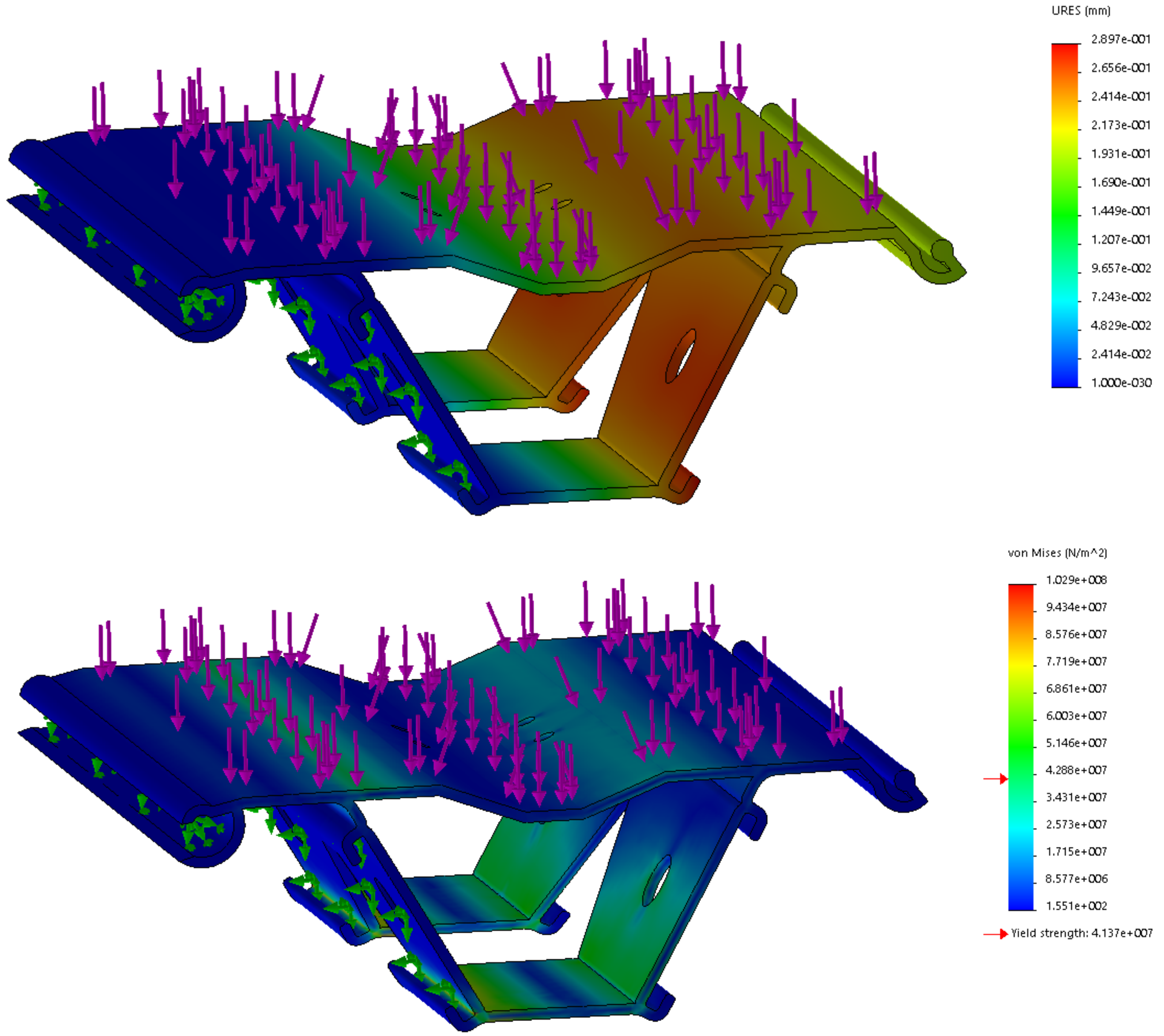


Figure 78 *Solidwork simulations of stress and displacement for segment body (by author)*

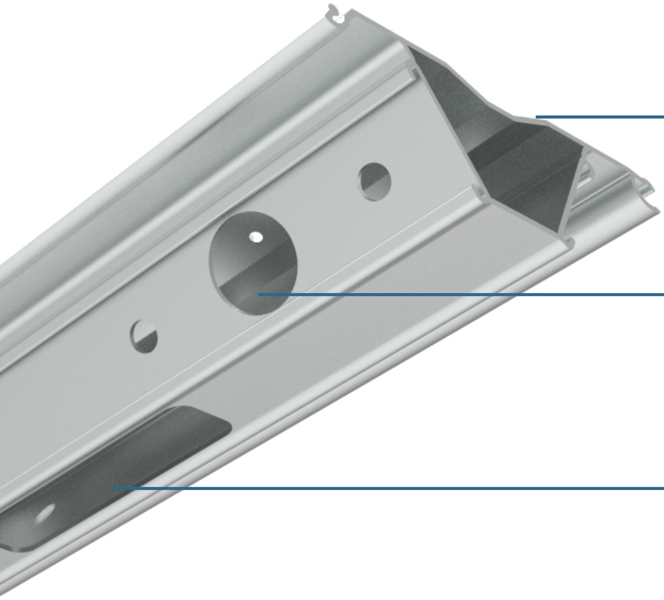
Frame Connection

The connection to the frame is made from the same aluminium extrusion profile as the modules. The only difference is the length of the profile, some extra holes and that the part in the bottom is not sawn out.

The connection is mounted on a beam which is connected to the rest of the bed frame.

The holes enable the bundled air hoses to go through the frame connection to the compressor box below.

Figure 79 *Frame connection (by author)*



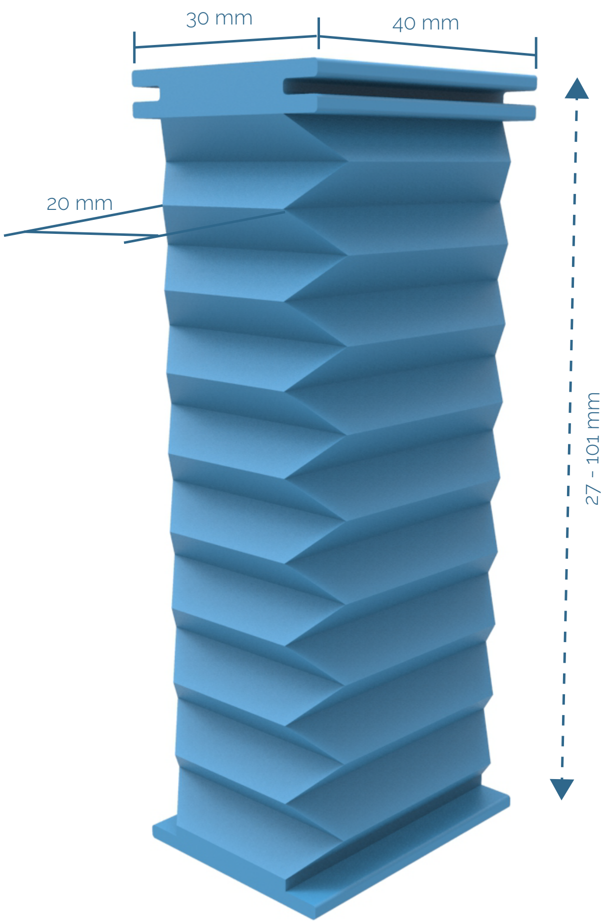
Extrusion profile
The same profile is used as for the modules which reduces production costs

Hole for air hoses
The bundles of air hoses can enter the frame connection through these holes

Exit for air hoses
The bundles of air hoses can leave the frame connection through these holes

Bellow

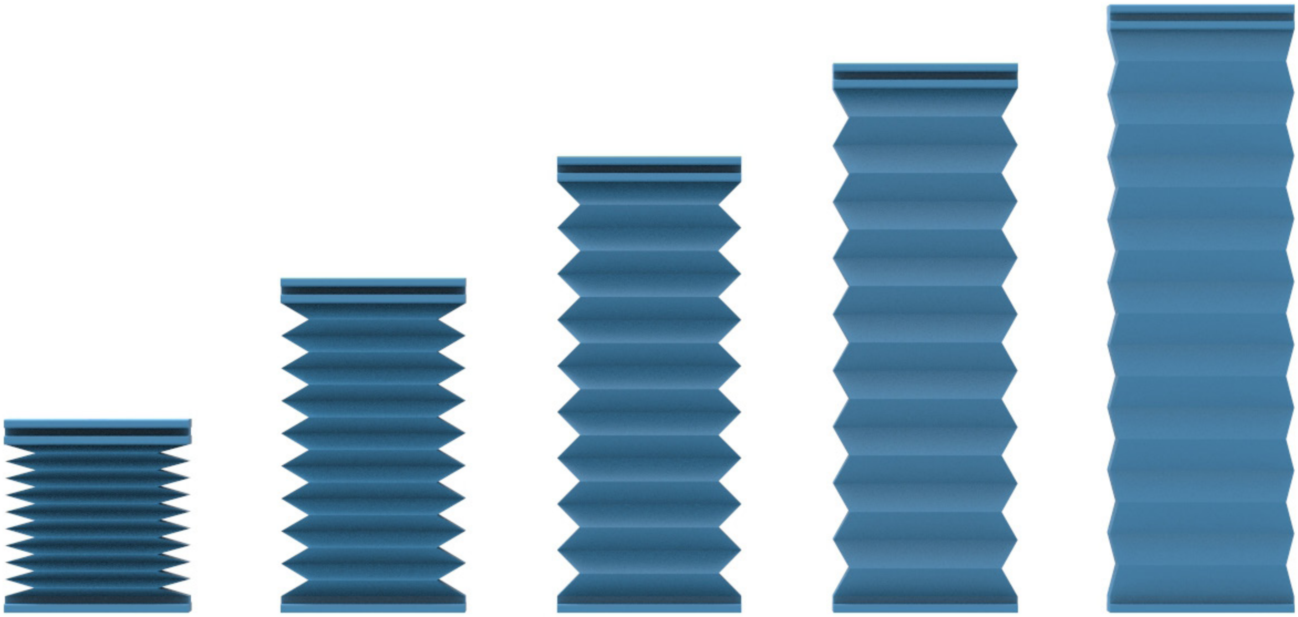
The bellow is based on a technical principle found in old cameras. Normally, the bellow is folded from a sheet of plastic, leather or paper, and glued together. In this case, the mechanism is already folded when the product is moulded. This type of bellow also exists, usually moulded in rubber, but is generally used as a protective cover for important machine parts. Hence, although the technical principle already exists, applying it as an actuator under pressure seems to be a new application.



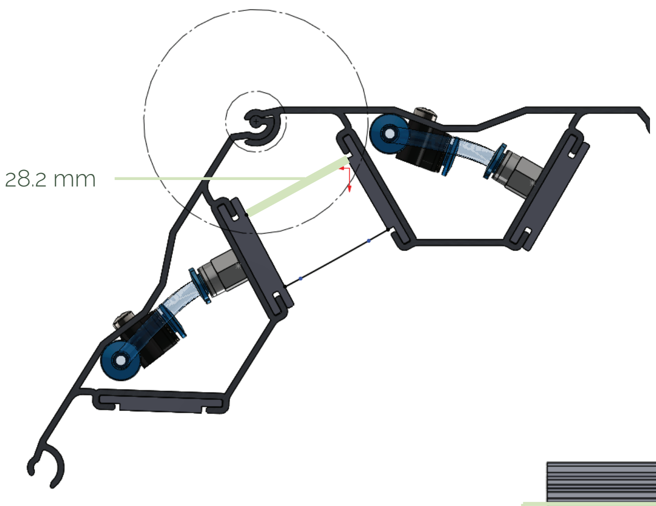
The bellow connects the segment bodies together and two are parallel connected per side of the segment body, meaning a total of four bellows per one segment body. By pressurizing the bellow, it expands pushing the two body segments away at an angle.

Main dimensions

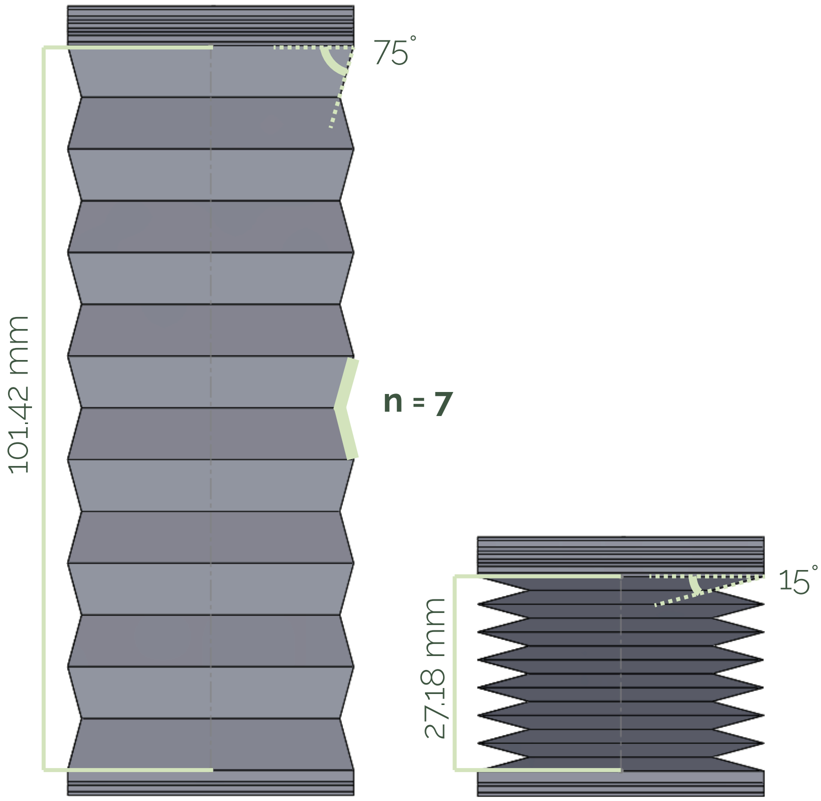
The width and depth of the bellow are 30x40 mm. The length varies with the air pressure inside the bellow. In the current design, the ideal minimum length to get the desired angle is 28.2 mm, and the ideal maximum length is 102.9 mm, as shown on the next page.

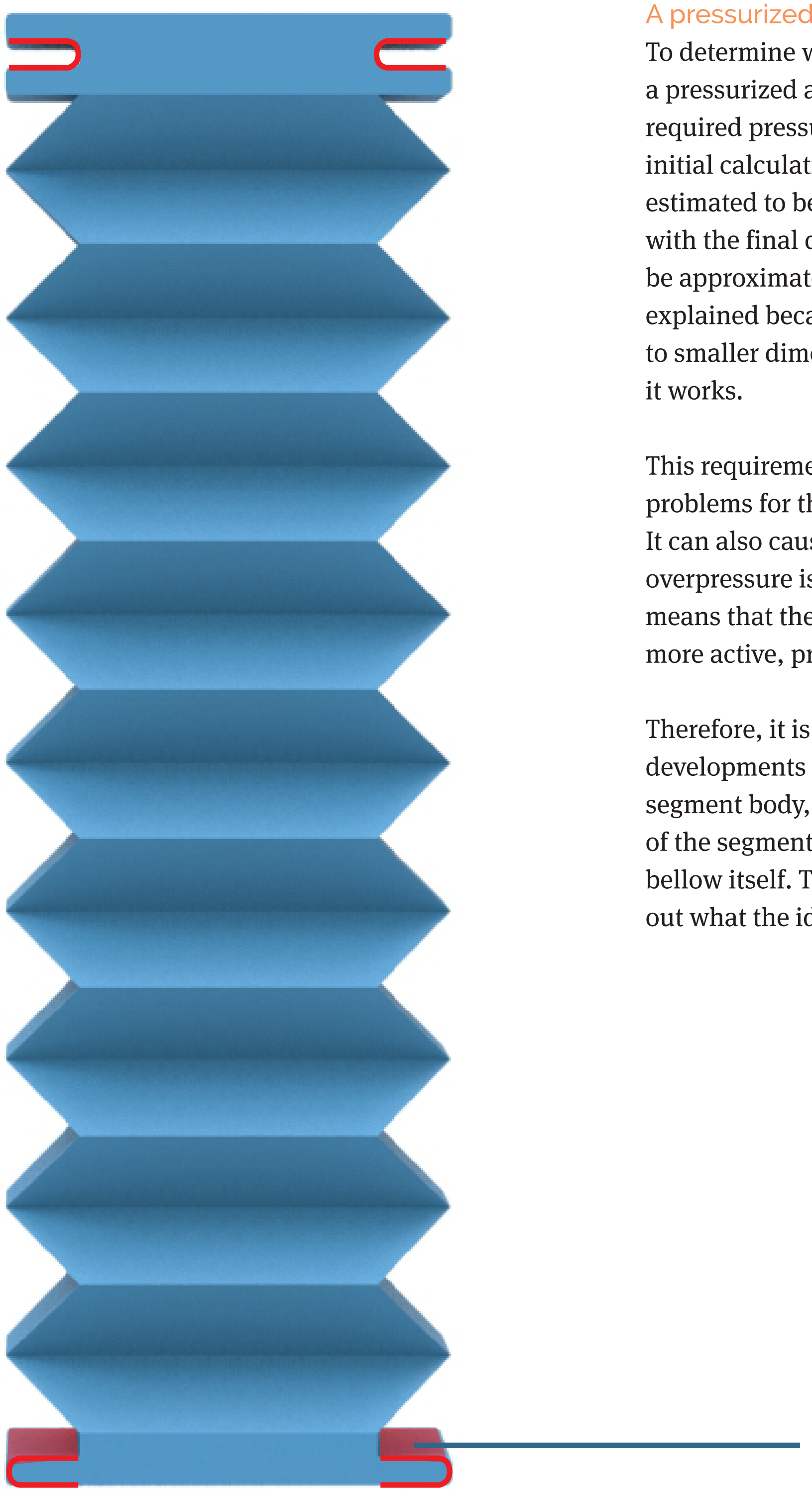


To achieve these lengths, seven folding segments are required. Doing so will result in a minimum length of 27.18 mm and a maximum length of 101.42 mm, with a 15 ° and a 75 ° angle, as shown below. These results are close to ideal.



The dimensions for the bellow are based on an iterative process of prototyping different bellows (see chapter 6.5).





A pressurized actuator

To determine whether the bellow can function as a pressurized actuator, it was calculated what the required pressure would be. For the concept, with initial calculations (see appendix C.2) this was estimated to become approximately 4 bar. However, with the final design (see appendix C.3) it turns out to be approximately 7.3 bar of gauge pressure. This can be explained because of certain design decisions that led to smaller dimensions for the bellow and arm on which it works.

This requirement of 7.3 bar gauge pressure may cause problems for the functioning of the folding mechanism. It can also cause problems because more air and overpressure is required from the compressor, which means that the compressor will increase in size and be more active, producing more noise.

Therefore, it is recommended (see chapter 9) for further developments of the design, to increase the arm of the segment body, which may involve an overall increase of the segment body's size, and increase the size of the bellow itself. Tests and prototyping will have to point out what the ideal dimensions are.

Figure 80 *Connection to segment body highlighted (by author)*

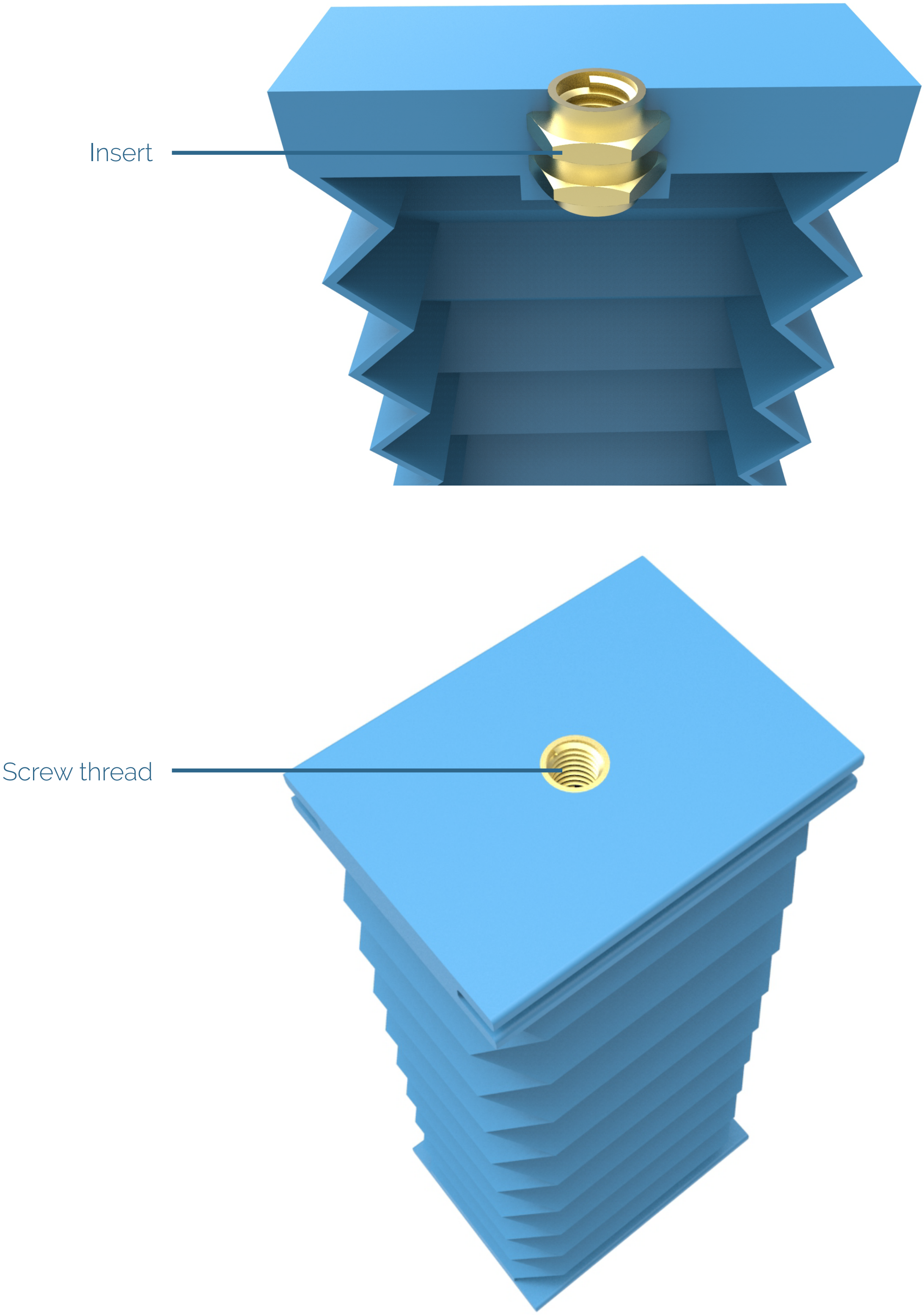


Figure 81 *Insert in bellow (by author)*

Material

The material chosen for the bellow is Thermoplastic Polyurethane Elastomer (Ether, aromatic) with a 20% barium sulfate filler. This is mainly due to its unique combination of a low Young's modulus and high yield strength. This is an essential combination for the bellow as flexibility as well as strength are required. In appendix C.3, the choice is explained in depth.

Production

As the function of the bellow is mainly defined by its shape, a manufacturing process is required that can create this shape using TPU as material. Three potential processes were selected that can create this shape and are shown in figure 82.

Whether these processes can indeed produce the bellow had to be verified with manufacturers. Therefore, several manufacturers were contacted to hear about the possibilities. Most of them verified that they can create the shape, but they said it was not possible to produce a bellow that would function under pressure.

However, it is likely that they are not familiar with putting pressure on a bellow and are therefore hesitant to make promises. Currently, they create bellows only for protection of other parts. Pressurized bellows do exist but are used for much heavier jobs, for example under trucks, where they are used as (convoluted) air suspension. However, these bellows are very heavy and much larger than intended for this project.

Manufacturers found via Alibaba all said they could produce it without any problems. However, language barriers and cultural differences could cause mis-communication and may lead to fake and unreliable promises.

Based on pros and cons of these processes, blow moulding (see figure 83) seems to be the most promising process as it is very suitable for processing TPU (CES EduPack, 2017) and the bellow can be redesigned in such a way that the screwing thread is inserted. Rotational moulding would be a good alternative option, although an insert part would be required there, which is less sustainable and costlier, and it is difficult to control the wall thickness. Dip moulding would be least favourable, although tooling is cheap, but it is not possible to create a closed bellow without multiple parts.

Cost estimation

The weight of the bellow is approximately 30 grams, which means that the material costs will only be a few eurocent. Comparable products as shown in figure 84 can be found on wholesale websites such as Alibaba in a price range of 0.20 - 2.00 EUR for large orders. It is expected that the bellow will not be much more expensive than this, although unique tooling costs maybe make the bellow more expensive. For example: If a mould is required that costs 50,000 EUR, at least 50,000 pieces should be created to not further increase the above mentioned price by more than 1 EUR per piece.

Process	TPU	Manufacturers	Pros	Cons
Blow moulding	Very suitable	Zuiderplastics	Screwing thread can be integrated, no insert needed	
Rotational moulding	suitable	Ridderflex	Easy to add insert	Hard to control wall thickness
Dip moulding	Less suitable	LoVen, R&K Venlo, RubberAndPlastics	Cheap tooling	Open end requires multiple parts

Figure 82 *Production processes (by author)*

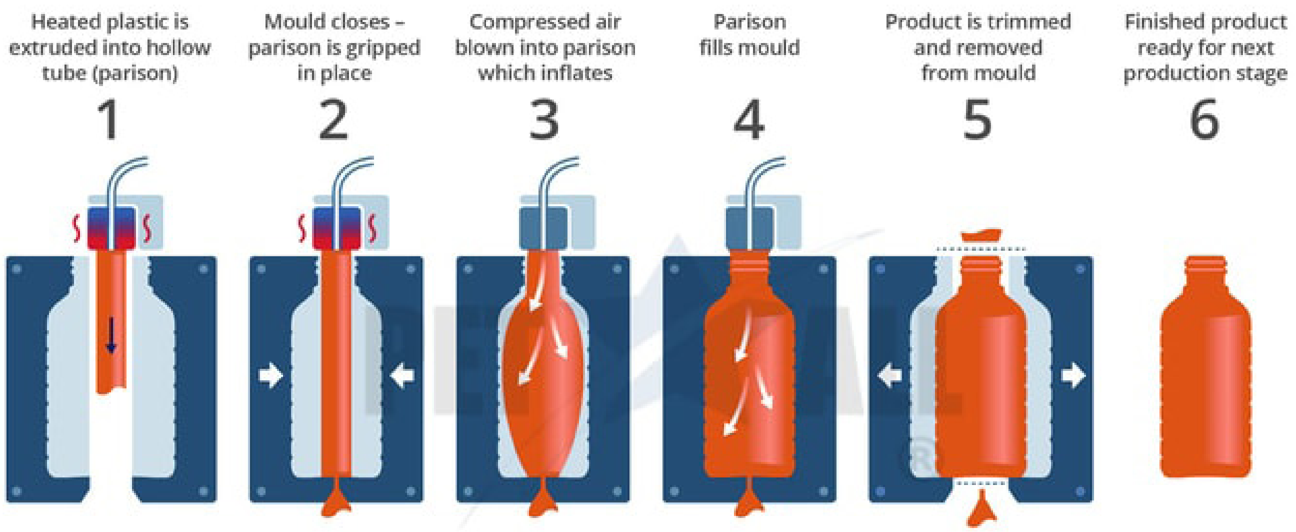


Figure 83 *Extrusion Blow Molding process (image obtained from www.petallmfg.com/blog/how-extrusion-blow-molding-differs-from-injection-molding/)*

Figure 84 *Similar products blow moulded (image obtained from www.naplasticsltd.com/blow-molded-bellows.html)*

Standard parts

Air Hose

The air hose has an outer diameter of 4 mm and an inner diameter of 2.5 mm. It is estimated that about 0.5 m is required per module for connecting both bellows and a piece to connect to the control box. This means an estimated total of 54 m of hoses per sleep system.

This hose is a standard to buy part and costs 0.13 EUR per m on Alibaba (www.alibaba.com/product-detail/High-quality-flexible-PU-pneumatic-hose_60667464832.html?spm=a2700.7724838.2017115.72.179f6382JOvoZB). For 54 m, that means a total of 7.02 EUR for a sleep system.

Connector type I

The first connector used is a single pneumatic connector that connects one air hose to a part with a screw thread. In this case, the connector screws into the bellow's insert, which immediately holds the bellow in place on the segment body.

This is a standard to buy part, which costs 0.12 EUR on Alibaba (www.alibaba.com/product-detail/PC-push-in-fitting-10mm-pneumatic_60739347821.html?spm=a2700.7724838.2017115.62.5c766008NWHTYa). A total of 216 (2 per module) leads to 25.92 EUR of these connectors.

Connector type II

The second connector used (see figure 85) is a T-style pneumatic connector that converts two air streams into one air stream. This is used because the bellows that are used parallel in one body segment require the exact same amount of pressure.

This is a standard to buy part, which costs 0.17 EUR on Alibaba (www.alibaba.com/product-detail/SNS-SPE-series-Three-way-quick_60728176765.html?spm=a2700.7724838.2017115.94.5c766008NWHTYa). For 108 of these connectors, that means a total of 18.36 EUR.

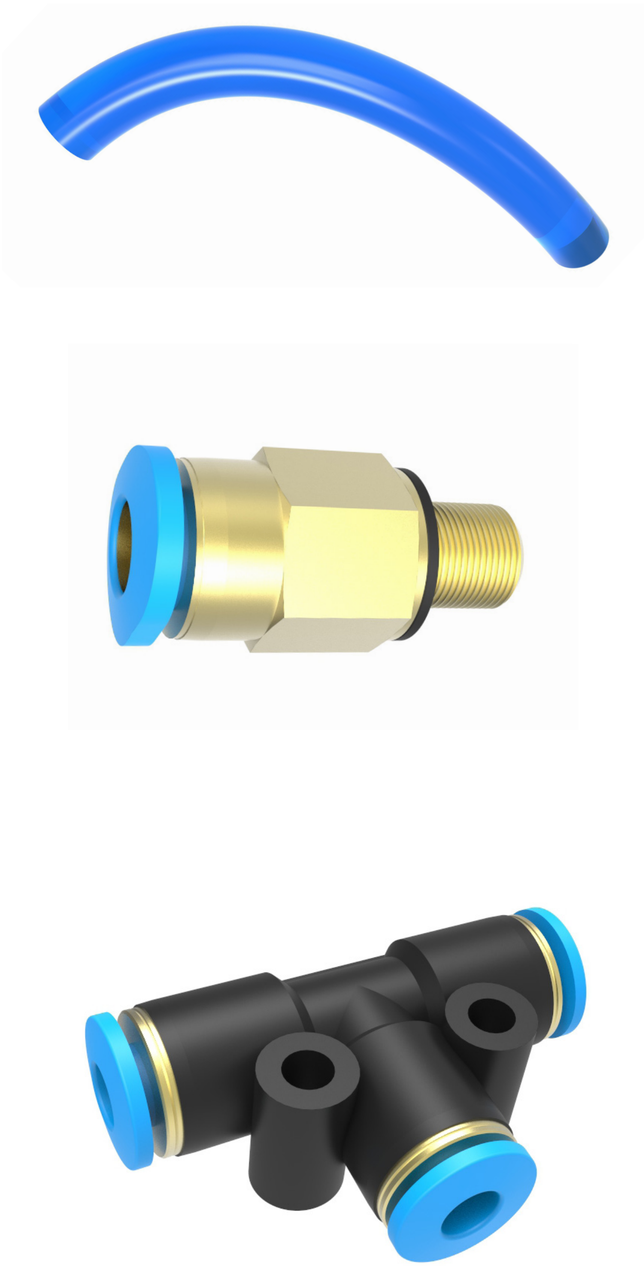


Figure 85 *Standard parts air hose, Connector Type I and Connector type II (by author)*

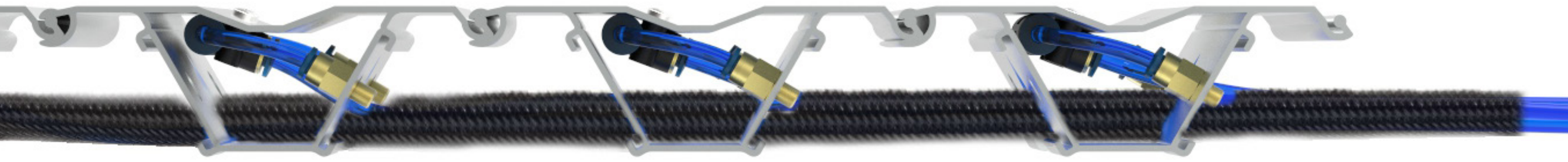


Figure 86 *Cable cover for air hoses (by author)*

Air hoses to frame

The air hoses used for the modules connect to the frame. These are inserted into the middle connection of the T-type connector (connector type II). This is shown in figure 87. Each module adds one air hose to the bundle, meaning that the final bundle will consist of 9 air hoses when 9 modules are used in a row. To keep these hoses together and protect them, a protective flexible and strechable cable cover is used (see figure 86).

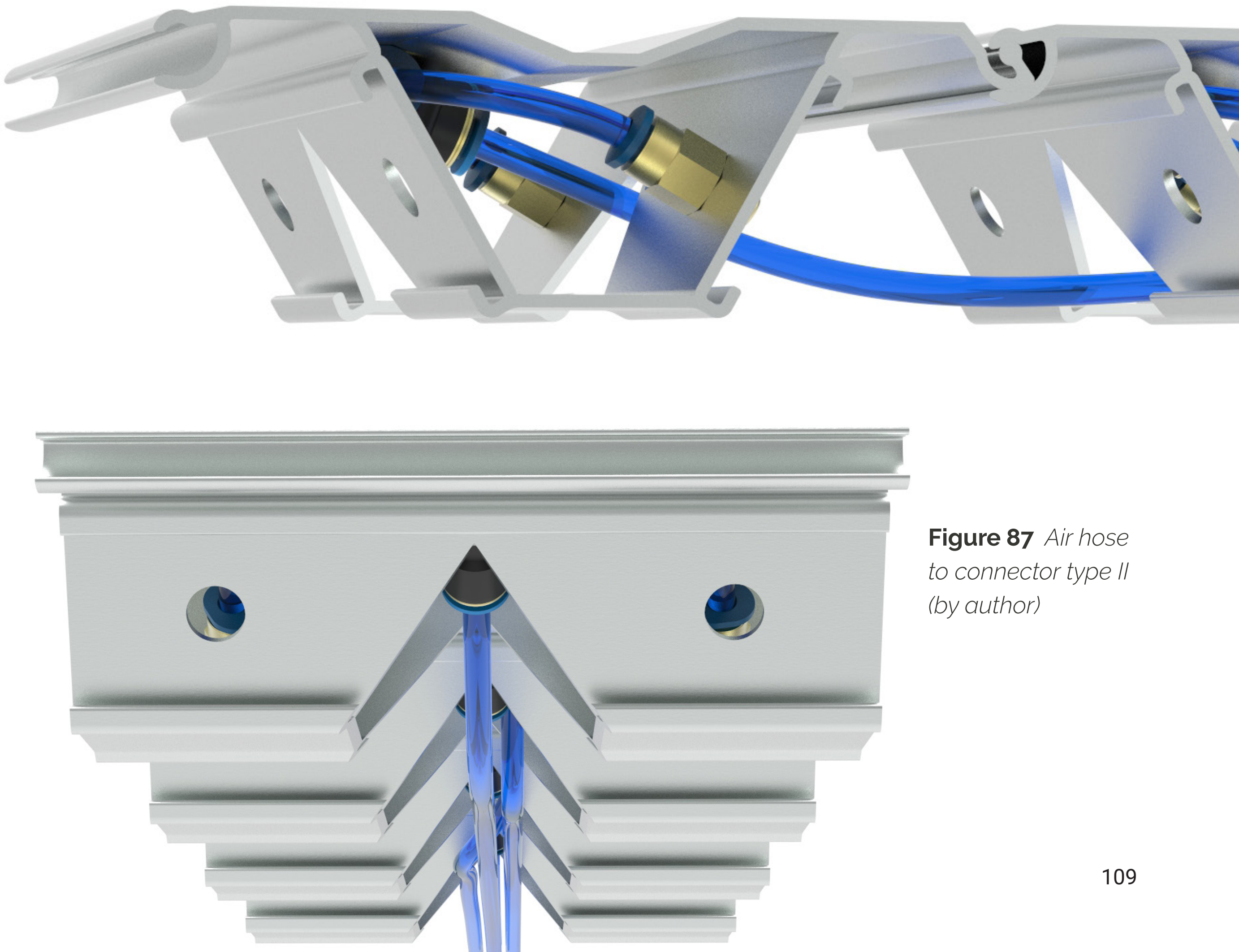


Figure 87 *Air hose to connector type II (by author)*

7.4. OVERALL DESIGN

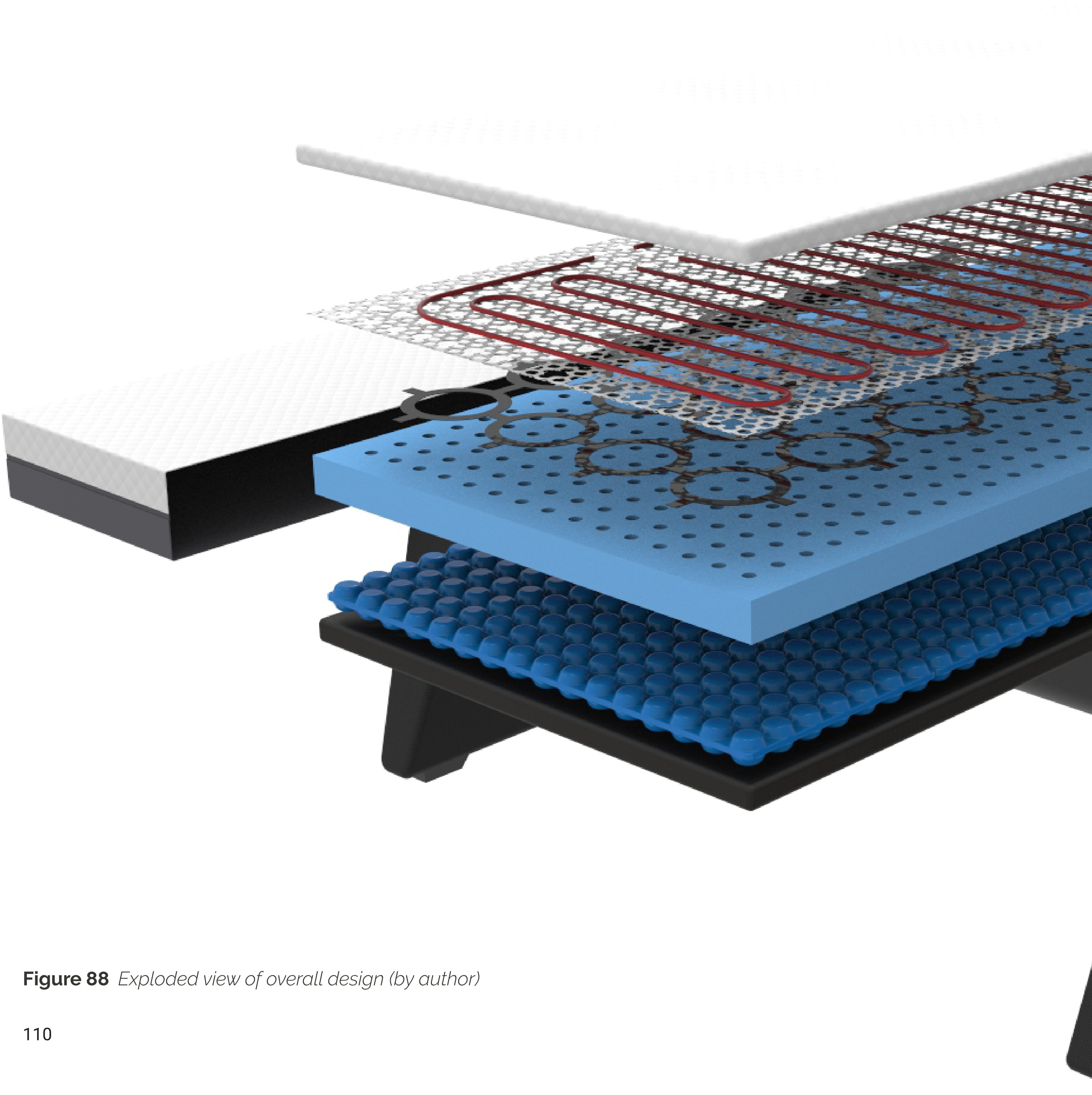
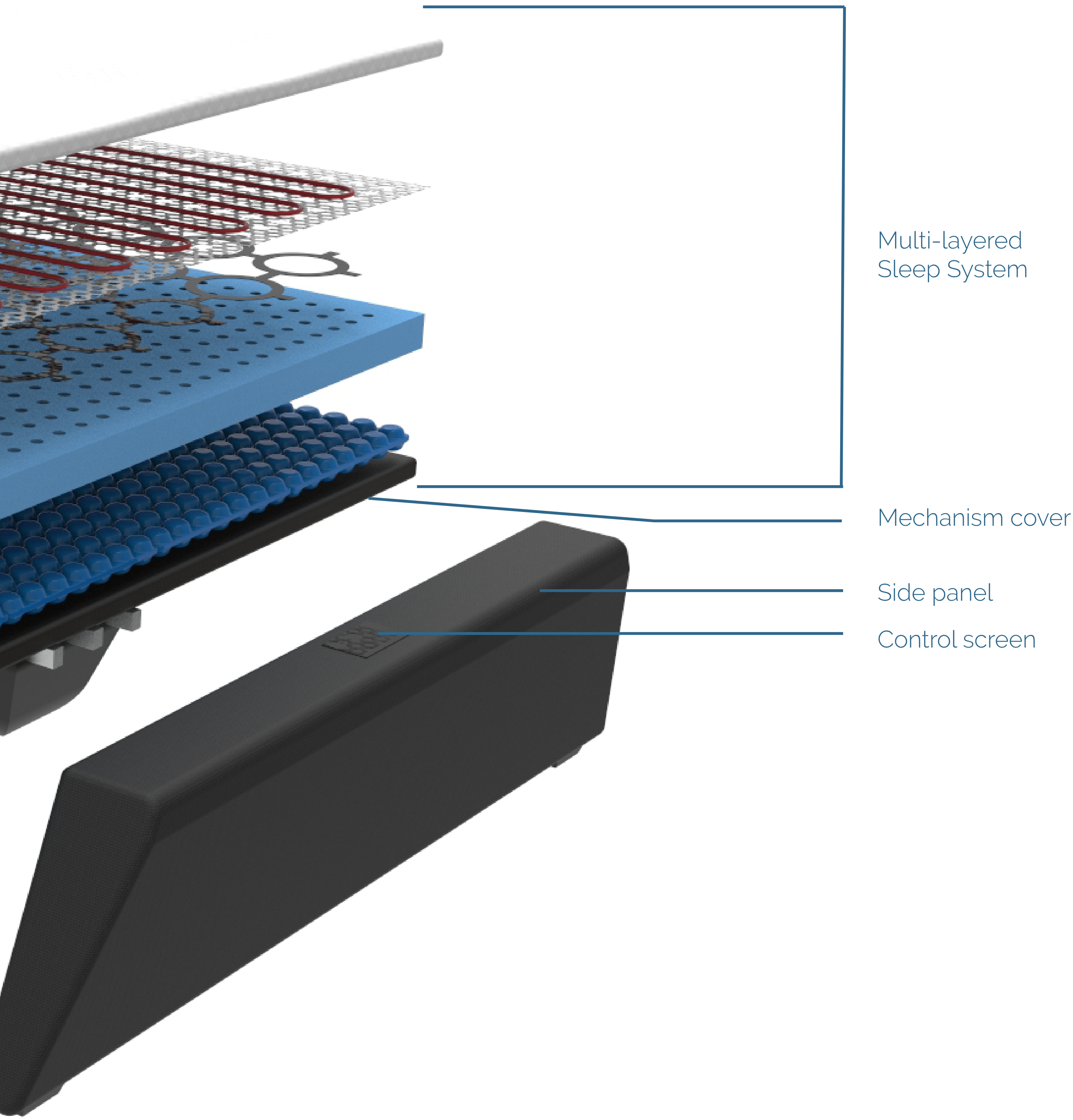


Figure 88 *Exploded view of overall design (by author)*


Multi-layered
Sleep System
Mechanism cover
Side panel
Control screen

To get an idea of what the bed could look like when finished, a concept design was made. Initially, the idea was to use one foot (as seen for example in figure 133). However, this resulted in a bed that looked like a dentist's chair. Therefore, in order to stay closer to an archetypical bed, it was chosen to use two side panels and rest the mechanism on a few beams that are attached in the centre. Using these side panels also adds stability and prevents the bed from tipping over.

Side panels

The panels are wider at the top than at the bottom, which gives an elegant appearance but longer at the bottom than at the top to create a feeling of a solid foundation. The bottom is lifted off the ground to make sure it is less likely to bump into the bed and break a toenail.

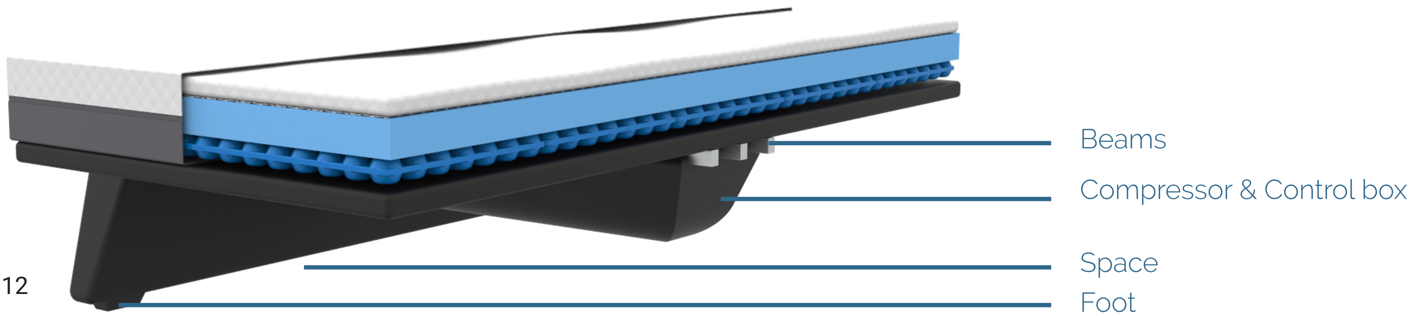
The side panels can be covered with alternative colours or patterns to offer multiple options to customers.

In the side panel, a touch screen is integrated that can be used to control the bed.

Compressor & Controls

The compressor and controls are hidden inside an embodiment that is fixated onto the bottom of the beams that also carry the sleep system. That means it is centered under the bed and therefore hidden from sight.

Figure 89 *Section cut (by author)*



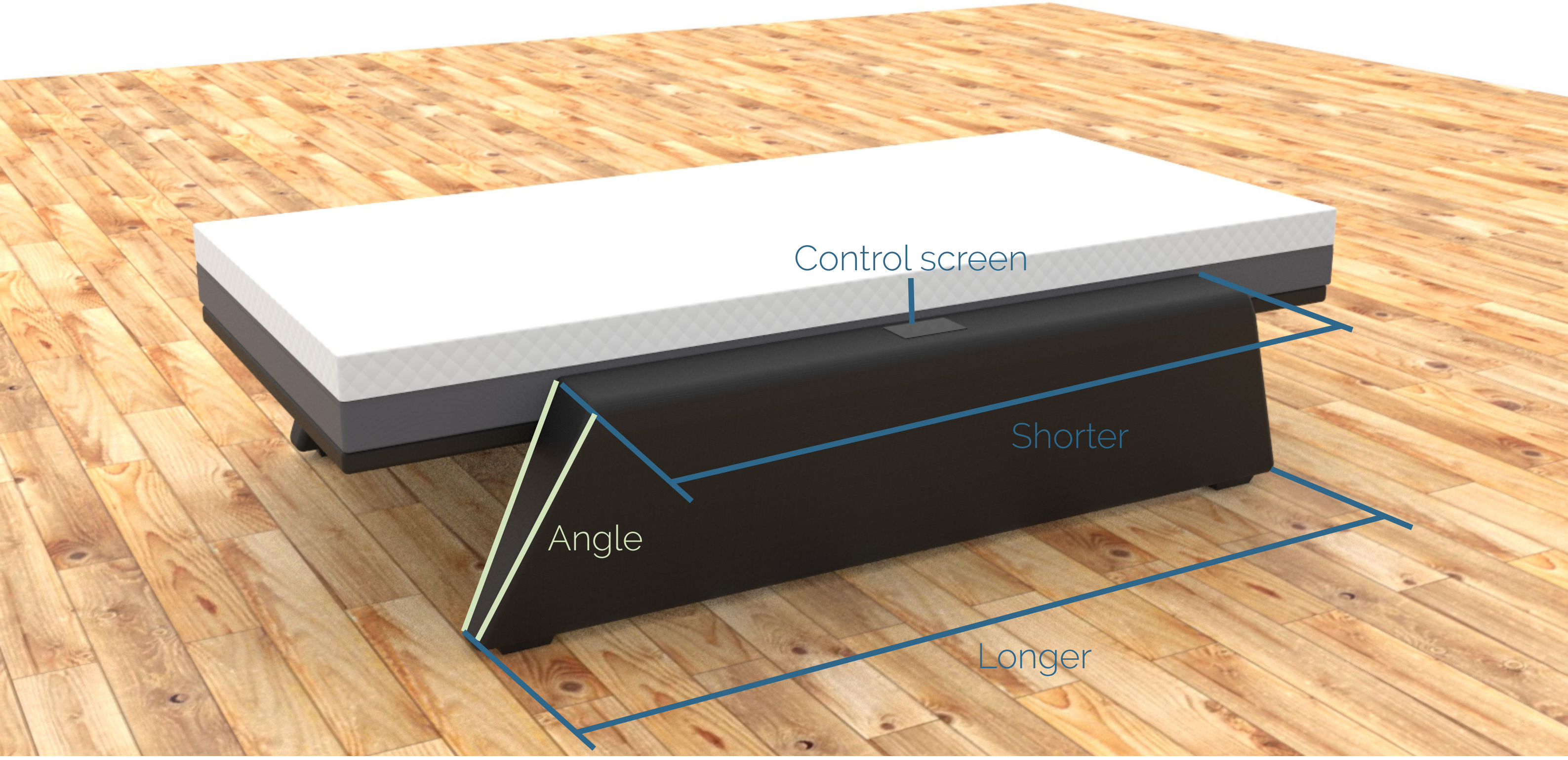
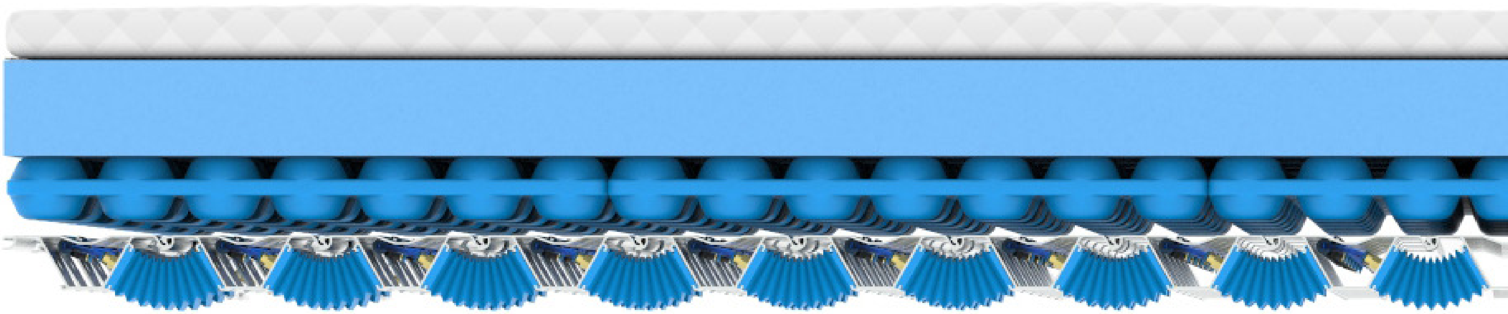


Figure 90 *Design choices (by author)*

Figure 91 *Context impression (by author)*

7.5. SLEEP SYSTEM



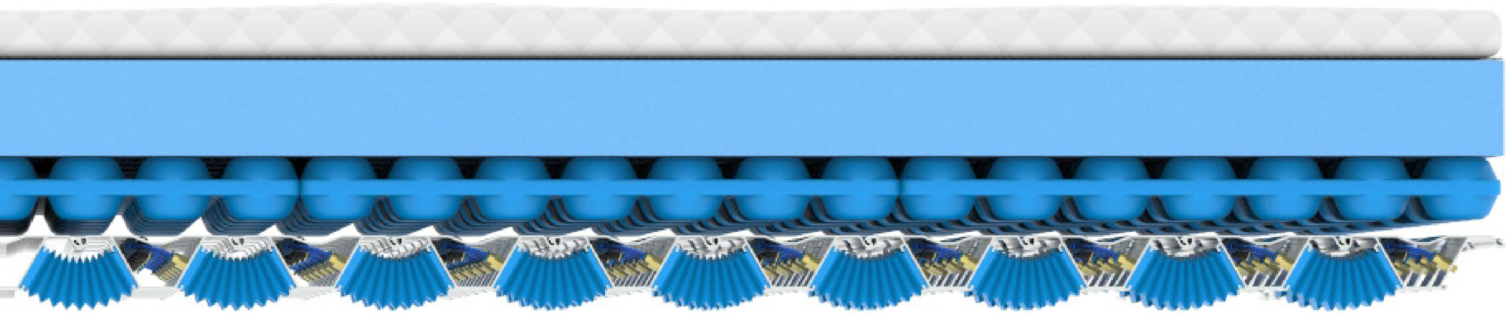


Figure 92 *Side view of SLeep System (by author)*

The complete sleep system consists of six layers. The bottom layer which consists of all the modules is already discussed before. However, as stated in the design vision, besides changing the shape, also changing firmness and temperature is important for a good quality sleep. Besides that, extra layers are required to make the sleep surface smooth and comfortable and to measure data which makes sure that the modules know which position to take.

Therefore, five more layers were added on top of the modular system to create a full sleep system. A mattress ticking covers and holds these five layers together. These layers are shown in figure 94 and will be discussed here.

Mattress ticking

The mattress ticking is the outer layer, visible in figure 90. It should be made from a material that feels soft and comfortable as this is what the user feels. This layer together with the soft pad are mainly responsible for the humidity regulation of the sleep system. The material should allow ventilation and not get moist to prevent shear forces. To prevent shear forces, the material should also have stretch (Haex, 2004).

The material should be washable at a temperature of 60 °C to kill house dust mites, which means that the ticking should be removable. This is done by adding a zipper around the sleep system.

Infusing copper wire into the ticking can give the material biocidal properties.

Soft pad

The soft pad is the first layer directly under the ticking and should have many of the same properties as the mattress ticking. It must also make sure that the user does not feel the temperature- and sensor mats. This layer should have both ventilation and insulation properties to keep the user cool in summer and warm in winter.

Common natural materials are wool, silk, cotton and linen. Synthetic alternatives are acrylic, polyester, rayon or nylon (Haex, 2004). Silk and Rayon seem the best options in this case, as the lack of heat insulation can be compensated by the temperature mat (see figure 93).

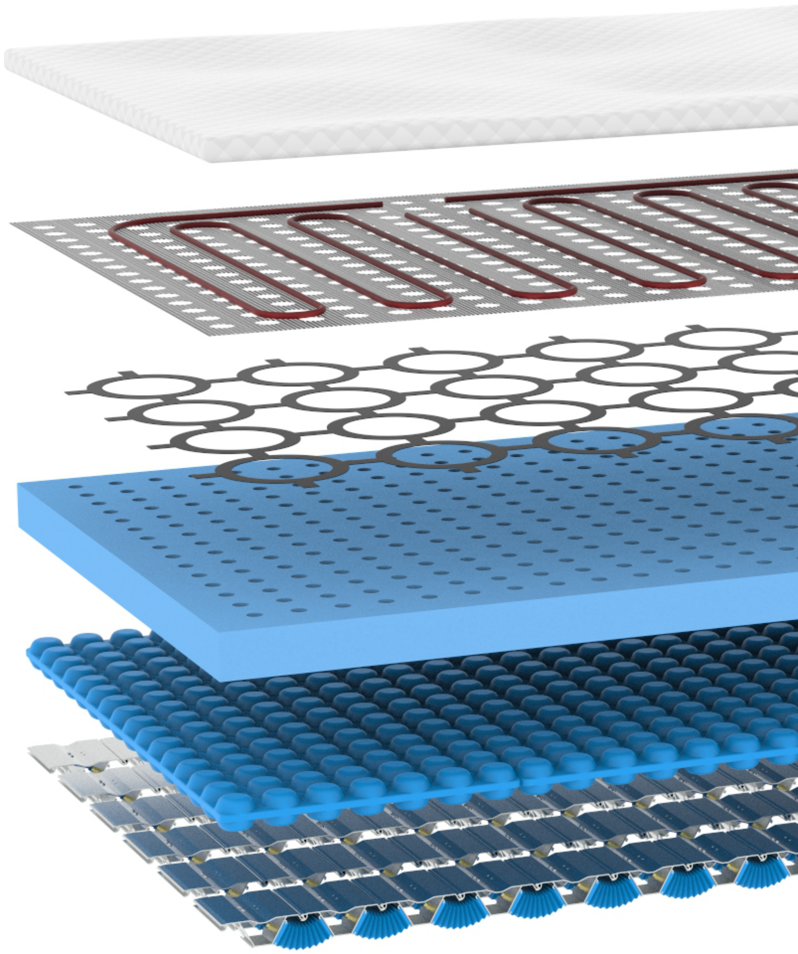


TABLE 2.3 Mattress Top Layer Properties

	Elastic Properties	Fluid Absorption/ Permeability	Heat Insulation	Antibacterial
Wool	+	+	+	–
Silk	+	+	–	+
Cotton	–	+	–	–
Linen	–	+	–	+
Acrylic	+	–	–	+
Polyester	+	–	–	+
Rayon	+	+	–	+
Nylon	+	–	–	+

Note: "–"=bad; "+"=good.

Figure 93 *Top layer material comparison (image obtained from Haex, 2004)*

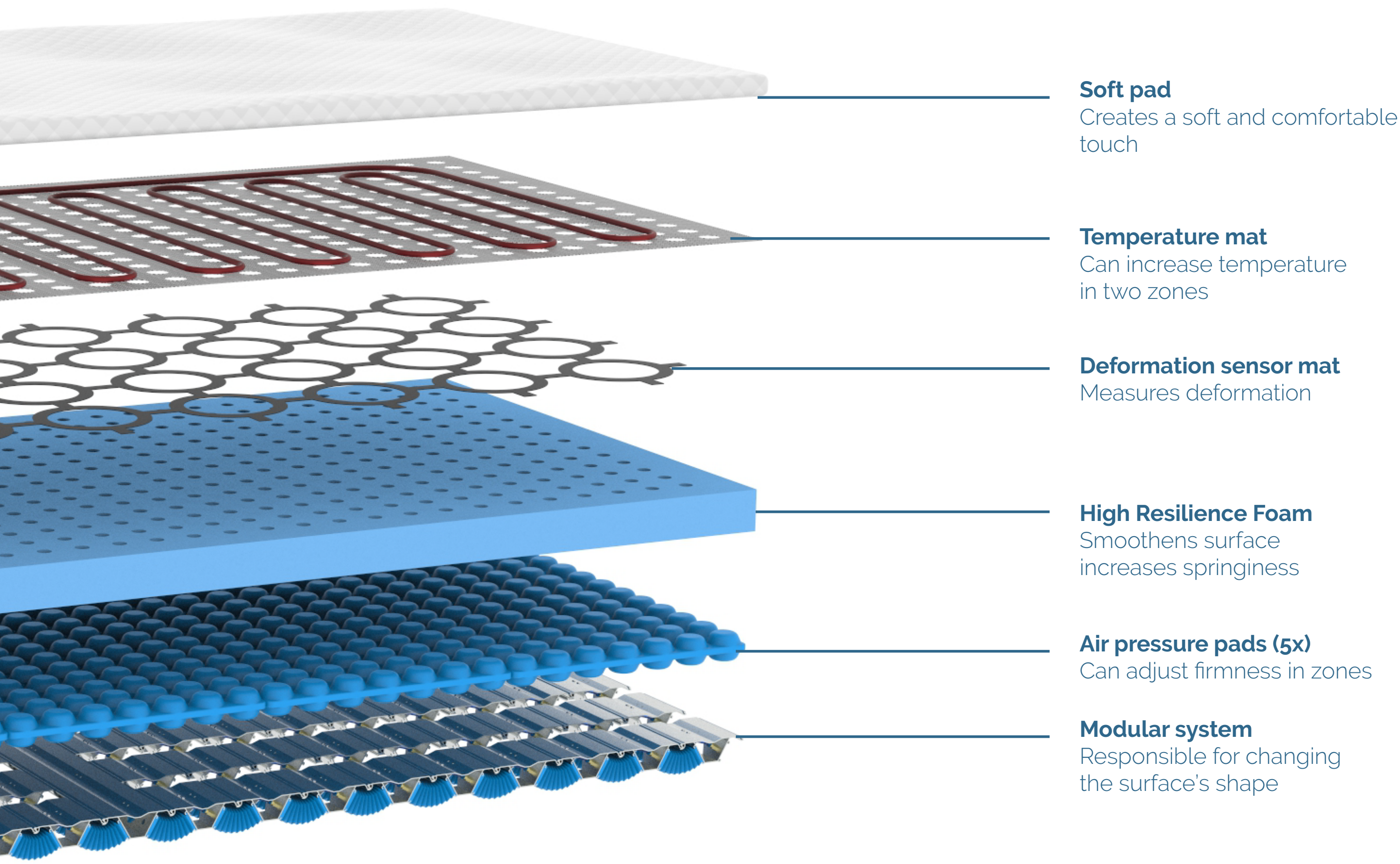


Figure 94 *Layers of Sleep System (by author)*

Temperature mat

As temperature is an important factor related to sleep quality, having some control over the temperature is a good function for a bed. Adding technology to a bed or fabric that can increase temperature is simple and cheap according to prof. dr. ir. K.M.B. Jansen (during a conversation in 2017), while using technology to cool is much more difficult and expensive. Therefore, the temperature mat can only increase temperature for when it is cold, while enough ventilation and humidity regulation should keep the bed cool enough during summer.

The temperature mat shown in figure 94 is based on a simple principle of using resistance wires that heat up with electrical current. It would be interesting for further research to consider using the heat generated by the air compressor and channel through air hoses to an air-heated temperature mat.

Deformation sensor mat

To measure spinal alignment it must be known what the final deformation of the sleep system is. To measure the deformation, a deformation sensor mat is used. A mat like this, called the IdoShape, is developed by Custom8 NV and can be seen in figure 95.

This mat will create a deformation map, which looks much like a heat map, as it lights up in a different colour depending on the deformation measured. In order to use this information to know whether the spine is aligned, the dimensions of the user must be known. These can be recorded during an initial calibration session for first use.

Using this mat, also movements by the user can be detected which is required for determining the sleep quality.

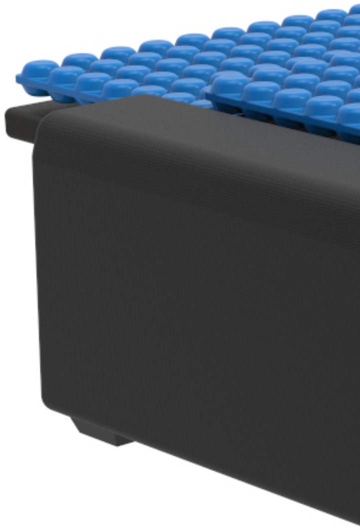
High Resilience foam

The foam layer is mainly responsible for smoothening the surface. The modules create a rough base and the air pressure pads create many bumps. Therefore, a layer is required that equalises the surface. High resilience foam is chosen due to its low hysteresis (see appendix C.1), open cell structure which allows for good ventilation and durability. Besides that, the material is hypoallergenic and does not smell.

Air pressure pads

Firmness is also an important factor for good sleep. People have different preferences when it comes to firmness and that is why most existing mattresses come in different types ranging from soft to very firm. The smarter mattresses mentioned in chapter 4.2 allow for automatic change of firmness during the night which relieves pressure for certain body parts in certain positions.

Therefore, it was chosen to also add firmness control to this sleep system. As the system already works with air, it was chosen to use five inflated pressure pads that are controlled by increasing or reducing the air pressure inside (see figure 96). The design of the air pressure pads allows to follow the shape created by the modular system underneath and helps to support the foam layer on top.



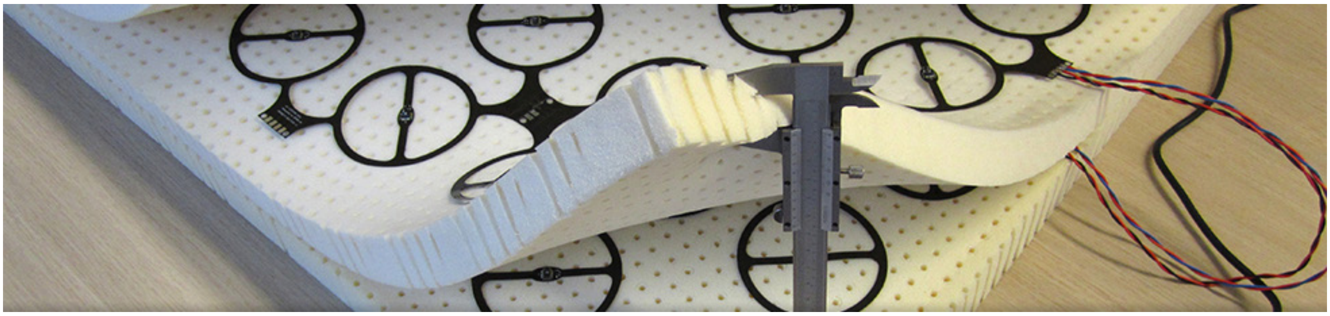


Figure 95 *IdoShape by Custom8 NV (obatined from www.custom8.be/sensor-mats/idoshape/)*

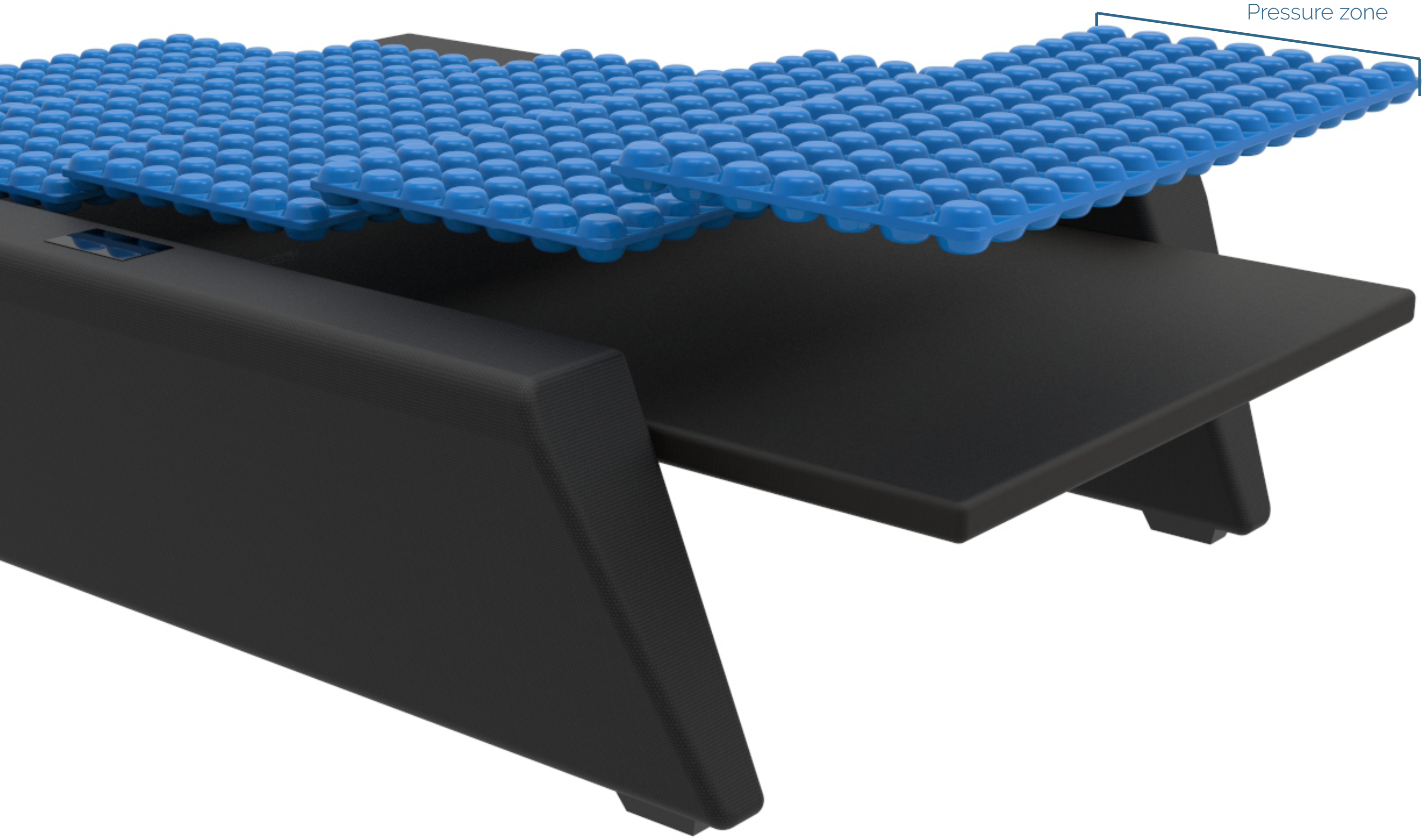


Figure 96 *Five pressure pads for firmness control (by author)*

8. BUSINESS ROADMAP

Although the design is in an early stage, it is important to plan ahead and determine a market and customer. Therefore, a brief outline for a roadmap to success is given here.

Potential market analysis

For future development of the design, it is important to determine who the customer will be. That will allow to design for a more specific user and use context. To determine what market to target, an analysis is made of potential business to business (b2b) markets and the business to consumer (b2c) market.

From a start-up company's perspective, targeting businesses has benefits, for example:

- Insurance of large orders (e.g. 200 mattresses at once instead of having to find 200 customers)
- Businesses can pay (partially) up front, providing essential financial resources.
- Sometimes international.

Starting with b2b can also offer benefits when later targeting b2c, as the product is already established. For example, when consumers experienced a mattress in a hotel or hospital, they might be familiar with the brand and can be easier convinced to buy one.
However, starting with b2c also has benefits, for example:

- Slow scalability, which means it is easier to grow with the market as a company.
- Lower risks because of smaller numbers.
- Easy to test interest through crowdfunding campaigns and close relationship with end user.

Several potential target markets were identified with a team of students during a weekend organised by YES!Delft Students in 2017. The concept of the adjustable mattress was in a much earlier stage at that moment, without a clear technology in mind. However, the identified markets are still interesting. The markets of Airplane Business Class, Truck Manufacturers and Home Care were added later. In figure 97, assumptions about the advantages and disadvantages of different markets are shown as well as the expected value proposition.

	Hospitals	Home Care	4/5-star hotel chains	Airplane business class	Truck Manufacturers	Consumer market
Advantages	High current expenditure	Beds are needed for a short time, meaning expenditure over time is high	(International) network Large quantities	High current expenditure	Low requirements	End user, thus biggest motivation for good sleep Biggest market
Disadvantages	High requirements Demand scientific proof	Low current expenditure per bed High requirements	Demand longer track record	High requirements Demand longest track record	Low current expenditure Few manufacturers	Sell per piece
Value proposition	Lower cost Reduction of work load	Lower cost Reduction of work load	Unique Selling Proposition Increased customer satisfaction	Light-weight Increased customer satisfaction	Increased customer satisfaction	Improved sleep New experience Comfort Extra functions

Figure 97 *Assessment of different market segments (by author)*

Based on these assumptions, a roadmap was made to target different markets in the future, shown in figure 98.

The strategy is to first target the consumer market through crowdfunding. By doing so, the start-up company has time to grow, improve and get a track record. After a year or so, when the first beds are in use by early adopters, smaller 4/5-star hotels might be willing to test products. By year three, the product should be available in several retail stores and available to order online. By then, the bigger hotel chains will gain trust and will start buying large quantities of products.

Other industries, such as health care and transport will have higher requirements or demand a longer track record before they trust new technologies, meaning that they are a difficult market entry point. Also, the product will have to be adapted to fit these specific markets.

Therefore, the consumer market is chosen as a starting point because of the easy entry, enormous market size and slow scalability. Besides that, most consumers of beds and mattresses are also the end users which reduces the requirements compared to markets where the customer adds extra requirements next to the end user. Less requirements make the development of a new product more feasible.

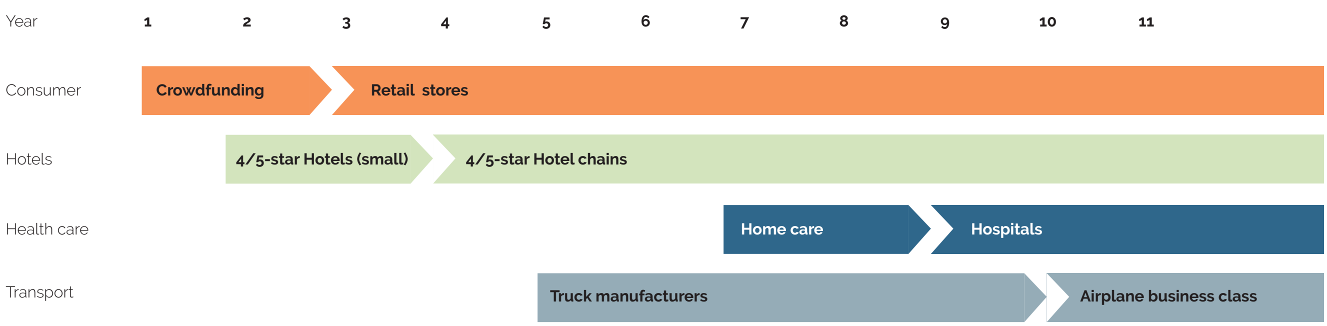


Figure 98 *Future target roadmap (by author)*

9. CONCLUSION & RECOMMENDATIONS

Conclusion

The purpose of this graduation project was to find a solution for static ergonomic systems and make a start in the design of this solution. In conclusion of the analysis phase, the following design vision was formed:

"Improving the quality of life for people suffering from low back pain by introducing a sleep system that relieves their pain, increases comfort and improves sleep quality through actively adjusting spinal alignment, pressure distribution and temperature to their personal needs."

This project proposed to design a dynamic sleep system to solve the problems that existing static sleep systems give and the final design succeeds in doing so, answering to the criteria determined in chapter 5.2.

During the project, a multi-layered sleep system was developed that can change the shape of the sleep surface to optimise the spinal alignment of the user in any position, it can change the firmness to optimise pressure distribution and regulate temperature.

The design accomplishes these tasks by a multi-layered design, in which each layer is responsible for one or more of the desired functions. The focus of the project was on the bottom layer of the sleep system, which consists of a unique mechanical system actuated using air pressure.

The contribution to the field of design is the introduction of an innovative system design, that uses an old technical principle of a folded bellow and applies it in a new way by using it as a pressurised actuator. This has not been done before, to the knowledge of the author. The author succeeded in 3d printing this principle in a TPU-based material, thus demonstrating that it feasible.

A contribution to society is made because this project is the start of a solution that can benefit many sleep-sufferers. Sleep- and medical disorders related to a sleep system can be prevented, maintained or even cured by such a system. Therefore, continuation of this project is recommended.

Recommendations

1. Developing the bellow

For the current design, the bellows are a crucial part of the working mechanism. During the project, the principle was demonstrated but not tested under high air pressure. It is recommended that the first step for further developments is creating a bellow from an airtight material that comes close to the properties from TPU and putting pressure on it to see what the behaviour is.

Based on the tests it can be determined what pressure is realistic to use. The dimensions of the bellow can be redesigned based on the results.

2. Improve for other types of use

The current design is based off a scenario where a person sits down in the middle of the bed and the use of sleep. It is not designed for other typical uses (described in chapter 3.3). But also, when a heavy person sits on the far edge of the bed, the moment caused on the central modules is too large. An option for the current design is to make sure people cannot sit on the edge by automatically positioning the modules in a seated position as shown in figure 99. However, it would be better to improve the design further to allow for more types of use. This can be done in several ways:

- Increasing the dimensions of the bellows or the arm of the segment body on which they push.
- Using different bellows (more strength is required from the bellows in the centre than those at the outer edge).

An alternative option is to first design this system for a smaller application, such as a chair. That will omit some of the more demanding types of use and reduces the number of modules required. It could be a good starting point for further developing this system.

3. Testing which precision is required

The precision of the system to match the body's shape is determined with a parametric computer model (see chapter 6.2). However, since such a system did not exist before it is not known to what extent this precision is necessary and noticeable by the user. It could be that the user does not notice the difference between modules of 100 mm and 150 mm. Therefore, it should be tested to what extent user can notice differences in the surface to know whether the system is not too precise.

4. Reducing the size of the surface

It should be considered that with a dynamic bed, less of the surface area is required in comparison with a static bed. That means that the width of the bed can be brought back to four or five rows as the sixth row may never be used (figures 70 and 71 show that the bed is too wide for the position taken). Also, the modules in the corners will likely never be beneficial for any position and can be omitted. The final surface could look something like figure 100.

5. Determining the size of the air hoses

Since a lot of air must be transported, it may be required to increase the diameter of the air hoses. This will reduce the noise created by the system and speed up the actuation. For the last prototype, connectors were ordered for a hose diameter of 8 mm. Unfortunately, these connectors did not fit the current design. In case this diameter is desired, the segment body must be increased in size as well. Therefore, it is recommended to determine the required diameter and adjusting the design of the segment body accordingly.

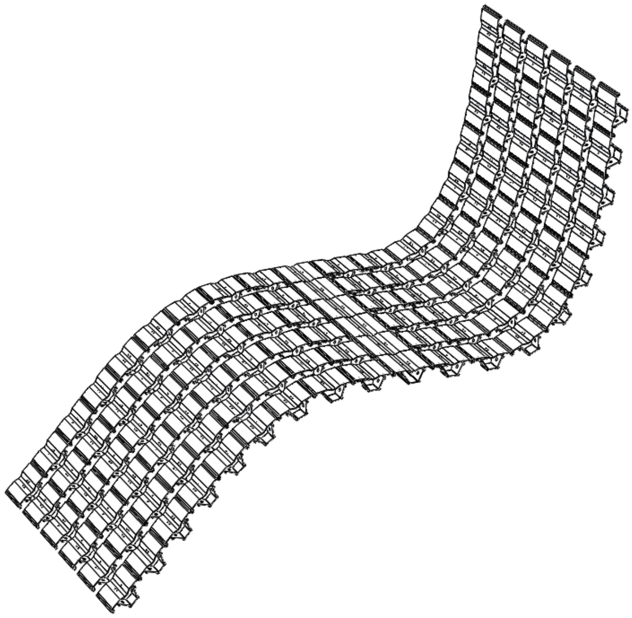


Figure 99 *Automatic position (by author)*

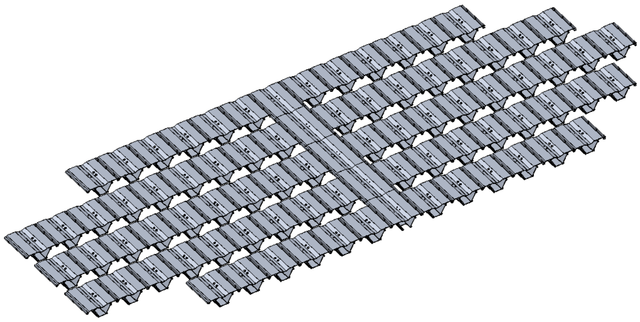


Figure 100 *Reduced surface (by author)*

10. LITERATURE LIST

This list is comprised of the sources used in-text. The sources are styled according to the American Psychological Association's (APA) fifth format.

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10.1. REFERENCES

Aeschbach, D., Sher, L., Postolache, T. T., Matthews, J. R., Jackson, M. A., & Wehr, T. A. (2003). A longer biological night in long sleepers than in short sleepers. The Journal of Clinical Endocrinology & Metabolism, 88(1), 26-30.

Al-Kandari, S., Alsalem, A., Al-Mutairi, S., Al-Lumai, D., Dawoud, A., & Moussa, M. (2017). Association between sleep hygiene awareness and practice with sleep quality among Kuwait University students. Sleep Health, 3(5), 342-347.

Alsaadi, S. M., McAuley, J. H., Hush, J. M., & Maher, C. G. (2011). Prevalence of sleep disturbance in patients with low back pain. European Spine Journal, 20(5), 737-743.

American Sleep Association. (2017). What is Sleep? Retrieved, October 2017, from https://www.sleepassociation.org/patients-general-public/what-is-sleep/

Amerisleep. (2017). What types of mattresses work best with adjustable beds? Retrieved, October 2017, from https://www.amerisleep.com/what-types-of-mattresses-work-best-with-adjustable-beds.html

Anders, J., Heinemann, A., Leffmann, C., Leutenegger, M., Pröfener, F., & von Renteln-Kruse, W. (2010). Decubitus ulcers: pathophysiology and primary prevention. Deutsches Ärzteblatt International, 107(21), 371.

Anisimov, V.N., Vinogradova, I.A., Panchenko, A.N., Popovich, I.G., & Zabezhinski, M.A. (2012). Light-at-night-induced circadian disruption, cancer and aging. Current aging science, 5(3), 170-177.

Arzi, A., Sela, L., Green, A., Givaty, G., Dagan, Y., & Sobel, N. (2009). The influence of odorants on respiratory patterns in sleep. Chemical senses, 35(1), 31-40.

Bain & Company Inc. (2016). The elements of value. Retrieved, may 2018, from https://hbr.org/2016/08/the-30-things-customers-really-value

Bader, G. G., & Engdal, S. (2000). The influence of bed firmness on sleep quality. Applied ergonomics, 31(5), 487-497.

Badia, P., Wesensten, N., Lammers, W., Culpepper, J., & Harsh, J. (1990). Responsiveness to olfactory stimuli presented in sleep. Physiology & Behavior, 48(1), 87-90.

Bakker, C., den Hollander, M., Van Hinte, E., & Zljlstra, Y. (2014). Products that last: Product design for circular business models. TU Delft Library.

Bakker, C., Wang, F., Huisman, J., & den Hollander, M. (2014). Products that go round: exploring product life extension through design. Journal of Cleaner Production, 69, 10-16.

Bakker, R. H., Pedersen, E., van den Berg, G. P., Stewart, R. E., Lok, W., & Bouma, J. (2012). Impact of wind turbine sound on annoyance, self-reported sleep disturbance and psychological distress. Science of the Total Environment, 425, 42-51.

Basheer, R., Strecker, R. E., Thakkar, M. M., & McCarley, R. W. (2004). Adenosine and sleep–wake regulation. Progress in neurobiology, 73(6), 379-396.

Beaumont, B., & Paice, E. (1992). Back pain. Occasional paper (Royal College of General Practitioners), (58), 36.

Bedtimes. (2009). Research finds 5 key mattress consumer segments. Retrieved, August 2017, from http://bedtimesmagazine.com/2009/01/research-finds-5-key-mattress-consumer-segments/

Bensons for bed. (2016). History of the bed. Retrieved, September 2017, from http://www.bensonsforbeds.co.uk/history_of_the_bed

Bergholdt, K., Fabricius, R. N., & Bendix, T. (2008). Better backs by better beds?. Spine, 33(7), 703-708.

Bharti, B., Malhi, P., & Kashyap, S. (2005). Patterns and problems of sleep in school going children. Indian pediatrics, 43(1), 35.

Billiard, M., & Bentley, A. (2004). Is insomnia best categorized as a symptom or a disease?. Sleep Medicine, 5, S35-S40.

Bocken, N. M., de Pauw, I., Bakker, C., & van der Grinten, B. (2016). Product design and business model strategies for a circular economy. Journal of Industrial and Production Engineering, 33(5), 308-320.

Bongers, P. M., de Vet, H. C., & Blatter, B. M. (2002). Repetitive strain injury (RSI): occurrence, etiology, therapy and prevention. Nederlands tijdschrift voor geneeskunde, 146(42), 1971-1976.

Boostani, R., Karimzadeh, F., & Nami, M. (2017). A comparative review on sleep stage classification methods in patients and healthy individuals. Computer Methods and Programs in Biomedicine, 140, 77-91.

Borbély, A. A. (1982). A two process model of sleep regulation. Human neurobiology.

Buysse, D. J. (2014). Sleep health: can we define it? Does it matter?. Sleep, 37(1), 9-17.

Cameron, A. J., Stralen, M. M., Brug, J., Salmon, J., Bere, E., ChinAPaw, M. J. M., ... & Velde, S. J. (2013). Television in the bedroom and increased body weight: potential explanations for their relationship among European schoolchildren. Pediatric obesity, 8(2), 130-141.

Cancel, O. (2011). Sleep and mental health. Sleep.

Carskadon, M. A., & Dement, W. C. (2005). Normal human sleep: an overview. Principles and practice of sleep medicine, 4, 13-23.

Carskadon, M. A., & Herz, R. S. (2004). Minimal olfactory perception during sleep: why odor alarms will not work for humans. Sleep, 27(3), 402-405.

Coenen, A. (2011). Sleep, the bedroom, and the bed. Sleep-Wake, 26.

Chokroverty, S. (Ed.). (2017). Sleep disorders medicine: basic science, technical considerations and clinical aspects. Springer.

Crivelli, F., Omlin, X., Rauter, G., Von Zitzewitz, J., Achermann, P., & Riener, R. (2016). Somnomat: a novel actuated bed to investigate the effect of vestibular stimulation. Medical & biological engineering & computing, 54(6), 877-889.

Davidson, R. J., Kabat-Zinn, J., Schumacher, J., Rosenkranz, M., Muller, D., Santorelli, S. F., ... & Sheridan, J. F. (2003). Alterations in brain and immune function produced by mindfulness meditation. Psychosomatic medicine, 65(4), 564-570.

Defloor, T. (2000). The effect of position and mattress on interface pressure. Applied nursing research, 13(1), 2-11.

De Koninck, J., Gagnon, P., & Lallier, S. (1983). Sleep positions in the young adult and their relationship with the subjective quality of sleep. Sleep, 6(1), 52-59.

De Koninck, J., Lorrain, D., & Gagnon, P. (1992). Sleep positions and position shifts in five age groups: an ontogenetic picture. Sleep, 15(2), 143-149.

DINED. (2017). Dined anthropometric database. Retrieved, March 2018, from https://dined.nl/en/database/tool

Doherty, M. J., Youn, C. E., Haltiner, A. M., & Watson, N. F. (2010). Do weather-related ambient atmospheric-pressure changes influence sleep disordered breathing?. Journal of clinical sleep medicine: JCSM: official publication of the American Academy of Sleep Medicine, 6(2), 152.

Drillis, R., Contini, R., & Bluestein, M. (1969). Body segment parameters. New York University, School of Engineering and Science.

Duffy, J. F., & Czeisler, C. A. (2009). Effect of light on human circadian physiology. Sleep medicine clinics, 4(2), 165-177.

Eckstein, S. (2010). Pets in Your Bed. Retrieved, October 2017, from https://pets.webmd.com/features/pets-in-your-bed#1

Eggermont, S., & Van den Bulck, J. (2006). Nodding off or switching off? The use of popular media as a sleep aid in secondary- school children. Journal of paediatrics and child health, 42(7- 8), 428-433.

Ekirch, A. R. (2001). Sleep we have lost: pre-industrial slumber in the British Isles. The American Historical Review, 106(2), 343-386.

Ellen MacArthur Foundation. (2017). Circular Economy System Diagram. Retrieved, May 2018, from https://www.ellenmacarthurfoundation.org/circular-economy/interactive-diagram

Findley, W. N., & Davis, F. A. (2013). Creep and relaxation of nonlinear viscoelastic materials. Courier Corporation.

Fleming, P., & Blair, P. S. (2007). Sudden infant death syndrome and parental smoking. Early human development, 83(11), 721-725.

Gatch bed. (n.d.). Retrieved October 6, 2017, from https://www.merriam-webster.com/medical/gatch bed

Gibofsky, A. (2012). Overview of epidemiology, pathophysiology, and diagnosis of rheumatoid arthritis. The American journal of managed care, 18(13 Suppl), S295-302.

Glew, D., Stringer, L. C., Acquaye, A. A., & McQueen-Mason, S. (2012). How do end of life scenarios influence the environmental impact of product supply chains? Comparing biomaterial and petrochemical products. Journal of Cleaner Production, 29, 122-131.

Goel, N., Kim, H., & Lao, R. P. (2005). An olfactory stimulus modifies nighttime sleep in young men and women. Chronobiology international, 22(5), 889-904.

Gradisar, M., Wolfson, A. R., Harvey, A. G., Hale, L., Rosenberg, R., & Czeisler, C. A. (2013). The sleep and technology use of Americans: findings from the National Sleep Foundation's 2011 Sleep in America poll. Journal of clinical sleep medicine: JCSM: official publication of the American Academy of Sleep Medicine, 9(12), 1291.

Groenesteijn, L., Commissaris, D. A. C. M., den Berg-Zwetsloot, V., & Mastrigt, H. V. (2016). Effects of dynamic workstation Oxidesk on acceptance, physical activity, mental fitness and work performance. Work, 54(4), 773-778.

Haex, B. (2004). Back and bed: ergonomic aspects of sleeping. CRC press.

Harvard Health Publishing. (2010). Medications that can affect sleep. Retrieved, December 2017, from https://www.health.harvard.edu/newsletter_article/medications-that-can-affect-sleep

Hegarty, S. (2012). The myth of the eight-hour sleep. Retrieved, September 2017, from http://www.bbc.com/news/magazine-16964783

Helander, M. G., & Zhang, L. (1997). Field studies of comfort and discomfort in sitting. Ergonomics, 40(9), 895-915.

Hogan, S. O., Krystal, A. D., Edinger, J. D., Bieler, G. S., & Mladsi, S. W. (2011). Choosing the Best Mattress: An Experiment in Testing Whether Individuals Choose a Bed That Leads to Improved Sleep.

Howsleepworks. (2017). What is sleep? Retrieved, October 2017, from https://www.howsleepworks.com/what_not.html

Huisstede, B. M., Wijnhoven, H. A., Bierma-Zeinstra, S. M., Koes, B. W., Verhaar, J. A., & Picavet, S. (2008). Prevalence and characteristics of complaints of the arm, neck, and/or shoulder (CANS) in the open population. The Clinical journal of pain, 24(3), 253-259.

Irwin, M., McClintick, J., Costlow, C., Fortner, M., White, J., & Gillin, J. C. (1996). Partial night sleep deprivation reduces natural killer and cellular immune responses in humans. The FASEB journal, 10(5), 643-653.

Jones, M. W. (2004). Supine and prone infant positioning: a winning combination. The Journal of perinatal education, 13(1), 10.

Kaestner, E. J., Wixted, J. T., & Mednick, S. C. (2013). Pharmacologically increasing sleep spindles enhances recognition for negative and high-arousal memories. Journal of Cognitive Neuroscience, 25(10), 1597-1610.

Kales, A., & Kales, J. D. (1974). Sleep disorders: recent findings in the diagnosis and treatment of disturbed sleep. New England Journal of Medicine, 290(9), 487-499.

Kelleher, M. E., Swan, K. G., & Kelleher, D. P. (2011). George Ryerson Fowler: Brooklyn's Surgical Pioneer: A Biographical Sketch Based on Historical Documents. Annals of surgery, 253(6), 1230-1232.

Khan, S., & Uddin, M. B. (2015, May). Effects of sleeping positions on cardiac output and cardiac activity analyzing blood perfusion. In Electrical Engineering and Information Communication Technology (ICEEICT), 2015 International Conference on (pp. 1-5). IEEE.

Khoury, B., Lecomte, T., Fortin, G., Masse, M., Therien, P., Bouchard, V., ... & Hofmann, S. G. (2013). Mindfulness-based therapy: a comprehensive meta-analysis. Clinical psychology review, 33(6), 763-771.

Knutson, K. L., Spiegel, K., Penev, P., & Van Cauter, E. (2007). The metabolic consequences of sleep deprivation. Sleep medicine reviews, 11(3), 163-178.

Kubota, S., Endo, Y., Kubota, M., Ishizuka, Y., & Furudate, T. (2015). Effects of trunk posture in Fowler's position on hemodynamics. Autonomic Neuroscience: Basic and Clinical, 189, 56-59.

Lack, L. C., Gradisar, M., Van Someren, E. J., Wright, H. R., & Lushington, K. (2008). The relationship between insomnia and body temperatures. Sleep medicine reviews, 12(4), 307-317.

Lai, H. L., & Good, M. (2005). Music improves sleep quality in older adults. Journal of advanced nursing, 49(3), 234-244.

Lee, H., & Park, S. (2006). Quantitative effects of mattress types (comfortable vs. uncomfortable) on sleep quality through polysomnography and skin temperature. International journal of industrial ergonomics, 36(11), 943-949.

Lockley, S. W., Evans, E. E., Scheer, F. A., Brainard, G. C., Czeisler, C. A., & Aeschbach, D. (2006). Short-wavelength sensitivity y for the direct effects of light on alertness, vigilance, and the waking electroencephalogram in humans. Sleep, 29(2), 161-168.

Madden, T. J., Hewett, K., & Roth, M. S. (2000). Managing images in different cultures: A cross-national study of color meanings and preferences. Journal of international marketing, 8(4), 90-107.

Marques, M., Genta, P. R., Sands, S. A., Azarbazin, A., de Melo, C., Taranto-Montemurro, L., ... & Wellman, A. (2017). Effect of Sleeping Position on Upper Airway Patency in Obstructive Sleep Apnea Is Determined by the Pharyngeal Structure Causing Collapse. Sleep, 40(3).

Matricciani, L., Bin, Y. S., Lallukka, T., Kronholm, E., Dumuid, D., Paquet, C., & Olds, T. (2017). Past, present, and future: trends in sleep duration and implications for public health. Sleep Health, 3(5), 317-323.

Maziak, W., Behrens, T., Brasky, T. M., Duhme, H., Rzehak, P., Weiland, S. K., & Keil, U. (2003). Are asthma and allergies in children and adolescents increasing? Results from ISAAC phase I and phase III surveys in Münster, Germany. Allergy, 58(7), 572-579.

McCabe, S. J., & Xue, Y. (2010). Evaluation of sleep position as a potential cause of carpal tunnel syndrome: preferred sleep position on the side is associated with age and gender. Hand, 5(4), 361-363.

McKenna, J. J., & McDade, T. (2005). Why babies should never sleep alone: A review of the co-sleeping controversy in relation to SIDS, bedsharing and breast feeding. Paediatric respiratory reviews, 6(2), 134-152.

Medscape Neurology. (2009). Common Comorbidities of Insomnia. Retrieved, December 2017, from https://www.medscape.org/viewarticle/585753

Miyawaki, S., Lavigne, G. J., Mayer, P., Guitard, F., Montplaisir, J. Y., & Kato, T. (2003). Association between sleep bruxism, swallowing-related laryngeal movement, and sleep positions. Sleep, 26(4), 461-465.

Montgomery-Downs, H. E., & Gozal, D. (2005). Sleep habits and risk factors for sleep-disordered breathing in infants and young toddlers in Louisville, Kentucky. Sleep medicine, 7(3), 211-219.

Moreno, M., De los Rios, C., Rowe, Z., & Charnley, F. (2016). A conceptual framework for circular design. Sustainability, 8(9), 937.

National Sleep Foundation. (2012). Sleep in America Poll. Exercise and Sleep. Retrieved, September 2017, from https://sleepfoundation.org/sleep-polls-data/other-polls/2012-bedroom-poll

National Sleep Foundation. (2013). Bedroom Poll. Summary of Findings. Retrieved, September 2017, from https://sleepfoundation.org/sleep-polls-data/other-polls/2012-bedroom-poll

National Sleep Foundation. (2017). ELECTRONICS IN THE BEDROOM: WHY IT'S NECESSARY TO TURN OFF BEFORE YOU TUCK IN. Retrieved, November 2017, from https://sleepfoundation.org/ask-the-expert/electronics-the-bedroom

Neel, A.B. (2017). 10 Types of Meds That Can Cause Insomnia. Retrieved, December 2017, from https://www.aarp.org/health/drugs-supplements/info-04-2013/medications-that-can-cause-insomnia.html

NERIS Analytics Limited. (2017). 16 Personalities test. Retrieved, September 2017, from https://www.16personalities.com/

Newman, T. (2017). Repetitive strain injury (RSI): Diagnosis, symptoms, and treatment. Retrieved, September 2017, from https://www.medicalnewstoday.com/articles/176443.php

Nilsson, U., Unosson, M., & Rawal, N. (2005). Stress reduction and analgesia in patients exposed to calming music postoperatively: a randomized controlled trial. European journal of anaesthesiology, 22(2), 96-102.

O'Donoghue, G. M., Fox, N., Heneghan, C., & Hurley, D. A. (2009). Objective and subjective assessment of sleep in chronic low back pain patients compared with healthy age and gender matched controls: a pilot study. BMC musculoskeletal disorders, 10, 122-122.

Ohayon, M. M. (2011). Epidemiological overview of sleep disorders in the general population. Sleep Medicine Research (SMR), 2(1), 1-9.

Oomen, P. (2003). Aan één stuk door slapen is een recent fenomeen. Retrieved, October 2017, from https://www.historischnieuwsblad.nl/nl/artikel/6145/aan-een-stuk-door-slapen-is-een-recent-fenomeen.html

Owen, S., Morganstern, M., Hepworth, J., & Woodcock, A. (1990). Control of house dust mite antigen in bedding. The Lancet, 335(8686), 396-397.

Owen, J. (2011). Oldest Known Mattress Found; Slept Whole Family. Retrieved, September 2017, from http://news.nationalgeographic.com/news/2011/11/111208-oldest-mattress-africa-archaeology-science/

Paiva, T., Gaspar, T., & Matos, M. G. (2015). Sleep deprivation in adolescents: correlations with health complaints and health-related quality of life. Sleep medicine, 16(4), 521-527.

Palm, J.A. (2017). BSC Survey Finds Consumers Adopting Savvier Shopping Habits. Savvy Sleep Magazine.

Pankhurst, F. P., & Home, J. A. (1994). The influence of bed partners on movement during sleep. Sleep, 17(4), 308-315.

Partinen, M. (2017). Nutrition and sleep. In Sleep Disorders Medicine (pp. 539-558). Springer New York.

Pasik, P. (2013). Sleep Mechanisms. Retrieved, October 2017, from https://www.youtube.com/watch?v=agRcU_Wz1hg

Patte, K. A., Qian, W., & Leatherdale, S. T. (2017). Sleep duration trends and trajectories among youth in the COMPASS study. Sleep Health, 3(5), 309-316.

Peigneux, P., Laureys, S., Fuchs, S., Collette, F., Perrin, F., Reggers, J., ... & Luxen, A. (2004). Are spatial memories strengthened in the human hippocampus during slow wave sleep?. Neuron, 44(3), 535-545.

Penzel, T., Möller, M., Becker, H. F., Knaack, L., & Peter, J. H. (2001). Effect of sleep position and sleep stage on the collapsibility of the upper airways in patients with sleep apnea. Sleep, 24(1), 90-95.

Poelman, W. (2012, October). Horse riding as a metaphor for man-machine interfaces. In Proceedings of the 1st workshop on Smart Material Interfaces: A Material Step to the Future (p. 5). ACM.

Rasch, B., Büchel, C., Gais, S., & Born, J. (2007). Odor cues during slow-wave sleep prompt declarative memory consolidation. Science, 315(5817), 1426-1429.

Rechtschaffen, A., & Kales, A. (1968). A manual of standardized terminology, techniques, and scoring systems for sleep stages of human subjects.

Pilcher, J. J., & Huffcutt, A. I. (1996). Effects of sleep deprivation on performance: a meta-analysis. Sleep, 19(4), 318-326.

Roozenburg, N.F.M., & Eekels, J. (1998). Productontwerpen, structuur en methoden.

Rudoy, J. D., Voss, J. L., Westerberg, C. E., & Paller, K. A. (2009). Strengthening individual memories by reactivating them during sleep. Science, 326(5956), 1079-1079.

Russo, K., & Bianchi, M. T. (2016). How reliable is self-reported body position during sleep?. Journal of clinical sleep medicine: JCSM: official publication of the American Academy of Sleep Medicine, 12(1), 127.

Sassin, J. F., Parker, D. C., Mace, J. W., Gotlin, R. W., Johnson, L. C., & Rossman, L. G. (1969). Human growth hormone release: relation to slow-wave sleep and sleep-waking cycles. Science, 165(3892), 513-515.

SCENIHR. (2015). Opinion on Potential health effects of exposure to electromagnetic fields.

Scharff, R. B., Doubrovski, E. L., Poelman, W. A., Jonker, P. P., Wang, C. C., & Geraedts, J. M. (2017). Towards Behavior Design of a 3D-Printed Soft Robotic Hand. In Soft Robotics: Trends, Applications and Challenges (pp. 23-29). Springer, Cham.

Sleep Satisfaction. (2017). The History of the Bed. Retrieved, September 2017, from http://www.sleepsatisfaction.com/history-of-the-bed.html

Sleeplikethedead. (2017). Mattress Types and Sex Suitability: Ratings and Comparisons. Retrieved, November 2017, from http://www.sleeplikethedead.com/mattress-sex.html#1

Sleepopolis. (2017). Best Mattress for Sex. Retrieved, October 2017, from https://sleepopolis.com/best-mattress/best-mattress-for-sex/

Slumberwise. (2013). Your Ancestor's Didn't Sleep Like You. Retrieved, September 2017, from http://slumberwise.com/science/your-ancestors-didnt-sleep-like-you/

Spriggs, W.H. (2015). Sleep Disorders. In Essentials of Polysomnography. Jones & Barlett Publishers.

Tasali, E., Leproult, R., Ehrmann, D. A., & Van Cauter, E. (2008). Slow-wave sleep and the risk of type 2 diabetes in humans. Proceedings of the National Academy of Sciences, 105(3), 1044-1049.

Thorpy, M. (2017). International classification of sleep disorders. In Sleep Disorders Medicine (pp. 475-484). Springer New York.

Taylor, D. J., Mallory, L. J., Lichstein, K. L., Durrence, H. H., Riedel, B. W., & Bush, A. J. (2007). Comorbidity of chronic insomnia with medical problems. Sleep, 30(2), 213-218.

United Nations. (2015). Transforming our world: the 2030 Agenda for Sustainable Development.

Van den Bulck, J. (2007). Adolescent use of mobile phones for calling and for sending text messages after lights out: results from a prospective cohort study with a one-year follow-up. Sleep, 30(9), 1220-1223.

Van Dijk, V. (2016). Leve de comfortabele cocon. Elsevier Juist, 4(31), 30-37.

Van Someren, E. J. (2004). Sleep propensity is modulated by circadian and behavior-induced changes in cutaneous temperature. Journal of Thermal Biology, 29(7), 437-444.

Varughese, J., & Allen, R. P. (2001). Fatal accidents following changes in daylight savings time: the American experience. Sleep medicine, 2(1), 31-36.

Verhaert, V., Haex, B., Wilde, T. D., Berckmans, D., Verbraecken, J., Valck, E. D., & Sloten, J. V. (2011). Ergonomics in bed design: the effect of spinal alignment on sleep parameters. Ergonomics, 54(2), 169-178.

Vincent, J. (2016). I had my bones rattled by the Balluga smart bed. Retrieved, May 2018, from https://www.theverge.com/2016/3/23/11289686/balluga-smart-bed

Vincent, A., Lahr, B. D., Wolfe, F., Clauw, D. J., Whipple, M. O., Oh, T. H., ... & St Sauver, J. (2013). Prevalence of fibromyalgia: A population- based study in Olmsted County, Minnesota, utilizing the Rochester Epidemiology Project. Arthritis care & research, 65(5), 786-792.

Vink, P., & Hallbeck, S. (2012). Comfort and discomfort studies demonstrate the need for a new model.

Volk, S.W. (2006). Peritonitis. Small Animal Critical Care Medicine, 579–583. doi: 10.1016/B978-1-4160-2591-7.10133-X

Wagner, U., Hallschmid, M., Rasch, B., & Born, J. (2006). Brief sleep after learning keeps emotional memories alive for years. Biological psychiatry, 60(7), 788-790.

Wehr, T. A. (1992). In short photoperiods, human sleep is biphasic. Journal of sleep research, 1(2), 103-107.

Xia, F., Yang, L. T., Wang, L., & Vinel, A. (2012). Internet of things. International Journal of Communication Systems, 25(9), 1101.

Yassi, A. (1997). Repetitive strain injuries. The Lancet, 349(9056), 943-947.

Zia, K. M., Bhatti, H. N., & Bhatti, I. A. (2007). Methods for polyurethane and polyurethane composites, recycling and recovery: A review. Reactive and functional polymers, 67(8), 675-692.

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APPENDICES

Background information for content found in the main report is collected in the appendices.

A. ASSIGNMENT DEFINITION

This appendix contains information that was required to get a better understanding of the assignment.

A.1. INITIAL CHALLENGE

The initial challenge formulated in the design brief was:

> *The main problem is that ergonomic systems currently used in bedding- and seating applications are static and do not sufficiently adjust to users and use, sometimes causing them to feel discomfort or in extreme situations decubitus.*

It was mentioned that the initial challenge would be solved using Soft Robotics, which would come with constraints in sustainability, feasibility and manufacturability. By implementing the Soft Robotics technology in a modular setup, a dynamic, interactive and smart system could be developed. This system would actively adjust to the user during sleep, to make up for this misfit between user and static bedding- and seating application.

As seen in figure 101, this system could consist of several elements, such as different applications, connectivity to the cloud, a database and mobile phones. The applications in turn contain different parts, such as sensors, a feedback/control system and different modules.

Developing such a system has been suggested as a potential solution for mattress-related problems by

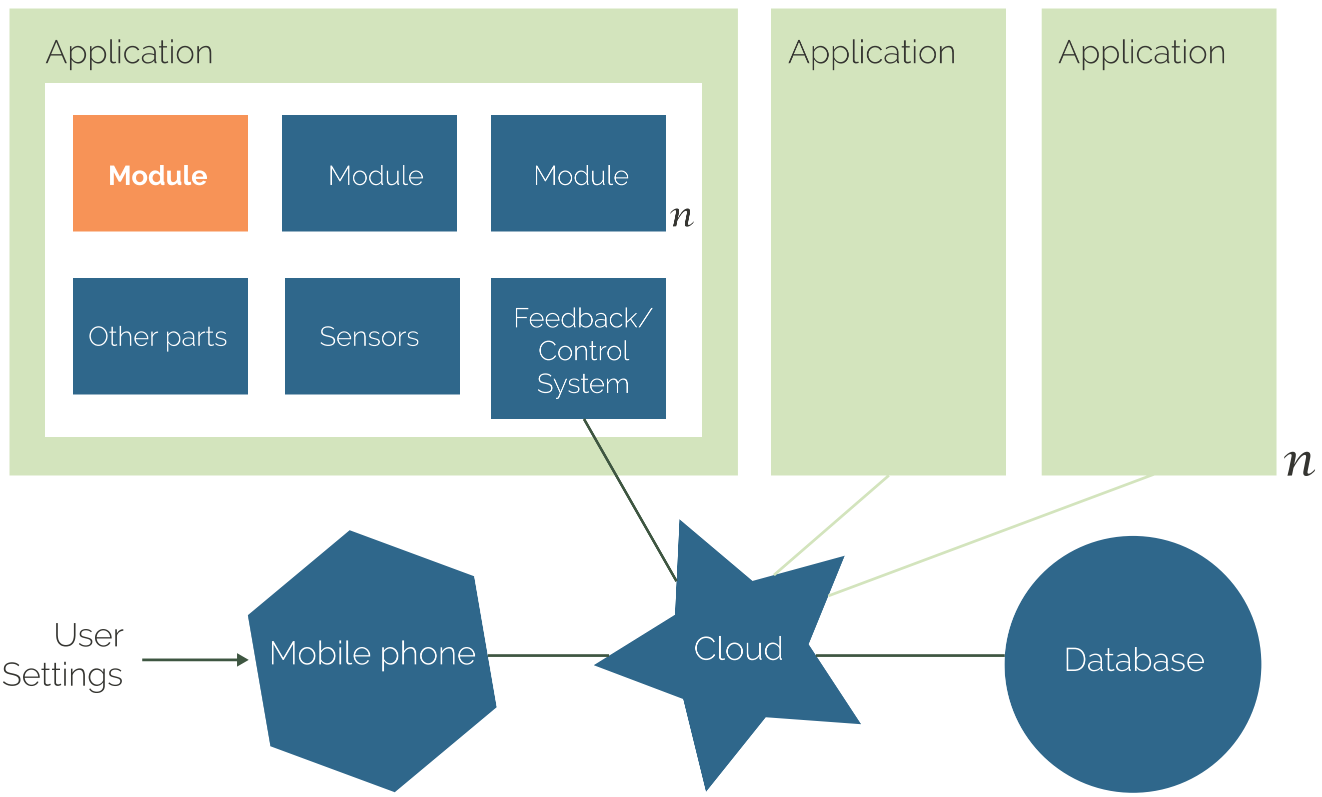


Figure 101 *System architecture and scope (by author)*

Verhaert et al. (2011). Other literature (e.g. Haex, 2004 and Bader & Engdal, 2000) also stresses the importance of an individually adapted sleep system.

As discussed in chapter 4.2, several attempts have been made to create such a system for mattresses. However, this graduation project hopes to go even further than these solutions, for example by creating a truly modular system that can also be implemented in other appliances besides the mattress. Other differences are discussed in chapter 4.2.

The initial challenge of this graduation project was to develop an ergonomic system that could be implemented in bedding- and seating applications and would actively adjust to the user's body posture. The system would be dynamic, interactive and smart and would consist of several modules.

A.2. SCOPE

Because designing the complete system shown in figure 101 is too much for a single graduation project, a scope was determined:

1 The focus will be on developing one module, as highlighted in orange in figure 101. This module contains the working mechanism that enables active adjustment. The control of this module, the sensors required for input data, and the relation to the other modules, the other parts of the application and other system elements (highlighted in blue) will be considered and implemented partially to get the desired proof of concept.

2 Ideally, problems of different bedding- and seating appliances were solved by introducing one and the same modular system (as proposed). However, to design for specific needs, it is helpful to focus on just one application to make it sure it has all the required functions. Otherwise, too many variables and elements must be considered, which makes designing more complex and might result in too much compromise to be effective in solving the problems. Therefore, the approach is to focus on one application and its problems to later consider whether alterations can be made to make it work for other applications.

To determine for which application to design the initial solution, a matrix (see figure 102) was made that rates ergonomic bedding- and seating appliances on the frequency of use and the duration of use. The arrows indicate that there is a difference between occasionally traveling for a long duration or on a more daily basis travelling for a shorter duration. This matrix shows that

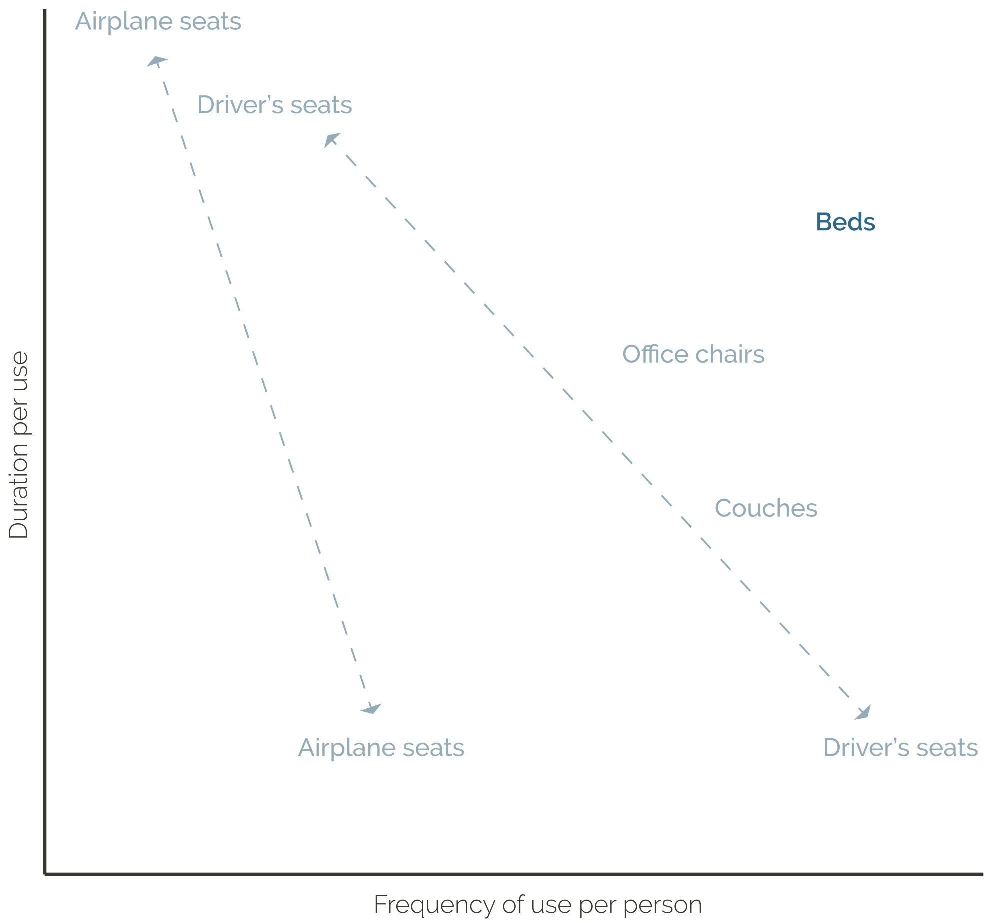
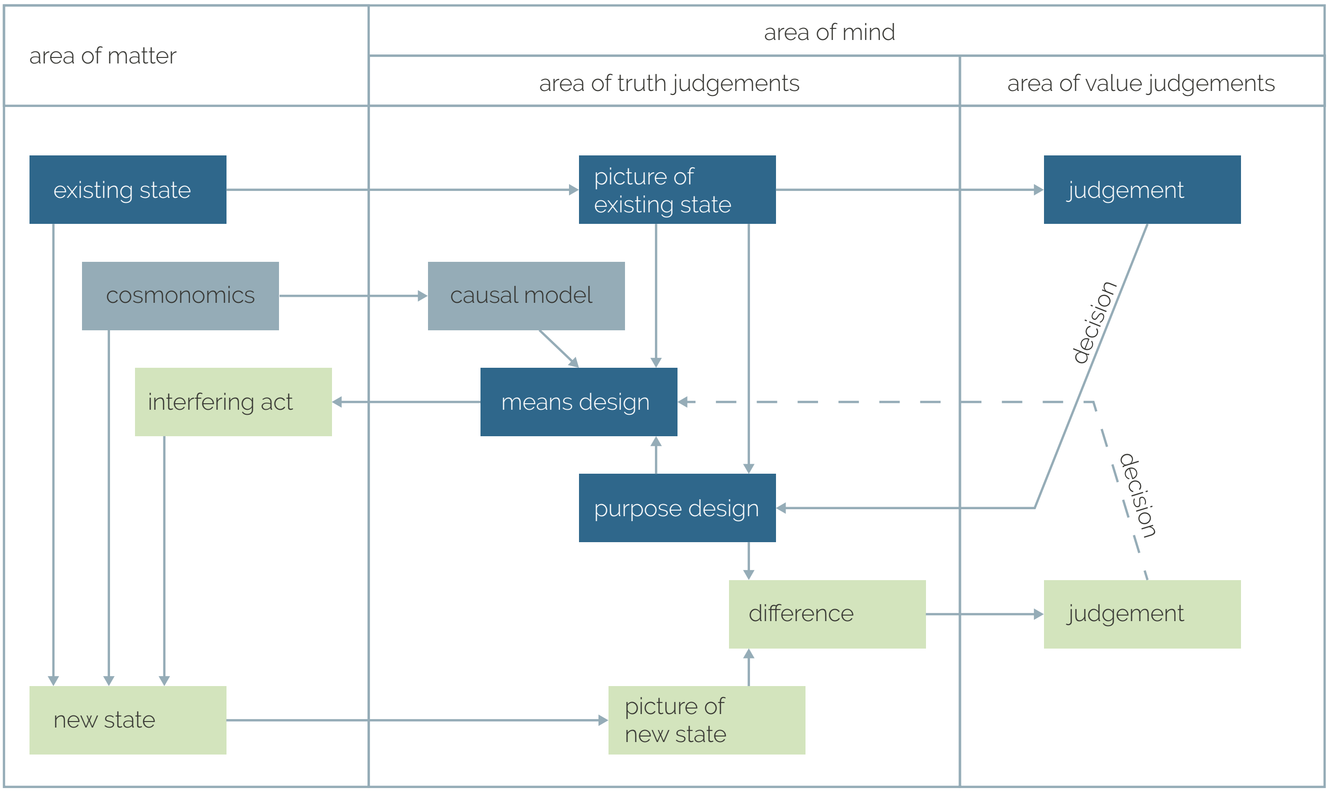


Figure 102 *Intensity of use for Bedding- and Seating Appliances (by author)*

the bed is on average the most intensively used product. Besides the use intensity, the bed is argued to be more important to health than the other mentioned appliances because of its influence on sleep, which influences not only physical but also mental health. Combine the importance of sleep with the trend that sleep is declining and it becomes clear that something needs to happen (Matricianni et al., 2017; Patte, Qjan, & Leatherdale, 2017). Therefore, the bed with all its aspects and parts (as explained in chapter 3.1), from here on referred to as "sleep system" will be the focussed on.

3 Besides the sleep system itself, sleep will be regarded as the most important use for a sleep system, and this graduation project will therefore focus on designing for this core use. This decision is elaborated in chapter 3.3.

This graduation project focusses on the development of one module as part of the system described in appendix A.1. This module will be specifically developed to function inside a sleep system and will be designed with a focus on facilitating the best sleep as opposed to optimising other uses for a sleep system.



*Translated from Roozenburg & Eekels (1998)

Figure 103 *The structure of an act (Roozenburg & Eekels, 1998)**

A.3. LIMITATIONS

Each project has limitations because not everything can be known. Designers try to include as much information as possible, but some effects cannot be predicted.

This chapter explains how this works and which topics are included in this project.

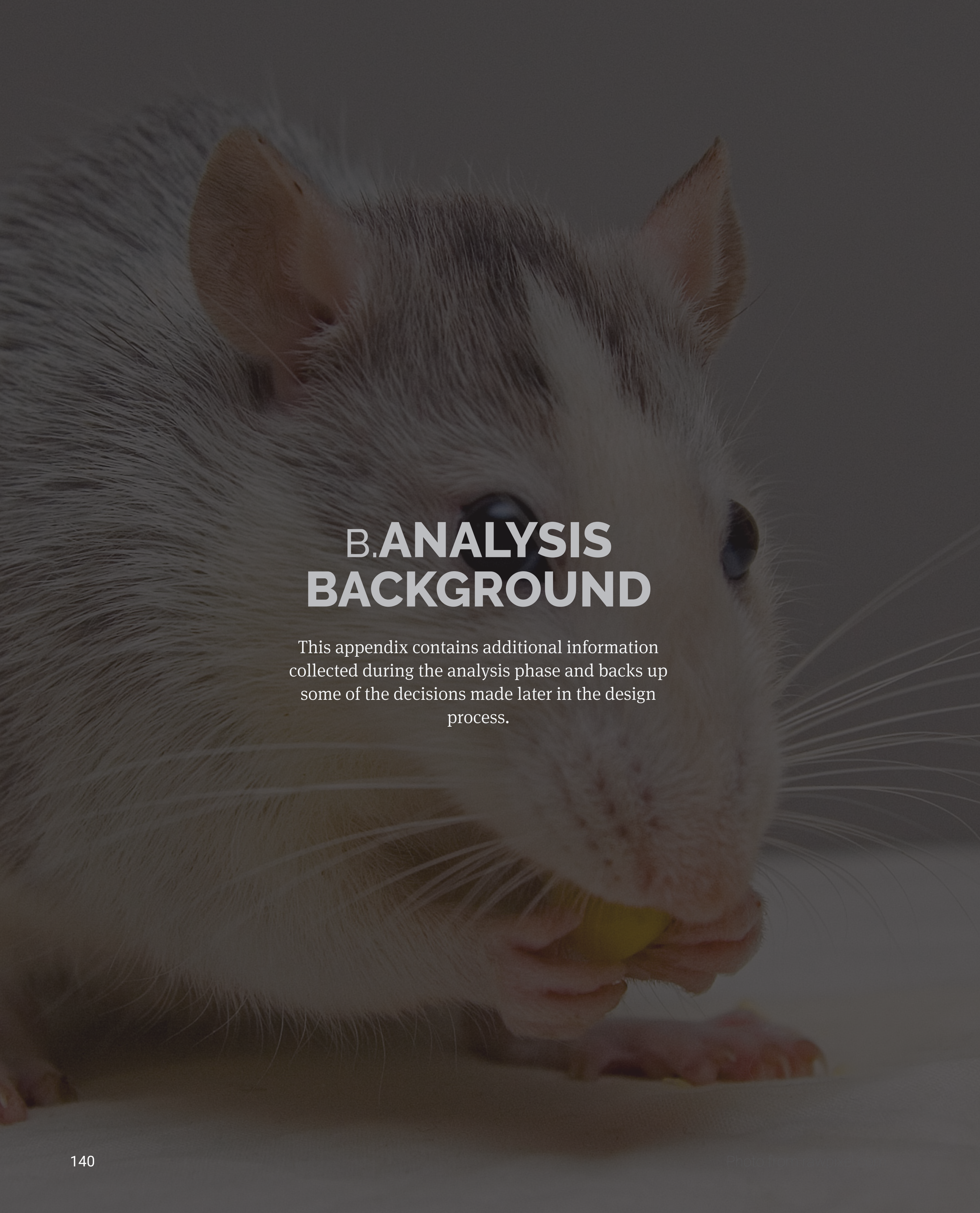
When designing, a designer has a purpose in mind and tries to interfere in the world's autonomous transformation by adding an artefact that helps create the desired situation. The designer does this based on his judgement of his picture of the existing state the world is in. Roozenburg and Eekels (1998) created a model that clarifies what happens (figure 103).

Highlighted in darker blue are the parts that are covered in this project. The light green blocks will only be partially included, because the interfering act cannot be tested or evaluated since the final application (i.e the mattress) will not be made during this project. Only some aspects, such as the potential of the final 'means design' and the user acceptance of a design visualisation can be tested and evaluated.

This model shows the importance for designers to get their picture of the world as realistic as possible, because based on this picture, designers judge whether they are content with the existing state or not. In case they judge that the situation can be improved, they create a purpose design (i.e. black box with desired functions defined), on which their means design (i.e. the actual product design) is based. But if designers have a wrong picture of reality, this could very well go wrong, as they might be solving non-existing problems. Therefore, the following research phase will focus on getting the right picture of the existing state and verifying the motives of the designer.

The picture of the existing state is never a complete picture of everything going on in the world, as that is too much. Therefore, the interfering act is always limited to a small fixed part of reality, as Roozenburg and Eekels (1998) explain in their book. The fixed part on which this project focuses consists of the following topics:

- Use context
- Consumer trends
- Technology
- Ergonomics
- Sustainability



B. ANALYSIS BACKGROUND

This appendix contains additional information collected during the analysis phase and backs up some of the decisions made later in the design process.

B.1. THE IMPORTANCE OF SLEEP

Scientists are gaining more understanding of what sleep is, but there are still many questions about what is going on during sleep. The reason why people sleep is therefore hard to answer. It is easiest to answer this question by looking at consequences from good or bad sleep.

It is known that rats under prolonged sleep deprivation have a deteriorating appearance, increase of skin lesions, changing brain activity, thermoregulatory failures and ultimately die. Unfortunately, the exact cause of these consequences remains unclear (Rechtschaffen & Bergmann, 2002). It is assumed that humans face similar consequences under prolonged sleep deprivation, but for practical reasons, humans cannot be tested under the same extreme conditions.

Less severe sleep deprivation however has been tested, and consequences are sleepiness and an impairment of performance, vigilance, attention, concentration and memory (Chokroverty, 2017). Besides that, it has shown the negative influence on metabolism, increasing the chance of diabetes and obesity, but also the reduction of immune responses (Irwin et al., 1996; Knutson, Spiegel, Penev, & Van Cauter, 2007). It has also been proven that sleep deprivation has a negative effect on motor functioning, an even stronger negative effect on cognitive functioning and the strongest negative effect on mood (Pilcher, & Huffcutt, 1996).

Another consequence of sleep deprivation can be excessive daytime sleepiness (EDS). Other causes could be medication, shift-work or disease, but sleep deprivation is the most common cause. EDS can cause severe psychological stress, loneliness and these people can be perceived as dull, lazy, or even stupid. Also, marital-, health- or social problems can occur and relationships can be difficult for people suffering EDS. Stimulating people to sleep more will help people suffering from sleep deprivation, as these effects are reversible (Chokroverty, 2017).

That sleep deprivation can even be dangerous becomes clear in the following example: Fatal accidents in the U.S. significantly increased the day after changes in daylight savings time, both in spring and fall. This is probably due to the effects of sleep loss in spring, and the resulting behavioural change of consuming more alcohol and driving sleepy due to the extra hour in fall (Varughese & Allen, 2001).

The exact function of sleep remains a biologic mystery, and several theories exist, but without consensus amongst scientists (Chokroverty, 2017). But it is clear that people sleep because it is an essential part of living, a basic human need, and that people should strive for good sleep in order to function well.

Despite the lack of knowledge on the exact biologic function of sleep, it is clear that humans cannot live without sleep and need it for normal daily functioning.

Photo by JESHOOTS.com from Pexels.com

B.2. UNDERSTANDING SLEEP

This chapter focuses on the physiology of sleep to understand what sleep is.

Definition of sleep

To the eye, sleep seems a passive process where nothing much happens, and for millennia people believed sleep was simply a passive state of unconsciousness. But one could not be more wrong, as sleep is in fact a complex and highly active process for the brains and has great impact on our daily functioning and health. Only for half a century people are beginning to understand what sleep really is, yet even today many questions remain unanswered (American Sleep Association, 2017).

The website 'Howsleepworks' (2017) summarises different definitions into the following:

> *A naturally-occurring, reversible, periodic and recurring state in which consciousness and muscular activity is temporarily suspended or diminished, and responsiveness to outside stimuli is reduced.*

This means sleep is not defined by outward signs like closed eyes, recumbent posture or immobility, as these can also be achieved by resting or meditating. Also, sleep must be distinguished from other states such as hibernation, aestivation (the hot weather equivalent of hibernation), coma, hypnotic trance and general anaesthesia and is usually defined as the opposite of wakefulness, which is regarded as absence of sleep (Howsleepworks, 2017; Pasik, 2013).

How sleep works

A typical night of sleep consists of several sleep cycles. In each cycle, a person has varying depth of sleep. According to Rachel van Sluijs (personal communication, October 25, 2017), who researches innovative sleep systems at the ETH Zürich, sleep depth is a gradual process. However, to simplify sleep and allow comparison between sleep cycles, the depth of sleep is commonly classified in several sleep stages. The main sleep stages are called non-REM (NREM) and REM stages. The NREM stage contains several stages. Typically, the most used classification of sleep stages is the one created by Rechtschaffen & Kales (1968), which includes the following seven stages:

- Wakefulness (W)
- Non-Rapid Eye Movement (NREM), consisting of stage 1, stage 2, stage 3 and stage 4
- Rapid Eye Movement (REM)
- Movement Time (MT)

The American Academy of Sleep Medicine (AASM) updated this classification and merged stages 3 and 4 into N3 (also called Slow-Wave Sleep (SWS) or 'deep sleep') and completely retracted the MT stage from analyses (Boostani, Karimzadeh, & Nami, 2017).

Measuring stages is done in several ways, but for research it is common to use an Electro-Encephalo-Gram (EEG) which measures brain activity.

These stages are part of a sleep cycle. A sleep cycle lasts approximately 90 minutes and a typical night contains about five cycles. In every sleep cycle, the time spent in different sleep stages is different as can clearly be seen in a hypnogram. Figure 104 shows an example of three possible sleep cycles for different ages. The REM sleep stage becomes longer with every cycle for children and young adults and SWS becomes shorter, young adults and elderly will not even go into stage 3 or 4 in some sleep cycles, which are considered the SWS stages. However, according to Van Sluijs, it cannot be said for certain that only these stages function as SWS,

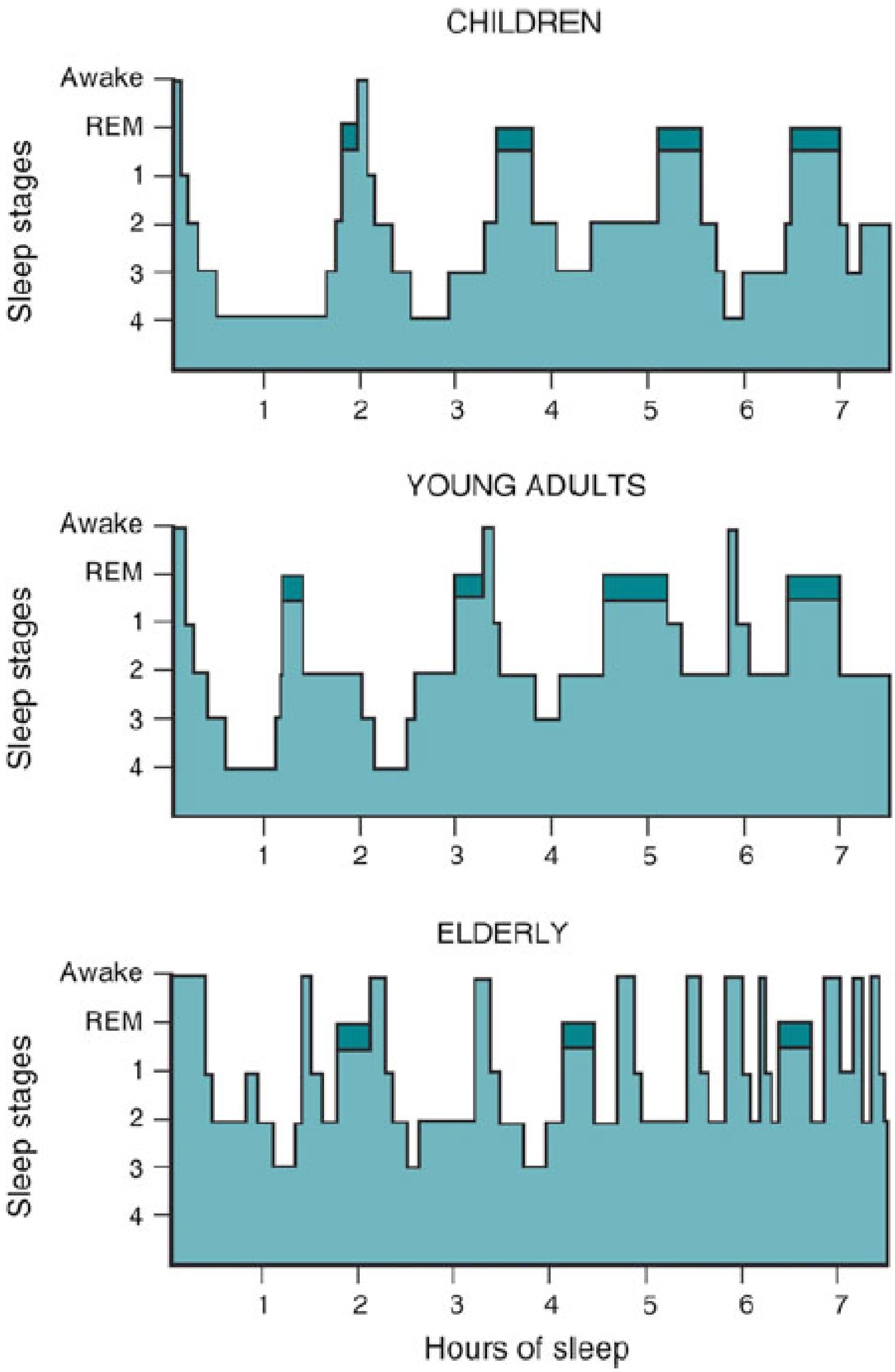


Figure 104 *Hypnogram for children, young adults and elderly,*
(reprinted version from Chokroverty, 2017, originally from Kales and Kales, 1974)

because the shape of the scalp changes, and therefore measuring equipment might measure different frequencies at different ages even though the actual sleep depth might be the same. Besides that, it is good to realise that these hypnograms are typical text-book examples, but are much less “perfect” in reality.

Memory consolidation

A research by Rudoy, Voss, Westerberg, and Paller (2009) has shown that people who hear sounds during the night, that they had earlier associated with objects at specific spatial locations, will recall these locations more strongly upon waking up than other locations for which they did not hear any reminder cues. And a research by Wagner, Hallschmid, Rasch and Born (2006) has shown that brief sleep after learning emotional texts will keep the memory alive for at least four years.

Interesting to review is that spindles support brain plasticity, which is underlying learning and memory. An increased spindle density will result in an increased memory performance (Kaestner, Wixted, & Mednick, 2013).

Deep sleep

Deep sleep, or SWS is extremely important and arguably the most important stage of sleep as it is said to be the most “restorative” sleep stage (Tasali, Leproult, Ehrmann, & Van Cauter, 2008). Several important processes take place primarily or solely during deep sleep. For example, certain memory traces are processed during this stage, which leads to better memory performance the next day (Peigneux et al., 2004). Low levels of SWS also increase the risk for type 2 diabetes due to its role in the normal glucose homeostasis (Tasali, Leproult, Ehrmann, & Van Cauter, 2008). Also, during deep sleep the growth hormone is released, which is necessary for cell repair after the stress of weight training (Sassin et al., 1969). SWS is also the most effective for decreasing sleep drive as a decrease of SWS will increase sleep propensity during the daytime (Dijk, Groeger, Stanley, & Deacon, 2010).

Sleep regulation

According to Borbély (1982), sleep is regulated by two processes, namely the sleep-dependent homeostatic process (Process S) and a sleep-independent circadian process (Process C). This is called the two-process model of sleep regulation.

Process S, representing sleep drive, increases during wakefulness and declines during sleep. The longer awake, the more pressure a person feels to sleep, all to keep the body in a stable and relatively constant condition. The exact biochemical processes behind sleep homeostasis are not all clear, but that the molecule adenosine plays a sleep inducing role is confirmed. Adenosine inhibits wakefulness-promoting neurons, causing a sleep-inducing effect. Stimulants like caffeine (e.g. in coffee, tea and energy drinks) and theophylline (e.g. in tea and chocolate) work as adenosine receptor antagonists, meaning that they bind to the receptors for adenosine and block them. This inhibits or dampens the sleepiness effect (Basheer, Strecker, Thakkar, & McCarley, 2004; Howsleepworks, 2017).

Process C is the body’s circadian rhythm (also called biological clock, see figure 105). This built-in rhythm is adjusted to the environment by external cues, known as Zeitgebers. The most important cues are daylight, temperature and food. These Zeitgebers help to synchronise or reset each day to match the Earth’s 24-hour rotation cycle. This reset is necessary because people’s natural circadian period is between 23.5 and 24.5 hours with an average of 24.2 hours, slightly more than the earth’s cycle (Howsleepworks, 2017). The length of people’s biological night programmed in this circadian rhythm also differs per person, and therefore one person can do with 7 hours of sleep while another needs 9 hours (Aeschbach et al., 2003).

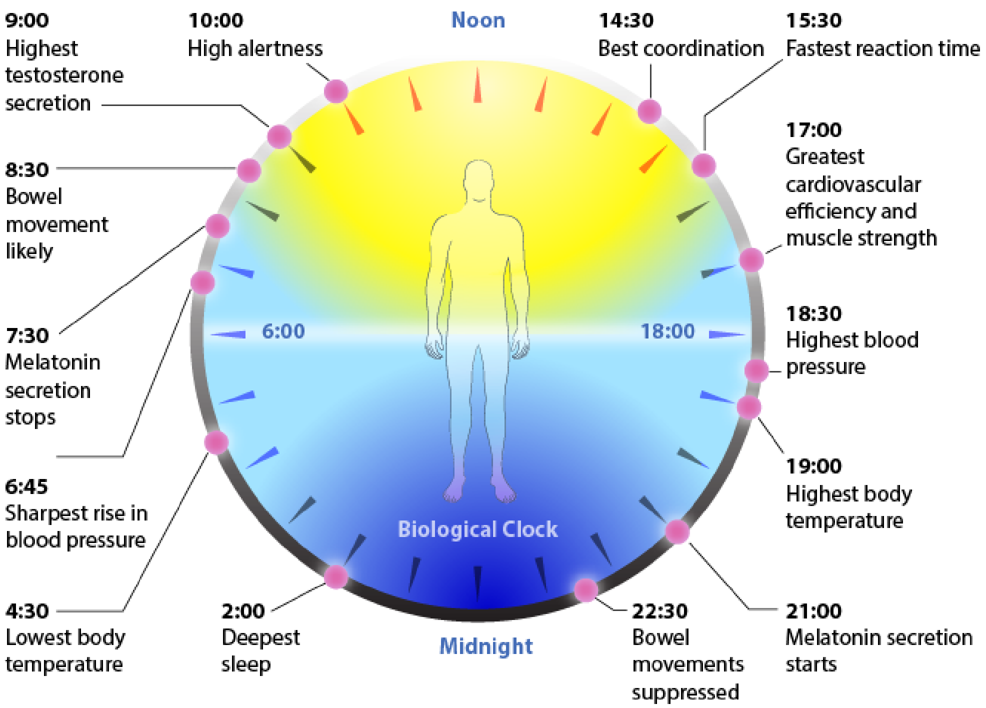


Figure 105 *Biological clock,*

(image from UNC Eshelman School of Pharmacy, 2016)

This two-process model determine when a person is likely to fall asleep. The circadian rhythm drives for arousal during the day, but at the end of the day starts the melatonin production which causes sleepiness. The homeostatic sleep drive increases during the day, but is countered by the arousal effect of the circadian rhythm. But when the circadian clock drops the arousal and starts the melatonin production, the sleep drive takes over. This is called the “sleep gate”, see figure 106. That is the moment a person usually goes to sleep. In case a person decides to stay awake, the sleep drive will keep on building until a person actually sleeps, during which the sleep drive will reset (Howsleepworks, 2017).

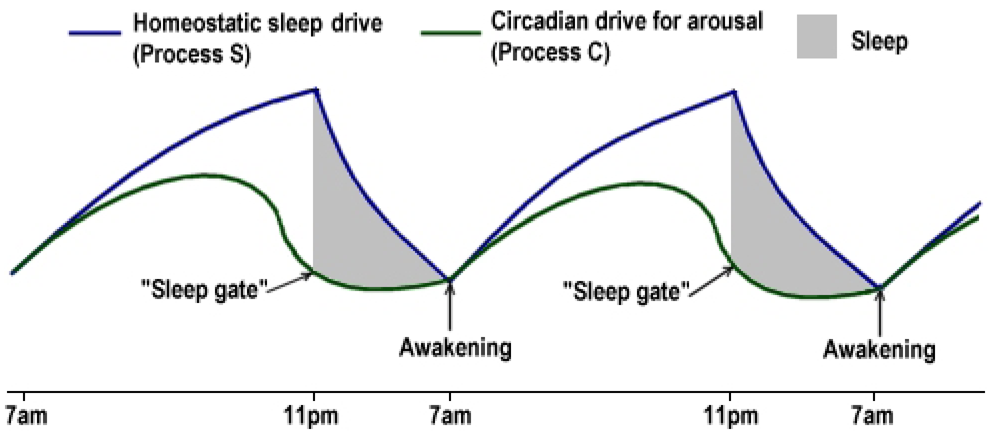


Figure 106 *Sleep-wake regulation (Howsleepworks, 2017)*

Definition of good or bad sleep

Good sleep means a certain minimum quantity of sleep and a good quality of sleep. Someone has slept enough when there is no daytime sleepiness or disfunction. The quality of sleep is good when someone has spent enough time asleep in the different stages, especially REM and SWS stages. Quality of sleep can also be measured quantitively using the sleep duration, sleep onset latency (SOL; time it takes to fall asleep), sleep efficiency (total sleep time divided by time in bed) and number of awakenings (Al-Kandari et al., 2017).

Sleep quality is affected by sleep hygiene, which refers to a set of rules that promote better sleep. The generally accepted rules according to Al-Kandari et al. (2017) are:

- Avoid strenuous exercise within a short time before bedtime.
- Not going to bed hungry or thirsty.
- Avoid caffeinated, nicotine or alcohol products within 4 hours before bedtime.
- Avoid regular use of sleep medication.
- Not taking naps during daytime.
- Making sure that the environment is comfortable and suitable for sleep.
- Avoid noisy places.
- Setting time to relax before sleeping.
- Keeping a regular sleep schedule.

This sleep hygiene is a known and validated treatment, e.g. used in Cognitive Behavioural Therapy (CBT), for insomniacs.

Besides sleep hygiene and sleep quality, sometimes the words ‘sleep health’ are used. Buyssee (2014) proposed to define sleep health as follows:

> *Sleep health is a multidimensional pattern of sleep-wake-fulness, adapted to individual, social, and environmental demands, that promotes physical and mental well-being. Good sleep health is characterized by subjective satisfaction, appropriate timing, adequate duration, high efficiency, and sustained alertness during waking hours.*

This definition seems to cover the same criteria as sleep quality and more, and includes subjective criteria as well. This makes it more difficult to measure, but also gives more valuable information when measured. Finally, the product designed following from this graduation project should contribute to good sleep health.

It should be realised that by objectively reviewing the quality of sleep and sharing the outcome with the reviewed individuals, their subjective satisfaction, i.e. attitude, could be influenced. This should be researched further.

Sleep is an active process that consists of several sleep cycles. Each cycle contains several stages that determine how deep an individual is asleep and the internal processes taking place during that time. Sleep patterns changes with age, which is important to consider for the design and confirms the need for a dynamic system. Sleep is regulated by two processes that together communicate to a person when it is time to sleep. Sleep quality can be determined subjectively and objectively. A review of objective sleep quality might influence the test subject's subjective satisfaction, this should be further researched.

B.3. INFLUENCES ON SLEEP

The previous chapters made clear what sleep is and why it is important to sleep. This chapter will go into the different factors that influence sleep.

Sleep is a primary life condition and essential for the functioning of the human body. It is related to many physiological, psychological and physical factors. Many of these have a bidirectional relationship, meaning that sleep affects these factors and these factors affect sleep. To get a grip on this complexity, a simplified model was created in figure 107 that shows the relation between sleep and other factors. An arrow indicates that one affects the other.

The environmental factors were discussed in chapter 3.2 and are highlighted in blue. The factors must be considered in the design because of their influence. However, controlling the environmental factors falls out of scope for this project and therefore they are treated as boundary conditions.

The physiological, psychological and physical factors are critical to understanding sleep. Therefore, the most important factors will be introduced here. However, many of these factors depend on behaviour, such as nutrition and physical exercise, or the environmental conditions and cannot be influenced by the sleep system. Factors that can be influenced are some health conditions some people suffer from. In the following chapter, the health conditions for which a new sleep system can have significant added value, are examined.

The sleep system can also influence sleep in other ways than through health conditions. These relevant influences are explained in chapter 3.1.

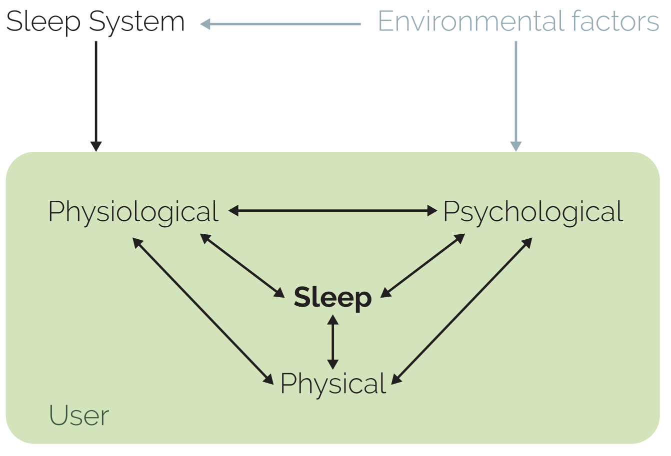


Figure 107 *The relations between sleep and different factors (by author)*

Physiological factors

The physiological process of sleep can also be influenced by other physiological factors, some of which are linked to physical factors present in the environment. Some have already been mentioned, such as bedroom environment (see chapter 3.2) and the sleeping proximity with possible bed partners (see chapter 3.5). But there are more relevant factors to consider, such as allergies, nutrition and medications.

Allergies

The most important sleep allergy is related to house dust mites. These small spiders (0.1 to 0.5 mm) populate mattresses, carpets, curtains and pillows in large quantities. These spiders degrade organic dirt (e.g. human skin peels) and produce the antigen heat-labile glycoprotein (Der P1). These faeces are easily respired, which may lead to asthma, coughing or irritated eyes. These mites prefer temperatures between 20° and 25°C and air humidity between 70 and 75%. Allergic symptoms decrease by keeping humidity below 55%, thorough sanitation, allergen-proof coating, 60°C machine washed top and using anti-microbial materials (e.g. copper) (Owen, Morganstern, Hepworth, & Woodcock, 1990; Haex, 2004).

There are also other relevant allergies in relation to sleep systems, such as the allergies for certain materials like natural latex, or allergies for chemicals present in some materials, such as treated wool.

Nutrition

Nutrition is of big influence. Some examples: Caffeine will affect sleep drive, but can also cause restlessness and anxieties. Carbohydrates and vitamin D are associated with better sleep and less awakenings. Eating carbohydrates in the evening can help to fall asleep, but during the lunch will increase sleepiness in the afternoon, which may be undesired. Drinking enough water is also important to prevent sleepiness during the day (Partinen, 2017).

Medications

Medications can be used to fall asleep. Taking sleeping pills is very common and many people depend on them to fall asleep. However, this is not without danger, as some of these drugs can be addictive or create physical dependence and should therefore only be used short-term (Neel, 2017).

Also, medications used against other disorders can sometimes have the negative side effect of impeding sleep or cause daytime drowsiness. This can problematic when no better alternatives are available (Harvard Health Publishing, 2010).

Psychological and physical factors

Psychological and physical factors also play an important role in affecting sleep. Sleep deprivation is associated with the perception people have of their health-related quality of life and their perceived physical and mental health (Paiva, Gaspar, & Matos, 2015).

Mental health

Mental health problems and sleep are often related. Mental problems can lead to bad sleep, but bad sleep can also cause mental illness. Anxieties, schizophrenia and depression are often related to sleeping problems.

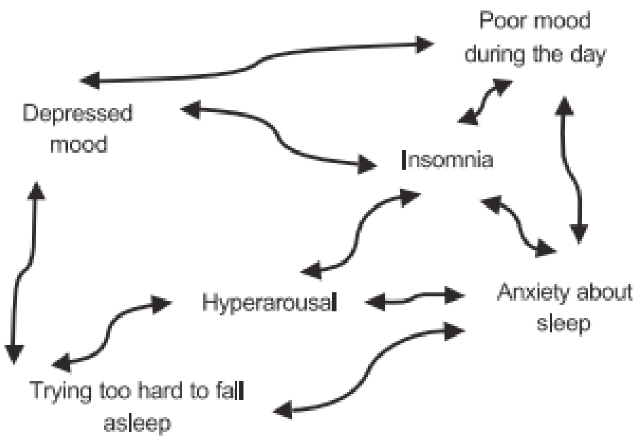


Figure 108 *Interactions between depression and insomnia (Billiard & Bentley, 2004)*

Stress can also lead to anxiety, which will make it more difficult to fall asleep, which can lead to more stress, causing a vicious cycle. Mood is also related to sleep and can worsen to become a depression or lead to anxieties as shown in figure 108 (Cancel, 2011; Billiard & Bentley, 2004).

Reducing stress or anxiety can be achieved through breathing and relaxation techniques, such as meditation and mindfulness. But also through calming music (Nilsson, Unosson, & Rawal, 2005) or certain colours in the room. In all examined cultures by Madden, Hewett & Roth (2000), the colours white, green and blue are considered calming. Painting a room in these colours could reduce stress.

Physical health

A poll in America by the National Sleep Foundation (2013) shows that exercise is related to good sleep. People who have more exercise sleep better and spend less time awake during the night. This same poll also shows that people associate less sitting with better sleep and overall health.

B.4. SLEEP DISORDERS & MEDICAL CONDITIONS

The previous chapters explained what sleep is, why it is important and which factors influence sleep. This chapter will look at one of these factors, namely the sleep disorders and medical conditions, and determine which ones are relevant to focus on. The following chapter will explain why these are relevant because of the influence the sleep system can have on these conditions.

Sleep disorders

Humans clearly need sleep, but sleeping is not that easy for everyone. Many different problems can occur. Several sleep associations worldwide together developed the International Classification of Sleep Disorders version 3 (ICSD-3), which was released in 2014 and is the most recent version to date (Thorpy, 2017). This classification contains seven major categories of sleep disorders:

Insomnia disorders

Insomnia can be defined as a complaint of a lack of sleep or of nonrestorative sleep. Symptoms are for example, difficulty falling asleep for at least three times a week. In case it lasts longer than three months, it will be diagnosed as a chronic disorder and otherwise as a short-term disorder (Thorpy, 2017; Spriggs, 2015).

Some sleep-related behaviour falls in the grey area between what is normal and abnormal sleep behaviour, these are referred to as isolated symptoms, normal variants or unresolved issues. The most applicable isolated symptoms, apparently normal variants, and unresolved issues for this category are: Excessive time in bed and short sleeper.

Sleep-related breathing disorders

Sleep-related breathing disorders include both types of sleep apnea (central and obstructive), sleep-related hypoventilation and sleep-related hypoxemia.

The most applicable isolated symptoms, apparently normal variants, and unresolved issues for this category are: Snoring and catathrenia (i.e. breath holding and expiratory groaning during sleep).

Apnea

During sleep, muscles surrounding the throat or base of the tongue relax, narrowing or closing the air passage. This can result in snoring. The greater the obstruction, the louder the noise. Sometimes, breathing can even stop, which is a sign of apnea. Two types of apnea can be distinguished: central and obstructive. Central sleep apnea is uncommon and is caused by the brain failing to send breathing signals. Obstructive sleep apnea (OSA) is very common and happens when air cannot flow into or out of the nose or mouth, despite continuing breathing efforts (Haex, 2004).

Sleep apnea may be associated with headaches, irregular heartbeat, high blood pressure, heart attack and stroke. Alcohol and sleeping pills may increase the duration and frequency of breathing pauses in people with sleep apnea. Changing sleeping position can help against OSA (see chapter 3.4).

Central disorders of hypersomnolence

Hypersomnolence is characterised by daytime sleepiness which is not caused by disturbed nocturnal sleep or misaligned circadian rhythms. This is sometimes accompanied with other symptoms, such as falling asleep at random moments, extreme muscle weakness while being conscious, or great difficulty being awakened from sleep. Causes vary from routinely spending not enough time in bed, medication, medical or psychiatric disorders, Kleine-Levin syndrome, or other causes (Thorpy, 2017; Spriggs, 2015).

The most applicable isolated symptom, apparently normal variant, and unresolved issue for this category is: Long sleeper.

Circadian rhythm sleep-wake disorders

Circadian rhythm sleep-wake disorders (CRSD) affect people's timing of sleep. Commonly, people fall asleep in the evening and wake up in the morning. For people with CRSD this can be difficult. Their rhythm can be delayed, advanced, irregular or not 24 hours long. This disorder also occurs in people with shift work or jet lags (Thorpy, 2017).

Parasomnias

Parasomnias are undesirable events or experiences that occur during entry into sleep, within sleep or during arousal from sleep. These are divided into three groups: NREM-related, REM-related and other parasomnias. Examples are: Sleepwalking, sleep terrors, nightmare, paralysis, hallucinations, and bedwetting (Thorpy, 2017).

The most applicable isolated symptom, apparently normal variant, and unresolved issue for this category is: Sleep talking.

Sleep-related movement disorders

Sleep-related movement disorders include several conditions where people make undesired movements before or during sleep. Common disorders include Restless Legs Syndrome (RLS), Periodic Limb Movement Disorders (PLMD), and sleep-related bruxism (i.e. teeth grinding during sleep) (Thorpy, 2017).

The most applicable isolated symptoms, apparently normal variants, and unresolved issues for this category are: Excessive fragmentary myoclonus (twitching, e.g. in the corners of the mouth), Hypnagogic foot tremor and alternating leg muscle activation (rhythmic foot or leg movements), and sleep starts (hypnic jerks).

Other sleep disorders

This category is meant for sleep-related disorders that cannot be fitted into any of the previously mentioned categories. The ICSD-3 does not list any sleep disorders in this category, but the ICSD-2 did list environmental sleep disorder here, which includes for example sleep disruption by a bed partner or due to environmental causes as mentioned in chapter 3.2 (Spriggs, 2015).

Bed-related disorders

All mentioned disorders have a relation to sleep, but not all can be directly linked to the sleep system. The possibility exists that an improved bed has positive effects on some of these disorders that are currently not associated with the sleep system, but this is uncertain and to base the design on this possibility would be a gamble. Therefore, the focus should be on disorders that have a clear relation with the used sleep system.

To know which disorders would belong in that category, a list of the presented sleep disorders was made and scored on whether a sleep system would be able to prevent, manage symptoms or even cure the disorder. As a result, it became clear that 'insomnia' had the biggest potential to be influenced with a sleep system. That is because there are occasions thinkable where the sleep system causes, manages symptoms of or might cure insomnia. whereas the sleep system would be limited to managing symptoms or not be relevant at all with other sleep disorders.

To determine which insomnia disorders can be influenced by the sleep system, insomnia was being zoomed into up to the level where it became clear which disorders would be relevant.

Insomnia can be divided into primary and comorbid types. The former is also referred to as insomnia syndrome and is treated as an independent disorder.

More prevalent however, is comorbid insomnia, which arises in context of another disorder, historically referred to as secondary insomnia (Medscape Neurology, 2009).

Primary insomnia is most often idiopathic (unknown aetiology), which means it will be impossible to make statements regarding the effectiveness of interfering in the sleep system. Therefore, the comorbid types of insomnia are targeted.

Comorbid insomnia can be caused by many different diseases and disorders, but the most relevant are back pain-related medical conditions because these can be influenced by the sleep system (Taylor et al., 2007). These conditions can be either chronic or acute. In the case they are acute conditions, it means that in some cases the sleep system can help in prevention or curing (e.g. with cases of low back pain or decubitus ulcers). With chronic conditions, the sleep system can help in symptom management. Some common conditions where the sleep system could contribute are rheumatoid arthritis (affects approximately 1% of the world population, Gibofksy, 2012), and fibromyalgia (prevalence rate of 1.3–4.7 % in the American general population, Vincent et al., 2013).

At this point it is not important to know every specific medical condition as it is likely that a system that can benefit users suffering from the mentioned conditions can also deal with similar conditions. It is also difficult to determine where most impact can be made because less than 20% of individuals with insomnia are correctly diagnosed and treated, which means the sleep disorders are poorly identified (Ohayon, 2011).

Sleep Disorder	Prevention	Symptom management	Cure
Insomnia	x	x	x
Primary Insomnia	?	?	?
Comorbid Insomnia	x	x	x
Psychiatric disorders			
Neurologic disorders			
Medications			
Medical conditions	x	x	x
Chronic Back Pain-related conditions		x	
Rheumatoid arthritis		x	
Fibromyalgia		x	
Facet Joint Osteoarthritis		x	
Degenerative disc disease		x	
Acute Back Pain-related conditions	x	x	x
Low Back Pain	x	x	x
Decubitus ulcers	x	x	x
Spinal Stenosis		x	
Isthmic spondylolisthesis		x	
Herniated lumbar disc		x	
Bursitis (hips)		x	
Other Medical conditions			
Breathing		x	
Hypersomnolence			
Circadian Rhythm			
Parasomnia		x	
Movement		x	
Other			

Figure 109 *Sleep disorders and the potential influence from a sleep system (by author)*

Back pain and sleep

Back pain-related medical conditions disturb sleep in many cases. According to the study by Alsaadi, McAuley, Hush, & Maher (2011), 58.9% of people with low back pain (LBP) reported that their back pain disturbed their sleep. This disturbed sleep likely complicates dealing with LBP, as these people visit the hospital more often than people suffering from LBP but without disturbed sleep. Also, because this sleep disturbance is highly prevalent among both acute and chronic low back pain patients, it is likely to occur early in the condition and not develop over time. In a study by O'Donoghue, Fox, Heneghan, & Hurley (2009), chronic low back pain (CLBP) participants also demonstrated poorer overall sleep, increased insomnia symptoms and less efficient sleep.

Pain and sleep have a bidirectional relationship; pain can cause sleep disturbance and sleep disturbance can increase pain. Alsaadi et al. (2011) mention: "Patients who reported disturbed sleep tended to report higher pain intensity than those without disturbed sleep." The disturbed sleep may however not directly follow from an increased pain intensity but due to psychological factors (e.g. depression or anxiety). These psychological factors are worsened by disturbed sleep, making it a complex situation to understand where to intervene. It is known that managing sleep disturbance can reduce the pain intensity for LBP, CLBP and rheumatoid arthritis (Alsaadi et al., 2011).

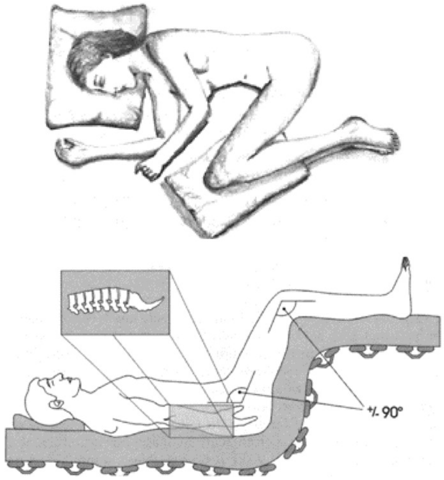


Figure 110 *Comfortable positions for people suffering from disk disruption (Haex, 2004)*

To illustrate how a dynamic bed can help in certain cases of LBP, an example from Haex (2004) for people suffering from disk disruption (e.g. herniated lumbar disc) is used: In lateral and supine position, it is possible to flatten the lumbar lordosis which can relief the pain for people suffering from disk disruption. These positions are not easy to maintain for a longer period, which is why Haex recommends using at least two different positions. For both lateral and supine position, the legs should be raised to obtain lumbar flattening. This will result in a close-to foetal position and a Fowler's position respectively (see figure 110).

In fact, this situation is where a dynamic sleep system can really thrive, because in current situations it is difficult and may be painful for patients to be moved. The sleep system can learn the best way to move the patient smoothly from one to the other position in the least painful way.

Concluding, an improved sleep system may lead to an indirect reduction of pain intensity by improving the sleeping conditions and to a direct reduction of pain by supporting more comfortable positions. In some cases, the sleep system might even contribute to the cure and in the best case even prevent medical conditions from occurring at all.

B.5. WHAT WE LEARN FROM HISTORY

The previous chapter explained what people look for when they buy a mattress and gave insights about certain market segments. The way in which these needs are addressed is by using technology. The first beds were very simple and made with few resources, while mattresses these days are often created with complex chemical processes that require a lot of knowledge. This chapter will show how technology progressed, what the state of the art is and what we can expect from the future and from this graduation project.

Beds from the past

The bed is a very old invention. The oldest mattress found is 77000 years old. Humans made the core from grasses and leafy plants and topped it off with leaves from a wild quince plant that repels insects. It was estimated to be a comfortable and long-lasting mattress (Owen, 2011).

Beds stayed like that for a long time, sometimes covered with animal skins and later evolved to a sack, usually woven out of cotton and stuffed with any soft material at hand, such as hay, straw, leaves, grain, husks, wool, cotton, animal hair, feathers or down. In some cultures, people slept on woven mats out of various plant fibres. For example, in Japan, people created tatami mats, which are still used today (mainly in temples) to cover floors (Sleep Satisfaction, 2017).

The first waterbeds were used in 3600 B.C. by the Persians, who filled goatskins with water, which they left to warm in the sun outside during the day to create a warm bed for the night (Sleep Satisfaction, 2017).

The first beds that were lifted off the ground date from 3100 B.C. in Egypt. This was done for hygiene, but also to symbolise social status. The higher up the bed, the more important the person. The highest elite people would have their beds decorated with jewels, gold and ebony. In Western cultures, it took much longer before beds were lifted off the ground. This became common throughout the Middle Ages, with mattress supports consisting of ropes or leather strips that had to be tightened every now and then. From this rose the expression of “sleep tight” (Sleep Satisfaction, 2017).

Very often, beds served multiple purposes because space was precious. Starting around the 14th century A.D., the bed started to

Figure 111 *History of the bed (part 1) (by author)*

become more of a status symbol in Western societies. Ornamented bedsteads and thick feather or down mattresses, dressed in fine linen and covered with fine woollen blankets, surrounded by curtains and very high from the ground. Those were the ultimate beds for the rich. They sometimes served whole other purposes besides sleep, for example to receive visitors, conduct business and eating meals (Sleep Satisfaction, 2017).

Cupboard beds were mainly used in the Netherlands during the 17th and 18th century, but also in parts of France and America. They were built-in and sometimes had curtains or doors that could be closed for privacy and warmth and to keep out drafts (Sleep Satisfaction, 2017).

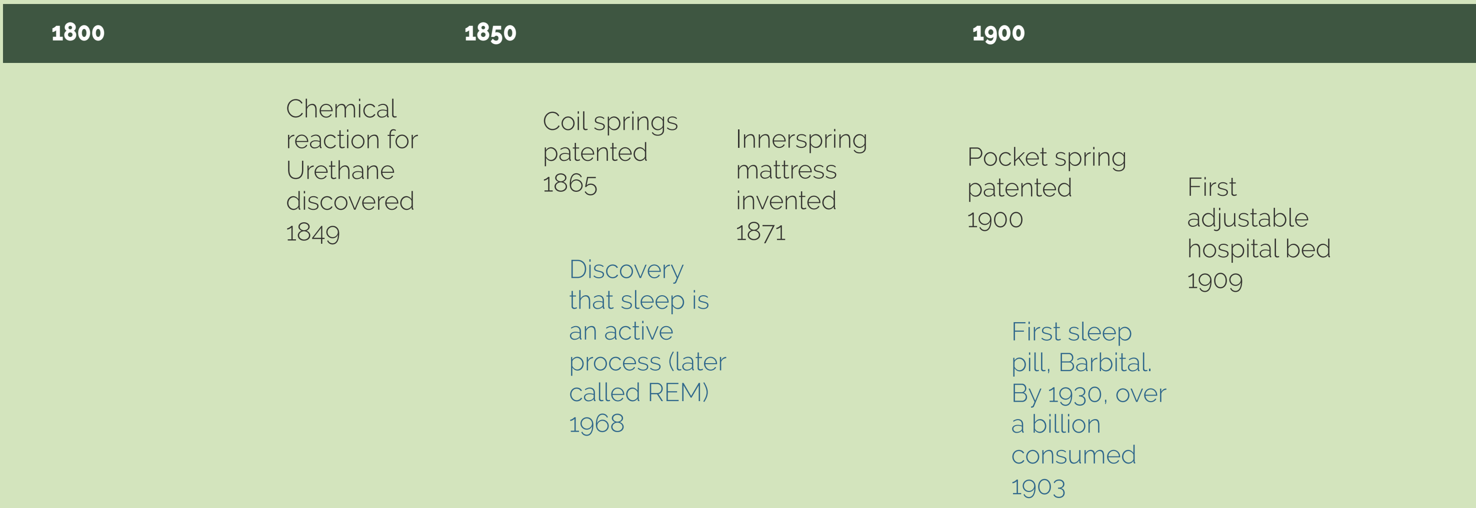
In the late 18th century, the first iron bed frames and cotton-filled mattresses were made. This was more hygienic than the wooden bed frames and more space-efficient (Sleep Satisfaction, 2017).

What becomes clear from history, is that the following aspects play an important role in the development of the bed:

- Hygiene
- Social status
- Warmth
- Space
- Privacy

Beds in recent times

In 1865, the coil spring was patented and used in an innerspring mattress in 1871. The start of the 20th century began with the invention of the pocket spring, by James Marshall, therefore also called Marshall springs. Then, in 1909, Willis Dew Gatch introduced



the first adjustable hospital bed, with three adjustable segments. Around 1929, the first latex mattress was made by Dunlopillo. These were very popular because of the natural, hypoallergenic and supportive material, but due to cut-off supply during the second World War, they became too expensive and people went back to sprung mattresses (Bensons for beds, 2016; Gatch bed, n.d.).

The next big change came in 1968, with the invention of the modern waterbed. After that, for twenty years these were extremely popular, especially in the United States, but not for the reason the inventor had hoped for. They became more of a sex symbol, and it was even marketed with slogans like “Two things are better on a waterbed. One of them is sleep” (Bensons for beds, 2016).

The waterbed was replaced by the rise of the memory foam mattresses, a foam developed by NASA. These mattresses are still popular today and have seen some minor innovations over the last years, such as gel top layers and multi-layered mattresses with different types of foam in every layer (Bensons for beds, 2016).

Today, all types of mattresses developed over the last hundred years are still sold and prices and margins have a great influence on what people buy. But different mattresses also offer different properties.

What can be learned from the developments of recent times, is that people will always seek for improvements. A division is made between timeless properties and trend-based properties.

The timeless properties are constantly improved according to knowledge on what is best. People would not want to go back to the hygiene of the first grass mattresses for example. But in some cases, these properties depend on personal preference (e.g. desired support depends on people’s perception of comfort). However, there is still a need for development of options and improving of these properties.

Culture-based properties on the contrary, depend on culture and trends. For example, size, shape and aesthetics change according to what people like. The properties that came with new technologies are divided into these categories and are shown in figure 113.

1950 **2000>**

Natural latex mattress invented 1929

Modern waterbed invented 1968

Airbeds introduced 1981

CPAP introduced for sleep apnea 1981

Memory foam mattress introduced 1992

Gel mattresses 2011

Octaspring mattresses 2011

Smart mattresses 2016

Figure 112 *History of the bed (part 2) (by author)*

Timeless

Desired property	Reason	Materials that meet needs
Temperature control (warm in winter, cold in summer)	Some mattresses are known to be hot (e.g. low-quality memory foam)	Gels, octaspring
Comfort	Reduction of pressure points and soft feel to the body	All materials can provide comfort, dependent on quality and people's
Hypoallergenic	Asthma and allergies in people are increasing (Maziak et al., 2003)	Natural latex
Spine support	Reduce back pains	All materials can provide support, dependent on quality
Forms to body	Reduce friction	Memory foam
Hygiene	Prevent pathogenic microorganisms and moist	Natural latex
Sound	Bed frames and especially spring systems can make noise during love making	All foams, latex, water
Support for love making	Preferences differ, but most requested properties are: responsive, bouncy, durable, rigid edge and comfort (Sleepopolis, 2017).	Mainly foams, but some prefer water or springs
Compatability with bed frame	Some bed frames offer alternative positions but not all matresses can match those (Amerisleep, 2017)	memory foam, latex
Changing bed (frame) shape	Has benefits for breathing, blood circulation, back pain, sleep apnea, snoring and non-medical reasons such as reading, watching or working on a screen.	Adjustable bed frames

Culture-based

Desired property	Reason
Size	For example: Small houses, trend of minimalism or some cultures demand space-efficient solutions.
Social status	The bed tells visitors something about the person, e.g. Wealth or certain values.
Aesthetics	Aesthetics are also important to feel at home.
Privacy	In some cultures sleeping together is common, while others want to have their private spot.

Figure 113 *Properties desired through recent times (by author)*

B.6. BUYING BEHAVIOUR

As the first three end-user groups are in most cases dependent on a business setting, buying behaviour is considered for the fourth group, the mass consumer market, to learn about user needs and values.

Currently, people spend a lot of time researching their mattress. According to an article by Julie A. Palm (2017), 49% takes more than a week before they decide (see figure 114). Ideally, there were not that many options to choose from, manufacturers and retailers could all be trusted and the consumer would end up with the right mattress. In reality, people spend a lot of time and still end up with the wrong mattress.

This becomes visible in a study by Hogan, Krystal, Edinger, Bieler and Mladsi (2011), who suggest that in an ordinary showroom experience, individuals are not led to select the mattress that leads to the best sleeping experience over an extended period. This is also supported by Palm who writes that comfort perception is the main driver for mattress purchases and for most consumers (89%) the most important feature. That means that when people test out different mattresses in a showroom, they buy the one that feels most comfortable at that moment, without knowing how it feels after weeks or months of sleep.

Individuals should buy a mattress that fits their needs. And because every individual has a different body and sleeping behaviour and different preferences, they need a different mattress firmness to match these (Bergholdt, Fabricius, & Bendix, 2008; Hogan et al., 2011).

Figure 114 *Time spent on mattress research (Palm, 2017)*

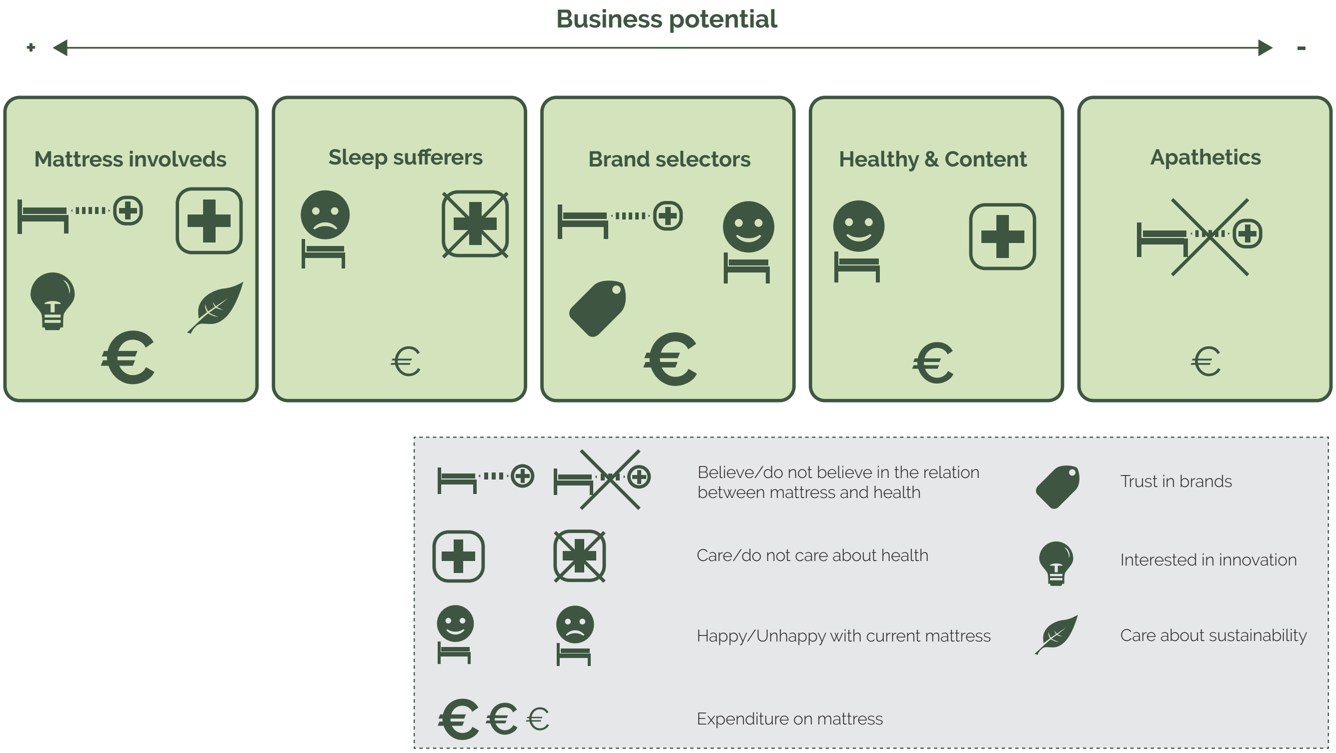


Figure 115 *Market segments, image by author, based on Bedtimes (2009)*

Mass consumer market segments

The same publication by Bedtimes (2009) distinguishes between five categories of mattress consumers which are summarised in figure 115. These different market segments from left to right have a decreasing market potential; mattress involveds have the highest potential and apathetics the least. Each type of consumer is summarised in the following paragrahps:

Mattress involveds: Highest business potential as they understand the relevance of a mattress for health and are highly engaged in the buying process. They do thorough research and care about health, innovation and sustainability. They replace their mattress most often while spending the most money on a mattress. These people are usually younger and have a high income.

Sleep sufferers: The second highest potential as they would benefit most from a mattress that can help them sleep. They are unhappy with their current mattress and have bad shopping experiences and are therefore afraid to spend a lot of money. When the mattress involveds are the early adopters, the sleep sufferers might follow as they trust the reviews of the mattress involveds. They need a mattress to alleviate pain or prevent pain. Usually, these people are middle-aged women with less education and lower incomes.

Brand selectors: Once the new mattress has become an established brand, brand selectors will follow and do not mind spending a lot of money as they see the relevance of a mattress for their health. They believe in brands and warranties and trust their current mattress, but also see the relevance of a mattress for their health.

Healthy & content: Low business potential because they do not recognise the need to replace their current mattress when sleep quality is poor and are content with the way things are. They do not care about technology or mattresses and are healthy in general. These people are most influenced in-store and by marketing and are usually 60 years or older with high educations.

Apathetics: Do not believe in the relation between mattress and health and do not want to spend money on a mattress, therefore they are least likely to be interested and are not targeted. They sleep easily and do not care about the buying process. These people are usually male and have a lower income.

High risk/low reward

In the same publication by Bedtimes (2009), the mattress market is categorised as "high-risk/low-reward". High-risk because the products are expensive and lock consumers into a time commitment, so consumers want the product to be right for them as the wrong choice would have major consequences. Low-reward because it is an essential, but not enjoyable purchase to make. Consumers look for ways to simplify and shorten the process.

The current categorisation for mattresses of being high-risk/low-reward products means that there lie opportunities in both directions, as shown below.

Lowering the risk

- Testing new business models, e.g. leasing systems, to lower the initial investments and change ownership to the manufacturer.
- Reducing the number of options, so that consumers will be less inclined to doubt and wonder if they made the right decision.
- Transparency about quality, manufacturers and prices.

Increasing the reward

- Add functionality to the mattress that can be experienced during active (non-sleep) hours.
- Make a mattress more fun or exciting.

Figure 116 *IKEA sleeping flashmob*

(obtained from https://i.ytimg.com/vi/6BPGdcZA5-I/maxresdefault.jpg)

B.7. SLEEP APPS & PRODUCTS

Besides looking at beds from the past and more recent times, it also important to look at the state of the art and realise what people buy today and current trends.

Sleep apps

There is a great number of apps for Android and iOS systems related to sleep (see figure 117). Some work together with smart watches to sense the heartbeat of the user, which allows for more accurate measuring of sleep stages. The apps serve some or multiple of the following purposes and some have extra features:

- Falling asleep: Usually achieved through playing or generating (nature) sounds or a voice over telling bed time stories or making meditative sounds. Other apps that help fall asleep reduce the blue light emitted from the screen, as this suppresses the release of the hormone melatonin which plays in essential role in the body's circadian clock.
- Sleep measuring: These apps measure the sleep cycles or even sleep stages. Some also record sleep talking, snoring, background noise and even make sounds to stop snoring.
- Waking up: Apps wake users up when they sleep light, based on the measurement of their sleep cycles. Usually waking is done through gentle (nature) sounds or with light. To keep users from going back to bed or snoozing, sometimes they are presented with a challenge that they must solve to silence the alarm, e.g. a physical exercise, puzzle to solve or scan a QR code in another room.
- Meditation: Some apps help with getting calm or in a relaxed state. This helps to fall asleep or to meditate. Usually, this is done through sounds or a voice over to listen to. There are also apps that achieve this through breathing patterns.
- Lucid dreaming: Some apps help people to accomplish a phenomenon called 'Lucid dreaming', which is a state in which people are aware that they are dreaming. These apps often work with coupling daytime reality checks to a certain sound, triggering a similar reality check during a person's sleep whenever the sound is played during the night. Because of this reality check during sleep, the person will realise to be dreaming.
- Personal training: Shows (yoga) exercises that help overcome insomnia or enables scheduled conversations with a professor who gives Cognitive Behavioural Therapy to help fall asleep.

Smartphone apps related to sleep

App name	Smart alarm	Sleep cycle/stages	Sleep quality	Heart rate	Extra's	Compatible devices
Sleep Cycle	x	x	x			iPhone
Sleep Cycle Power Nap	x	x			Sound generator	
Pillow	x	x	x	x	Sleep sound recordings, power nap mode	iPhone, Apple Watch
Sleep As Android	x	x		x	Wake up and Fall asleep nature sounds, morning wake-up puzzles, Sleep talk, room noise and snore recording, anti-snoring sounds	Android, Smart wear, Philips wake-up light
Autosleep	x	x	x			iPhone, Apple Watch
Sleep Time+	x	x	x			iPhone, Android
Twilight					Adapting screen LED colours, reducing the blue light at nighttime	iPhone, Android
Sleep					Sound generator, large sound library, fall asleep and wake-up with sound	iPhone
Noisli					Fall asleep sounds	iPhone, Android
Pzizz					Fall asleep sounds	iPhone, Android
White Noise					Fall asleep sounds	iPhone
Sleep Genius	x	x			Fall asleep and wake-up sounds, relaxation and power nap sounds	iPhone, Android
Digipill					Sounds and meditation voice to help fall asleep	iPhone, Android
Sleep Well Hypnosis					Sounds and meditation voice to help fall asleep	iPhone, Android
Lucid Dreamer		x			Help achieve a lucid dreaming state through audio and visuals	iPhone, Android
F.lux					Adjusts colour of screen	iPhone, Android
Sleepio					Personal sessions with a professor to improve sleep based on CBT	iPhone
Yoga for insomnia					Shows yoga exercises to overcome insomnia	iPhone, Android
Universal breathing - Pranayama					Guide to meditative breathing	Android
Sleepmaker Rain					Rain sounds to fall asleep	Android
Spin me Alarm clock					Turn off alarm by spinning around	iPhone, Android
Sunriser					Wakes you up at local sunrise time	iPhone

Figure 117 *Smartphone apps related to sleep (by author)*

Sleep products

Besides apps, there is an increasing number of smart products related to sleep:

a. Somnox, a breathing robot

(image obtained from www.somnox.nl/features/)

Pillows (figure 118)

- Somnox (a): A sleep robot pillow that has a relaxing breathing rhythm and helps induce sleep.
- Moona (b): A crowdfunding campaign on the website kickstarter.com about a pillow that allows for temperature control.
- Chrona (c): A pillow insert that tracks sleep and plays low-frequency sounds that should stimulate deep sleep. It also has smart wake-up technology and is connected to the smartphone.

b. Moona, a temperature controlled pillow

(image obtained from www.kickstarter.com/projects/276774983/moona-smart-pillow-temperature-regulation-to-impro)

c. Chrona, a smart pillow insert

(image obtained from www.kickstarter.com/projects/ultradia/chrona-sleep-smarter-not-longer)

Figure 118 *Smart pillows*

Mattress cover (figure 119)

- EIGHT Sleep Tracker & Smart Bed Cover: A crowd-funding campaign on the website Indiegogo.com about a mattress cover that tracks sleep, warms up the bed and connects to other products (IoT).

Figure 119 *EIGHT, a smart mattress cover*

(image obtained from www.indiegogo.com/projects/eight-sleep-tracker-smart-bed-cover#/)

Bed sheets (figure 120)

- Modern Zinc (a): Zinc-infused bed sheets on which the company claims that they provide skin care, possess antibacterial properties and inhibit odors.
- 29 Linens (b): Copper-infused bed sheets on which the company claims that they are antibacterial. Run successful crowdfunding campaigns on both Indiegogo and Kickstarter.

a. Modern Zinc, zinc-infused bed sheet
(image obtained from www.modernzinc.com/pages/fabric)

b. 29 Linens, copper-infused bed sheets
(image obtained from www.ippinka.com/blog/29-linens-copper-infused-bedding/)

Figure 120 *Smart bed sheets*

Duvet (figure 121)

- Smartduvet Breeze: A duvet that has both heating and cooling temperature control and automatically makes the bed. The duvet can be controlled remotely by a smartphone.

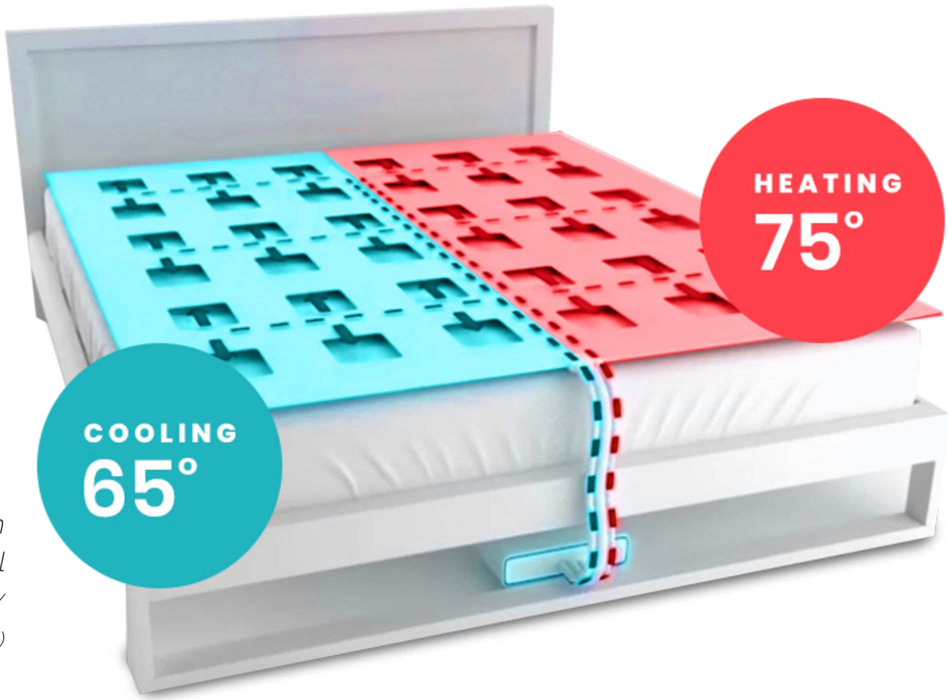


Figure 121 *Smartduvet Breeze with temperature control*
(image obtained from www.smartduvet.com/features/)

Other bedroom innovations (figure 122)

- NightBalance (a): A device that prevents people to sleep in the supine position, which is relevant for people suffering from certain types of obstructive sleep apnea.
- SNOO (b): A baby bed that can soothe and gently rock a baby to sleep, using white noise combined with motion. The bed also allows to fixate the baby flat on his back.
- Philips Wake-up light (c): Simulates a natural sunrise and sunset and has integrated breathing control exercises called RelaxBreathe.

a. NightBalance, against sleep apnea
(image obtained from www.nightbalance.com)

b. SNOO, a smart baby bed
(image obtained from www.happiestbaby.com/pages/snoo)

c. Philips Wake-up Light
(image obtained from www.philips.nl/c-p/HF3650_01/somneo-sleep-wake-up-light-met-relaxbreathe-om-te-gaan-slapen)

Figure 122 *Other bedroom innovations*

B.8. MATTRESS TYPE SEX COMPARISON

This image was obtained from Sleeplikethedead (2017).

Mattress Type Sex Comparison

	Inner Spring	Memory Foam	Hybrid	Foam	Air	Latex	Water
Easy To Move On	A-	D	C-	B-	B	C+	C-
Bouncy	A-	D	C-	C+	C+	B	D-
Comfortable	D+	B-	A-	B	C+	B+	C
No Bottoming Out	B-	B-	A-	C-	C-	B	D+
Allows Discretion	C-	A	B	B-	D+	B+	B-
Durable	D+	A-	C+	B+	D+	A-	B-
Position Variety	B-	C-	A-	C+	C	B-	D+
Whole Bed Suitable	C+	C-	B+	C-	D+	B-	D+
Allows Fast Climax	B-	B	B-	C+	C	C+	C-
Fluid, Stain Cleanup	D	D	D	D	B	C	A-
Overall Rating*	B-	C	B-	C+	C	B-	C

* Determined by averaging the above ratings.

Figure 123 *Comparison of bed types for having sexual activites (by Sleeplikethedead, 2017)*

B.9. LIST OF REQUIREMENTS

List of Requirements (Conceptual bed)

#	W/D/O	Description	Source
1		**Health**	
1.1	W	Should prevent, manage or cure users' back pain-related disorders.	# Sleep disorders & Medical conditions
1.2	W	Should allow to painlessly move people suffering from back pain-related disorders.	# Sleep disorders & Medical conditions
1.3	W	Should minimise shear forces to the skin.	# Bedroom environment
1.4	W	Should prevent bacteria and mildew formation.	# Bedroom environment
1.5	D	Use of materials known to commonly cause allergies must be avoided.	# Influences on sleep
2		**Sleep and comfort**	
2.1	D	Should optimise the contact surface to enhance sleep.	# Influences on sleep
2.2	D	Should maximise contact area without restricting movement.	# Sleep positions
2.3	D	Smell may not disturb or negatively influence respiration.	# Bedroom environment
2.4	W	Should not require the use of media (e.g. mobile phone) after the lights are out.	# Bedroom environment
2.5	W	Should optimise temperature to enhance sleep.	# Bedroom environment
2.6	D	Minimise noises caused by different types of usage.	# What we learn from history
2.7	W	Should allow for different bed sizes.	# What we learn from history
2.8	W	Should learn about the user's physical pain areas.	# Sleep disorders & Medical conditions
2.9	D	Should sense and judge the user's sleep quality.	# Understanding sleep
3		**Ergonomics**	
3.1	D	Should support and facilitate a user's desired position.	# Sleep positions
3.2	D	Should enhance users' spinal alignment.	# Sleep positions
3.3	W	Should allow for precise control of the users' position.	# Sleep positions
3.4	D	The controlled position should allow for the spine to relax.	# Sleep positions
3.5	W	The height of the head support should be controlled based on the users' position.	# Sleep positions
3.6	W	The sleep system should learn about the users' musculoskeletal structure.	# Sleep positions
3.7	D	Should prevent the user from lying still for too long.	# Sleep positions
3.8	W	Should prevent the user from moving too often.	# Sleep positions
3.9	D	Should sense and judge the user's body position and spinal alignment.	# Sleep positions

4	**Aesthetics**	
4.1 W	Use colours white, green and blue.	# Bedroom environment
4.2 W	Must convey reliability.	# Buying behaviour
4.3 D	Must look comfortable.	# Buying behaviour
5	**Technical**	
5.1 W	Minimise Electromagnetic fields (EMF).	# Bedroom environment
5.2 D	During sleep, the user may not be disturbed by sounds from the sleep system.	# Bedroom environment
5.3 D	Ventilation must allow for transporation of body fluids.	# Bedroom environment
5.4 W	Reduce the number of parts required in a sleep system.	# sleep system, # Consumer needs & Values
5.5 W	Should allow for sleep onset temperature control.	# Bedroom environment
5.6 D	Use long wavelength light (~550 nm) in a dark room for interfaces.	# Bedroom environment
6	**Safety & Durability**	
6.1 D	Should endure lying, sitting and moving bed interactions.	# Uses for a sleep system
6.2 W	The bed should allow multiple people using the bed simultaneously.	# Sleep proximity
6.3 D	The bed must recognise infants co-sleeping in the bed and cause them no harm.	# Sleep proximity
6.4 D	Must recognise pets using the bed and cause them no harm.	# Sleep proximity
6.5 D	Must be easy to keep hygienic.	# What we learn from history
6.6 D	Should keep its spine support and comfort qualities over time.	# Consumer needs & Values
6.7 D	Should last for at least ten years.	# Consumer needs & Values
7	**Sustainability**	
7.1 W	Materials are fully recyclable.	# Sustainability
7.2 D	Must be designed for reparability and disassembly.	# Sustainability
8	**Emotional**	
8.1 W	Should provide hope for sleep sufferers.	# Consumer needs & Values
8.2 W	Should be entertaining and fun.	# Consumer needs & Values
8.3 W	Should relieve users' stress for feeling responsible for correct sleeping behaviour.	# Consumer needs & Values
8.4 W	Should allow the user control and variety in options.	# Consumer needs & Values

9 Opportunities

9.01 O	Aromatherapy can be incorporated into the sleep system.	# Bedroom environment
9.02 O	Using sound or music to reduce sleep onset latency.	# Bedroom environment
9.03 O	Using audio to consolidate memories.	# Bedroom environment
9.04 O	Incorporate light alarm to adjust circadian clock to artificial environment.	# Bedroom environment
9.05 O	Could be adjustable to preferences for performing sexual activities.	# Uses for a sleep system
9.06 O	Incorporate features for an optimal meditation environment.	# Uses for a sleep system
9.07 O	The sleep system could teach people to sleep in the 30-degree Fowler's position for certain health benefits.	# Sleep positions
9.08 O	The sleep system could be adjusted for improved co-sleeping experience.	# Sleep proximity
9.09 O	The sleep system could give suggestions on how to improve the sleep schedule.	# Understanding sleep
9.1 O	Incorporate breathing and relaxation exercises and support to reduce stress and optimise mood.	# Influences on sleep
9.11 O	Help people suffering from OSA take better sleep positions.	# Sleep disorders & Medical conditions
9.12 O	Make a sleep system more fun or exciting.	# Buying behaviour
9.13 O	Change the traditional business model.	# Buying behaviour
9.14 O	Customise the appereance of the bed for different cultures and preferences.	# What we learn from history
9.15 O	Incorporate smart alarams, sleep trackers and other smart functions.	# State of the art, # Consumer needs & Values

B.10. FUNCTIONS, NEEDS & VALUES

The artefact created by the designer to interfere in the existing state of reality should answer to functions desired by the envisioned user. It is important to understand where these desired functions come from. As shown in figure 124, Roozenburg & Eekels (1998) differentiate between product planning and product design. The 'desired functions' creates the link between the two and is also the core of the design problem.

To properly define the desired functions, needs and values should be known. Roozenburg & Eekels also introduced a model that shows more of the complexity related to finding needs and values, as shown in figure 125.

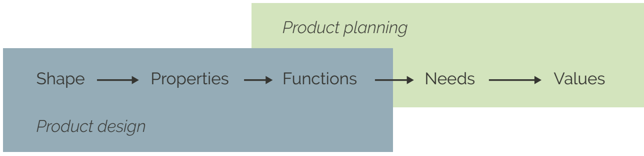


Figure 124 *Function as link between product planning and product design (image translated from Roozenburg & Eekels, 1998)*

However, only user and manufacturer are included which means that the model still misses out on other important stakeholders. To get a more complete picture, the author introduces a new model based on Roozenburg & Eekels (1998), as shown in figure 126.

This model incorporates values and needs from company/designer (assuming they cooperate), manufacturer, customer and user. There could also be multiple users, for example when a hotel buys a mattress, both cleaners and hotel guests are users of the mattress, but both have different needs. All these stakeholders' values are subject to cultural and societal values, which also influence the specific product needs and can determine the success or failure of a company. The stakeholders mentioned in the model all influence the desired functions and therefore the properties and shape of the design.

Desired functions that follow from this model could for example be technological, socio-economic or emotional functions. Following, a summary is given on the values and needs for the different stakeholders mentioned:

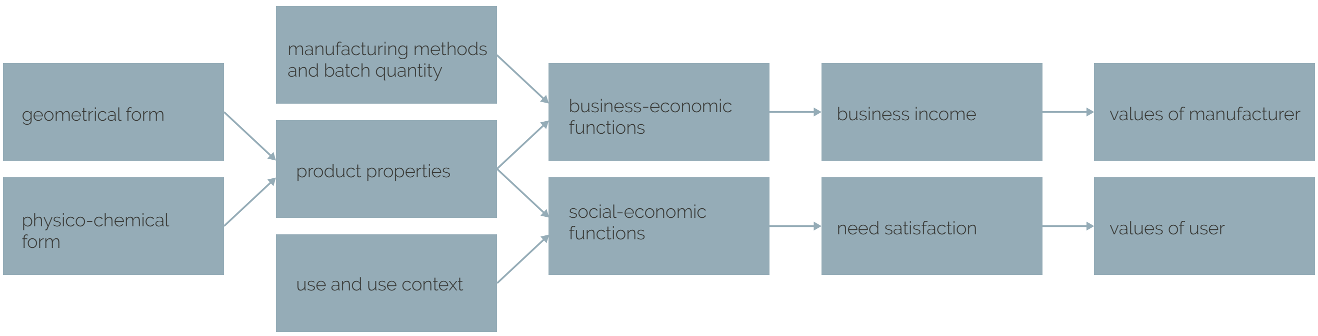


Figure 125 *Double-functioning of a product (image translated from Roozenburg & Eekels, 1998)*

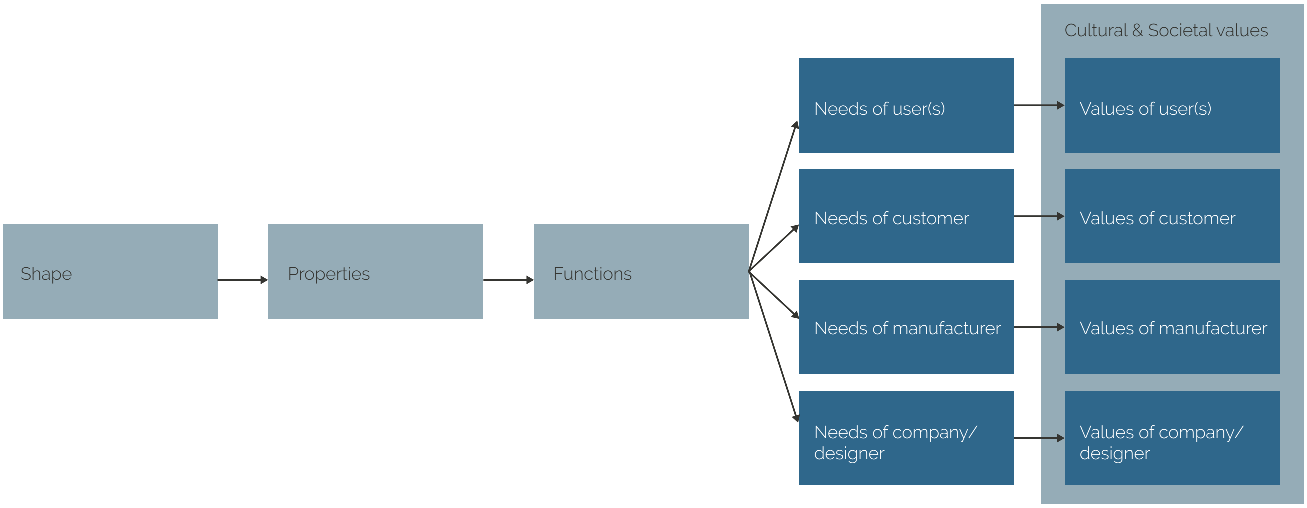


Figure 126 *Values and needs of important stakeholders for function determination (model by author based on a model by Roozenburg & Eekels, 1998)*

User

In the last chapter, user needs and values were determined. A summary of the values with accompanying needs is:

Comfort	Wellness, Therapeutic value, Simplifies, Avoids hassles, Sensory appeal
Confidence	Provides hope, Wellness, Therapeutic value, Quality
Curiosity	Fun/entertainment, Variety, Sensory appeal
Enjoyment	Design/aesthetics, Wellness, Fun/entertainment, Variety, Sensory appeal
Control	Variety, Informs

Customer

As the user is unknown, also the customer is unknown. But obviously, if the mass consumer market is targeted, the customer and user are one and the same.
In chapter 8, several potentially interesting market segments are mentioned. However, going deeply into specific customer values and needs is out of the project's scope, only some general needs are mentioned that are applicable to most potential customers:

- Price: Customers are concerned with price as public-sector customers have limited budgets and commercial customers want to maximise their own profits.
- Safety: The customer will be held accountable for any failures of the products they distribute, which could lead to expensive lawsuits.
- Reputation: A customer puts their own reputation on the line by distributing a product and will prefer thorough user testing, a track-record of the company/designer or other types of insurances that the product will function and deliver as promised.

Manufacturer

Manufacturers also have their values and needs. For example: Some are more expensive because they want to deliver the best quality or focus on more expensive sustainable materials. But often, values of the other stakeholders are more important as they influence the choice for working with a certain manufacturer. Although this does not always work, for example in a niche market where the options of manufacturers are limited. But as this design project is still in a premature stage, the values of the manufacturer are not taken into consideration.

Company/Designer

In this project, the company, designer and author are one and the same person, because the designer will potentially start up the company. Therefore, his values and needs are mentioned here, to explain the motivation behind the project and for the reader to understand how his values and needs influence the design choices made.

For this self-analysis, an external test, called the MBTI test (NERIS Analytics Limited, 2017), was completed three times over a year time to determine the personality of the designer and with it, his core values. To verify this analysis, the designer himself and several people close to him were asked if they could confirm this image. This led to the following personality, which seems accurate and describes the personality of the designer well: “The Advocate”, as described by NERIS Analytics Limited (2017).

This personality type has the following values:

- Fix the core of the problem
- Balance
- Authenticity
- Honesty
- Meaningful Work
- Community Service

Following from these values are the following needs for the company and the product design:

Company

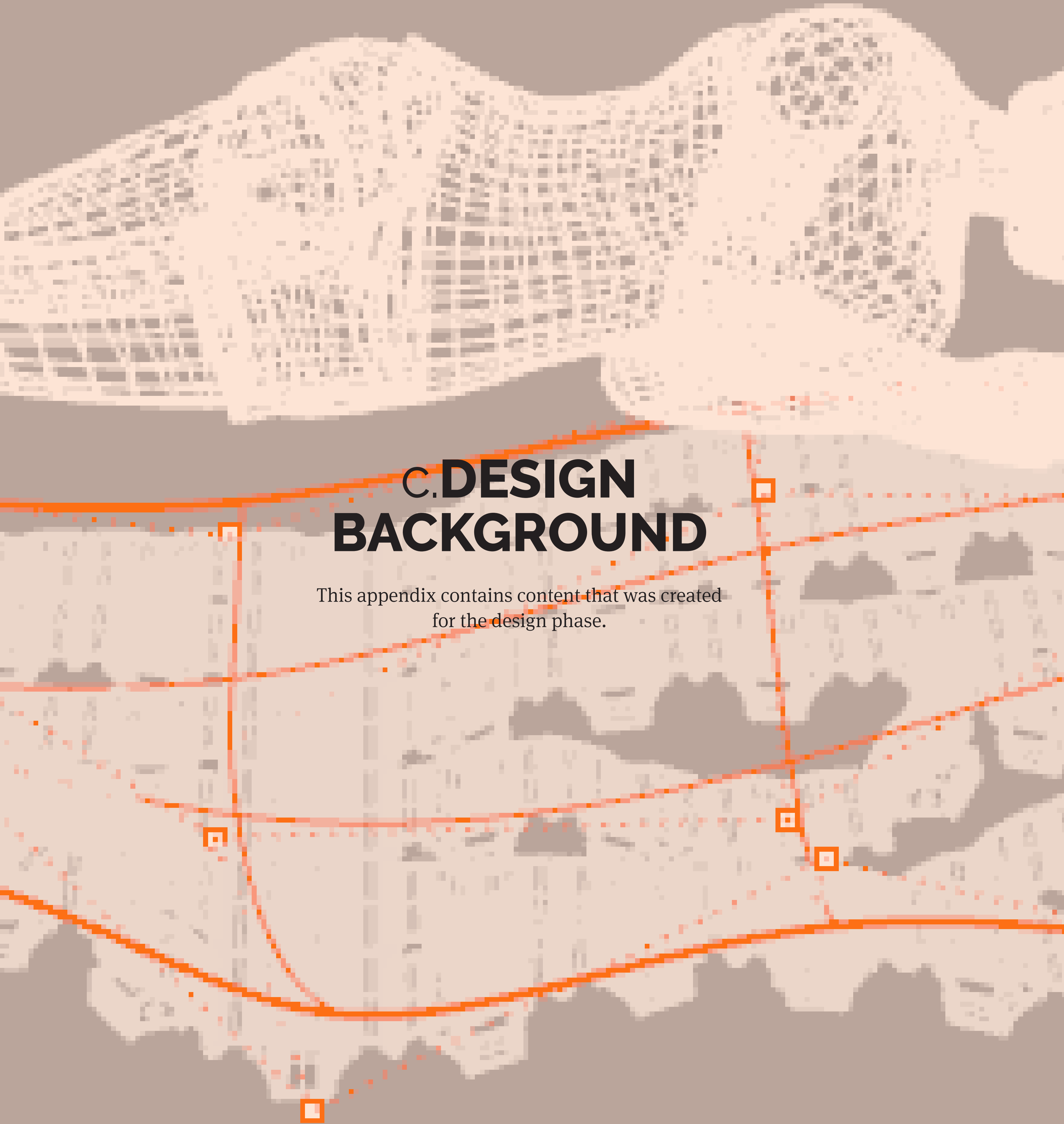
- Transparency
- Cooperation
- Strong vision

Design

- Quality
- Meaning
- Sustainable
- Healthy

These needs form soft boundaries to the design solution space (see figure 127), as it would go against the designer’s vision to act outside of these boundaries. Of course, a designer can create something for another person’s needs, but his design motivation will likely be low if the design is too far off from his personal values. For example, strong marketing driven strategy or trend-based design are not likely to form the base for this design, although some users are interested in fun ‘irrelevant and gimmicky’ features.

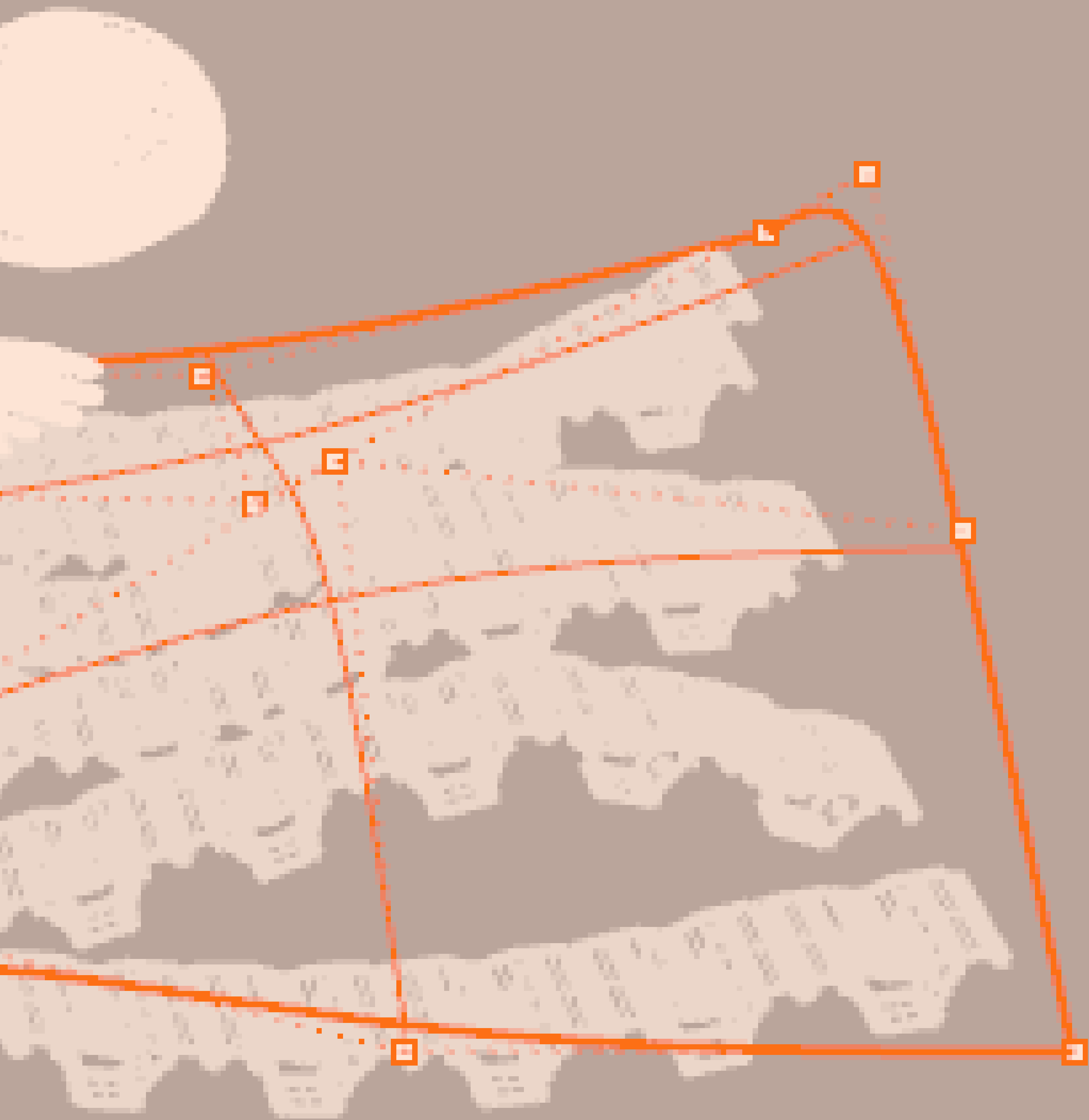
Figure 127 *Solution space based on designer’s needs (by author)*



C.DESIGN BACKGROUND

This appendix contains content that was created for the design phase.

Photo from rawpixel.com



C.1. MATERIALS

To determine which materials to use, it is helpful to look at existing and comparable products. In this case, existing sleep systems and inflatables have been researched.

Common materials

The most used materials for mattresses in the Western world are foam mattresses (e.g. Polyurethane), latex mattresses (e.g. synthetic latex), spring mattresses (e.g. pocket springs) and fluid-based beds (e.g. waterbeds). In other parts of the world, other fillings are used, for example cotton, kapok or straw (Haex, 2004).

Because the design solution will be sought in Soft Robotics, fluid-based beds are the closest thing and are therefore carefully examined, to see benefits and disadvantages from this technique.

Fluid-based beds

To minimise pressure and shear forces, the contact area must be as large as possible. Too firm mattresses do not distribute body weight homogeneously which reduces contact pressure. Some fluid-based beds are good at distributing weight. Alternating pressure (anti-decubitus) mattresses used in hospitals are an example of this. But standard waterbeds (contrary to what manufacturers say), are not necessarily better in distributing pressure compared to standard foam or latex mattresses (Haex, 2004).

The downside of pressure relieving mattresses in general is that they do not necessarily support the spine correctly; places where weight is concentrated sink deeper into the mattress and cause other places to rise, which results in sagging (see figure 128). And this sagging will also limit mobility. Water oscillations will also obstruct stability in case only one fluid chamber is employed. To improve these qualities, combinations with other materials are often made, for example by adding foam elements to waterbeds. Also wave motion minimising waterbeds exist, and heating options are sometimes available to speed up the relaxation. Also, top layers are often added to deal with ventilation as waterbeds are impermeable and generate higher temperatures and humidity compared to other mattresses (Haex, 2004).

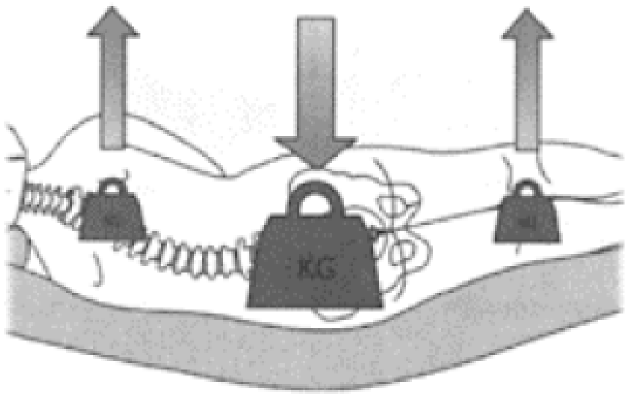


Figure 128 *Example of sagging*

image obtained from Haex (2004)

Material properties

Mechanical requirements differ per person. Heavier people need firmer mattresses, to prevent the pelvic girdle to sink too deep into the mattress. The material elasticity should guarantee a correct support of the human body, hysteresis should be minimized to avoid exaggerated energy consumption while moving, and material density mainly affects fatigue resistance of the mattress itself (Haex, 2004)

In this chapter, the different material properties and their relation to the sleep system properties and finally to the ergonomic properties will be explained.

Young's modulus

The Young's modulus (i.e. elastic modulus) of a material is the relation between the stress and strain in a material. The more force is required to reach a certain indentation, the firmer the mattress is. The difference between a firm and a soft polyurethane mattress is visualised in figure 129 (Haex, 2004).

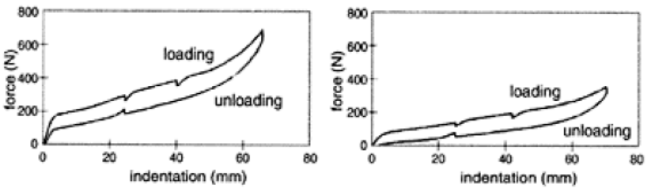


Figure 129 *Elasticity curves for a firm (left) and soft (right) polyurethane mattress*

image obtained from Haex (2004)

In a purely elastic material (ideal spring), the stress/strain relation is linear and no energy is lost. However, polyurethane can range from highly elastic to viscoelastic material. When it has viscoelastic properties, it means that this material combines elasticity and viscosity (viscous flow) and is significantly influenced by the rate of straining or stressing; e.g., the longer the time to reach the final value of stress at a constant rate of stressing, the larger is the corresponding strain. Because of the importance of time for the behaviour of viscoelastic materials, they are also called time-dependent materials (Findley & Davis, 2013; Haex, 2004).

Elastic hysteresis

An important property of foams is elastic hysteresis. This hysteresis is the energy absorbed by the material during loading. This is seen in the lag in response of the strain upon a change of the stress applied on a body. When a force is applied on such a material, more energy is required to achieve a certain strain due to internal friction than to recover the original strain when the force is removed. This excess energy is dissipated as heat. The area between the load and relaxation curve in figure 130, determines the hysteresis. The hysteresis in a mattress should be minimised to avoid exaggerated energy consumption while moving. Memory foam for example has a very large hysteresis (Haex, 2004).

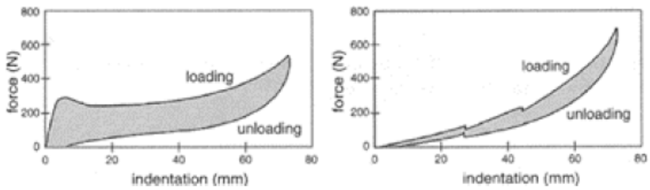


Figure 130 *Hysteresis for a viscoelastic foam mattress (left) and latex mattress (right)*

image obtained from Haex (2004)

Fatigue resistance

In terms of durability, the fatigue resistance of a foam mattress is an important property. Fatigue resistance depends on the density and resilience; a higher density means a higher fatigue resistance but is usually also related to the stiffness of the material, which is not always desired. The resilience of a material refers to its ability to spring back into shape. The more resilient the material, the more energy is recovered when unloaded (see figure 130). Highly resilient foams (HR foams) are designed to show this spring back behaviour and ensure to stay in shape for years. Despite their relative low density (ranging from 28 kg/m3 up to 37 kg/m3) they have a good resistance to fatigue and good elastic properties (Haex, 2004).

C.2. INITIAL CALCULATIONS

The design of the bed requires a lot of free movement. However, this creates large forces on the ends of the bed. This chapter calculates what forces the bed has to deal with and what this means for the material and air pressure.

As marked orange in figure 132, most positions have an overlap in the middle where the bed surface can be kept in the same position. This means that this surface area can be connected to a foot hat stands on the ground, as shown in figure 133.

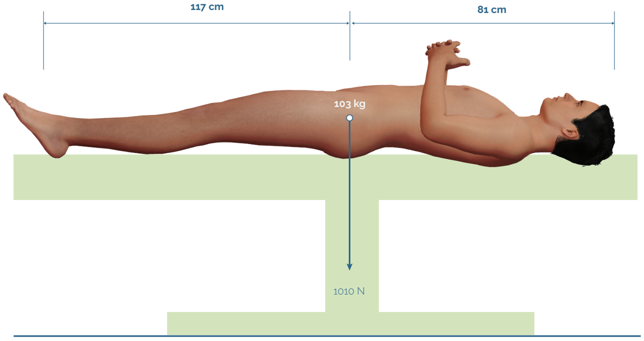


Figure 131 *Body's centre of mass (by author)*

The positions in figure 132 with the green outline do not share this overlap, but are also rare positions, mainly used for medical purposes. If the desired angle of rotation is not too big, these positions can still be achieved through small displacements.

Fortunately, the orange area is also approximately where the body's centre mass is located (see figure 134). This is another good reason to connect this part of the bed to the foot, as it will prevent the bed tilting as result of a moment on one of both sides.

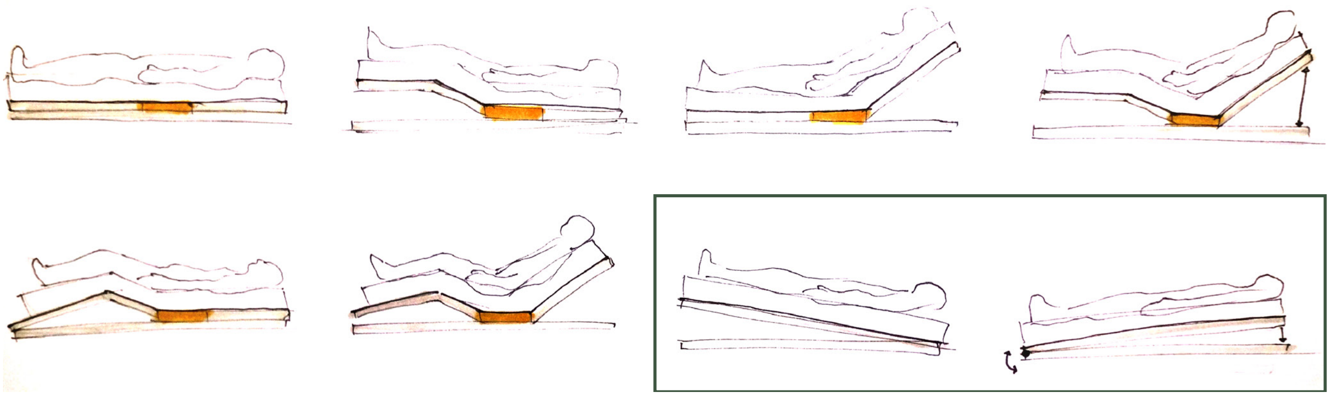


Figure 132 *Several positions desired from the sleep system (by author)*

When connected to the ground as shown in figure 133, the dimensions of the foot influence the moment created by the user. The smaller the dimensions, the more freedom the bed surface has to move and adjust. To find the optimal dimensions, calculations were made using the most extreme moment during normal use, which is created when the bed is in a flat position.

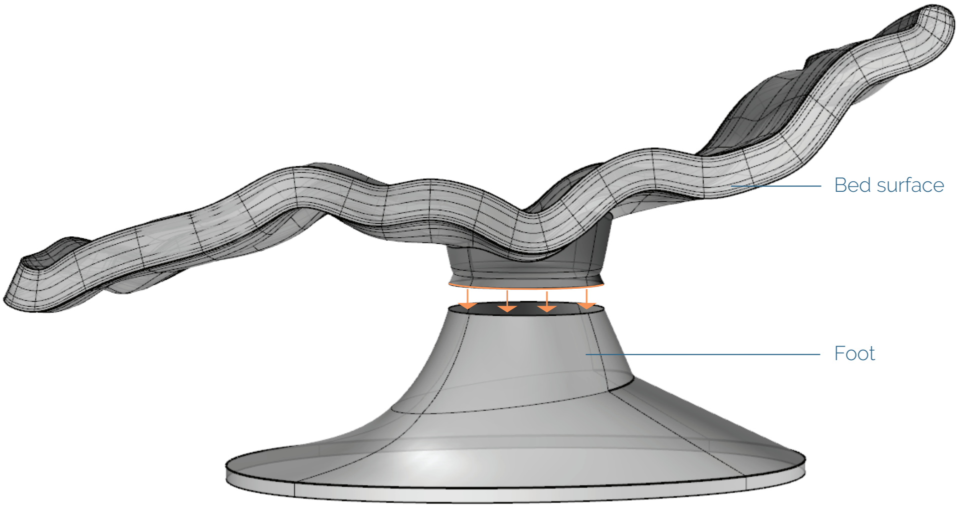


Figure 133 *Connection to the ground (by author)*

Stresses

For ease of calculation, the body is divided into five segments (see figure 134) and the assumption is made that each segment's mass is equally divided over the absolute length of these segments. The total body mass used is of subject B (from figure 35) and the total length of subject A. The mass distribution and length distribution per body segment was calculated with data retrieved from Harless by Drillis, Contini and Bluestein (1969)..

The lower trunk's centre mass almost perfectly aligns with the calculated total body's centre mass. Therefore, in the calculation, the lower trunk's length was used as the initial dimension for the foot.

The data used is that of the measurements of the tallest subject from Harless. The subject was 173 cm tall, which means that the subject used for this calculation (193 cm) is much taller and might have different proportions.

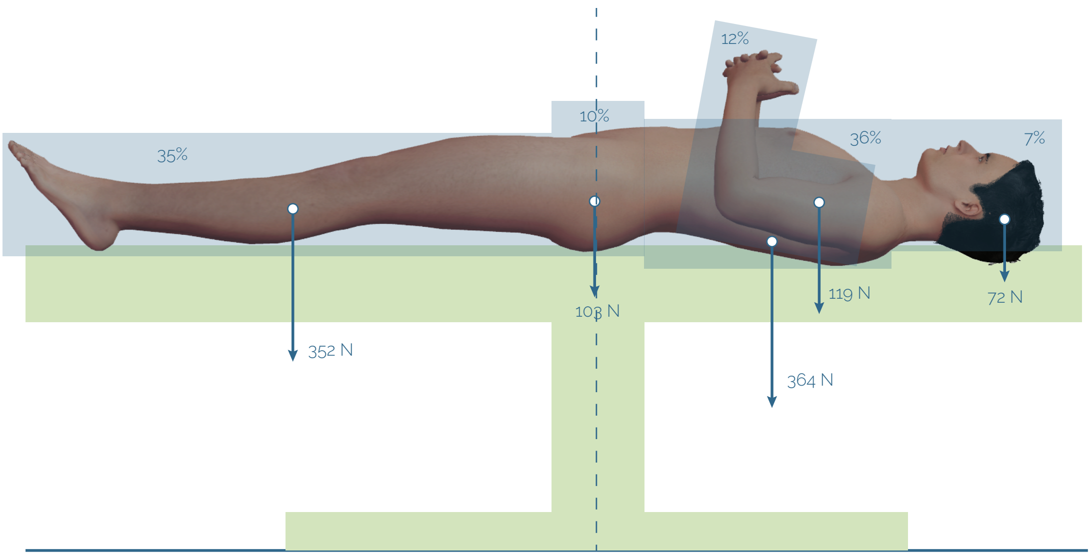


Figure 134 *Centre mass of different body areas (by author)*

This is considered for the final safety requirements by including a safety factor of 1.5. For the calculations, the arms were rested on the chest, and the mass centre of the upper arm was used for the total mass of both upper extremities. Because the right side got more mass than the left side, this one was chosen to use for calculations.

Unfortunately, the absolute segment's lengths of Harless' data do not add up to the whole body's length. In this situation, that leaves a length of 5.41 cm which is not appointed to a body part. Therefore, the full body mass was distributed over the known lengths. By doing so, the lengths of the combined loads are longer than the upper body with some space left in-between these loads. This space in-between was removed to create a more realistic load. This load was used to create a shear and moment diagram, see figure 135.

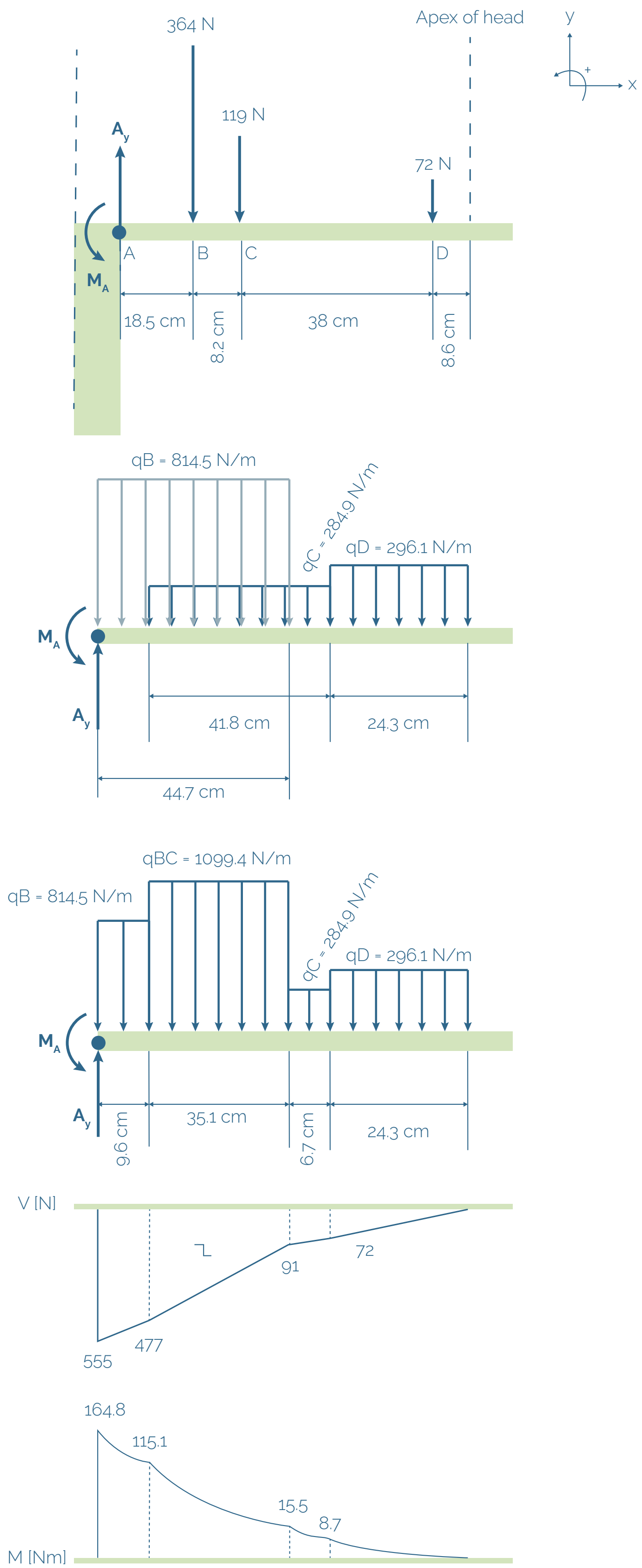


Figure 135 *Distributed load and moment and shear diagram (by author)*

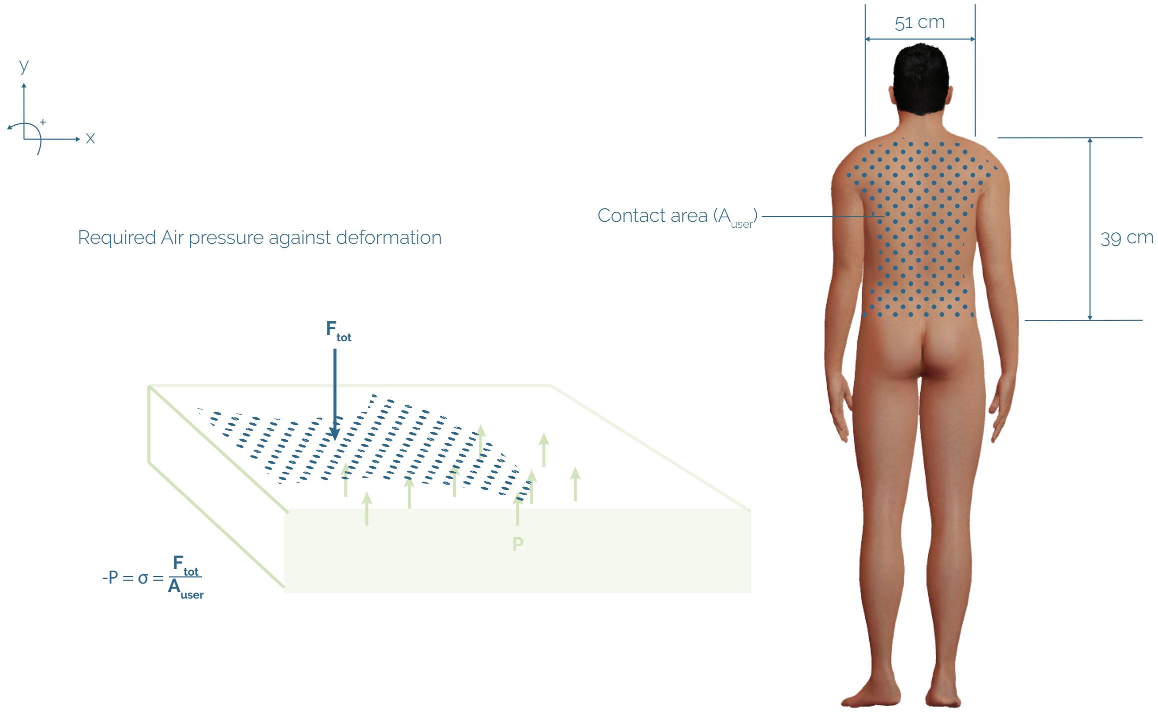
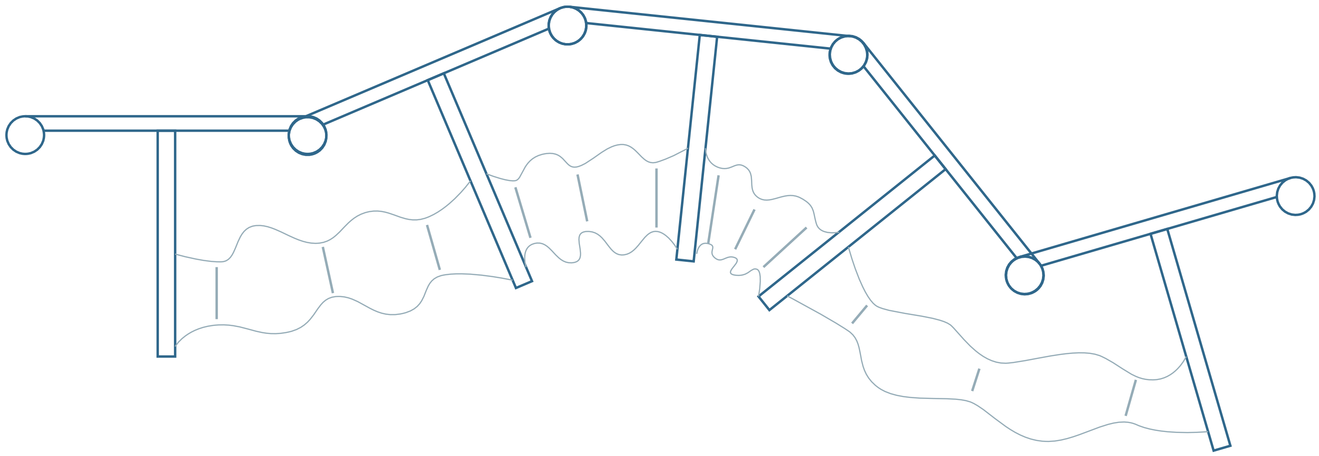


Figure 136 *Contact area and counter pressure required (by author)*

Normal stress

The normal stress caused by the upper body follows from the total force exerted by the upper body divided by the contact area of the upper body (see figure 136). The contact area was determined by using the shoulder breadth and difference between shoulder- and elbow height of subject A (see figure 136). The force used is the maximum shear force from figure 135.

Calculation results in a normal stress of 2.79 KPa, which is also the gauge pressure required to hold the body. Although very low, this number makes sense considering that a human can blow enough air into an air mattress for it to hold him and to sleep comfortable on it.



Moment on bellow

The chosen design solution is connecting multiple segments using bellows that can lift the next segment up by inflating or lower it by deflating (see figure 137).

Figure 137 *Example of segment connection (by author)*

In the ideal situation, the angles as presented in figure 44 can be created using this method, but that would require a bellow to extend from 25 mm to 127 mm length if the dimensions are used as shown in figure 138.

To calculate the required pressure in the bellow, the most extreme moment exterted on a segment is used (visible in figure 135), which is 164.8 Nm.

This moment is divided by the number of rows of segments that have to deliver the moment. The rows have a width of 120 mm, and dividing the body's contact area (see figur 139) over rows of 120 mm means that the minimum number of rows used is 4, which is a safe assumption.

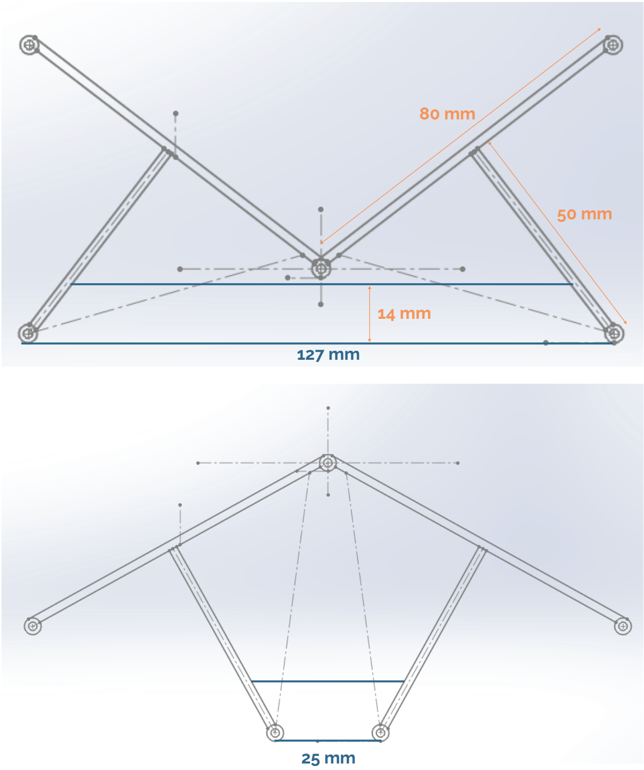


Figure 138 *Dimensions of segment (by author)*

The force Fax (see figure 139) pressing against the bellow is calculated using Maple and depends on the dimensions used in the design. Two examples:

50 mm arm
Fax would be 824 N.
Pressure in a 12x120 mm bellow would be 4.9 bar gauge pressure.

60 mm arm
Fax would be 687 N
Pressure in a 12x120 mm bellow would be 2.6 bar gauge pressure.

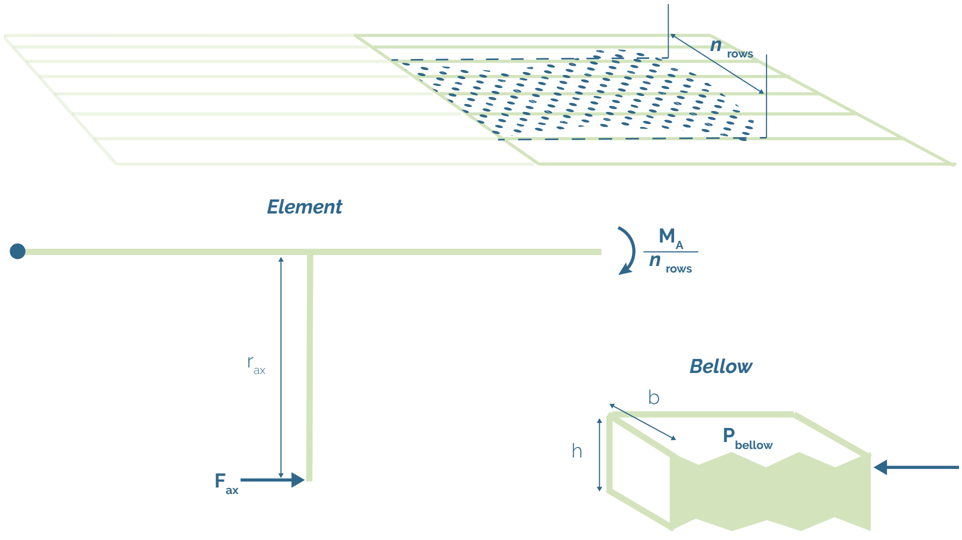
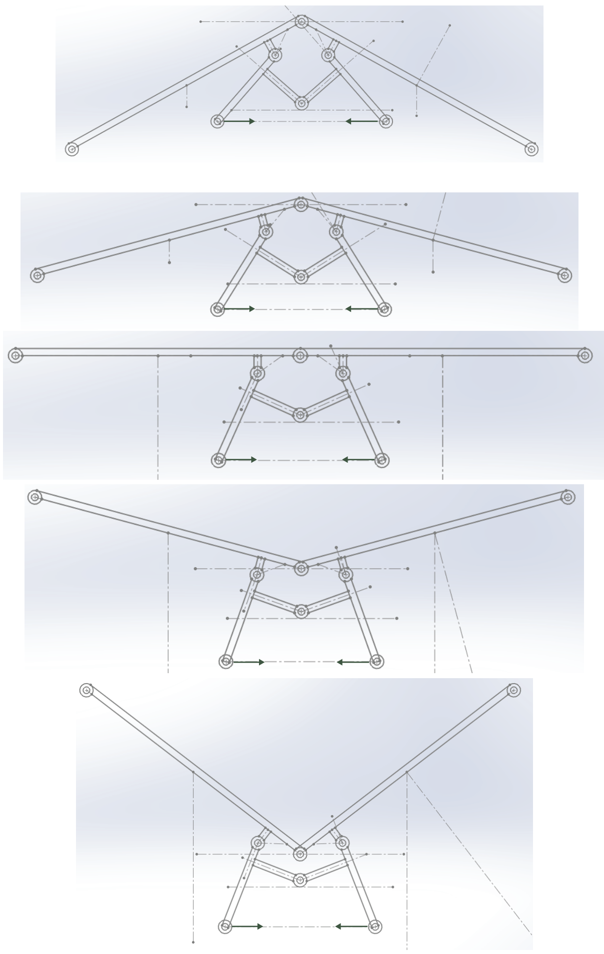


Figure 139 *Free body diagram of situation (by author)*



These pressures are feasible and can be adjusted by changing the dimensions of the design. Reaching the ideal angles using this method is less likely since the displacement the bellow had to make is large. Using a movement enhancing mechanism (e.g. shown in figure 140) could fix this problem.

Figure 140 *Movement enhancing mechanism (by author)*

C.3. BELLOW

Final calculations of bellow pressure

The calculation of the pressure applied on the bellow is based on the current design of the bellow. The calculation is set up parametrically, and the influence of design changes can easily be calculated. The initial calculations found in appendix C.2 were based on a concept design and turn out to be too optimistic compared to the final design.

The final calculations shown in figure 141 use the same Moment used for the initial calculations, but takes the final dimensions of the bellow and segment body, which results in a maximum pressure of 7.37 bar gauge pressure.

The initial calculations do show that with some design adjustments, it is possible to bring the required pressure back to more reasonable amounts.

> restart;

> $MA := 164.8;$

$$MA := 164.8$$

> $rax := 0.03436; \; alpha1 := \frac{(32.11) \cdot Pi}{180};$

$$rax := 0.03436$$
$$\alpha 1 := 0.1783888889\,\pi$$

> $Rows := 4; \; nBellows := 2;$

$$Rows := 4$$
$$nBellows := 2$$

> $Area := h \cdot b; \; h := 0.024; \; b := 0.04;$

$$Area := h\,b$$
$$h := 0.024$$
$$b := 0.04$$

> $\mathrm{Fax} := \frac{\left(\frac{MA}{Rows}\right)}{rax};$

$$Fax := 1199.068685$$

> $Fa := evalf\left(\frac{Fax}{\cos(alpha1)}\right);$

$$Fa := 1415.616769$$

> $Pbellow := \frac{Fa}{Area \cdot nBellows};$

$$Pbellow := 7.373004005\ 10^{5}$$

> $evalf(Pbellow, 4);$

$$7.373\ 10^{5}$$

Figure 141 *Final pressure calculation (by author)*

Material requirements

As older people take sleep positions for 30 minutes on average (see chapter 3.4), it is estimated that people ultimately take a position for 60 minutes. The bellows should maintain their position for at least that duration without requiring additional air pressure to not disturb their sleep. That means that the permeability of the material should not allow more than 1% of gas to escape in 60 minutes, as this amount will not be noticeable. Although air is used for the system, O2 permeability is used as this material property is known in CES EduPack (2017), v17.1.0.

Calculation of O2 permeability

A bellow with a volume of approximately 0.024*0.04*0.101 (in the maximum extended position) with a wall thickness of 1 mm with an absolute pressure of 8.4 atm that is allowed to lose 1% of its volume in 60 minutes is calculated as follows:

Volume = 0.024*0.04*0.101 = 0.00009696 m^3 = 96.96 cm^3
1% of that volume = 0.9696 cm^3 per 60 minutes
Area = 2*(0.024*0.04+0.04*0.101+0.024*0.101) = 0.014848 m^2

0.9696 cm^3 * 24 hours / 0.014848 m^2 / 8.4 atm =
186.58 cm^3.mm/(m^2.day.atm)

The yield strength should be at least 1.5 times the maximum applied stress, which means 1.5*35.23 MPa = 52.9 MPa. The applied stress is simulated in Solidworks (see figure 144).

To make some estimations on the requirements for the mechanical folds of the material, the folds are treated as bends which mean they cause an extension and compression in relation to the neutral axis. When the folding mechanism is produced with 90 degrees between the folds, the maximum required elongation of the material is 85%, meaning a strain of 0.85. Taking the minimum yield strength of 52.9 MPa that results in a maximum young's modulus of 62.2 MPa or else the material is not flexible enough.

The maximum displacement of the outer walls of the bellow has to be assumed as it cannot be tested without a functioning bellow. The estimation is that if the displacement is too large, the folding mechanism will no longer function. The material should therefore not be too flexible, which means that the young's modulus should be high enough. This directly interferes with the folding mechanism. To see whether the resulting displacement seems acceptable, it is simulated in Solidworks (see figure 144). Based on this simulation, the maximum displacement (in the middle of the bellow) is 3.8 mm. This seems acceptable, but this must be tested.

One bellow weighs approximately 30 grams, depending on the chosen material. One sleep system may require a number of 216 bellows, meaning a total weight of about 6.5 kg of bellows. This should be taken into account for the price of the material, as it can quickly become expensive.

Fatigue strength scenario: 15 years, for 365 days, 100 movements a night means 547500 movements, which means it is relevant to use the fatigue strength to be certain. Fatigue ratios to tensile strength according to CES EduPack (2017) are 0.3-0.4 for semi-crystalline plastics and 0.2-0.3 for amorphous plastics. For TPU, that means that the fatigue strength after 10 million cycles is estimated to be 24 MPa, which is lower than the required 35 MPa. yield strength. Therefore, a fatigue test is recommended to make sure that the parts will not fail within 15 years.

Simulating different materials

To verify the reliability of the material choice, several simulations were run in Solidworks using different materials for the bellow. The bellows were fixated at the top and bottom in the simulation and a pressure of 100 PSi (approximately 7 bar) was applied on the inside.

The following materials were tested:

- Natural Rubber (NR)
- Polypropylene (PP)
- Thermoplastic Polyurethane (TPU)

For NR, this resulted in a maximum stress of 36 MPa with a maximum displacement of 800 m, which basically means the bellow exploded under this pressure.

For PP, this resulted in a maximum stress of 38 MPa, with a maximum displacement of 0.4 mm, which is expected due to the high Young's modulus of the material.

For TPU, this resulted in a maximum stress of 35 MPa, with a maximum displacement of 3.8 mm, which is expected due to the small Young's modulus of the material.

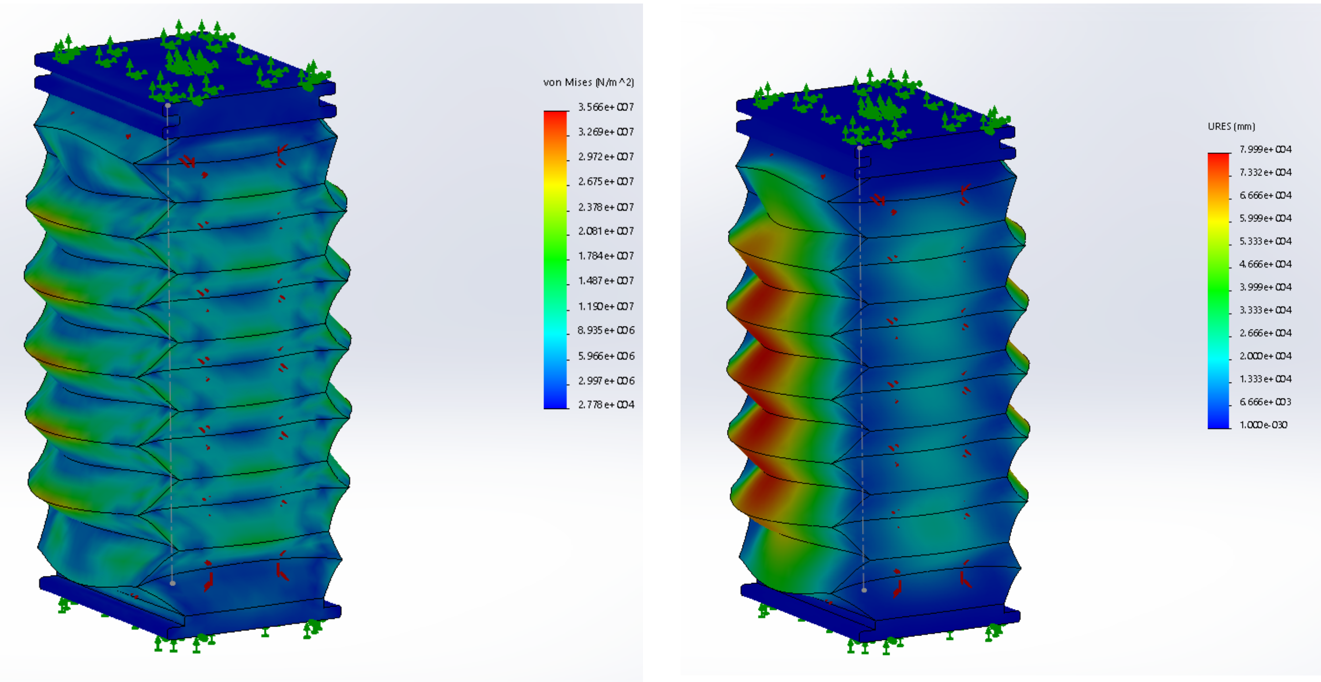


Figure 142 *Stress and displacement Natural Rubber (by author)*

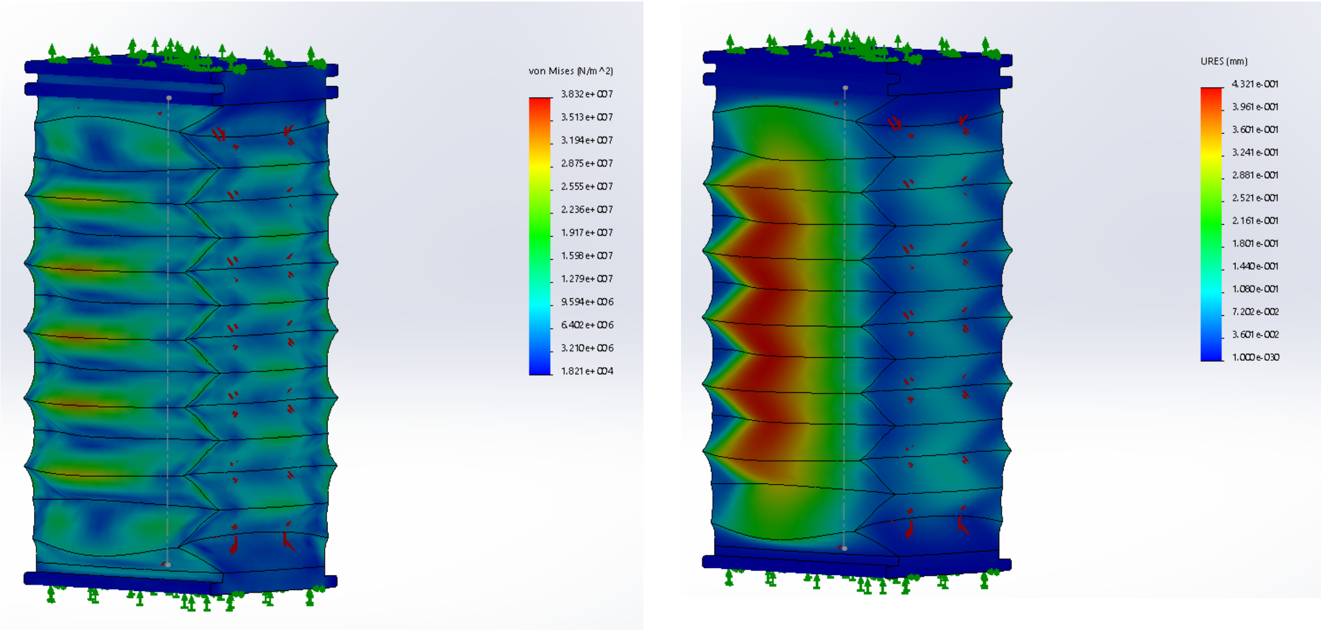


Figure 143 *Stress and displacement Polypropylene (by author)*

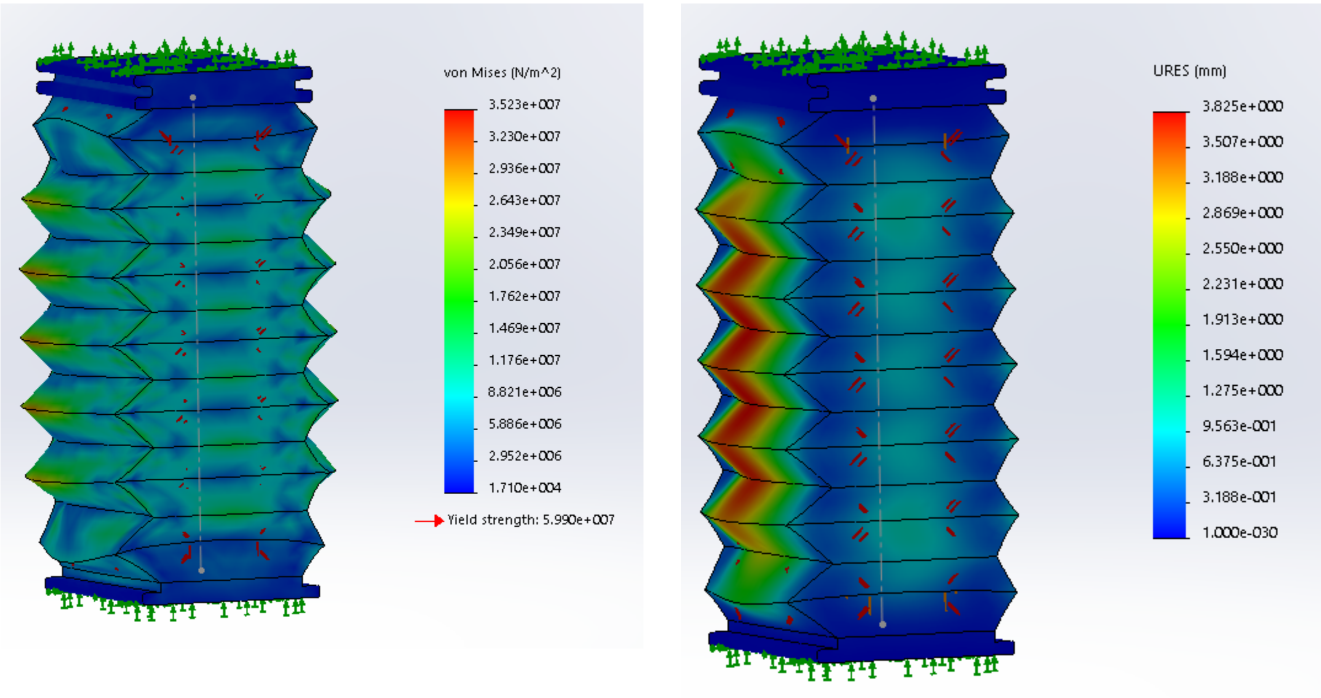


Figure 144 *Stress and displacement Thermoplastic Polyurethane (by author)*

C.4. **IMAGES OF POSITIONS**