# Sustainable supply chain design choices to support the upcoming implementation of the Wearable Breathing Trainer

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This report outlines the master's thesis titled "Sustainable supply chain design choices to support the upcoming implementation of the Wearable Breathing Trainer" and is written as the final part for the master Business Administration at the University of Twente.

The assignment was carried out for the department of sustainable and functional textiles at Saxion. With this assignment I had the opportunity to address a practical issue and learn how different strategies could be applied to the supply chain of the Wearable Breathing Trainer to move from a linear economy to a circular economy. I, therefore, hope that the findings of this research help this department in making informed decisions regarding a sustainable implementation of the Wearable Breathing Trainer, so that the environmental impact of medical wearables will be reduced.

I would like to convey my heartfelt appreciation to everyone who has supported me, while I was writing my thesis. To begin with, I would like to express my gratitude to my two supervisors at the University of Twente, Patricia Rogetzer and Xiaohong Huang, for their expertise and guidance. Their feedback and support enabled me to complete this thesis and enhance the overall quality of this thesis. Furthermore, I am thankful for all the stakeholders I could have an interview with. Their willingness to participate and share their knowledge and opinions on various matters have been of significant value to this study. Finally, I would like to express my gratitude to my family and friends for their constant support during this process.

I wish you great enjoyment in reading this.

Nina Schreuder

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## Management summary

Humanity faces several global crises, which are largely driven by unsustainable consumption and production patterns. The linear economy model, characterised by a take-make-use-dispose approach, aggravate these issues. Wearable devices, while offering potential benefits such as an improved healthcare and lifestyle, also present environmental challenges due to short lifecycles, e-waste, and energy consumption. However, through sustainable supply chain design choices, the supply chain of wearables, such as the Wearable Breathing Trainer, can become more sustainable, reducing environmental impacts. Existing literature discusses how sustainability regarding wearables is often times overlooked and states that there is still a lack of knowledge in this area. To address this gap, this research investigated the following research question:

"How can the upcoming implementation of a wearable for children with dysfunctional breathing into physiotherapy practices be supported by sustainable supply chain design choices?"

The NASSS framework, which is a well-known framework to assess the success of a healthcare technology, has been used to analyse and address challenges in the upcoming implementation of the Wearable Breathing Trainer with a focus on the design of the technology and the value proposition. Next to this, an economic business model and an environmental life cycle business model have been developed to present the value proposition of the Wearable Breathing Trainer, while also measuring the wearable's environmental impact across all stages of its life and spot its environmental benefits along the way. This helps envisioning how a business could move away from a linear economy and move towards a circular economy, in which the value of the product remains in the loop and waste is eliminated.

Three different design options have been developed for the Wearable Breathing Trainer. These are the modular design, the knitted-in design and the laminated design. Multiple circular product design and business model strategies can be applied to the three design options and the two business models of the Wearable Breathing Trainer to slow or close the loop of this product. Additionally, the waste pyramid can be used to manage and minimise the waste of the Wearable Breathing Trainer. These forementioned strategies can be realised by reusing, repairing, refurbishing, remanufacturing, and recycling the wearable. If that is not possible the wearable ought to be incinerated or landfilled. Applying these strategies could be a way of integrating sustainability into the supply chain of the Wearable Breathing Trainer.

The intermediary users of this wearable, the physiotherapists, place significant emphasis on that the wearable must be easy to use, is comfortable for the patient, has an aesthetically pleasing design, and is not too expensive. A production company would not want to apply circular strategies when the strategies hinder the user satisfaction, as this also directly affects sales. The knitted-in design can be considered the best design in this case, as a weighed method showed that the knitted-in design is most preferred by the involved stakeholders, in this case the physiotherapists and the production company, whose support is critical for a successful implementation.

By incorporating the forementioned strategies to the supply chain of the Wearable Breathing Trainer, the chain can become more sustainable. This research describes how these strategies can be applied to the supply chain of the Wearable Breathing Trainer to move from a linear economy to a circular economy, thereby making a meaningful contribution to scientific literature on how the environmental impact of a medical wearable can be reduced.

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# Chapter 1: Introduction

There are a number of severe global crises that humanity is being confronted with in the early 21st century, such as global warming, a growing ecological overshoot, the widespread lack of human basic needs, and an increase in inequality and social exclusion (Bengtsson et al., 2018).

These challenges are closely related to the consumption and production of goods and services. Due to mass production and mass consumption there is an overuse of natural resources and risks of pollution. Furthermore, an unequal access to energy and materials results in the deprivation of human needs (Bengtsson et al., 2018). As long as the production and consumption of products follows the linear economy, the manufacturing approach stays unsustainable as this concept does not consider the environmental, societal and economic impacts (Jawahir & Bradley, 2016). The essence of the linear economy could be summarised as a concept of taking, making, using and disposing products after they have been used (Sariatli, 2017).

Simultaneously, there has been a rapid increase in the number of consumer targeted high-tech products. A rapidly developing trend of consumer electronics is wearable technology. Wearables are technologies that can be worn on the body, where the technology interacts with the consumer (Lee et al., 2016). These wearables are the combination of electronics with textile. An abundance of wearables are sold and used in the general population (Canali et al., 2022). Examples of such consumer products are wellness gadgets or fitness trackers (Kang & Exworthy, 2022).

Wearable devices can also have a medical purpose, where the technology interacts with a patient to, for instance, collect data or provide exercise guidance. With wearables patients can get access to real-time and accurate data, which they can use for self-diagnosis and self-monitoring (Lu et al., 2020). Applying medical wearables in the healthcare field could not only support the self-management of patients and improve their symptoms and overall quality of life, it could also reduce the burden on health care professionals (Nagase et al., 2022).

While the emergence of wearables provide opportunities to adopt a healthier lifestyle and could make the life of patients more convenient, it must be carefully developed (Kang & Exworthy, 2022). If not carefully developed, wearables can negatively impact the environment due to different reasons. First of all, there is an increased production of electronic components, which often consist of scarce materials, such as gold for wires or neodymium used for magnets (Gurova et al., 2019). Furthermore, there is e-waste accumulation due to abandoned wearables (Gurova et al., 2020). At the moment, existing wearables have a short life cycle. For example, approximately every third American consumer uses a wearable for only six months (Lee et al., 2016). Since wearables run on electricity, there is also an increase in energy consumption (Gurova et al., 2020). Lastly, wearables are proven to be very difficult to recycle (Köhler, 2013).

Despite wearables being difficult to recycle, there are ways in which wearables can be produced on a large scale in a more sustainable manner compared to the linear economy. According to the study of Gurova et al., (2020) the choices made in the design of wearables is significantly proven to impact the sustainability cost of a product's lifecycle. One of the reasons for the abandonment of wearables by consumers in these early stages is that they are difficult to use, not perceived as useful, and often have an unattractive design. Through different design options, designers are able to influence the whole life cycle of a product. Hence, the product's design should be a priority, because otherwise wearables end up being a short-lived and mass-consumed product that contributes to the global environmental crises (Gurova et al., 2020).

The growth of wearables in the Dutch market in the last few years is remarkable (Djapic et al., 2018). In 2019, the department of sustainable and functional textiles at Saxion started designing a wearable that could support the treatment of children with dysfunctional breathing. Dysfunctional breathing is a respiratory condition affecting adults as well as children. However, it is viewed as a significant health problem among children (Trompenaars et al., 2020). Even though the prevalence of this disorder is imprecise, it affects approximately more than 5% of the children in the Netherlands (SIA Projecten, z.d.). Children with this condition have an abnormal breathing pattern, such as breath holding or hyperventilation (Vidotto et al., 2019). It can cause a variety of symptoms, such as chest pain and shortness of breath (Barker & Everard, 2015). Thus, it is crucial to develop an optimal treatment approach for dysfunctional breathing to prevent long-term health issues and improve the quality of life (Connect & Thomas, 2018). The wearable that is being developed is the so called Wearable Breathing Trainer. It is a textile vest integrated with electronics. It also has an app with daily breathing exercises and thereby supports the self-management of patients at home (Siering et al., 2019).

While the life cycle of wearables, such as the Wearable Breathing Trainer, could be more sustainable through product design, few pay attention to it due to a lack of knowledge in this field. Furthermore, stakeholders might be hesitant to apply sustainable practices, as they fear those practices might affect their technology or commercial success negatively (Gurova et al., 2020). Nonetheless, having the support of stakeholders is crucial before a wearable is introduced to the Dutch market (Kang & Exworthy, 2022). On top of that, it is difficult to implement medical wearables into the Dutch healthcare system due to a variety of regulations.

Considering the points discussed above, the implementation of wearables that are not only sustainable, but also align with the expectations of the involved stakeholders, can be quite a challenge. To study how the upcoming implementation of the Wearable Breathing Trainer can be supported by sustainable supply chain design choices, two different methods are used in this research. Secondary data is collected through literature research and primary data is collected through qualitative research, in which semi-structured interviews are conducted with various stakeholders in the Netherlands about the process of implementing the Wearable Breathing Trainer considering sustainable design choices.

## 1.1 Research question

To study how the upcoming implementation of the Wearable Breathing Trainer could be supported by sustainable supply chain design choices, the following research question has been formulated:

"How can the upcoming implementation of a wearable for children with dysfunctional breathing into physiotherapy practices be supported by sustainable supply chain design choices?"

To gain an understanding of the topics mentioned in the research question, four sub-questions are formulated. Each of these sub-questions are structured according to the dimensions of the NASSS framework (Greenhalgh et al., 2017), which is explained in more detail in Chapter 3. Respectively, these dimensions are condition, technology, value proposition, adopters and organisation. The NASSS framework has these different dimensions, which together could be used to help predicting the success of a healthcare technology, in this case the Wearable Breathing Trainer. Therefore, the sub-questions – along the lines of the dimensions – are:

1. What is dysfunctional breathing?
2. What is the technology behind the Wearable Breathing Trainer?
3. What is the value proposition of the Wearable Breathing Trainer?

4. What are the requirements from the perspective of physiotherapists?

## 1.2 Scientific relevance

In scientific literature the importance of integrating sustainable practices into the life cycle of wearables is extensively described. Gurova et al. (2020) address that wearables can negatively impact the environment if not developed in a sustainable manner. This study also emphasizes that sustainability should be prioritised in the life cycle of wearables to prevent wearables becoming short-lived and mass-consumed products (Gurova et al., 2020). Furthermore, Powell and Godfrey (2023) state that wearables often get discarded due to a lack in accessibility or modification. Most of the time sustainability is overlooked and there is more focus on technical, professional and policy and social issues. Therefore, it is important to consider sustainability, especially during the design phase of wearables (Powell and Godfrey, 2023).

Even though the life cycle of wearables could be sustainable through product design, there is a lack of knowledge in this field (Gurova et al., 2020). Dulal et al. (2022) elaborate on this statement by discussing that there is a lack in sustainable e-textiles due to various reasons. Most wearables are made with the use of scarce materials, there are complicated manufacturing processes used, and there is an abundance of toxic waste generated (Dulal et al., 2022).

With the increasing integration of textile into the design of wearables, concerns about the sustainability of such practices have grown. This makes the link between wearables and sustainability, visualised in Figure 1, an important and relevant topic to study and hence the research gap that this thesis focuses on (Gurova et al., 2020).

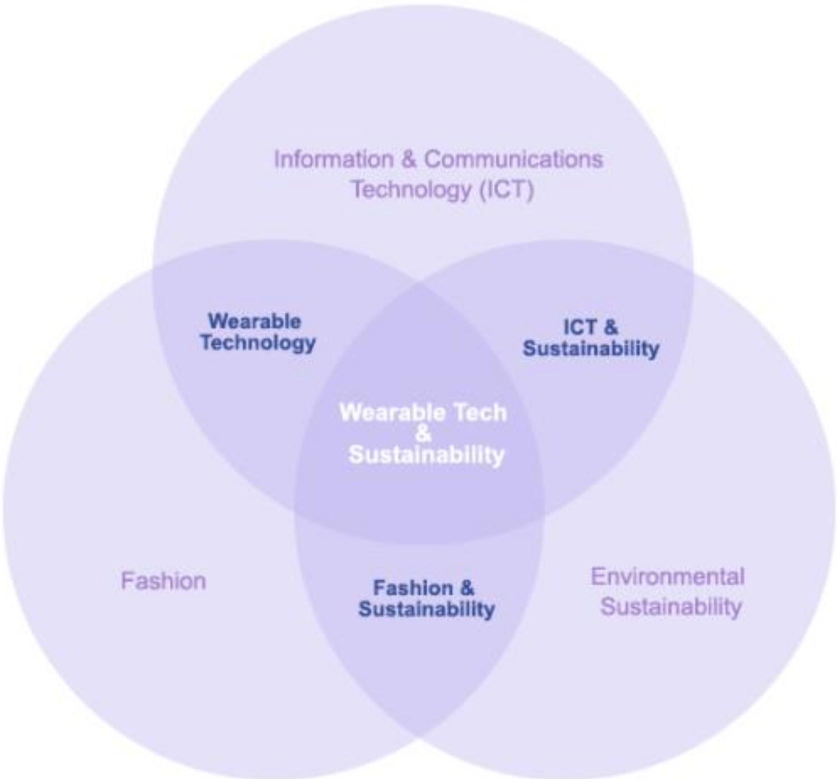


*Figure 1. The key themes of this research: fashion, technology and sustainability*

*(Source: Gurova et al., 2020)*

Furthermore, the knowledge on the clinical implementation of wearables into the healthcare system is limited in scientific literature. According to the study of Smuck et al. (2020), there is not much known about the factors that facilitate the implementation of wearable devices into the healthcare sector. Additionally, wearables drive a change in the healthcare sector, raising challenges on how such wearables ought to be integrated into the workflow of healthcare providers (Lewy, 2015). However, it is of great importance that these topics are included in scientific research, as wearables can greatly benefit the healthcare sector by reducing the burden on health care professionals, and by supporting patient self-management as well as overall quality of life (Nagase et al., 2022).

With this lack of knowledge about a sustainable life cycle for wearables and the lack in research about the clinical implementation of wearables into the healthcare system, it is of scientific relevance to study how the upcoming implementation of the Wearable Breathing Trainer could be supported by sustainable supply chain design choices.

## 1.3 Practical relevance

Next to the scientific relevance of this research, it is also important to consider the practical relevance. Currently, the department of sustainable and functional textiles at Saxion in Enschede wants to improve the treatment for children with dysfunctional breathing. Therefore, they have created a prototype of the Wearable Breathing Trainer that supports adequate breathing for children and for which the first clinical trial has started in September of 2024. In order to help these children, the Wearable Breathing Trainer needs to be implemented in the Dutch healthcare system. With the results of this research, Saxion might be able to take sustainable practices into account during the implementation process of the Wearable Breathing Trainer, which in turn could reduce the environmental impact of wearables. Additionally, the results could give Saxion relevant information regarding the perspective of involved stakeholders on the implementation of the Wearable Breathing Trainer. Knowing their perspective and having their support is critical for a successful integration of wearables. Therefore these results could help Saxion get closer to providing a better treatment option and thus providing a higher quality of care for children with dysfunctional breathing problems. Lastly, the involved stakeholders benefit from the results of this research. Through this research they could reflect on what they think about sustainability and to what degree they think it is important to apply sustainable practices in the implementation of a product. Therefore, a sustainable implementation of other medical wearables might be easier in the future.

## 1.4 Conclusion

To conclude, humanity faces several global crises, which are largely driven by unsustainable consumption and production patterns. The linear economy model, characterised by a take-make-use-dispose approach, aggravate these issues. Wearable devices, while offering potential benefits such as improved healthcare and lifestyle, also present environmental challenges due to short lifecycles, e-waste, and energy consumption. However, through sustainable supply design chain choices, the supply chain of wearables, such as the Wearable Breathing Trainer, can become more sustainable, reducing environmental impacts.

# Chapter 2: Current situation

Wearable devices have become a valuable tool to monitor an individual's health and well-being (Izu et al., 2024). Due to the growth in personalised health monitoring, wearable devices developed rapidly in the healthcare field (Lu et al., 2020).

A medical wearable that the department of sustainable and functional textiles at Saxion is currently doing research on is the Wearable Breathing Trainer. In this chapter the current situation is explained in more detail by describing the project plan of the Wearable Breathing Trainer, the consortium partners and the state of the art.

## 2.1 Project plan Wearable Breathing Trainer

In the Netherlands, children with dysfunctional breathing are referred to a physiotherapist to get treatment (Vidotto et al., 2019). This treatment includes performing breathing exercises at home, so that children return to a normal breathing pattern (Barker et al., 2020). However, it is difficult for parents and healthcare providers to monitor a child's progress. Additionally, children often think these exercises are boring and are therefore not motivated to do these exercises daily, which slows down the progress a child makes (Siering et al., 2019).

A solution to this problem could be the Wearable Breathing Trainer. The concept of the Wearable Breathing Trainer was developed in a previously subsidized process financed by Pioneers in Healthcare (PIC) and Stimuleringsfonds Creatieve Industrie (SCI). The content of this wearable has been developed in consultation with children to include their perspective on this technology. For example, games will be integrated into an app to motivate children to do their breathing exercises (*SIA Projecten*, z.d.).

The so called RAAK-MKB project plan is a current follow-up process of the Wearable Breathing Trainer. This project plan is aimed at the further development of the prototype into a robust system, validating the technology with a user study with children, and creating an implementation plan (*SIA Projecten*, z.d.). This last step is the main focus of this thesis.

## 2.2 Consortium partners

The RAAK-MKB project has multiple partners in the consortium. The mixture of the consortium consists of several paediatric physiotherapy practices, small and medium sized enterprises (SME) development partners, a trade association for the Dutch clothing and textile industry, educational institutions, healthcare institutions, and the Network Exertion complaints. Each of these partners fulfil different roles within the project (*SIA Projecten*, z.d.).

The long term ambition of the consortium is to improve the quality of treatment of children with dysfunctional breathing through a wearable that is suitable for home training. The main focus is a long-term collaboration that leads to the actual implementation of the Wearable Breathing Trainer, and where the SME development partners can generate business during the development phase as well as with the end product (*SIA Projecten*, z.d.).

## 2.3 State of the art

In the current market there are two products available that are similar to the Wearable Breathing Trainer. These products are a shirt from the company Hexoskin and a pillow from the company Somnox.

Hexoskin offers shirts to COPD patients that have fitness applications. They have also developed a version specifically intended for children. This product is similar to the Wearable Breathing Trainer, since it also has a sensor which measures how the fabric stretches when the individual's chest expands and contracts. Furthermore, it can also send the monitored data to a mobile application. However, a big difference in comparison to the Wearable Breathing Trainer, is that Hexoskin is not a medical device. Therefore, it cannot be used as a form of treatment by medical professionals (Hexoskin, z.d.). The second product that is similar to the Wearable Breathing Trainer is Somnox. Somnox is a pillow, meant for adults as well as children, that also improves breathing through sensors and it settles the mind and allows for better sleep. Somnox is also not a medical device, but a lifestyle product. This product, however, is included in an additional insurance of a Dutch insurance provider ´Het Zilveren Kruis´ (Somnox, z.d.).

## 2.4 Conclusion

To conclude, medical wearables are on the rise, including the Wearable Breathing Trainer. For the further development of this wearable a project plan has been made on which a diverse group of people is working. The goal of this wearable is to improve the treatment by offering a wearable that motivates children to perform their breathing exercises at home. One step in the project plan is the implementation process, which is further studied in this thesis. Chapter 3 provides a more detailed explanation of the methodology used for the implementation process.

# Chapter 3: Theoretical framework

In this chapter the theory and strategies, used to structure the thesis, are described. The NASSS framework gives structure to the research, as it theorizes and evaluates the non-adoption, abandonment, and struggles to the scale-up, spread, and sustainability of a healthcare technology (Greenhalgh et al., 2017). Two business models are explained that serve as building blocks to the third dimension of the NASSS framework, which is the value proposition. Furthermore the waste pyramid, and the circular product design and business model strategies are explained as those strategies could respectively manage the waste of the Wearable Breathing Trainer and slow and close the loop of this product, to create a circular economy instead of a linear economy.

These theories together could gain relevant insights into a sustainable way of implementing a healthcare technology and could help answering the following research question of this thesis: How can the upcoming implementation of a wearable for children with dysfunctional breathing into physiotherapy practices be supported by sustainable supply chain design choices?

## 3.1 The NASSS framework

Technology can empower patients and staff by improving the efficiency, quality and safety of care. However, in reality there are challenges with the implementation of technological innovations, such as professionals resisting to use them or technologies clashing with legacy systems and work routines (Greenhalgh et al., 2017). Therefore, a framework should be used that is developed to help predicting the success of a healthcare technology (Abimbola et al., 2019).

To study how the Wearable Breathing Trainer could be implemented into a physiotherapy practice, the NASSS framework (see Figure 2) could be used. The NASSS framework is an evidence-based, theory-informed, and pragmatic framework that helps with either predicting or evaluating the success of a healthcare technology.

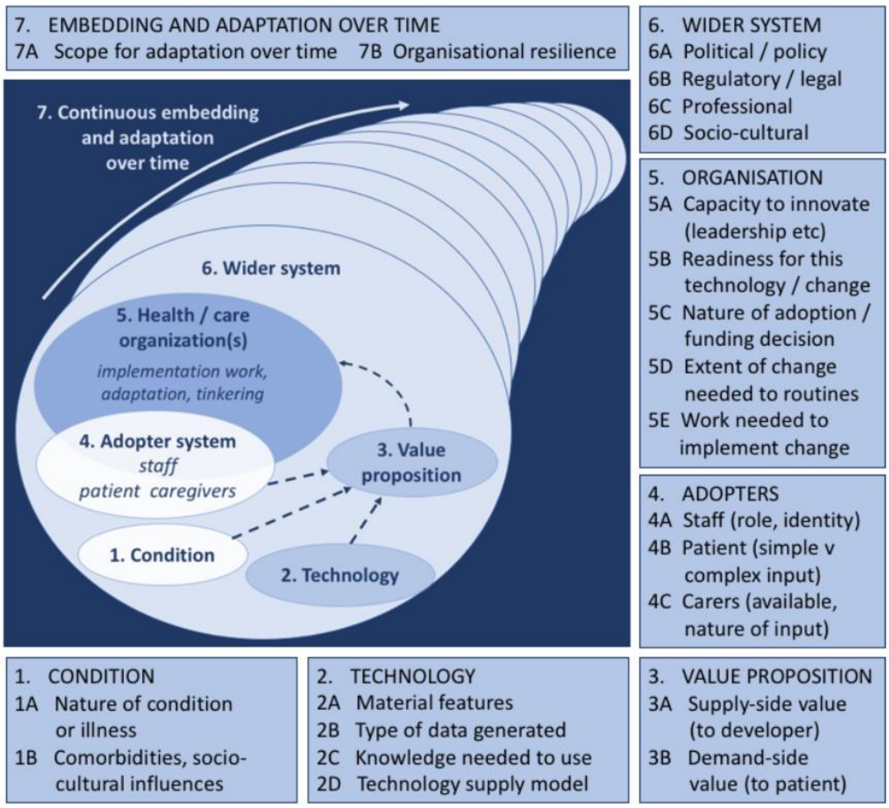


*Figure 2. The NASSS framework*

*(Source: Greenhalgh et al., 2017)*

The NASSS framework consists of seven different domains. The first domain discusses the condition of the patient group, including how complex it might be due to its comorbidities and sociocultural influences. This part addresses which potential end users could use the technology, which is in this case children with dysfunctional breathing (Abimbola et al., 2019).

The second domain discusses the material and technical features of the technology in order to construct a prototype. Furthermore, it describes the type of data that is generated and which knowledge and support a user needs to interact with the technology (Greenhalgh et al., 2017).

The third domain, the value proposition, addresses whether it is worth it to develop a new technology and whether it creates added value. To study this, the upstream value should be investigated, which follows the supply-side value of financial markets and investment decisions. Also, the downstream value should be explored, to follow the demand-side value of health technology appraisal, reimbursement, and procurement (Greenhalgh et al., 2017).

The fourth domain discusses the adopter system. It addresses the healthcare providers and patients who will potentially use the Wearable Breathing Trainer. It also describes what roles and practices will need to change to use the technology and what is expected of the patients and caregivers (Abimbola et al., 2019).

The fifth domain is about the integration of the technology within the organisation. It relates to the capacity of an organisation to see whether they are ready to innovate in terms of resources and leadership. The organisation itself also has to decide whether they want to adopt it and what their funding decision would be. Furthermore, the extent of work that has to be changed are addressed (Abimbola et al., 2019).

The sixth domain is the wider system in which the innovation has to be implemented. It discusses the political, regulatory, professional and socio-cultural aspects regarding the technology (Greenhalgh et al., 2017).

The last domain is the embedding and adaptation over time. This domain focuses on all levels since they are interlinked with each other and evolve dynamically. It addresses the long-term feasibility of the technology and it considers the organisational resilience (Greenhalgh et al., 2017).

In this thesis the focus is on the condition (dimension one), the technology (dimension two) and the value proposition (dimension three). Lastly, the adopters (dimension four) and the organisation (dimension five) are also included to give a more complete overview of the implementation from the perspective of physiotherapists. Wider system (dimension six) and embedding and adaptation over time (dimension seven) are excluded from this research, as the project regarding the Wearable Breathing Trainer is not at that stage yet.

## 3.2 Business Model Canvas

The Business Model Canvas is a business model that consists of nine building blocks that help businesses to develop a roadmap towards achieving their goals (Fakieh et al., 2022). Joyce et al. (2015) describe the so called Triple Layer Business Model Canvas (TLBMC) that complements and extends the original Business Model Canvas, which is an economically-oriented business model (see Figure 3). Added layers to this Business Model Canvas are the Environmental Life Cycle Business model Canvas (see Figure 4), and the Social Stakeholder Business model Canvas (Joyce et al. (2015). This last layer is not included in this research, since the focus is not on the social impacts.

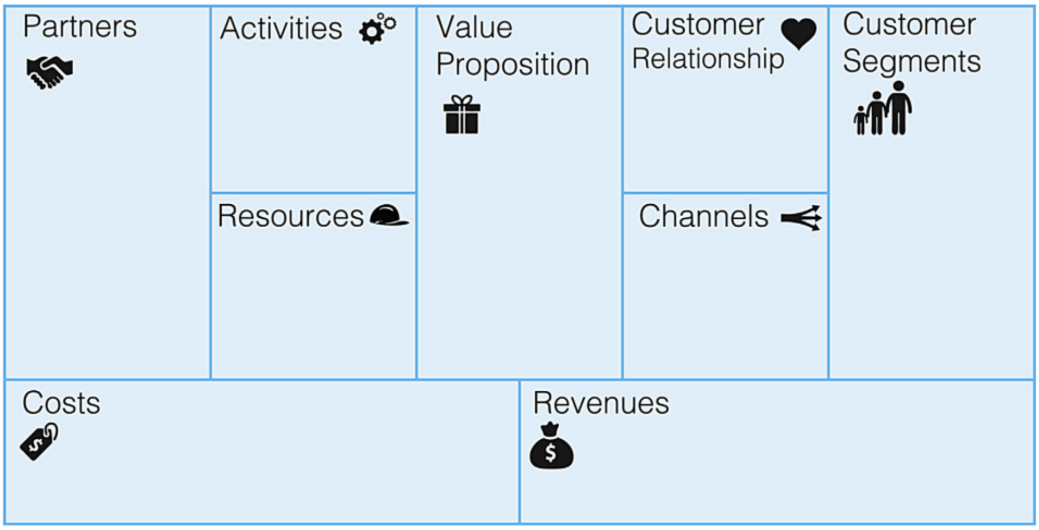


*Figure 3. Economic Business Model Canvas*

*(Source: Joyce et al., 2015)*

The Environmental Life Cycle Business Model Canvas is an approach that measures a product´s environmental impact across all stages of its life. The aim of this layer is to assess how a business creates more environmental benefits than environmental impacts. By assessing this, it becomes clearer what a business's biggest environmental impacts are and on what they could focus to enhance any environmental benefits (Joyce et al. (2015).

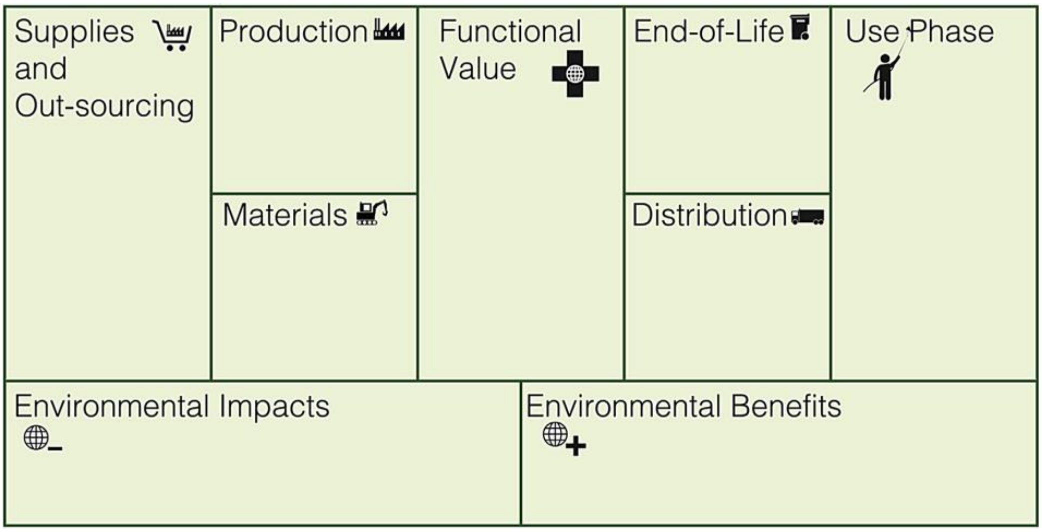


*Figure 4.* Environmental Life Cycle Business Model Canvas

(Source: Joyce et al., 2015)

## 3.3 Moving from a linear economy to a circular economy

As described before, humanity faces several global crises, largely driven by unsustainable consumption and production patterns. These issues grow worse through the linear economy model. The essence of the linear economy could be summarized as a concept of taking, making and disposing products (see Figure 5). The concept of the linear economy is taking the resources that are needed, making the products, selling the products, and then disposing leftovers that are not needed anymore, including the product itself. It has unrealistic assumptions that the Earth has infinite resources available and that the capacity of the Earth is infinitely regenerative (Sariatli, 2017).

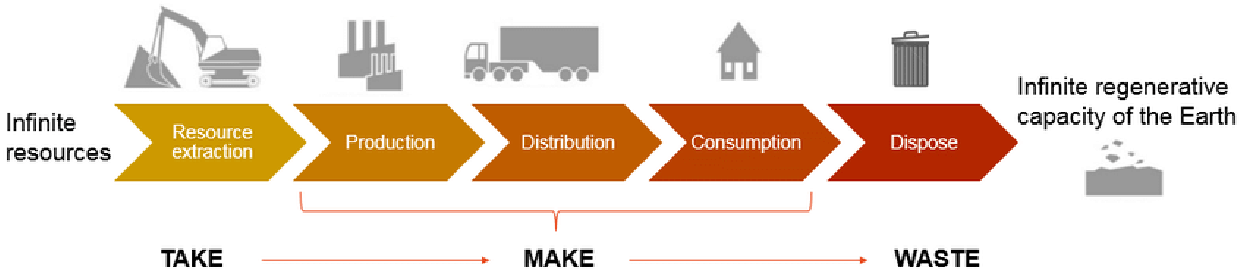


*Figure 5. Linear economy*

*(Source: Sariatli, 2017)*

This current economic design originates from an uneven division of wealth. Whereas the consumers of products have been mostly concentrated in developed countries, the recourses have been, and to this day are, deployed from all over the world. The materials have been cheap in comparison to the cost of employees. Therefore, business models have been made that rely on an extensive use of materials and cut down on human labour to gain a competitive advantage. Since material seemed to be available in abundance and was also cheap, there has been a neglect in recycling, reusing and waste management (Sariatli, 2017).

The circular economy is a concept which has gained prominence around the world as a pathway towards sustainability (Oliveira et al., 2021). The principles of the circular economy are to keep the value of the product in the loop and eliminate the waste. At the end of a product's life cycle, the products should be kept within the economy as a resource and should be reused to create further value (Sariatli, 2017). The circular economy is a cyclical ecological system and is visualised in Figure 6. The pressure on companies to reduce waste emissions, has led to the introduction of Industrial Symbiosis (Yazan et al., 2016). Industrial Symbiosis is a strategy that looks at waste to see how it could be used as input for another product (Bocken et al., 2016).


*Figure 6. Circular economy*

*(Source: Oliveira et al., 2021)*

## 3.4 Waste pyramid

The waste pyramid (see Figure 7) has been identified as a roadmap for the European waste management. It aims to manage and decrease the amount of waste of a product using different strategies (D'Inverno et al., 2024). This hierarchy distinguishes different levels of waste management (Zhang et al., 2021). The most desirable level is prevention, in which no waste is created. This is followed by preparing for reuse, in which goods are used again. Next is recycling, which is the recovering of materials as secondary materials. The recovery level, then, looks at how waste can be used as a source to generate energy. The last and least desirable level, is disposal (D'Inverno et al., 2024). This level does not support the circular economy, but is in line with the linear economy (Zhang et al., 2021).


*Figure 7. Waste pyramid*

*(Source: D'Inverno et al., 2024)*

## 3.5 Circular product design and business model strategies

Bocken et al. (2016) describe in their article also different strategies, either in product design or in a business model, for a circular economy. These different strategies could help slowing and closing the loops of, in this case, the Wearable Breathing Trainer. Slowing loops is keeping products as long as possible in the loop and closing loops is recycling products to ensure a circular flow of resources. The strategies can be subdivided into circular product design strategies and circular business model strategies and are visualised in Figure 8.

### 3.5.1 Circular product design strategies

Slowing the loops through circular product design strategies can be achieved by either designing long-life products or designing for product-life extension. Designing long-life products can be attained by creating a design that customers trust and to which they form an attachment. The design must also be user-friendly, reliable and durable. Designing for product-life extension can be realised by making a design suitable for maintenance, repair, technical upgrading, and dis- and reassembly (Bocken et al., 2016).

Closing the loops through circular product design strategies can be for a technological cycle, a biological cycle or for dis- and reassembly. In the case of the Wearable Breathing Trainer, a design for a technology or dis- and reassembly can be applied. These cycles aim to separate and reassemble products and parts easily (Bocken et al., 2016). The difference between those cycles and the biological cycle is displayed in the butterfly diagram in Figure 9.

### 3.5.2 Circular business model strategies

In terms of a circular business model strategies loops can be slowed down through the access and performance model, extending product value, providing a classic long life, and encouraging sufficiency. The access and performance model provides services to customers in such a way that they do not need to own the product. Extending the product value is a strategy that exploits the residual value of products. The strategy of the classic long life model focuses on delivering a long product life. A last strategy to slow down the loop of a product, is to encourage sufficiency.

These loops can also be closed by extending the resource value of the product or through industrial symbiosis. Extending the resource value of a product is the exploitation of residual value of otherwise wasted resources. Industrial symbiosis is a strategy that considers the waste of one company as resources for another company (Yazan et al., 2016).

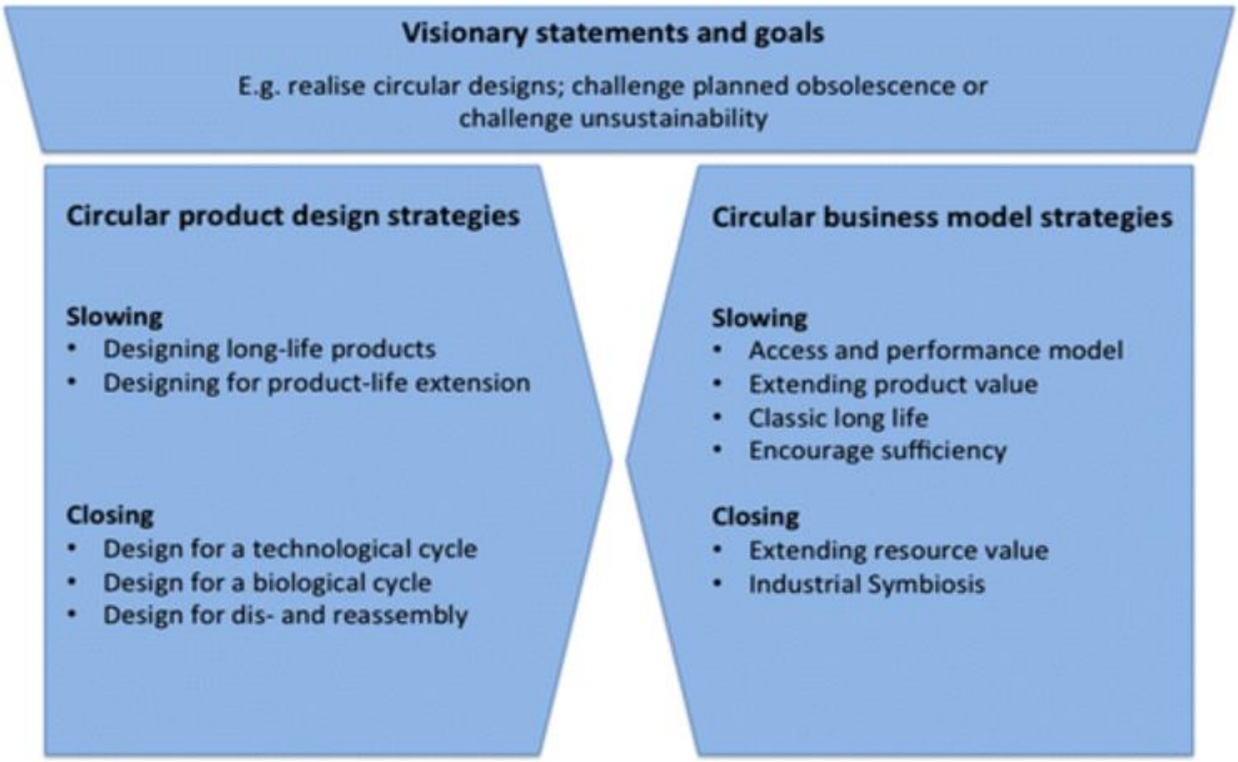


*Figure 8. Product design and business model strategies for a circular economy*

*(Source: Bocken et al., 2016)*

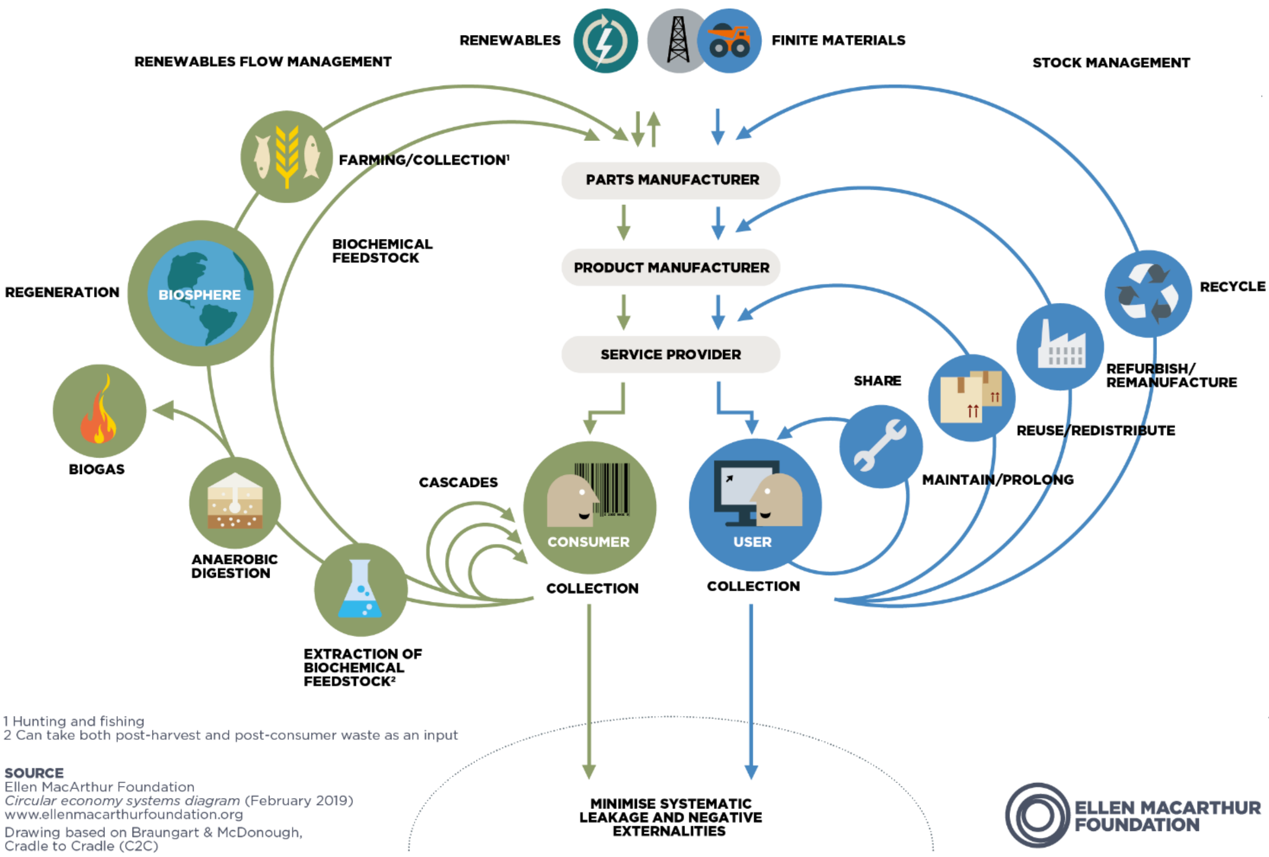


*Figure 9. The butterfly diagram*

*(Source: The Ellen MacArthur Foundation, 2021)*

## 3.6 Conclusion

To conclude, the NASSS framework has different dimensions, which together could be used to help predicting the success of the Wearable Breathing Trainer. The Economic Business Model Canvas and the Environmental Life Cycle Business Model Canvas help a business to develop a roadmap aimed at achieving its goals, while also measuring a product's environmental impact across all stages of its life and seeing how environmental benefits can be enhanced. This helps envisioning how a business could move away from a linear economy and move towards a circular economy, in which the value of the product remains in the loop and waste is eliminated. This could be realised by applying strategies that closes and slows the loop of a product and strategies that manage the waste of a product.

# Chapter 4: Methodology

In this chapter the methodology of the research is described: research design (Section 4.1), data collection (Section 4.2), measuring method (Section 4.3), study population (Section 4.4), inclusion criteria (Section 4.5), recruitment of respondents (Section 4.6), data analysis (Section 4.7) and finally the ethical considerations (Section 4.8).

## 4.1 Research design

This research is a qualitative, exploratory case study and is carried out for the department of sustainable & functional textiles at Saxion in Enschede. There has been chosen for this design, as this research aims to explore new insights and opinions. In this research multiple stakeholders have been interviewed to discover how the upcoming implementation of the Wearable Breathing Trainer can be supported by sustainable supply chain design choices. The Business Model Canvas and the business model strategies (Section 3.2 and 3.6) give structure to these interviews.

## 4.2 Data collection

The data in this study was collected through literature research to collect information about the first dimension of the NASSS framework, which is the condition. Furthermore, primary data was collected through qualitative research, in which semi-structured interviews were conducted. This data has been collected to receive information about dimension two and three of the NASSS framework, which are respectively the technology and the value proposition.

## 4.3 Measuring method

The interviews have been conducted through a semi-structured interview guideline (see Appendix B). Having a semi-structured interview guideline with topics and questions will strengthen the validity of the research, because this keeps the structure of all interviews quite the same. The design of the interviews are semi-structured, so there is still room to ask further questions regarding the respondent's answers.

The concepts used for the interviews stem from the circular product design strategies and the circular business model strategies. To study these concepts, an operationalisation table has been made which explains the concepts through different dimensions and indicators (see Appendix A). The themes for the interviews were determined based on the nine building blocks of the Business Model Canvas and the different strategies from the circular business model strategies. The themes of the interviews are: key partners, key activities, key resources, value proposition, customer relationships, channels, customer segments, cost structure, revenue streams, slowing loops and closing loops. The questions for the interview were subsequently drawn up and based on the indicators. The interview consists of some closed questions to rule out situations, but it mainly consists of open questions to obtain an explanation from the respondents.

## 4.4 Study population

The study population, shown in Table 1, consists of a designer of a research group, a Chief Executive Officer (CEO) of a production company, two advisors from two insurance companies, and twelve paediatric physiotherapists. These individuals are the ones that either design the Wearable Breathing Trainer, will produce the Wearable Breathing Trainer, possibly have to reimburse it or apply it in their treatment plan.

| Respondent number | Profession |
|---|---|
| 1 | Designer from a research group |
| 2 | CEO of a production company |
| 3 | Advisor from an insurance company (a) |
| 4 | Advisor from an insurance company (b) |
| 5 | Paediatric physiotherapist |

*Table 1. Study population*

## 4.5 Inclusion criteria

The participants in this research must be directly or indirectly involved in the upcoming implementation of the Wearable Breathing Trainer. Furthermore, they must have some expertise in either the design, production process, insurance or the integration of wearables into the health care system.

## 4.6 Recruitment of respondents

The respondents of the study population were recruited by sending them an email in which a description of the research topic was written and in which they were asked whether they were willing to participate in this research. The interviews have been held online via Microsoft Teams.

## 4.7 Data analysis

The interviews were transcribed using the program Amberscript. To safeguard the privacy of the respondents, the transcripts are anonymised and not shared with third parties to ensure the privacy of the respondents. The data has been summarised, where findings emerged from the data organically, without being restricted by the predetermined coding scheme.

## 4.8 Ethical considerations

Prior to conducting this research, this research is ethically approved by the ethics committee at the University of Twente. In addition, as is noted in the ethical approval, respondents will give verbal consent that their answers are allowed to be analysed in this study. This is asked prior to an audio recording and is repeated at the beginning of an audio recording.

## 4.9 Conclusion

To conclude, this research is a qualitative, exploratory case study in which multiple stakeholders have been interviewed to discover how the upcoming implementation of the Wearable Breathing Trainer can be supported by sustainable supply chain design choices. The study population consists of a designer of a research group, a CEO of a production company, and an insurance company. These individuals are the ones that either design the Wearable Breathing Trainer, will produce the Wearable Breathing Trainer, or possibly reimburse it. After the interviews, the data has been transcribed and summarised.

## Chapter 5: Condition

This chapter dives into the first dimension of the NASSS framework. The condition studied in this research is dysfunctional breathing. This is a respiratory disorder characterised by an abnormal breathing pattern, such as hyperventilation (see Figure 10).

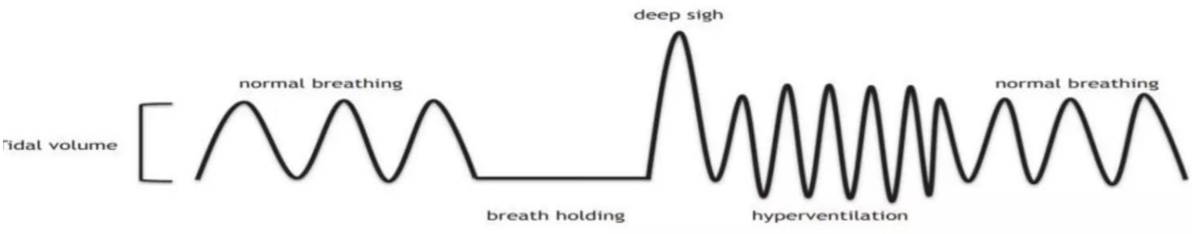


*Figure 10. A dysfunctional breathing pattern*

*(Source: Vidotto et al., 2019).*

### 5.1 Prevalence

Because of an underdiagnosis or misdiagnosis in clinical practice, the prevalence of dysfunctional breathing is imprecise (Vidotto et al., 2019). However, it is estimated to affect more than 5% of the children (*SIA Projecten*, z.d.). For the whole population this estimation is 9.5% (Vidotto et al., 2019), being more common in women and in people with asthma (Thomas et al., 2005).

### 5.2 Comorbidities

Dysfunctional breathing can be simultaneously present with other cardiopulmonary diseases or other neurological diseases. An example of this would be heart failure or asthma. Moreover, dysfunctional breathing can also be caused by psychogenic causes, like anxiety (Vidotto et al., 2019).

### 5.3 Symptoms

People with dysfunctional breathing can experience various symptoms, including shortness of breath, chest tightness, fatigue, and dizziness. Symptoms of dysfunctional breathing are often times provoked by for example a panic attack, exercising, or by singing (Barker et al., 2020). Exhibiting these symptoms can make comorbidities even worse (Vidotto et al., 2019).

### 5.4 Diagnostic methods

The gold standard diagnostic criteria, which is a test that has a definitive diagnosis for a disease (Gold et al., 2010), is missing for the diagnosis of dysfunctional breathing. Due to the absence of a golden standard, there are high rates of misdiagnosis or underdiagnosis. Therefore, it is difficult to accurately determine the prevalence of dysfunctional breathing (Boulding et al., 2016), and thus difficult to give patients the correct treatment (Vidotto et al., 2019).

The path of a patient with dysfunctional breathing starts at a general practice. The general practitioner then does an anamnesis, which is fundamental in making a diagnosis. The patient is then referred to the physiotherapist to be examined and get treatment. The physiotherapist examines firstly a patient's breathing pattern during rest and during a provoked attack. It is common for children with dysfunctional breathing to exhibit a thoracic dominant pattern, have an increased respiratory rate, an increased sigh rate, and do a lot of mouth breathing (Barker et al., 2020).

### 5.5 Current treatment

The treatment of dysfunctional breathing starts with body awareness, where patients become aware of their breathing (Gard et al., 2019). Subsequently, patients start with their daily breathing exercises, which are coordinated by a physiotherapist (Vidotto et al., 2019). The breathing exercises are tailored to match with the patient's goals, aiming to return to a normal breathing pattern (Barker et al., 2020).

## 5.6 Conclusion

To conclude, dysfunctional breathing is a respiratory disorder that is characterised by an abnormal breathing pattern and can be simultaneously present with other cardiopulmonary diseases or other neurological diseases. The prevalence is imprecise due to an underdiagnosis or misdiagnosis in clinical practice, but it affects approximately of the children. People with dysfunctional breathing can experience various symptoms and therefore an optimal treatment approach is necessary to prevent long-term health problems. The current treatment consists of appointments at a physiotherapy practice and daily breathing exercises that patients are required to do at home.

# Chapter 6: Technology

The technology that is explored within this research is the Wearable Breathing Trainer, which is a personalised medical wearable. Medical wearables are currently one of the most promising devices in modern medicine (Kang & Exworthy, 2022).

This chapter dives into the second dimension of the NASSS framework (see Figure 2) to help predict whether and how this healthcare technology could be successfully implemented, while also applying sustainable supply chain design choices. First of all, it dives into the material features of the technology in order to fully understand the three different prototypes of the Wearable Breathing Trainer. Next to this, multiple strategies are described that could potentially slow and close the loop of the Wearable Breathing Trainer. Lastly, this chapter describes the type of data that this wearable generates.

## 6.1 Material features

The Wearable Breathing Trainer is a smart textile vest. Smart textile can be defined as electronic systems with advanced functionalities that are integrated into fabric or clothing (Siering et al., 2019).

For the product design of the Wearable Breathing Trainer, three different options have been designed by designers from a research group. One of these designers has been interviewed to collect information about each of the three design options. One design is based on a modular approach. The other two designs are not modular and the sensor is either knitted-in or laminated onto the vest. Modular products contain separable parts that can be replaced.

### 6.1.1 Modular design

The modular design option is the functional prototype, which has been described by the designer (2024). This design is used during the user study of the Wearable Breathing Trainer and has been visualised in Figure 11. It has a sensor, which is developed by the company Breathpal, and can be removed from the vest. The sensor can be placed into a tunnel in the vest which could be compared to a skirt that contains an elastic band. This sensor can monitor the breathing, as it can measure the change in circumference of the chest and abdominal height.

*Figure 11. The modular design of the Wearable Breathing Trainer*

*(Source: SIA Projecten, z.d.).*

During the exercises at the physiotherapy practice, the hands of both the physiotherapist and the patients are held on the chest and the abdomen. The patients then has to breath towards the hands on the abdomen, while the hands on the chest remain still. To mimic these exercises of the paediatric physiotherapist, the Wearable Breathing Trainer needs to have tactile stimulation, which are gentle vibrations. This requires complex patterns, which are also called vibration motors. According to a CEO from a production company (2024), they have a product that can be used for this. As stated by the designer (2024), the vibration motors are also removable and can be installed modularly based on the patient's body measurements for optimal placement of the vibration motors. This is a string with either three or five vibration motors which are placed onto the vest with Velcro tape. The bellybutton of a patient would be the centre of the vibration motors. Two of these motors have to be placed on the side of the belly and the other motors could be placed in between. With this design option, paediatric physiotherapists would have to be made responsible for the correct placement of the sensor and motors onto the vest. Since this could be slightly difficult in the beginning, a manual would be required.

The advantages of this modular design is that the components can be removed, it is washable when the components are removed from the vest, it is flexible in placing the components on a patient, and if one component is broken it can be replaced. Since the vest will be used daily for ten minutes in resting state, the expectation from the designer (2024) is that the vest should not have to be washed often.

This modular design, however, has different components that should be taken into account as it could potentially hinder the use of the Wearable Breathing Trainer according to the designer (2024). Since these components can be removed, a child could remove everything themselves, which could damage the wearable more quickly. In terms of regulations regarding the safety of children's clothing one must pay attention to loose parts and batteries. For example the control module has to be closed in such a way that a child cannot touch the battery. Another disadvantage is that the paediatric physiotherapist could place the components incorrectly. Furthermore, these different components could be less aesthetically pleasing to wear. This is due to the fact that this modular design does not have two layers of textile, making the electronics visible. This could lead to patients feeling ashamed to wear this wearable.

As described before, the sensor could be removed and replaced once it is broken. However, it is up to the production company whether they choose to repair or even remanufacture a component or immediately dispose it. Also, the control module, where the sensor and vibration motors must be clicked onto, is a weak point according to the designer (2024). If this sensor is replaced too often, the control module can thus break. The sensor is also clicked onto the connection point with a metal snap button. Therefore, this design has metal in the textile. Cutting the hard parts from the textile, could be a viable option to use during the recycling process, as metal must be separated from plastic (Stubbe et al., 2024). It is up to the company, responsible for this recycling process, whether the metal will be cut out from the textile as it adds another step into the recycling of this wearable.

### 6.1.2 Knitted-in design

In the non-modular design, the sensor is knitted into the vest. It consists of two layers with the inner layer containing all electronics, which is shown Figure 12. According to the designer (2024) the electronics are attached to the fabric by pouring, for example silicone. Everything, except the control module which will be clicked on, is therefore no longer removable and stuck to the fabric making it more difficult to separate it from the textile. The knitting of the vest is done in one production step with a circular knitting machine. The sensor and also the outer layer and inner layer are thus made in the same production step.

*Figure 12. The knitted-in design of the Wearable Breathing Trainer*

*(Source: SIA Projecten, z.d.).*

An advantage of this non-modular option is that the components are seamlessly integrated. The vest also has no loose components and the electronics are not visible from the outside, which could improve the ease of use and make the vest more aesthetically pleasing to wear. Previously there has been a design where the vest was in a bright colour with light bulbs attached to it, according to the designer (2024), which is visualised in Figure 13. This shirt was designed specifically for a younger target group of children between six and twelve years old. Since it was noticed by the research group that the target group would be a wider range of patients – between eight and eighteen – the design was not suitable anymore given that most patients voiced a preference towards a design that is not really noticeable.

*Figure 13. A previous and more colourful design option*

*(Source: SIA Projecten, z.d.).*

According to the designer (2024), a disadvantage of the knitted-in design (see Figure 12) could be that the components are always in a fixed place which might not be necessarily the optimal placement of these components as the product will be used for different patients. This could be solved by providing different sizes of the vest, thus making it possible to wear for all users.

As described before, the control module is in this design still removable as it can be clicked on and off the wearable. So if there is a malfunction with this control module, it can be repaired or remanufactured. Since this control module contains a battery, it is required to be removable to be able to charge it. According to the designer (2024), it is most likely that if something is malfunctioning, it is probably the control module. The sensor and vibration motors are integrated into the vest and are not loose components. Furthermore, they are protected in a layer of plastic, called epoxy. The control module also does not have to be clicked on and off the loose components, which is necessary with the modular design.  Therefore it is assumed by the designer (2024) that they last longer in comparison to the modular design. There are no results yet if this knitted-in design can be washed, but the expectation is that it can be washed.

A disadvantage of this design is that if one of the component breaks that are integrated into the vest, the whole product would have to be replaced. According to the designer (2024), there are different options that would make it possible to disassemble. An example of this, could be unravelling the threads. The yarn can then be knitted again. However, this process will cost a lot of money, so it is up to the producer to decide whether it is feasible. The only problem is that where the piece of electronics is located, the yearn is rolled up. This is similar to metal studs on jeans, as that is not possible to disassemble either. To this day jeans are separated by simply cutting out the fabric containing the metal press studs. That is also what could happen with this wearable. The rolled up yarn would have to be cut out to separate it from each other in the waste. It would not be possible to reuse it, because there is an epoxy layer over it, but it can be separated. Another option would be to have the base yarn in a material that dissolves at a certain temperature, so that only the silver yarn remains and are therefore separated from each other. The question is whether it is ultimately profitable.

### 6.1.3 Laminated design

With this third design option, the sensor would be laminated onto the vest. This means that meandering conductive structures are applied to a foil, which is then laminated to textile. For the production of this design the vest would first need to be knitted. Only then the sensor can be laminated on there. According to the designer (2024), laminating is often a heat process to press the sensor on. This ensures a polished result, but is sensitive to washing, in addition to being an extra production step. For the laminated design, there is one textile layer needed, one adhesive layer, and then the laminate that is placed upon the vest. The advantage of laminating is that it only happens on one side of the textile. Therefore, it could be laminated onto the inside of the textile to ensure it will not be visible from the outside. A disadvantage of laminate is that there is often no stretch, which reduces the comfort of wearing this vest.

Another advantage of laminating is that it can be delaminated afterwards. After the wearable has been used, a heat treatment can be performed to remove the sensor. The question, however, is whether a production company would want to perform this process of delamination. After this process, the components can be separated.

If the sensor can also be reused, is not yet known by the designer (2024). The sensor is laminated onto the vest at a certain temperature, but if the temperature during the delamination process is too high it could damage the whole sensor or make it less reliable (Ho et al., 2014). An alternative approach to preserve sensor functionality, could be using lower-temperature delamination techniques or use non-thermal methods, such as laser cutting (Wang et al., 2023).

## 6.2 Circular product design strategies for slowing and closing loops

With the data collected about the different design options, multiple strategies have been formed to help slow and close the loop of the Wearable Breathing Trainer. These strategies are based on the strategies of Bocken et al. (2016), shown in Figure 9.

### *6.2.1 Designing long-life products*

To slow down the loop of the Wearable Breathing Trainer, it is beneficial if the wearable would be designed in such a way that customers trust it and can easily use it (Bocken et al., 2016), as this fosters product longevity (Dissanayake, 2019). This level of trust could be different for each of the three designs.

The designer (2024) assumes that the use of the modular design is slightly more difficult to use in comparison to the other designs, since the end-user is responsible for the correct placement of the sensor and vibration motors onto the vest. With this design a child is also able to remove all components themselves, with could make it less safe. Another assumption from this designer is that this design is less aesthetically pleasing to wear due to the fact that the electronics are visible.

With the knitted-in design the components are seamlessly integrated. The vest has therefore no loose components and the electronics are thus not visible. The designer (2024) assumes this could improve the ease of use and make the vest more aesthetically pleasing for patients to wear.

With the laminated design, the electronics can be laminated onto the inside of the textile and are therefore not visible from the outside. However, according to the designer (2024) there is often no stretch in laminate, which could possibly reduce the comfort of wearing this vest.

### *6.2.2 Designing for product-life extension*

Another strategy to slow down the loop, is by designing for a product-life extension. This strategy is aimed to create a design that is suitable for maintenance, repair, technical upgrading, and dis- and reassembly (Bocken et al., 2016).

According to the designer (2024), the modular design is quite easy to repair, upgrade, and to dis- and reassemble, since all components can be removed from the vest. For example, if one of the components is broken, it can be repaired or replaced by a new component. If the wearable is then fully restored, it can be reused and sold again, or leased again as a refurbished product.

For the knitted-in design, this is more difficult. Here the components are knitted into the vest and only the control module is removable from the vest and can be repaired. The other components are integrated into the vest and can therefore not be repaired. So if the control module is broken, it can still be repaired and then sold or rented as a refurbished product. If one of the other components are broken, it would not be possible to repair it, as they are integrated into the vest. According to the designer (2024), it would not be possible to reuse components integrated into the vest, since there is a layer of epoxy over it.

With the laminated design, the components are also integrated onto the vest. The control module can be removed and could therefore be repaired or replaced. After this, it could still be reused as a refurbished product. The sensor can be delaminated from the vest. However it is unknown whether the sensor will still work, since the delamination process could damage the sensor. If a delamination technique is chosen where the sensor continues to work, it could be reused and laminated onto a refurbished product (designer, 2024).

The modular design is less suitable to be maintained, compared to the other two designs, as the components are loose and could therefore break more easily.

### *6.2.3 Design for dis- and reassembly*

To close the loop of the Wearable Breathing Trainer, the wearable can in this case be designed for dis- and reassembly. This strategy aims to separate and reassemble products and parts easily (Bocken et al., 2016).

According to the designer (2024), the modular design can easily be reassembled, since the components can be removed and not integrated into the vest. Furthermore, this design can also be separated. There is metal from the sensor incorporated into the textile and this should be cut out during the recycling process.

Whenever the control module of the knitted-in design is broken, it can still reassembled. However, the other components are integrated into the vest and can thus be not reassembled anymore. This design could be separated by unravelling the threads. Wherever the yarn is rolled up, it would have to be cut out, to separate is from the other pieces.

For the laminated design only the control module can be reassembled, just like the knitted-in design. This design could be separated through a delamination process. The components are then delaminated from the textile through a heat treatment.

## 6.3 Type of data generated

With the use of the Wearable Breathing Trainer data is generated and processed. Good and reliable measurements of breathing patterns in wearables are a challenge (*SIA Projecten*, z.d.). Current measurements of the respiratory rate (RR) can be made with electrocardiogram (ECG) plaque sensors (Charlton et al., 2016). While this method is quite accurate, they can be uncomfortable for the patient (Hussain et al., 2023). There is also a non-invasive method that can measure someone's lung volume using two bands that are around the thorax and the abdomen. This alternative method is called the Respiratory Inductance Pethysmography (RIP) method (Marlin & Deaton, 2000). To apply this method on the Wearable Breathing Trainer, the Breathpal sensor has been developed (*SIA Projecten*, z.d.).

Besides the sensor that generates data on the lung volume, the Wearable Breathing Trainer also has vibration motors. These vibration motors provide vibrotactile feedback, which are vibrations to make patients more aware of when they are breathing through their abdomen (Siering et al., 2019). The aim is to return to a normal breath, which is an abdominal breath (Chapman et al., 2016). This helps children to gain skills that solve the problem of dysfunctional breathing. Additionally, the mobile device has added game elements to enhance the engagement of children (Siering et al., 2019).

## 6.4 Conclusion

To conclude, the modular design is the functional prototype for the clinical studies. All components of this design option can be removed and repaired, but may get damaged more easily. Only the control module from the knitted-in design and the laminated design can be removed and repaired, as the sensor and vibration motors are integrated into the wearable. However, these designs may last longer, as it is protected by a layer of epoxy. Multiple strategies can be applied to each of these designs to potentially slow and close the loop of the Wearable Breathing Trainer. These strategies are designing long-life products, designing for product-life extension, and a design for dis- and reassembly. The Wearable Breathing Trainer is able to measure a patient's lung volume and provide vibrotactile feedback, which can help patients to return to a normal breathing pattern.

# Chapter 7: Value proposition

This chapter dives into the third dimension of the NASSS framework (see Figure 2). Two business models have been made according to a Business Model Canvas structure to determine the value proposition of the product. The first business model is the Economic Business Model Canvas and the second business model is the Environmental Life Cycle Business Model Canvas (see Section 3.2). The information incorporated into the business models is derived from an interview with a CEO from a production company and an interview with a designer from a research group. Since there are three design options possible for the Wearable Breathing Trainer, all three designs are considered in the business model. Since it is not clear yet what the customer segments are, more options in terms of purchasing or renting the product are considered in this business model. The last part of this chapter discusses multiple strategies that could potentially slow and close the loop of the Wearable Breathing Trainer. These strategies have been explained in Section 3.6.

In the last part of this chapter (Section 7.4) the criteria to reimburse the Wearable Breathing Trainer are described. Reimbursement is part of the downstream value of the Wearable Breathing Trainer, which is another topic in dimension three of the NASSS framework (Greenhalgh et al., 2017). The information regarding the reimbursement of the Wearable Breathing Trainer is derived from an interview with an advisor from an insurance company.

## 7.1 Business Model Canvas economic layer

In Figure 14 the Economic Business Model Canvas is shown. It gives an overview of the nine fundamental elements of an organisation´s business model. This business model visualises the interconnections between the elements and the added value from creating a new product (Joyce et al., 2015). In the following subsections each of these elements are described in more detail.

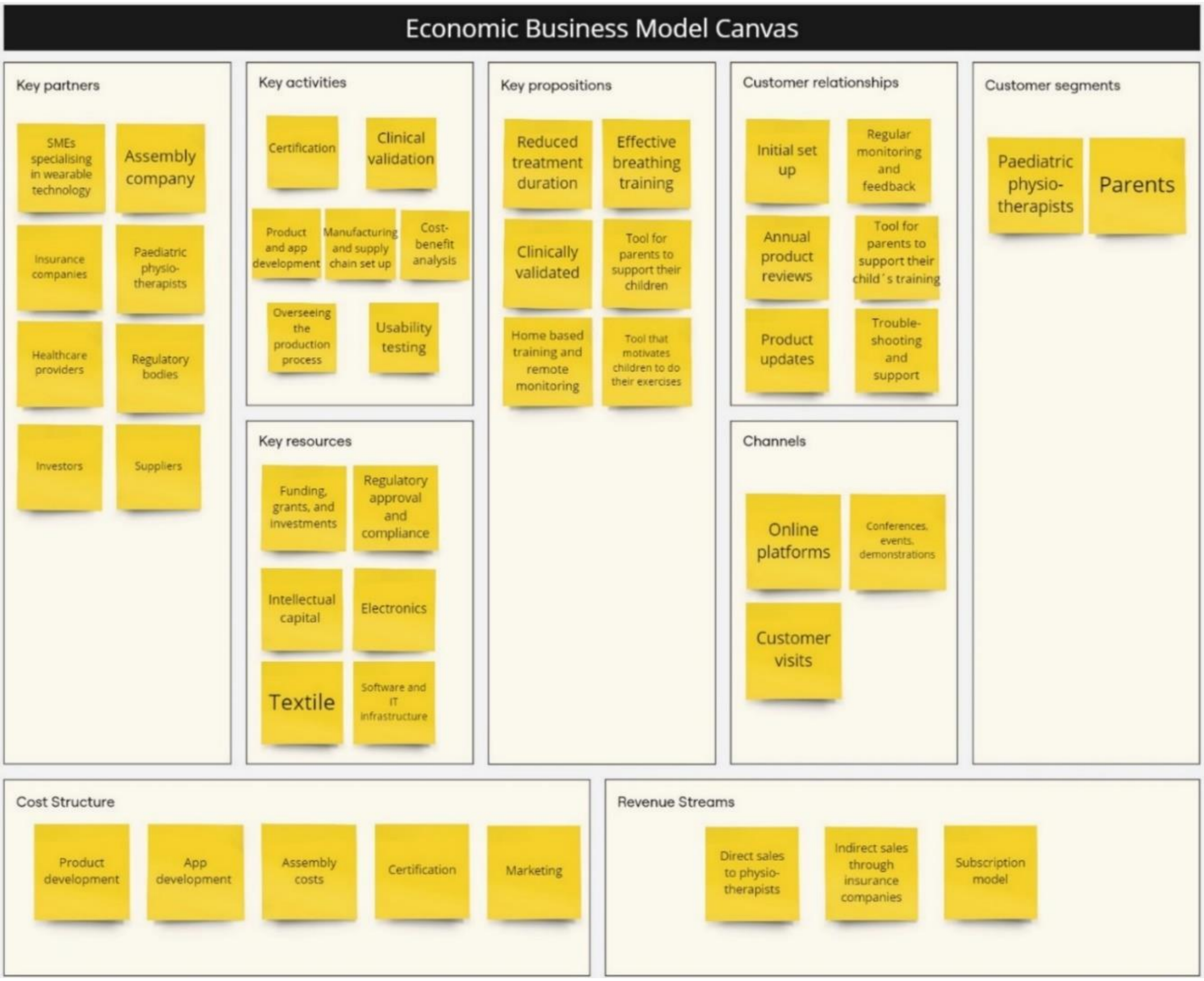


*Figure 14. Economic Business Model Canvas for the Wearable Breathing Trainer*

### 7.1.1 Key partners

According to the CEO (2024), there are multiple key partners that enhance the operations and success of the production company. First of all, there are SMEs specialising in wearable technology. The production company collaborates with them for the development of new products. Next to this, the company converses with insurance companies and health care providers to discuss whether the product can be reimbursed and how it should be brought into the healthcare industry. The company also, in this specific case, converses with paediatric physiotherapists to discuss their vision and wishes for the new product.

Furthermore, the company has contact with regulatory bodies to ensure that the product follows all the fitting standards and safety measures before it is brought to the market. Next to this, the company searches for investors to invest in the product and for suppliers to make different components of the product. Lastly, the company enters an agreement with an assembly company to assemble the product for them.

### 7.1.2 Key activities

According to the CEO (2024), there are certain activities this company intends to do in order to deliver its value proposition. One of these activities is getting the certification of this wearable, by following the Medical Device Regulations (MDR), to get access to the market. Next to this clinical studies will be done to prove and claim that the wearable is clinically validated. On top of this, a cost-benefit analysis will have be done, as it helps determining whether the benefits outweigh the costs.

In terms of the product itself, the wearable and app should be developed until there is a final approved product. During this time the manufacturing and supply chain will also be set up. After this the production process will be overseen by the company. At the same time usability testing should be done to ensure end-users will have little trouble using the Wearable Breathing Trainer.

### 7.1.3 Key resources

To develop, produce and bring this wearable to the market, multiple resources are needed. During the research & development phase, funding comes from sponsorships. When the prototype is finalised, the production company will have to allocate its finances toward the key activities that are necessary for bringing the product to the market. Furthermore, textile and materials for the electronics need to be available to produce the Wearable Breathing Trainer. There should also be a software and IT infrastructure for this medical application. Lastly, intellectual capital is needed to oversee the activities and the overall direction and health of the company (CEO 2024).

### 7.1.4 Key propositions

The key propositions of the Wearable Breathing Trainer are reasons as to why buyers would want to buy this wearable. This wearable is currently not clinically validated and therefore the following reasons are assumptions from the CEO (2024). The value of the Wearable Breathing Trainer could be described via pain relievers and gain creators. Pain relievers can help alleviate customer pains and gain creators state how a product or service adds value to the customer (Pokorná et al., 2015). A big pain reliever is that using this wearable leads to a reduced treatment duration for children, as it is an effective form of breath training. Gain creators are that this wearable is a tool for parents to support their child in their training, it motivates children to do their breathing exercises, and it enhances the accessibility and convenience through home based training and remote monitoring.

### 7.1.5 Customer relationships

To build and maintain customer relationships, the company has multiple strategies. First of all, the company offers a manual and guidance to customers for the initial set up of the Wearable Breathing Trainer. The company also performs troubleshooting to identify and solve problems of this product, which strengthens the relationships with customers. Furthermore, the company engages with their customers to receive feedback from them. Lastly, the company plans to look at product reviews from customers (CEO 2024).

### 7.1.6 Channels

Customers can reach the company behind the Wearable Breathing Trainer through different channels. The production company has a website, first of all, where customers can contact personnel. The company also attends medical conferences and organizes events and demonstrations. Lastly, visits to customers are planned, according to the CEO (2024), to discuss the customer’s level of satisfaction with the product. The delivery channels of the Wearable Breathing Trainer are directly via the production company or via a renting company.

### 7.1.7 Customer segments

In this case of the Wearable Breathing Trainer the customer segments are either directly or indirectly physiotherapists. It is not clear yet whether physiotherapists buy the wearable directly or lend them from a rental company or if such a wearable will be reimbursed. Another viable option would be that parents rent the wearable from a rental company.

### 7.1.8 Cost structure

According to the CEO (2024), there are several costs involved in creating a product, getting access to the market and then trying to sell it to customers. For the Wearable Breathing Trainer the largest expenses go to the development of the product (100 to 200 thousand euros), the development of the app (50 to 100 thousand euros), the assembly costs, including samples and templates (50 thousand euros), certification costs (50 to 100 thousand) and marketing costs (50 thousand). Yearly costs, for example for marketing or the assembly costs per batch, is not known yet. This depends on the what the market approach will be and how many products approximately will be sold.

### 7.1.9 Revenue streams

Since it is not clear for the company yet who will directly buy this product, there are multiple types of revenue streams possible. The company will either receive direct sales from physiotherapists, indirect sales through insurance companies or receive money through subscriptions of clients.

## 7.2 Environmental Life Cycle Business Model Canvas

Joyce et al. (2015) created also an environmental layer to study the environmental impacts of a business case. This environmental version of the Business Model Canvas is shown in Figure 15.

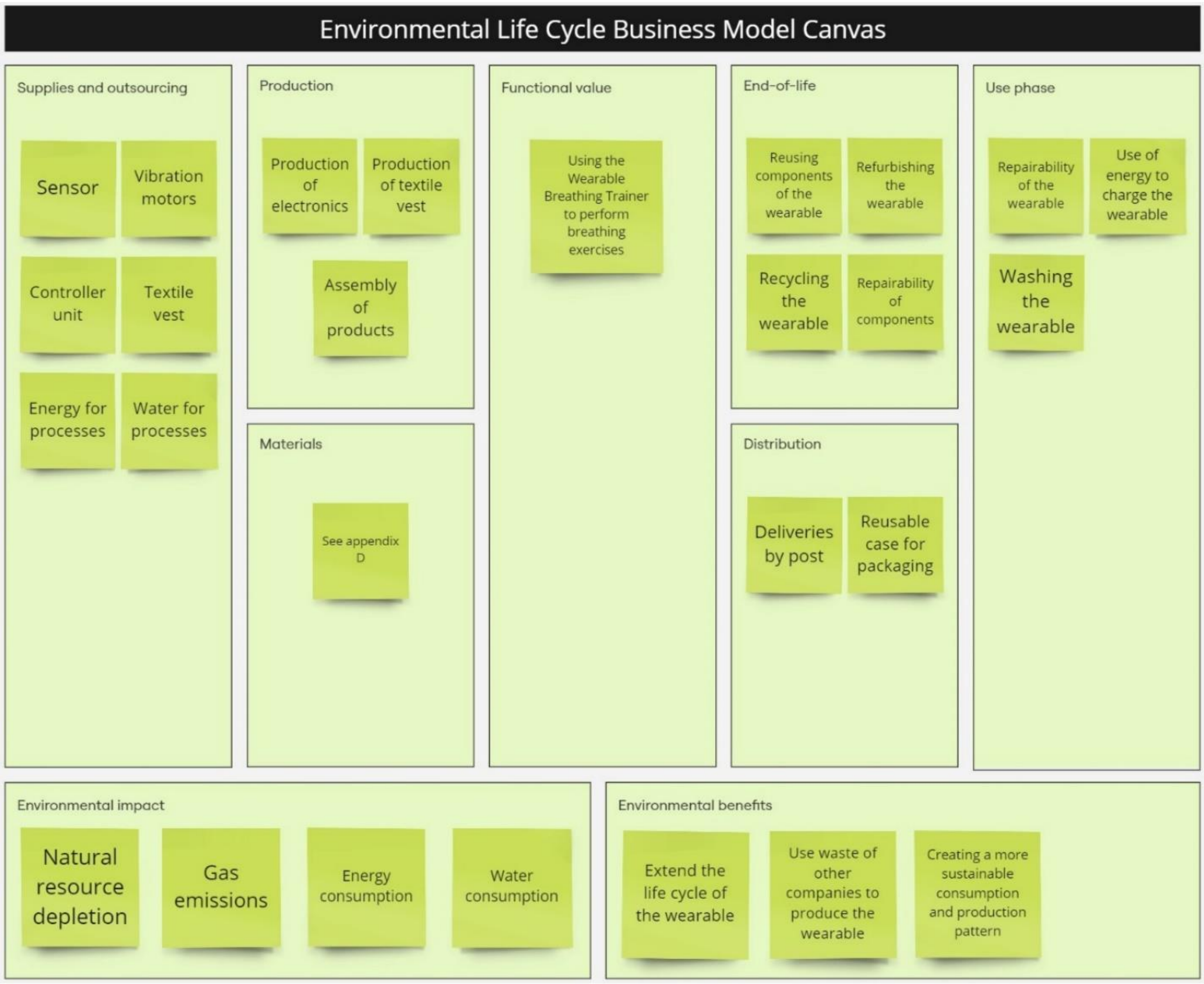


*Figure 15. Environmental Life Cycle Business Model Canvas for the Wearable Breathing Trainer*

### 7.2.1 Supplies and outsourcing

The Wearable Breathing Trainer consists of different components that each will be made by different suppliers. This means that there needs to be a supplier who makes the sensor, one who makes the vibration motors, one who makes the wiring loom for the vibration motors, one who makes the printed circuit boards for the vibration motors and the sensor, and one who makes the app. As described before, the company enters an agreement with an assembly company to assemble the product for them. The company recommends multiple suppliers to the assembly company, which they can contact to produce components of the Wearable Breathing Trainer. According to the CEO (2024), the assembly company can also choose other suppliers as long as they fit the requirements of the production company. Therefore it means that all components are sourced from other companies. It is not clear yet whether these components will be sourced from the Netherlands, countries close to the Netherlands or from countries in for example Asia. The CEO (2024) states that a supplier is chosen based on how much the price for the components are, what quality it is, and how much control they want over this process. With countries in Asia, the company assumes that the price will be lower, but the control over the process will also be lower.

### 7.2.2 Production

For the production of the Wearable Breathing Trainer two industries are involved: textile and electronics. Different components from these industries would have to be produced in order to assemble the product. This entails a Nylon vest from the textile industry, and the sensor and vibration motors from the electronics industry.

How the assembling process is structured, depends on the design that is chosen for the Wearable Breathing Trainer. With a modular design, all components can be removed and would not have to be assembled. With the knitted-in design, there would be one production step where the sensor and vibration motors, and also the inner and outer layer of the vest, are knitted with a circular knitting machine. The production process of the laminated design is similar to the knitted-in design, as the vest itself would first have to be knitted, but there is an additional step where the electronics would have to be laminated onto the vest (designer, 2024).

### 7.2.3 Materials

The vest from the Wearable Breathing Trainer is made of many materials. The list of materials needed to make each of the three possible design options are displayed in Appendix C.

### 7.2.4 Functional value

The functional value is the essence of a product. In this case the wearable is made to be worn and used by children with dysfunctional breathing problems to perform breathing exercises.

### 7.2.5 End-of-life

The end-of-life of the Wearable Breathing Trainer is the moment the wearable is not functioning anymore. The company then decides what is most beneficial for them to do with the returned products. They can simply dispose it, but if the company wants to explore ways to expend their responsibility beyond the value of their products, the company can try do diminish its impact on the environment by either repairing, refurbishing, or recycling the product (Joyce et al., 2015). There are different circular design and business model strategies this company could apply to each of the design options. These are described in more detail in Section 6.2 and 7.3.

### 7.2.6 Distribution

According to the CEO (2024), the company plans to ship their products by post with for example PostNL or DHL. If the product is sold directly to physiotherapists it will have to be sent to their address. If physiotherapists lend the product from a service point, the products will be shipped to different service points all over the country.

### 7.2.7 Use phase

The use phase describes the user´s impact on the wearable in terms of damage to the product and the environment (Joyce et al., 2015). First of all, when a client uses the product and it gets damaged it will need to be repaired or disposed by the company. Furthermore, energy is used every time the client charges the Wearable Breathing Trainer. Since this wearable is worn by children, it also needs to be washed sometimes. This way water as well as energy is consumed. To give an example, a fleece jacket, which is made of polyester, could be compared with the modular design that is also made of polyester. The fleece jacket has a total footprint of 66 pounds, which amounts to the weight of carbon dioxide ($CO_2$) emissions generated over its lifecycle (Toyota et al., z.d.).

### 7.2.8 Environmental impact

The development of wearables involves two different production lines: textile manufacturing and electronic manufacturing. Textile production impacts the environment in different ways. The textile manufacturing is known to pollute the environment and damage the water, air and soil (Norarmi et al., 2022). The main issues facing this industry are the greenhouse gas emissions, water use and pollution, toxic chemicals and waste disposal (Bianco et al., 2023). First of all lots of water is needed to produce textile and to grow fibres on land (Sandin & Peters, 2018). Next to this various chemicals are needed to grow crops for natural fibers (Bianco et al., 2023). Additionally, the production of textile pollutes approximately 20% of global clean water, where the dyeing and finishing of products releases toxic emissions. Moreover, it is responsible for 10% of global carbon emissions. For the spinning or knitting of textiles, for example, fossil energy is often needed, which causes emissions like $CO_2$ (*European Parliament*, z.d.) (Sandin & Peters, 2018). In terms of waste, less than half of the clothes people wear are currently being collected to reuse and recycle. The other half ends up in landfills. Only 1% of the clothes is actually recycled into new clothes. This is largely due to the fact that technologies that can recycle clothes into virgin fibres only recently emerged (*European Parliament*, z.d.) (Bianco et al., 2023).

Electronic manufacturing does also have an impact on the environment. Electronic waste, also known as e-waste is made up of old electronic devices that are discarded by their owners, often due to a short lifespan (Jain et al., 2023). Electronic waste is currently one of the largest and fastest growing waste streams, where approximately 62 million tonnes of waste is produced in the world. In 2022, less than a quarter of this waste had been recycled even though this waste contains valuable resources that can be reused if they are recycled (World Health Organization: WHO, 2024). E-waste is also considered hazardous waste. If the recycling of electronics is not properly managed, it may release toxic chemicals, which negatively impacts the environment and human health (Jain et al., 2023)(World Health Organization: WHO, 2024).

### 7.2.9 Environmental benefits

As described in Chapter 1, humanity faces several global crises, largely driven by unsustainable consumption and production patterns. Wearables currently contribute to these unsustainable practices due to short lifecycles, e-waste and energy consumption. Since this research studies circular strategies (see Figure 9) that could for example extend the life cycle of the Wearable Breathing Trainer by repairing the product or use the waste from other companies to produce parts of the Wearable Breathing Trainer, it potentially creates a more sustainable consumption and production pattern, which is beneficial for the environment. Sandin and Peters (2018) confirm that the reuse and recycling of textile reduces the environmental impact by reducing the production of virgin fibres and the amount of clothes that are incinerated and landfilled (Sandin & Peters, 2018).

## 7.3 Circular business model strategies for slowing and closing loops

Based on the business models that are formed in this chapter, multiple circular business model strategies can be applied to the supply chain of the Wearable Breathing Trainer. These strategies are based on the strategies shown in Figure 9.

### 7.3.1 Access and performance model

The loop of the Wearable Breathing Trainer could be slowed down through the access and performance model. This model provides a service to customers that they do not have to own the product. This could also be possible with the Wearable Breathing Trainer whenever the company would sell their products to a rental company or rent it to clients for a period of time. Another possibility is selling it to a physiotherapist, who then lets multiple patients use it instead of only using it for one patient and then returning it already. This way, the same product can be used by more customers as long as it is functioning well.

### 7.3.2 Extending product value

When the Wearable Breathing Trainer cannot be repaired anymore due to a broken component, there are still ways to exploit the residual value of the product and thus slowing down the loop of the Wearable Breathing Trainer. In the modular design, all components can still be used for another product, except for the component that is broken. For the knitted-in design and laminated design, the control module could still be used for another product if it is intact despite the sensor or vibration motors being broken. If the control module is broken, but the other components are still intact, they can be reused for a new product (designer, 2024).

### 7.3.3 Classic long life

This strategy focuses on delivering a long product life. There are differences in the expected life duration of the three design options. For example, the components of the knitted-in design is protected in a layer of epoxy. The control module also does not have to be clicked on and off the loose components, which must be done with the modular design. Therefore it is assumed by the designer (2024) that the knitted-in design, but also the laminated design, last longer in comparison to the modular design and therefore contributes to slowing down the loop of the Wearable Breathing Trainer.

### 7.3.4 Encourage sufficiency

Another strategy to slow down the loop of a product, is to encourage sufficiency and thus reducing the consumption of end-users. This can be achieved by offering service to customers when they need help and offer repairment services, so wearables do not have to be disposed as quickly.

### 7.3.5 Extending resource value

One strategy to close loops is extending resource value, which means a company can look into the possible ways the wasted or leftover materials can be recycled. However, at the moment the recycling of wearables faces significant challenges. There has been no feasible recycling classifications established for wearables yet and recycling technologies are not yet developed to recycle wearables (Xie et al., 2021)(Köhler & Som, 2013). Therefore, the recycling possibilities for the Wearable Breathing Trainer are excluded in this research and shall need to be studied in further research.

### 7.3.6 Industrial Symbiosis

Another strategy to close the loop of the Wearable Breathing Trainer, is considering the waste of this product as a resource for another product for another company. As of now, the company does not have an idea for this yet (CEO, 2024). Waste from other companies who have recycled their used or leftover nylon fibres, could be used for the production of the Wearable Breathing Trainer to decrease virgin material use (designer, 2024).

## 7.4 Reimbursement of the Wearable Breathing Trainer

In order for the Wearable Breathing Trainer to be reimbursed, there are certain criteria a wearable must comply with before the costs can be covered by an insurance company.

Brönneke et al. (2021) describe that in order for wearables with a medical purpose to be either reimbursed or compensated, they often need to fulfil additional requirements. Even with having a CE-marking and complying to the Medical Device Regulations (MDR), it does not guarantee a direct claim to remuneration. Getting reimbursement within the healthcare industry depends on various factors including the type of technology, the structure of the healthcare system (e.g. public or private insurance companies), insurers and regulatory authorities assessing the device, and the medical contexts of use (e.g. diagnosis or treatment). Additionally, the decision for remuneration on new medical wearables is based on the evaluation of the Health Technology Assessment (HTA). The clinical effectiveness and the economic effectiveness can be respectively proven with randomised controlled trials (RCTs) and health economic evaluations (Brönneke et al., 2021).

An advisor from an insurance company (2024a) confirmed that it is indeed necessary to prove the clinical effectiveness of the wearable by doing an RCT, in which the treatment with the Wearable Breathing Trainer is compared with the current treatment to see whether the new treatment provides significant health benefits (Advisor, 2024).

As described Brönneke et al. (2021), the insurers and regulatory authorities assess the device. More specifically, the outcomes of the clinical study are discussed by an expert group of the ‘Zorgverzekeraars Nederland’ (ZN) association. Together with experts from the healthcare sector, patient representatives, and the developer of the Wearable Breathing Trainer, they will decide whether the Wearable Breathing Trainer will be admitted to the insurance package (Advisor, 2024b).

This decision will not only be based on the clinical effectiveness of the wearable, but also on the cost-effectiveness. This means even if a wearable is proven to be effective, it will not be insured if disproportionately expensive (being excessively costly compared to its value). Another way the cost-effectiveness of this wearable will be assessed, is by analysing which future health costs can be avoided (Advisor, 2024a). In this case the wearable could potentially avoid the costs of more physiotherapy appointments or other costs related to long-term complaints of someone with dysfunctional breathing.

Moreover, the wearable should comply indeed with the MDR, the General Data Protection Regulation (GDPR) and other regulatory requirements. Another criteria that influences the decision is what the added value of this wearable is to the patient as well as the healthcare professional, in this case the physiotherapist (Advisor, 2024a).

Currently, much research regarding the reimbursement of wearables is done by Zorginstituut Nederland (ZIN), NZA and DigiZo. They are studying whether and when a wearable will be reimbursed, since wearables are still a new form of care within the healthcare system (Advisor, 2024b).

## 7.5 Conclusion

To conclude, the economic business model helps envisioning a production company what the business case of the Wearable Breathing Trainer looks like and what value it brings to their customers. Simultaneously, the environmental life cycle business model helps bringing to light how the product impacts the environmental across all stages of its life and how environmental benefits could be enhanced. Creating an access and performance model, extending the product value, delivering a classic long life, encourage sufficiency, extending resource value, and applying industrial symbiosis, are all strategies that could potentially slow and close the loop of the Wearable Breathing Trainer. The different design options and different ways of purchasing the wearable, result in different scenarios on how the strategies can be used to slow down or close the loop of the Wearable Breathing Trainer. Lastly, in order for the Wearable Breathing Trainer to be covered by insurance, it should be clinical effective, cost effective, comply with the MDR, GDPR and all associated regulations, and add value to the patient as well as the healthcare professional.

# Chapter 8: Requirements from the perspective of physiotherapists

To study how the upcoming implementation of the Wearable Breathing Trainer could be supported by sustainable supply chain design choices, it is also relevant to reflect on findings regarding the fourth and fifth dimension of the NASSS framework (Chapter 3). These dimensions focus respectively on the adopters of the healthcare technology and the organisation, which are in this case paediatric physiotherapists working in a physiotherapy practice. They are the ones who ultimately have to use this wearable in their treatment and it is therefore relevant to identify the requirements that the Wearable Breathing Trainer must adhere to before they would want to implement it in their practice. In this chapter the main requirements for the implementation of the Wearable Breathing Trainer are described. These findings are derived from another research on the implementation of the Wearable Breathing Trainer and are from the perspective of paediatric physiotherapists (Schreuder, 2024).

The findings of Schreuder (2024) suggest that a big requirement is that the Wearable Breathing Trainer must be easy to use, since physiotherapists need to apply it in their treatment (Schreuder, 2024). As described in Chapter 6, the knitted-in design and the laminated design are more easy to use compared to the modular design, since all components are already in place. With the modular design the physiotherapist would have to be made responsible for the correct placement of the sensor and motors onto the vest. Moreover, usability testing could be done to see whether there are any other usability issues with the prototype of the product (Almasi et al., 2023).

Another significant outcome is that physiotherapists think the wearable must be comfortable to wear for the patient (Schreuder, 2024). The comfort level depends on wearing the right size, but it also differs per design choice (designer, 2024). For example, the knitted-in design is the most comfortable to wear, followed by the laminated design and then the modular design.

Moreover, the price is also proven to be quite important for physiotherapists in case the wearable will not be reimbursed. Given that every physiotherapy practice has a certain budget, it may not be financially feasible to buy or rent it if the cost of the wearable is too high. Even if they are able to afford it, they might not want to purchase or rent it if they think the price is too high compared to the value of the wearable (Schreuder, 2024).

Additionally, the Wearable Breathing Trainer must also have an aesthetically pleasing design, since patients have to wear this. However, since these patients wear and use this wearable at home, this requirement is less important (Schreuder, 2024).

Other important requirements from the perspective of physiotherapists are that the technical usability of the wearable is not that difficult to learn as physiotherapists need to learn this outside of working hours, that the wearable is empirically proven to be effective, and that they have access to a free trial of the Wearable Breathing Trainer (Schreuder, 2024).

To conclude, physiotherapists place significant emphasis on the wearable being easy to use for them and the patient and it being comfortable for patients to wear. Additionally, the price of the wearable is also quite important. Lastly, if possible, it should also be an aesthetically pleasing design.

# Chapter 9: A comparison of the different design and purchase options

As described in Chapter 6, there are different options for the design of the Wearable Breathing Trainer. First of all, there is the modular design in which all components can be removed from the vest. There is also the knitted-in design in which the components are knitted into the vest. Lastly, there is the laminated design option in which the components are laminated onto the design. Since it is not clear yet what the final design of the Wearable Breathing Trainer will be, a comparison between the different design options has been conducted.

## 9.1 Comparison of different design options

Several criteria, that deem to be relevant in the decision regarding the design choice, are derived from the interviews with the designer, the CEO from a production company and the findings from a physiotherapist's perspective. From an economic perspective, the criteria are user comfort, ease of use, aesthetics and price deem relevant. Criteria that are relevant from an environmental perspective are maintenance, repairability, refurbishing, remanufacturing and a long-life product.

To discover what design is most suitable from an economic perspective and from an environmental perspective, a Multi-Criteria Decision Criteria Analysis (MCDA) has been carried out. The technique that has been used for this is the Analytical Hierarchy Process (AHP). The detailed procedure of conducting an AHP for our design options is displayed in Appendix D.

With the AHP a score for each of the design alternatives has been developed that is based on comparisons of each design under different criteria reflecting the stakeholders preferences. The stakeholders that are included for the economic point of view are the CEO of a production company and a group of physiotherapists. These stakeholders have been chosen, because they both need to invest money in this wearable. The CEO needs to invest money to produce the wearable, and the physiotherapists to buy or rent the wearable. Therefore, their preference as to what design is most beneficial for them are taken into account.

From an environmental point of view, the preferences of the CEO of the production company has been taken into account. The CEO is able to actually influence what sustainable practices will be applied to the life cycle of the Wearable Breathing Trainer. Therefore it is critical to know what design options align the most with his preferences regarding sustainable practices.

From studying the criteria regarding the design of the Wearable Breathing Trainer from an economic point of view, it seems that the knitted-in design would be the most suitable option to choose and the modular option the least suitable option to choose (see Table 2).

| **Design** | **Score from economic perspective** |
|---|---|
| Knitted-in design | 0.443 |
| Laminated design | 0.333 |
| Modular design | 0.225 |
| Sum | 1.000 |

*Table 2. Overall ranking from an economic perspective*

When the criteria regarding the design of the Wearable Breathing Trainer are taken into consideration from an environmental point of view, as can be seen in Table 3, it seems that the knitted-in design would also be the most suitable option to choose and the laminated design the least suitable option to choose.

| **Design** | **Score from environmental perspective** |
|---|---|
| Knitted-in design | 0.359 |
| Modular design | 0.335 |
| Laminated design | 0.306 |
| Sum | 1.000 |

*Table 3. Overall ranking from an environmental perspective*

## 9.2 Conclusion

To conclude, by carrying out a MCDA, it appears that the knitted-in design would be the most preferred design to choose when taking economic criteria into account, but also when taking environmental criteria into account.

# Chapter 10: Discussion

The primary aim of this thesis is to investigate how the upcoming implementation of a wearable for children with dysfunctional breathing into physiotherapy practices can be supported by sustainable supply chain design choices. This chapter discusses the key findings, the theoretical and practical implications, the limitations within this research, and recommends areas for future research.

## 10.1 Key findings

A combination of strategies can be applied to the supply chain of the Wearable Breathing Trainer to encourage sustainability. There are circular product design and business model strategies to slow and close the loop of the Wearable Breathing Trainer, which can be applied to the three design options and the two business models of the wearable. Additionally, the waste pyramid can be used to minimise the waste of the Wearable Breathing Trainer. The strategies that can be applied to the Wearable Breathing Trainer are illustrated in Figure 16, which is adapted from Thierry et al. (1995).

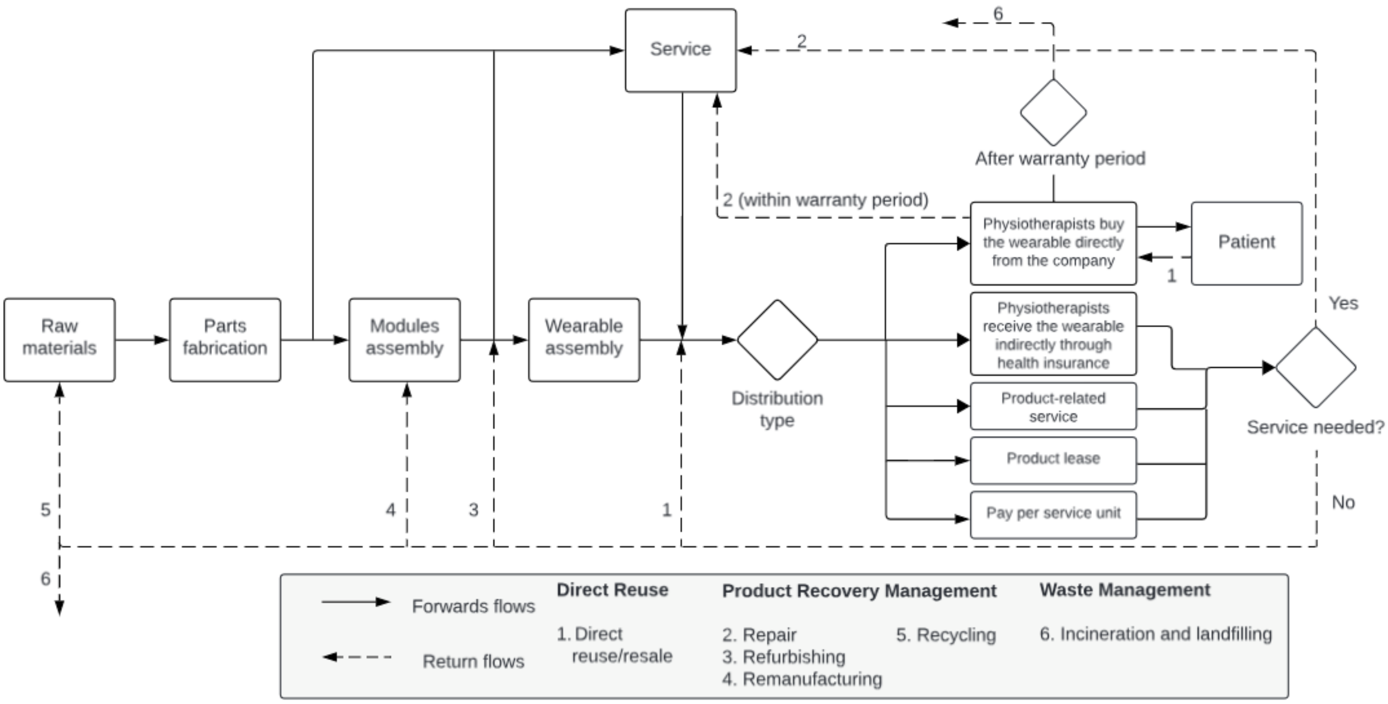


*Figure 16 Supply chain of the Wearable Breathing Trainer*

*(Source: (Thierry et al., 1995))*

(1) If the Wearable Breathing Trainer has been used by a patient and it is not damaged in any way, the wearable could be reused by another patient, which slows the loop of the Wearable Breathing Trainer. In case it does not work as effectively anymore or does not comply with medical standards anymore, it could still be reused as a breathing trainer that is sold on the consumer market.

(2) Even if the wearable is damaged, it might be possible to repair it. With the modular design, all components can be removed and therefore be repaired. With the knitted-in design and the laminated design only the control module can be repaired, as the sensor and vibration motors are integrated into the vest.

(3) For the Wearable Breathing Trainer to turn into a refurbished product, the components that were broken should be repaired and then assembled again. For the modular design all components can be repaired, if broken, and then turned into a refurbished product. For the

knitted-in design and the laminated design the sensor and vibration motor can be used for an refurbished product in case they are both not damaged, but only the control module is. The control module can be repaired and then be used again for the refurbished product. In case the sensor or vibration motor is damaged, the control module can be reused, but a new sensor and vibration motor should be integrated into the wearable to create a refurbished product.

(4) For the modular design it is possible to remanufacture a part of the control module, sensor or vibration motor, since all parts can be removed from the wearable. For the knitted-in design or the laminated design only parts from the control module can be remanufactured.

(5) In order to recycle materials from the Wearable Breathing Trainer, the electronic components ought to be separated from the textile. However, as described in Section 7.3.5, the recycling of wearables faces significant challenges. Therefore, the recycling possibilities for the Wearable Breathing Trainer are excluded in this research and shall need to be studied in further research.

(6) The materials that cannot be recycled, should unfortunately be incinerated or landfilled.

Applying these strategies could be a way of integrating sustainability into the supply chain of the Wearable Breathing Trainer.

The findings reveal that the knitted-in design is the most preferred design to choose for the Wearable Breathing Trainer when economic as well as environmental criteria are taken into account. This design is the most preferred primarily because it aligns with the wishes of the involved stakeholders. As previously stated, getting the support from stakeholders is crucial for a successful implementation (Kang & Exworthy, 2022). In this case, the support of physiotherapists is crucial, because they are ultimately the ones who have to implement it in their work. Therefore, it seems the knitted-in design is in this case the best design option to choose from, as it complies with the requirements and preferences of physiotherapists and the production company who hopes to sell this product to them. Moreover, incorporating the wishes and preferences of stakeholders in the design choice may foster sustainability as it enhances product longevity by fostering stronger user satisfaction. Their influence directly contributes to creating a product that better meets the user's needs (Dissanayake, 2019).

The findings also reveal that the CEO from the production company is willing to apply circular strategies into the production the supply chain of the Wearable Breathing Trainer. Simultaneously, the CEO does not want the strategies to hinder the user satisfaction as this also directly affects the sales. This aligns with the study of Gerova et al. (2020) who describe that stakeholders might be hesitant to apply sustainable practices, as they fear those practices might affect their technology or commercial success negatively (Gurova et al., 2020). This highlights that employees from a production company will think twice about the proposed circular strategies before they apply it in the supply chain of their products.

Lastly, the findings demonstrate that the Wearable Breathing Trainer should be clinically effective, cost effective, it should comply with the MDR, GDPR and other associated regulations, and add value to the patient as well as the healthcare professional. Much research is currently done on whether and when a wearable will be reimbursed, because wearables are still a new form of care within the healthcare system (Advisor, 2024). This highlights that it is quite uncertain to know in advance whether the Wearable Breathing Trainer will be reimbursed. Even though there is no certainty in advance, it is important that the wearable complies with the forementioned criteria to increase the likelihood that it will be reimbursed.

## 10.2 Theoretical implications

This qualitative research about sustainable supply chain design choices for the upcoming implementation of the Wearable Breathing Trainer, contributes to scientific literature in a number of ways.

The study of Powell and Godfrey (2023) describe how sustainability is most of the time overlooked and that it is therefore important to consider sustainability, especially during the design phase of wearables (Powell and Godfrey, 2023). However, there is a lack of knowledge in this field (Gurova et al., 2020). This study offers new insights into how sustainable supply chain design choices can be applied to different design options of the Wearable Breathing Trainer, thereby contributing to scientific literature.

Moreover, wearables are often times forgotten or thrown away, because the user is not involved in the design process of a wearable (Dissanayake, 2019). Simultaneously, the support of healthcare professionals is critical to successfully implement a wearable into the healthcare system (Kang & Exworthy, 2022). The fact that this study incorporates the wishes of the user in the design choice of the Wearable Breathing Trainer (see Chapter 8) does not only give an advanced understanding on what criteria a medical wearable must comply with to get support from healthcare professionals, but also enriches scientific literature with novel findings on how the user can be involved in the design process to foster product longevity.

Lastly, with the increasing integration of textile into the design of wearables, there are, according to the study of Gurova et al., (2020), concerns about the sustainability of such practices. At the same time, there is a lack of knowledge about a sustainable life cycle for wearables, making the link between fashion, technology, and sustainability an important topic. Since this research encompasses all those three areas, and describes how the life cycle of wearables could be more sustainable, it contributes to the scientific literature.

## 10.3 Practical implications

The findings from this study can give guidance to designers and developers of medical wearables, and production companies who produce medical wearables in regards to the reimbursement of medical wearables and to sustainable practices in the supply chain of medical wearables.

This study highlights that a production company can be willing to apply circular strategies as long as those strategies do not hinder the user satisfaction as that directly affects the sales. Therefore, a suggestion would be to have early on discussions with a company that is planning on producing a medical wearable to see what circular strategies are strategic to apply. Applying such strategies does not necessarily decrease profit (Porter and Kramer, 2007). Embracing such strategies to get a more sustainable supply chain can strengthen the value proposition of a product by fulfilling its corporate social responsibility (CSR), which can even create a competitive advantage and lead to competitive success (Porter and Kramer, 2007). This emphasises how important it is to inform a production company on what kind of circular strategies could be applied to their product's supply chain.

Furthermore, much research is currently done on whether and when a wearable will be reimbursed, because wearables are still a new form of care within the healthcare system (Advisor, 2024b). This highlights that it is still uncertain to know in advance whether the Wearable Breathing Trainer will be reimbursed. If it does not get reimbursed, the wearable would have to be bought by physiotherapists or rented by physiotherapists or parents. Physiotherapists have split opinions about what options they most prefer and see advantages and disadvantages in both options (Schreuder, 2024). A suggestion would therefore be to sell the Wearable Breathing Trainer as well as rent the wearable to reach a bigger customer group.

## 10.4 Limitations

A limitation of this research is that only one researcher conducted the interviews, meaning that no other researcher has checked whether the interview schedule has been followed correctly or if all the questions have been asked. This could influence the internal validity of the research. Furthermore, the data of the interviews has also been analysed by only one researcher. Therefore, this data could not be reviewed together with another researcher and be studied for differences or similarities. This too, could impact the internal validity, as one researcher could miss patterns in the data or place excessive emphasis on certain topics that the researcher considers significant.

Furthermore, only one person from a production company was asked about their preferences. Therefore, it might not accurately represent the thoughts on implementing sustainable practices of all production companies that produce wearables. Nonetheless, this person has been involved in the whole project of the Wearable Breathing Trainer and is therefore very knowledgeable on what the right steps are for the implementation of the Wearable Breathing Trainer and could therefore give a well-informed answer on what would be possible in terms of sustainability.

## 10.5 Future research

Upon reflection on the results of this study, there are several promising directions for future research. This research aimed to study how the implementation of the Wearable Breathing Trainer could be supported by sustainable supply chain design choices. Recycling is part of a sustainable supply chain. However, how the Wearable Breathing Trainer could exactly be recycled is out of scope in this research. As of right now, only 1% of the clothes is actually recycled into new clothes, which is largely due to the fact that technologies that can recycle clothes into virgin fibres only recently emerged (*European Parliament*, z.d.)(Bianco et al., 2023). Moreover, when searching for recycle companies to interview, none of them had recycled wearables yet. Therefore, it would be interesting to study the possibilities for recycling in another research and study how likely the chance is it will be recycled.

In this study the business case of the Wearable Breathing Trainer has only focused on children with dysfunctional breathing. However, according to physiotherapists the Wearable Breathing Trainer might be relevant to use during the diagnosis of dysfunctional breathing or for people with sleeping problems, patients with chronic obstructive pulmonary disease (COPD), children who are quickly overstimulated or during pelvic floor therapy (Schreuder, 2024). This way the Wearable Breathing Trainer can serve multiple users, thus is multifunctional, which is a strategy to make the design of the Wearable Breathing Trainer more sustainable (Koo et al., 2013). Therefore, it would be interesting to explore whether the Wearable Breathing Trainer could also be applied for other purposes.

This study has also developed an Economic and Environmental Life Cycle Business Model Canvas to present the value proposition of the Wearable Breathing Trainer, while also measuring the wearable's environmental impact across all stages of its life and spot its environmental benefits along the way. A third layer of this TLBMC is the Social Stakeholder Business Model Canvas. It would also be interesting to include this layer in future research to foster a stakeholder approach to social issues of the Wearable Breathing Trainer.

Lastly, it would be interesting to calculate with a life cycle analysis what the environmental impact of the Wearable Breathing Trainer throughout the entire lifecycle is after it has been implemented and circular strategies have been applied to then see whether it is less harmful for the environment in comparison to other wearables.

# Chapter 11: Conclusion

The aim of this research was to study how the upcoming implementation of a wearable for children with dysfunctional breathing into physiotherapy practices can be supported by sustainable supply chain design choices.

Multiple circular product design and business model strategies can be applied to the three design options and the two business models of the Wearable Breathing Trainer to slow or close the loop of this product. Additionally, the waste pyramid can be used to manage and minimise the waste of the Wearable Breathing Trainer. These forementioned strategies can be realised by reusing, repairing, refurbishing, remanufacturing, and recycling the wearable. If that is not possible the wearable ought to be incinerated or landfilled. Applying these strategies could be a way of integrating sustainability into the supply chain of the Wearable Breathing Trainer.

Nonetheless, a production company would not want to apply circular strategies when the strategies hinder the user satisfaction, as this also directly affects sales. The knitted-in design can therefore be considered the best design in this case, as it complies with the wishes and preferences of the end-user and the production company, whose support is critical for a successful implementation. Moreover, incorporating their wishes and preferences may promote sustainability as it enhances product longevity by fostering a strong user satisfaction.

By incorporating the forementioned strategies to the supply chain of the Wearable Breathing Trainer, the chain can become more sustainable, and move from a linear economy to a circular economy, thereby making a meaningful contribution to scientific literature on how the environmental impact of a medical wearable can be reduced.

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## Appendix A: Operationalisation table

| Concept | Category | Sub category | Indicators |
|---|---|---|---|
| Business model | Key partners | | Collaboration with key partners |
| | | | The resources key partners offer |
| | | | Key suppliers of the Wearable Breathing Trainer |
| | | | Product outsourcing |
| | Key activities | | Production process |
| | | | Key activities for selling the Wearable Breathing Trainer |
| | | | Key activities for maintaining customer relationships |
| | Key resources | | Resources needed from suppliers for the production process |
| | | | Resources needed to sell the Wearable Breathing Trainer |
| | | | Resources needed to maintain contact with customers |
| | | | Resources needed for transportation and wrapping of the product |
| | Value proposition | | The value of the Wearable Breathing Trainer |
| | Customer relationships | | Developing and maintaining a relationship with customers |
| | | | The customer service of Wearable Breathing Trainer |
| | | | Services to offer customers in terms of repairment of the product |
| | Channels | | The channels to reach customers |
| | | | Transportation and wrapping of the Wearable Breathing Trainer |
| | Customer segments | | Most important customer groups |
| | Cost structure | | The largest expenses and investments |
| | Revenue streams | | Revenue streams of the Wearable Breathing Trainer |

| | | | |
|---|---|---|---|
| Circular product design strategies | Slowing loops | Designing long-life products | Product is designed for attachment and trust |
| | | Designing for product-life extension | Suitable for maintenance, repair, technical upgrading, and dis- and reassembly |
| | Closing loops | Design for dis- and reassembly | Ensuring that products and parts can be separated and reassembled |
| Circular business model strategies | Slowing loops | Access and performance model | Thoughts on selling the products versus leasing the product |
| | | Extending product value | Possibilities for exploiting residual value of the product |
| | | Classic long life | Considering a long-product life in terms of design options |
| | | Encourage sufficiency | Reducing end-user consumption through service and reparability |
| | | | Reducing end-user consumption through upgrades and adaptations |
| | Closing loops | Extending resource value | Possibilities for the recycling of wasted materials and resources |
| | | Industrial symbiosis | Possibilities in the use of waste |

*Table A 1. Operationalisation table*

## Appendix B: Interview schedule

**Questions about the design of the Wearable Breathing Trainer (Respondent: employee at Saxion who has developed these different design options)**

1. Could you describe how the modular design option is constructed?
2. Could you describe how the knitted-in design option is constructed?
3. Could you describe how the laminated design option is constructed?
4. Could you explain whether you think each of the design options for the Wearable Breathing Trainer is comfortable to wear and aesthetically pleasing to wear for patients?
5. Do you think there is a difference in consumer preference for these different design options? And if so, why?
6. In terms of durability, what are your thoughts on how much each of these designs can be worn without breaking down?
7. What are the recyclability options for each of these designs?

**Questions about business model strategies for slowing and closing loops (Respondent: CEO from a production company)**

1. What are your thoughts on selling the product versus leasing the product?
    a. Why would you choose this option over the other option?
    b. Do you think this is most beneficial for the company or for your customers?
2. If the customer would returns the product at the end of its life cycle to your company, what possibilities would there be to give value to this product or make it into another product that can be used by customers?
3. What design option for the Wearable Breathing Trainer do you think is most suitable for your company and why?
    a. Do you think this is also a design option that will last the longest?
4. How does your company manage the maintenance for technologies, such as the Wearable Breathing Trainer?
5. Which of these design options would be the most easy to maintain?
6. Would your company be open for upgrades and adaptations of the Wearable Breathing Trainer, for example in quality, value, effectiveness or performance?
    a. How would this be managed?
7. Which of these designs would be most suitable to dis- and reassemble?
8. If the Wearable Breathing Trainer were to be disassembled, what possibilities would there be for recycling?
    a. Which parties would be involved in the recycling process?
9. How much of the waste from producing the Wearable Breathing Trainer, do you think could be used for something else?

**Questions about the business model (Respondent: CEO from a production company)**

Key partners

10. Who are the key partners with whom you would like to collaborate to produce and sell the Wearable Breathing Trainer?
11. What resources or knowledge do these key partners have as to why you would want to collaborate with them?

12. Who are your key suppliers that you would need for the production of the Wearable Breathing Trainer?
    a. From which countries are these suppliers?
13. What do you consider when you choose between outsourcing and producing something yourself?

Key activities

14. What would the production process look like?
15. What key activities would take place to sell the Wearable Breathing Trainer?
16. What key activities would take place to maintain customer relationships?

Key resources

17. Could you explain what resources you would need from suppliers in order to produce the Wearable Breathing Trainer?
18. What resources would you need to sell the Wearable Breathing Trainer?
19. What resources would you need to maintain contact with your customers?
20. What resources would you need for transportation and wrapping of the Wearable Breathing Trainer?

Value proposition

21. What value do you bring to the customer by selling the Wearable Breathing Trainer?

Customer relationships

22. What type of relationship do you want to develop with your customers and how do you want to maintain this?
23. What would your customer service look like?
24. What services would you offer customers in terms of repairment of the product?

Channels

25. Through which channels do you want to reach your customers?
26. How would you transport and wrap the Wearable Breathing Trainer?

Customer segments

27. Who are your most important customer groups?

Cost structure

28. Could you sum up where (the largest) expenses and investments go to?

Revenue streams

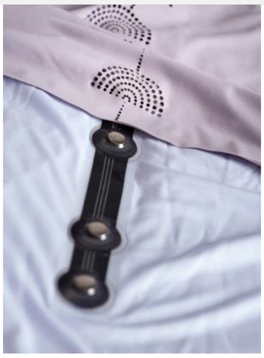
What revenue streams would you get from selling the Wearable Breathing Trainer?

**Questions about the potential reimbursement of the Wearable Breathing Trainer (Respondents: advisors from insurance companies)**

1. What data and results should be documented before one could decide whether a wearable will be reimbursed?
2. What criteria must a wearable meet in order to be reimbursed?
3. What does your decision-making process look like?
4. Which stakeholders are involved in this process?
5. How does your organisation involve stakeholders, such as patients and healthcare providers, in the decision-making process?
6. Besides basic insurance, there is also supplementary insurance. What criteria must a wearable meet in order to be included in supplementary insurance?
7. Are some or many wearable currently already reimbursed?
8. What do you think are the most important challenges that influence the implementation of medical wearables such as the Wearable Breathing Trainer?
9. How does the communication with physiotherapists proceed when they would like to use this wearable once it is covered in basic or supplementary insurance?

## Appendix C: Material list Wearable Breathing Trainer

| MATERIALS | MODULAR | KNITTED-IN | LAMINATED |
|---|---|---|---|
| **Material chest sensor** | Elastic band with copper wire   | Knitting structure 3x3 MISS Shieldex® RAW: 117/17, Silverized: 142/17 dtex Z-turns HC+B (Shieldex 235/36 2-ply HCB) | PhantomTape X. |
| **Material abdomen sensor** | Elastic band with copper wire | Knitting structure 3x3 MISS Shieldex® RAW: 117/17, Silverized: 142/17 dtex Z-turns HC+B (Shieldex 235/36 2-ply HCB) | PhantomTape X |
| **Electronics chest sensor** | PCB (37,5 mm x 27 mm) that can be attached and detached with two press studs | PCB (37,5 mm x 27 mm) | PCB (37,5 mm x 27 mm). Same attachment as below:  |
| **Electronics abdomen sensor** | PCB (60mm x 27mm) that can be attached and detached with two press studs | PCB (60mm x 27mm) | PCB (60mm x 27mm) same attachment as below |
| **Chest sensor protection** | 3D printed material (PLA) or plastic casing | Flexible polyurethane for casting (3g) and mold 3D printed with PLA (8g) (attach PCB to shirt) | See image above |
| **Abdomen sensor protection** | 3D printed material (PLA) or plastic casing | Flexible polyurethane for casting (3g) and mold 3D printed with PLA (10g) (attach PCB to shirt) | See image above |

| | | | |
|---|---|---|---|
| **Connection between abdomen and chest sensor** | Wire (see image above) | Elastic band 20 cm, 3 wires. (Not knitted in for consistent data processing)<br> | See image above |
| **Connection between abdomen and control module** | Wire | Elastic band 20 cm, 3 wires. (Not knitted in for consistent data processing) | See image above |
| **Shirt (2 layers: 1 layer with conductive yarn, 1 layer without)** | Knitting structure 1x2 Rib Ynviron PA 6.6 78/2 dtex with covered lycra.<br>Even: 0033, Uneven: 0031<br><br>PA6.6, covered Lycra and bare Lycra | Knitting structure 1x2 Rib Ynviron PA 6.6 78/2 dtex with covered lycra.<br>Even: 0033, Uneven: 0031<br><br>PA6.6, covered Lycra and bare Lycra | Knitting structure 1x2 Rib Ynviron PA 6.6 78/2 dtex with covered lycra.<br>Even: 0033, Uneven: 0031<br><br>PA6.6, covered Lycra and bare Lycra |
| **Vibration motors (3x)** | <br>Vibration motors are attached to a PCB. A mold of this is 3D printed and then the PCB is cast in it with a cable between the vibration motors. Vibration motors are attached to the fabric with Velcro. | Soldered on a flexible PCB then cast in flexible polyurethane. An elastic band with two cables goes to the control module. | <br>Attached like above. (These are three laminated vibration motors) |
| **Vibration motor protection (3x)** | Flexible polyurethane for casting (3g) and mold 3D printed with PLA (7g) | Flexible polyurethane for casting (2g) and mold 3D printed with PLA (6g) (attach PCB to shirt) | See image above |

| | | | |
|---|---|---|---|
| **Connection vibration motors and control module** | Wires (25 cm) | Elastic band 20 cm, 2 wires. | See image above |
| **Control module** | The control module is not discussed in detail here as the components used in each method are the same such as a battery and microcontroller. | | |

*Table C 1. Material list*

## Appendix D: Analytical Hierarchy Process for design options

| Preference level | Numeric value |
|---|---|
| Equally preferred | 1 |
| Moderately preferred | 2 |
| Strongly preferred | 3 |

*Table D 1. Preference scale for pairwise comparisons*

| | **User comfort** | | |
|---|---|---|---|
| **Design** | Modular design | Knitted-in design | Laminated design |
| Modular design | 1 | 1/3 | 1/2 |
| Knitted-in design | 3 | 1 | 2 |
| Laminated design | 2 | 1/2 | 1 |
| Sum | 6 | 11/6 | 7/2 |

*Table D 2. Pairwise comparison matrix for alternatives*

| | **User comfort** | | |
|---|---|---|---|
| **Design** | Modular design | Knitted-in design | Laminated design |
| Modular design | 1/6 | 2/11 | 1/7 |
| Knitted-in design | 3/6 | 6/11 | 4/7 |
| Laminated design | 2/6 | 3/11 | 2/7 |

*Table D 3. Dividing each value by its column sum*

| | **User comfort** | | | |
|---|---|---|---|---|
| **Design** | Modular design | Knitted-in design | Laminated design | Row average |
| Modular design | 0.167 | 0.182 | 0.143 | 0.164 |
| Knitted-in design | 0.500 | 0.545 | 0.571 | 0.539 |
| Laminated design | 0.333 | 0.273 | 0.286 | 0.297 |
| | | | | 1.000 |

*Table D 4. The normalised matrix with row averages*

| | **Ease of use** | | |
|---|---|---|---|
| **Design** | Modular design | Knitted-in design | Laminated design |
| Modular design | 1 | 1/3 | 1/3 |
| Knitted-in design | 3 | 1 | 1 |
| Laminated design | 3 | 1 | 1 |
| Sum | 7 | 7/3 | 7/3 |

*Table D 5. Pairwise comparison matrix for alternatives*

| | Ease of use | | |
|---|---|---|---|
| **Design** | Modular design | Knitted-in design | Laminated design |
| Modular design | 1/7 | 1/7 | 1/7 |
| Knitted-in design | 3/7 | 3/7 | 3/7 |
| Laminated design | 3/7 | 3/7 | 3/7 |

*Table D 6. Dividing each value by its column sum*

| | Ease of use | | | |
|---|---|---|---|---|
| **Design** | Modular design | Knitted-in design | Laminated design | Row average |
| Modular design | 0.143 | 0.143 | 0.143 | 0.143 |
| Knitted-in design | 0.429 | 0.429 | 0.429 | 0.429 |
| Laminated design | 0.429 | 0.429 | 0.429 | 0.429 |
| | | | | 1.000 |

*Table D 7. The normalised matrix with row averages*

| | Aesthetics | | |
|---|---|---|---|
| **Design** | Modular design | Knitted-in design | Laminated design |
| Modular design | 1 | 1/3 | 1/3 |
| Knitted-in design | 3 | 1 | 1 |
| Laminated design | 3 | 1 | 1 |
| Sum | 7 | 7/3 | 7/3 |

*Table D 8. Pairwise comparison matrix for alternatives*

| | Aesthetics | | |
|---|---|---|---|
| **Design** | Modular design | Knitted-in design | Laminated design |
| Modular design | 1/7 | 1/7 | 1/7 |
| Knitted-in design | 3/7 | 3/7 | 3/7 |
| Laminated design | 3/7 | 3/7 | 3/7 |

*Table D 9. Dividing each value by its column sum*

| | Aesthetics | | | |
|---|---|---|---|---|
| **Design** | Modular design | Knitted-in design | Laminated design | Row average |
| Modular design | 0.143 | 0.143 | 0.143 | 0.143 |
| Knitted-in design | 0.429 | 0.429 | 0.429 | 0.429 |
| Laminated design | 0.429 | 0.429 | 0.429 | 0.429 |
| | | | | 1.000 |

*Table D 10. The normalised matrix with row averages*

| | Price | | |
|---|---|---|---|
| **Design** | Modular design | Knitted-in design | Laminated design |
| Modular design | 1 | 2 | 3 |
| Knitted-in design | 1/2 | 1 | 2 |
| Laminated design | 1/3 | 1/2 | 1 |
| Sum | 11/6 | 7/2 | 6 |

*Table D 11. Pairwise comparison matrix for alternatives*

| | Price | | |
|---|---|---|---|
| **Design** | Modular design | Knitted-in design | Laminated design |
| Modular design | 6/11 | 4/7 | 3/6 |
| Knitted-in design | 3/11 | 2/7 | 2/6 |
| Laminated design | 2/11 | 1/7 | 1/6 |

*Table D 12. Dividing each value by its column sum*

| | Price | | | |
|---|---|---|---|---|
| **Design** | Modular design | Knitted-in design | Laminated design | Row average |
| Modular design | 0.545 | 0.571 | 0.500 | 0.539 |
| Knitted-in design | 0.273 | 0.286 | 0.333 | 0.297 |
| Laminated design | 0.182 | 0.143 | 0.167 | 0.164 |
| | | | | 1.000 |

*Table D 13. The normalised matrix with row averages*

| | Criteria | | | |
|---|---|---|---|---|
| **Design** | User comfort | Ease of use | Aesthetics | Price |
| Modular design | 0.164 | 0.143 | 0.143 | 0.539 |
| Knitted-in design | 0.539 | 0.429 | 0.429 | 0.297 |
| Laminated design | 0.297 | 0.429 | 0.429 | 0.164 |

*Table D 14. Criteria preference matrix*

| **Criteria** | User comfort | Ease of use | Aesthetics | Price |
|---|---|---|---|---|
| User comfort | 1 | 1 | 3 | 2 |
| Ease of use | 1 | 1 | 3 | 2 |
| Aesthetics | 1/3 | 1/3 | 1 | 1/2 |
| Price | 1/2 | 1/2 | 2 | 1 |
| Sum | 17/6 | 17/6 | 9 | 11/2 |

*Table D 15. Pairwise comparison matrix for criteria*

| **Criteria** | User comfort | Ease of use | Aesthetics | Price |
|---|---|---|---|---|
| User comfort | 6/17 | 6/17 | 3/9 | 4/11 |
| Ease of use | 6/17 | 6/17 | 3/9 | 4/11 |
| Aesthetics | 2/17 | 2/17 | 1/9 | 1/11 |
| Price | 3/17 | 3/17 | 2/9 | 2/11 |

*Table D 16. Dividing each value by its column sum*

| **Criteria** | User comfort | Ease of use | Aesthetics | Price | Row averages |
|---|---|---|---|---|---|
| User comfort | 0.353 | 0.353 | 0.333 | 0.364 | 0.351 |
| Ease of use | 0.353 | 0.353 | 0.333 | 0.364 | 0.351 |
| Aesthetics | 0.118 | 0.118 | 0.111 | 0.091 | 0.110 |
| Price | 0.176 | 0.176 | 0.222 | 0.182 | 0.189 |

*Table D 17. Normalised matrix for criteria with row averages*

| **Overall score** | |
|---|---|
| Modular design | 0.351(0.164) + 0.351(0.143) + 0.110(0.143) + 0.189(0.539) = 0.225 |
| Knitted-in design | 0.351(0.539) + 0.351(0.429) + 0.110(0.429) + 0.189(0.297) = 0.443 |
| Laminated design | 0.351(0.297) + 0.351(0.429) + 0.110(0.429) + 0.189(0.164) = 0.333 |

*Table D 18. Overall score*

| **Design** | **Score** |
|---|---|
| Knitted-in design | 0.443 |
| Laminated design | 0.333 |
| Modular design | 0.225 |
| Sum | 1.000 |

*Table D 19. Overall ranking*

| Preference level | Numeric value |
|---|---|
| Equally preferred | 1 |
| Moderately preferred | 2 |
| Strongly preferred | 3 |

*Table D 20. Preference scale for pairwise comparisons*

| | **Maintenance** | | |
|---|---|---|---|
| **Design** | Modular design | Knitted-in design | Laminated design |
| Modular design | 1 | 1/3 | 1/3 |
| Knitted-in design | 3 | 1 | 1 |
| Laminated design | 3 | 1 | 1 |
| Sum | 7 | 7/3 | 7/3 |

*Table D 21. Pairwise comparison matrix for alternatives*

| | **Maintenance** | | |
|---|---|---|---|
| **Design** | Modular design | Knitted-in design | Laminated design |
| Modular design | 1/7 | 1/7 | 1/7 |
| Knitted-in design | 3/7 | 3/7 | 3/7 |
| Laminated design | 3/7 | 3/7 | 3/7 |

*Table D 22. Dividing each value by its column sum*

| | **Maintenance** | | | |
|---|---|---|---|---|
| **Design** | Modular design | Knitted-in design | Laminated design | Row average |
| Modular design | 0.143 | 0.143 | 0.143 | 0.143 |
| Knitted-in design | 0.429 | 0.429 | 0.429 | 0.429 |
| Laminated design | 0.429 | 0.429 | 0.429 | 0.429 |
| | | | | 1.000 |

*Table D 23. The normalised matrix with row averages*

| | **Repairability** | | |
|---|---|---|---|
| **Design** | Modular design | Knitted-in design | Laminated design |
| Modular design | 1 | 3 | 3 |
| Knitted-in design | 1/3 | 1 | 1 |
| Laminated design | 1/3 | 1 | 1 |
| Sum | 5/3 | 5 | 5 |

*Table D 24. Pairwise comparison matrix for alternatives*

| | Repairability | | |
|---|---|---|---|
| **Design** | Modular design | Knitted-in design | Laminated design |
| Modular design | 3/5 | 3/5 | 3/5 |
| Knitted-in design | 1/5 | 1/5 | 1/5 |
| Laminated design | 1/5 | 1/5 | 1/5 |

*Table D 25. Dividing each value by its column sum*

| | Repairability | | | |
|---|---|---|---|---|
| **Design** | Modular design | Knitted-in design | Laminated design | Row average |
| Modular design | 0.600 | 0.600 | 0.600 | 0.600 |
| Knitted-in design | 0.200 | 0.200 | 0.200 | 0.200 |
| Laminated design | 0.200 | 0.200 | 0.200 | 0.200 |
| | | | | 1.000 |

*Table D 26. The normalised matrix with row averages*

| | Refurbishing | | |
|---|---|---|---|
| **Design** | Modular design | Knitted-in design | Laminated design |
| Modular design | 1 | 3 | 2 |
| Knitted-in design | 1/3 | 1 | 1/2 |
| Laminated design | 1/2 | 2 | 1 |
| Sum | 11/6 | 6 | 7/2 |

*Table D 27. Pairwise comparison matrix for alternatives*

| | Refurbishing | | |
|---|---|---|---|
| **Design** | Modular design | Knitted-in design | Laminated design |
| Modular design | 6/11 | 1/2 | 4/7 |
| Knitted-in design | 2/11 | 1/6 | 1/7 |
| Laminated design | 3/11 | 2/6 | 2/7 |

*Table D 28. Dividing each value by its column sum*

| | Refurbishing | | | |
|---|---|---|---|---|
| **Design** | Modular design | Knitted-in design | Laminated design | Row average |
| Modular design | 0.545 | 0.500 | 0.571 | 0.539 |
| Knitted-in design | 0.182 | 0.167 | 0.143 | 0.164 |
| Laminated design | 0.273 | 0.333 | 0.286 | 0.297 |
| | | | | 1.000 |

*Table D 29. The normalised matrix with row averages*

| | Remanufacturing | | |
|---|---|---|---|
| **Design** | Modular design | Knitted-in design | Laminated design |
| Modular design | 1 | 3 | 2 |
| Knitted-in design | 1/3 | 1 | 1/2 |
| Laminated design | 1/3 | 2 | 1 |
| Sum | 11/6 | 6 | 7/2 |

*Table D 30. Pairwise comparison matrix for alternatives*

| | Remanufacturing | | |
|---|---|---|---|
| **Design** | Modular design | Knitted-in design | Laminated design |
| Modular design | 6/11 | 1/2 | 4/7 |
| Knitted-in design | 2/11 | 1/6 | 1/7 |
| Laminated design | 3/11 | 2/6 | 2/7 |

*Table D 31. Dividing each value by its column sum*

| | Remanufacturing | | | |
|---|---|---|---|---|
| **Design** | Modular design | Knitted-in design | Laminated design | Row average |
| Modular design | 0.545 | 0.500 | 0.571 | 0.539 |
| Knitted-in design | 0.182 | 0.167 | 0.143 | 0.164 |
| Laminated design | 0.273 | 0.333 | 0.286 | 0.297 |
| | | | | 1.000 |

*Table D 32. The normalised matrix with row averages*

| | Long-life product | | |
|---|---|---|---|
| **Design** | Modular design | Knitted-in design | Laminated design |
| Modular design | 1 | 1/3 | 1/2 |
| Knitted-in design | 3 | 1 | 2 |
| Laminated design | 2 | 1/2 | 1 |
| Sum | 6 | 10/6 | 7/2 |

*Table D 33. Pairwise comparison matrix for alternatives*

| | Long-life product | | |
|---|---|---|---|
| **Design** | Modular design | Knitted-in design | Laminated design |
| Modular design | 1/6 | 1/10 | 1/7 |
| Knitted-in design | 3/6 | 6/10 | 4/7 |
| Laminated design | 2/6 | 3/10 | 2/7 |

*Table D 34. Dividing each value by its column sum*

| | Long-life product | | | |
|---|---|---|---|---|
| **Design** | Modular design | Knitted-in design | Laminated design | Row average |
| Modular design | 0.167 | 0.100 | 0.143 | 0.137 |
| Knitted-in design | 0.500 | 0.600 | 0.571 | 0.557 |
| Laminated design | 0.333 | 0.300 | 0.286 | 0.306 |
| | | | | 1.000 |

*Table D 35. The normalised matrix with row averages*

| | | Criteria | | | |
|---|---|---|---|---|---|
| **Design** | Maintenance | Repairability | Refurbishing | Remanufacturing | Long-life product |
| Modular design | 0.143 | 0.600 | 0.539 | 0.539 | 0.137 |
| Knitted-in design | 0.429 | 0.200 | 0.164 | 0.164 | 0.557 |
| Laminated design | 0.429 | 0.200 | 0.297 | 0.164 | 0.306 |

*Table D 36. Criteria preference matrix*

| **Criteria** | Maintenance | Repairability | Refurbishing | Remanufactu ring | Long-life product |
|---|---|---|---|---|---|
| Maintenance | 1 | 1 | 1 | 2 | 1/2 |
| Repairability | 1 | 1 | 1 | 2 | 1/2 |
| Refurbishing | 1 | 1 | 1 | 2 | 1/2 |
| Remanufacturing | 1/2 | 1/2 | 1/2 | 1 | 1/3 |
| Long-life product | 2 | 2 | 2 | 3 | 1 |
| Sum | 11/2 | 11/2 | 11/2 | 10 | 16/6 |

*Table D 37. Pairwise comparison matrix for criteria*

| **Criteria** | Maintenance | Repairability | Refurbishing | Remanufactu ring | Long-life product |
|---|---|---|---|---|---|
| Maintenance | 2/11 | 2/11 | 2/11 | 2/10 | 3/16 |
| Repairability | 2/11 | 2/11 | 2/11 | 2/10 | 3/16 |
| Refurbishing | 2/11 | 2/11 | 2/11 | 2/10 | 3/16 |
| Remanufacturing | 1/11 | 1/11 | 1/11 | 1/10 | 1/16 |
| Long-life product | 4/11 | 4/11 | 4/11 | 3/10 | 6/16 |

*Table D 38. Dividing each value by its column sum*

| **Criteria** | Maintenance | Repairability | Refurbishing | Remanufactu ring | Product longevity | Row averages |
|---|---|---|---|---|---|---|
| Maintenance | 0.182 | 0.182 | 0.182 | 0.200 | 0.188 | 0.187 |
| Repairability | 0.182 | 0.182 | 0.182 | 0.200 | 0.188 | 0.187 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Refurbishing | 0.182 | 0.182 | 0.182 | 0.200 | 0.188 | 0.187 |
| Remanufacturing | 0.091 | 0.091 | 0.091 | 0.100 | 0.063 | 0.087 |
| Long-life product | 0.363 | 0.363 | 0.363 | 0.300 | 0.375 | 0.353 |

*Table D 39. Normalised matrix for criteria with row averages*

| **Overall score** | |
|---|---|
| Modular design | 0.187(0.143) + 0.187(0.600) + 0.187(0.539) + 0.087(0.539) + 0.353(0.137) = 0.335 |
| Knitted-in design | 0.187(0.429) + 0.187(0.200) + 0.187(0.164) + 0.087(0.164) + 0.353(0.557) = 0.359 |
| Laminated design | 0.187(0.429) + 0.187(0.200) + 0.187(0.297) + 0.087(0.297) + 0.353(0.306) = 0.306 |

*Table D 40. Overall score*

| **Design** | **Score** |
|---|---|
| Knitted-in design | 0.359 |
| Modular design | 0.335 |
| Laminated design | 0.306 |
| Sum | 1.000 |

*Table D 41. Overall ranking*