Exploring circular possibilities for using End-of-Use Dyneema® from the commercial marine market

Vincent Otto
Faculty of Industrial Design Engineering

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Delft University of Technology
Faculty of Industrial Design Engineering

V.R.P. Otto
4216563

Supervisory team:
Chair: Prof. dr. Balkenende, AR
Mentor: Ir. Bluemink, RGH

Company mentors:
Coracki Donato, B
Roozemond, P
Spijkers, J.

Confidentiality
Some information in this report is confidential and is only accessible to DSM and the supervisors. The confidential information can be found in the confidential appendix.

Abstract

Dyneema® fiber is a high-performance fiber that is sold by *DSM Dyneema BV* to product producers all around the world. Dyneema® fiber is marketed as the world strongest synthetic fiber, its high strength for its weight provides value over competing materials. Dyneema® fiber products include ropes and netting for commercial marine and armor plates for life protection. DSM is moving towards a sustainable and circular corporate strategy. This graduation assignment is to investigate possibilities for *DSM Dyneema BV* to make the transition towards the circular economy with Dyneema® fiber.

Theory of the circular economy was used to create a framework for the circular possibilities. The Dyneema® fiber itself was analyzed. Where is was discovered that circularity is complex due to the significant value loss during conventional recycling processes. Reuse and remanufacturing of End-of-Use Dyneema® was chosen as the most interesting circular direction for Dyneema® fiber for the extension of lifetime of the fiber.

It was chosen to analyze the Dyneema® Commercial marine market as the source of End-of-Use material. This market was chosen because of market size and type of products. Stakeholders and the business models of *DSM Dyneema BV* and a Dyneema® customer were analyzed. From these analyses it was learned that the possible circular value chains depend on the specific market or application where the End-of-Use Dyneema® will be used in. From an analysis on the competitors of Dyneema® fiber it was learned that other high-performance fibers are being recycled, although not with high quality. The competitors still face the same challenges as *DSM Dyneema BV*.

The End-of-Use material from the commercial marine market was analyzed by experiments. Two End-of-Use ropes were taken apart to see what value was left in the material and with prototyping possible ways of value recovery were explored.

A list of criteria for finding an application for a design case was set up. The list of criteria was to find, evaluate and choose an application to analyze further in the form of a design case. Seaweed farming was chosen as the application to investigate further.

Seaweed farming is an upcoming technology that could provide society with healthy food and energy and play a role in the conservation of the environment. Seaweed is grown on lines that lie underwater in the sea. Possibilities of using End-of-Use Dyneema® were analyzed in the design case and it was found that, the design of the farm should be adapted to the material to make optimal use of the End-of-Use material. A re-design was made that showed that End-of-Use Dyneema® is an interesting opportunity. The use of End-of-Use Dyneema® in seaweed farming comes with both opportunities and barriers that need further investigation. Because of the environmental and circular benefit of the seaweed farming market. Further investigation in the use of End-of-Use Dyneema® in seaweed farming is recommended.

From the design case it was learned that there are feasible opportunities for reusing End-of-Use Dyneema® to extend the lifetime of the fiber. Further research will be required to look for possible ways to produce the ropes with the intention to reuse them after the first product life cycle.

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Glossary

EoL – End of Life

EoU – End of Use

NGO's - Non-governmental Organizations

PE - Polyethylene

UHMWPE - Ultra High Molecular Weight Polyethylene

Chapter 1 - Introduction

Chapter one describes the assignment given by *DSM Dyneema BV* that started this graduation assignment. Information on DSM and the circular economy is given to put the assignment in context and indicate relevance that is followed through this graduation assignment.

1.1 *DSM Dyneema BV*

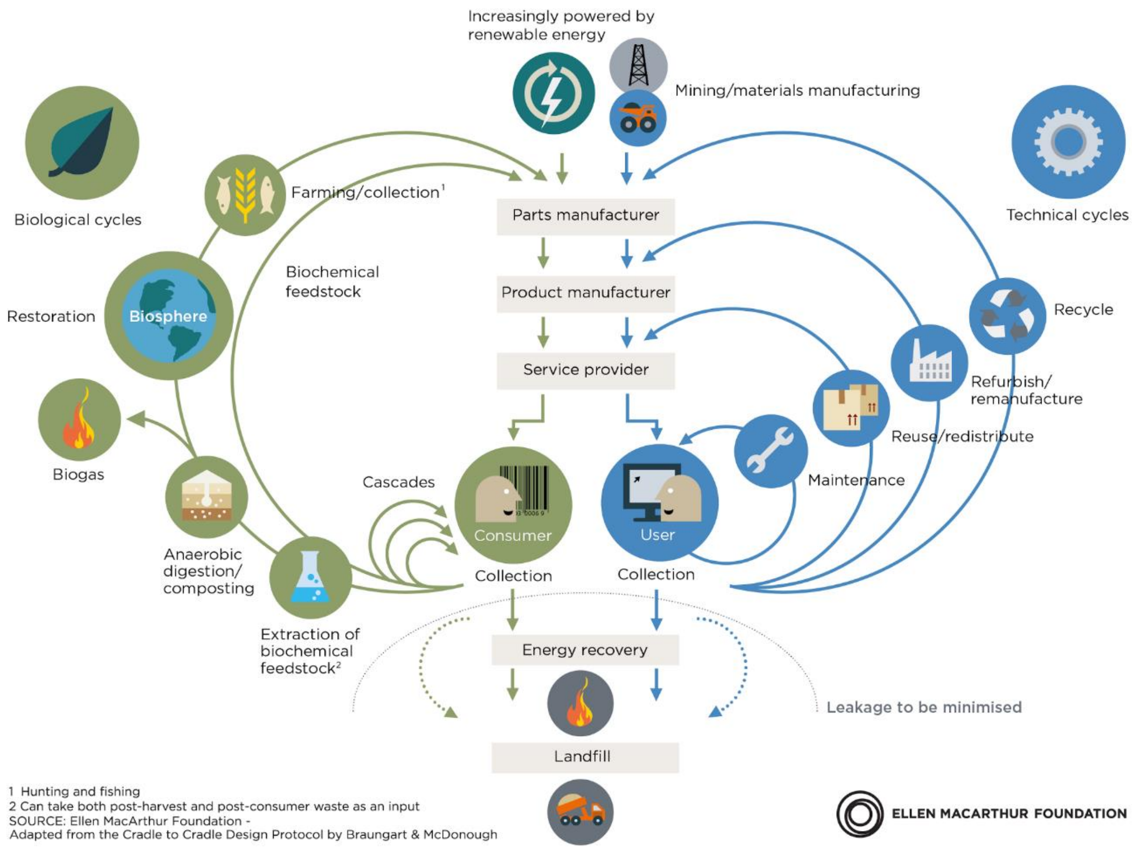
DSM N.V. is a Dutch multinational company in the fields of health, nutrition and sustainable living. *DSM Dyneema BV*, HQ situated in *Geleen* in the *Netherlands*, is a business group in the DSM materials cluster. *DSM Dyneema BV* sells Dyneema® fiber to product manufactures. *DSM Dyneema BV* is established in 2004 to further develop Dyneema® fiber since its development in 1979. Dyneema® fiber is the world strongest synthetic fiber that is used in maritime, military, industry, medical and sports markets.

DSM wants to evolve into a sustainable company by laying the focus on: 1. Nutrition & Health, 2. Climate & Energy and 3. Resources & Circularity. DSM wants to create a more sustainable world and grow as a company. As stated by DSM *"We will create brighter lives for all"* (DSM, 2014).

To fulfill the sustainable goals *DSM Dyneema BV* has the ambition to make the transition towards the circular economy. *DSM Dyneema BV* has asked students from the faculty of *Industrial Design Engineering* from the *TU Delft* to explore ways to make this transition.

1.2 The Circular Economy

The circular economy is developed to preserve the economic and environmental value of materials for as long as possible. By rethinking how we produce and use products and materials the lifetime products can be extended to save energy and materials. Graphic 1.1, called the Butterfly diagram, shows the basic elements of the circular economy. The blue circles stand for the technical material cycle, the green circles for the biological material cycle. Dyneema® fiber is a synthetic fiber that falls within the technical cycle



Graphic 1.1. The Butterfly diagram. Source: Ellen Macarthur foundation, 2013

The technical cycle, as seen in graphic 1.1, is about extending the product lifetime if possible, by maintenance, reuse and or remanufacturing. When extending lifetime is no longer an option the best possible method of recycling the material should be chosen. By closing these loops, the embedded energy, the energy needed to make the material, is used effectively.

The term *product lifetime* is often used to describe the time a product is functional. However, products are discarded before they are no longer useful. In the Circular economy the product lifetime is described in terms of *obsolescence,* obsolescence is when a product is discarded (den Hollander, 2017). The *product use cycle* is the duration of the period that starts at the moment a product is released for use after it is manufactured and ends at the moment the product becomes obsolete (den Hollander, 2017). *Product lifetime* is the duration of the period that starts at the moment a product is released for use after manufacture and ends at the moment a product becomes obsolete beyond recovery at product level (den Hollander, 2017). *Recovery* is a term for any operation with the primary aim of reversing obsolescence (den Hollander, 2017).

For Dyneema® fiber the product use cycle is e.g. a shipping company that uses a Dyneema® rope until they declare it unfit for use, making the Dyneema® rope obsolete. Currently there is no strategy to extend the product lifetime beyond its first product use cycle, this will make the ropes End-of-Life. In this graduation assignment the Dyneema® ropes are regarded as End-of-Use because possibilities for extending the product lifetime beyond its first product use cycle are explored.

For Dyneema® fiber the following terms for product lifetime extension are relevant: *Reuse* is any operation by which products or components that are not waste are used again for the same purpose for which they were conceived. (den Hollander, 2017). *Repair* is the correction of specific faults in an obsolete product, bringing the product back to working condition (den Hollander, 2017). *Remanufacturing* is to return a used product to at least its original performance with a warranty that is equivalent or better than that of the newly manufactured product (Bakker, 2014). *Recycling* is any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes (Bakker, 2014).

There is *Open & closed-loop recycling*. In *closed-loop recycling*, the stream of waste is pure, the inherent properties of the recycled material are not considerably different from those of the virgin material and can be used for similar applications, image 1.2. In *open-loop recycling*, the waste stream is mixed, the inherent properties of the recycled material differ from those of the virgin material in a way that it is only usable for other product applications (Huysman, 2015), this is also called downcycling, image 1.3. Part of the plastics in the open-loops are burned for energy recovery because of their low value.

Image 1.2: PET bottle collection is an example of the idea of closed-loop recycling. Only PET is collected to make the waste stream pure, so the quality of recycled material is close to the virgin material. Source: Ad.nl, 2019.

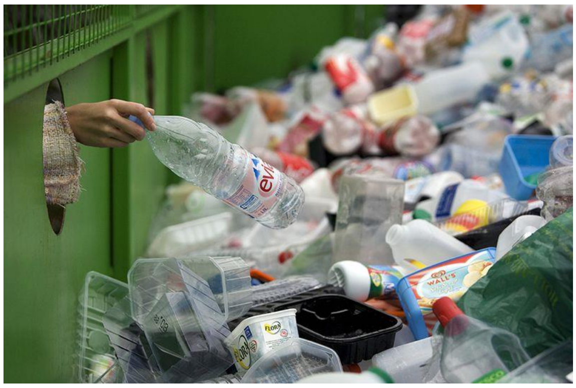


Image 1.3: An example of open-loop recycling where a mix of plastics is collected, the quality of the recycled material is lower or only used for energy recovery. Source: smithsonianmag.com, 2019.

1.2.1 Possible additional values for *DSM Dyneema BV* in the circular economy

Table 1.4 present possibilities for additional values that the transition towards the circular economy can offer for *DSM Dyneema BV* and its stakeholders. These values are the result of closing the material loops, the values go beyond generating economic benefits (Schenkel et al, 2015). These values are relevant to explore to get an idea of which values could be created from the transition towards the circular economy.

Table 1.4	
Value	**Explanation**
Sourcing value	Direct cost reductions, additional revenue and reduced risk of supply disruptions from the closed loop business practices.
Environmental value	Companies can reduce their ecological footprint by closing the loops of materials. This closing of the loops will result in two main benefits. The first, ease of compliance with regulations and secondly the improved green corporate image. Communication is needed to create the green image value
Customer value	Increased customer loyalty, better customer satisfaction and superior brand protection. These three customer values can be induced by serving the customer better, offering improved product characteristics and a good corporate image.
Informational value	Closed loop systems will more easily provide valuable data on production and supply problems, failure rates, useful lifetime of the product, consumer complaints and usage patterns.
	Source: Schenkel et al. 2015.

1.2.2 Challenges for *DSM Dyneema BV* in the circular economy

If *DSM Dyneema BV* wants to make the transition towards the circular economy the following general challenges from the circular economy must be taken into account.

Collection after the 1st product life cycle

A challenge is to collect obsolete products back from the market to make recovery possible. Large volumes are needed to make collection of EoU products and materials feasible (Green Alliance, 2017) and consist of as little different products as possible. Business to Business recollection is a challenge but a manageable one, the biggest challenge will be products sold to consumers. Once products end up in ordinary consumer waste streams it will be harder to economically recollect materials and reuse it.

Collection after the 2nd product life cycle

The make a product fully circular the reused EoU materials should be recollected to the proper waste stream, so the product lifetime can be extended further or processed into new material. It would be possible that circular Dyneema® would be used in consumer products making recollection more of a challenge.

An interesting option will be to find manufacturing partners that already have a reverse logistics system. Companies that already have invested in the circular economy and have a way to recollect materials. If a manufacturer currently does not have a recollection system, this could still be organized.

Sorting

Once the obsolete products are collected, the different types of products should be separated for reprocessing. For the case of Dyneema®, EoU Dyneema® will be a mix of Dyneema® products that vary in type and quality. Value recovery depends on the availability of infrastructure to convert the EoU material into a re-sellable product or material (Green Alliance, 2017). Sorting will be part of the investment needed to reuse the material. Any systems or machines that must be developed in order to sort the waste raise initial investments. Higher investments increase the price of reuse making it less competitive.

Reprocessing

After the material is collected it could be reprocessed into a new material or product. The cost, time and value increase of the reprocessing determines a large part of the material value. The challenge is to keep the processing cost and time as low as possible while increasing the value as much as possible. Just as with the sorting processes, the development of machines for reprocessing is not desired. Necessary development of machines would raise initial investment and increase the cost of reuse.

1.2.3 Regulations and the circular economy

The Dutch government has the target to have a fully circular economy by the year 2050. In 2030 the government together with the business community have setup a goal for a reduction of 50% primary resource use (Rijksoverheid, 2016). To fulfill the goal to become circular by the year 2050, the Dutch government created regulations, and more regulations are to come. For companies there are regulations for how the waste should be processed, these regulations for the processing of waste are based on the waste hierarchy, see image 1.5.

Image 1.5. The waste management hierarchy. Source: (EPA.gov, 2019)

The current EoU solutions for Dyneema® fiber, could score better on the waste management hierarchy. To prevent further regulations having a negative impact on *DSM Dyneema BV*, it would be wise to investigate recovery solutions. Because the regulations are based on the waste hierarchy (EU, 2018) it would be recommendable that *DSM Dyneema BV* starts looking at which possibilities for the reduction and reuse of obsolete Dyneema® would create the largest potential benefit.

Even when it is likely that after the reuse the material still has to be disposed reuse is still interesting because it possibly can create extra revenue for the same amount of material produced.

The European union is actively doing research to avoid the use of toxic materials (EU, 2017). Regulations on using toxic materials are becoming stricter, meaning that it would be best to avoid using or disposing materials that could potentially be harmful to the environment.

1.3 Project setup

An interesting strategy for *DSM Dyneema BV* to close the loops is to investigate possibilities of reuse & remanufacturing to extend the product lifetime of Dyneema® that comes back from the market rather than recycling. Closing the loops by reuse and remanufacturing potentially provides more value than recycling.

Assignment

Currently, *DSM Dyneema BV* is exploring opportunities to make the transition towards the circular economy. *DSM Dyneema BV* approached students from the faculty of industrial design from the *TU Delft* to investigate circular opportunities for Dyneema® fiber. The following research question was stated by *DSM Dyneema BV*.

Research question: What are the circular possibilities for *DSM Dyneema BV*?

Further research on Dyneema® fiber, literature studies. The following problem definition is set up that would fit into the IPD master's program, *DSM Dyneema BV* its wishes and my personal ambitions.

***This resulted in the following problem definition*:** Design and build conceptual prototypes to investigate circular possibilities of End-of-Use Dyneema® from the commercial marine market and obtain insight on potential circular strategies regarding design and business

In the following chapter on method and process it is explained how the research question is answered in this graduation assignment.

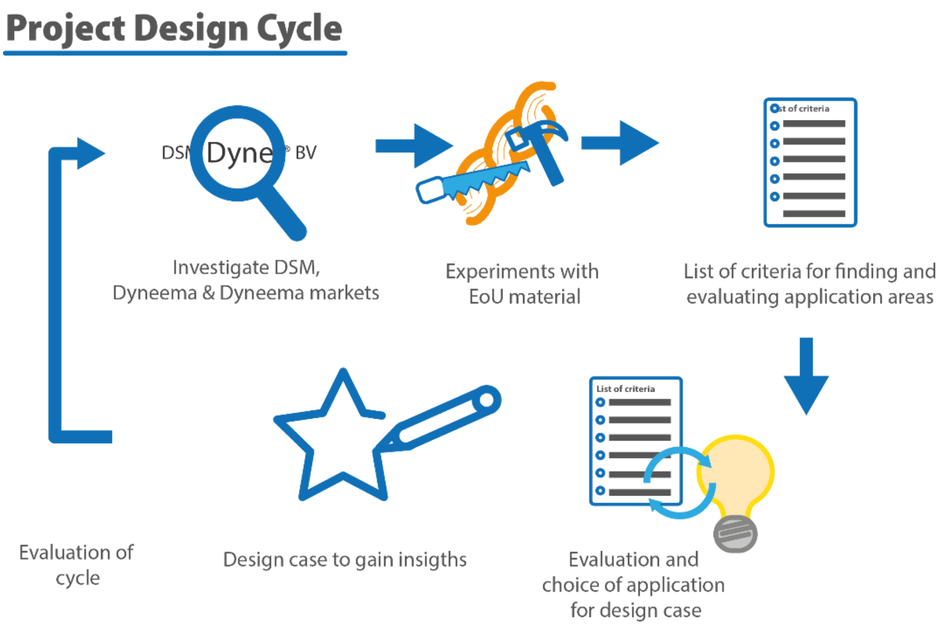
1.3.1 Methods, process & reading guide

To investigate the circular opportunity for Dyneema® the research question is translated to a design case that is used to explore possibilities of reusing Dyneema® fiber in a specific application. A design case on seaweed farming, as a specific application, is used to explore possibilities of reuse of EoU Dyneema® in general.

First, a design scope and context were determined by using relative design methods to investigate the market, material and circular opportunities. Literature studies were conducted to provide information on the principles of the circular economy. Literature studies and interviews provided information on the and technical aspects of Dyneema® fiber and processing methods of synthetic fibers. Market research led to the choice of analyzing only products from the commercial marine market as a source of EoU material. The commercial marine market and the EoU material where analyzed to investigate the market. In a collaborative session a stakeholder analysis, for the current and future circular situation, provided insights on how the transition towards a circular economy has impact on the stakeholders. Business model analysis provided insights on how value is created with Dyneema® fiber. A competitor analysis was done to find inspiration on the possibilities of circularity by analyzing what other high-performance fiber competitors do on circularity.

In chapter three experiments with EoU material from the commercial marine market where conducted to explore the value left in the EoU material and possibilities for value recovery. In the experiments EoU ropes from the commercial marine market where taken apart, analyzed with a microscope and braided into new ropes.

The scope formed by these analyses is used to set up criteria for finding possible use applications. A trend analysis provided insights on market developments and potential markets for using EoU Dyneema®. Within this scope, creative problem solving was used to find possible application areas. A design case on seaweed farming was done to evaluate the possibilities of using EoU Dyneema® in a specific market. In this design case interviews with seaweed farm builders and rapid prototyping was used to analyze how seaweed farms are constructed and possibilities for using EoU material in these farms. The insights from the design case will provide insights on circular possibilities of Dyneema® fiber. The research and design case performed will be in alignment with the design cycle which presented in graphic 1.6.



Graphic 1.6: The design cycle that shows how the research question is approached via a design cycle. Source: self-made image.

Chapter 2 - *DSM Dyneema BV* & Dyneema® fiber

In chapter two, Dyneema® fiber, the processing of Dyneema® fiber, the Dyneema® markets and its competitors are analyzed to gain insights and context to create a list of criteria for evaluating circular use applications in chapter four.

2.1 Dyneema® fiber

Dyneema® fiber is a high-performance fiber, high performance meaning that the tensile strength properties are much higher than commodity plastics. Dyneema® made from Ultra High Molecular Weight Polyethylene (UHMWPE). The length of the molecular chains of Polyethylene (PE) is very long increasing the molecular weight of the molecule. The higher the molecular weight, the higher the strength obtained. The strength of the Dyneema® fiber comes from the orientation of these UHMWPE strings, see image 2.1 (Vlasblom, 2018). When Dyneema® fiber is heated above melting point the orientation of the molecules is lost that causes that all the Dyneema® properties are lost.

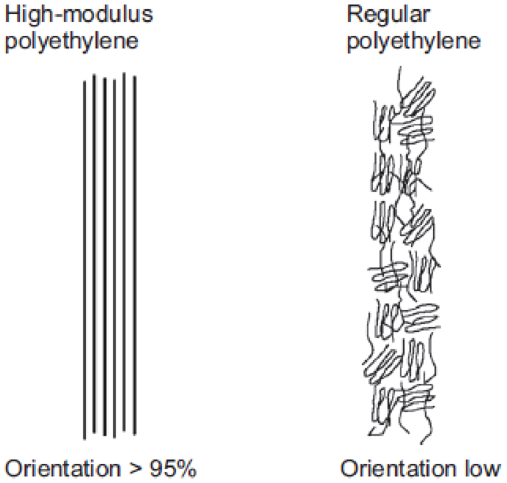


Image 2.1: The orientation of the PE fibers. Source: Vlasblom, 2018.

Properties of Dyneema® fiber

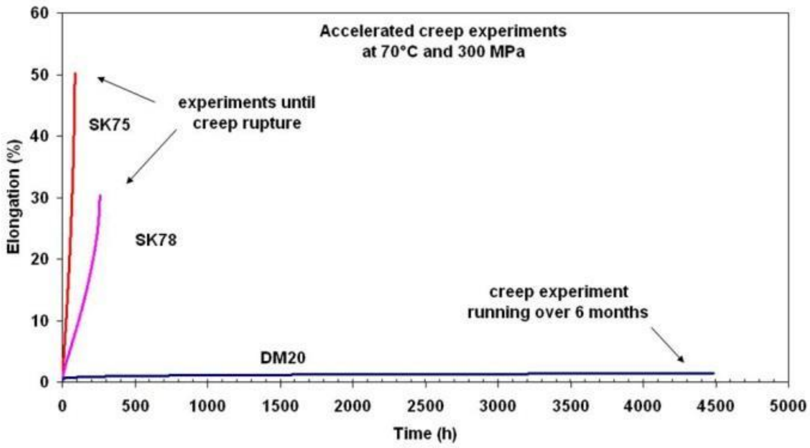
Dyneema® has the highest strength compared to its weight of all the currently available fibers, and in theory, the material can be developed even further (Werff, 2018). The strength combined with the excellent secondary properties like abrasion and chemical resistance, see table 2.2 for a complete overview of the properties of Dyneema® fiber. With exploring via web research on the different applications of Dyneema® fiber, we learned that the strength per weight unit and secondly the abrasion/cutting resistance are the properties that are used most to create value, table 2.3, see appendix A for the analysis. These properties provide cost savings for the end users, see chapter 2.5.

Table: 2.2	Source:	(Vlasblom, 2018)		
Direction	Axial	Transverse	**Fiber thickness**	0.00658 – 0.048 mm
Tensile strength	3.95 GPa	0.03 GPa	**Glass transition temperature**	- 78 C
Compressive strength	0.1 GPa	0.05 GPa	**Friction coefficient**	0.05 – 0.07
Density	970 - 980	kg/m3	**Chemical resistance**	Excellent
Melting point	144 - 152	°C	**Abrasion & cutting resistance**	Excellent

Table 2.3: Strengths and less valuable properties of Dyneema®	
Dyneema® strengths	**Dyneema® less valuable properties**
Tensile strength per weight unit	No compression strength
Abrasion resistance	Low melting point
Cutting resistance	Can suffer from creep
Bending fatigue	
Chemical resistance	

Creep

Dyneema® can suffer from creep, elongation under continuous tension, looking at graph 2.4 at the red line, the effect of creep on Dyneema® can be seen that is put under heavy load, > 90 % of fiber breaking strength. Dyneema® will elongate up to 50 % before failing after four days at high temperature. The blue line in graph 2.4 represents Dyneema® *DM20*, a more creep resistant Dyneema®. The effect of creep needs to be taken into account when considering Dyneema® for applications where it endures continuous tension.

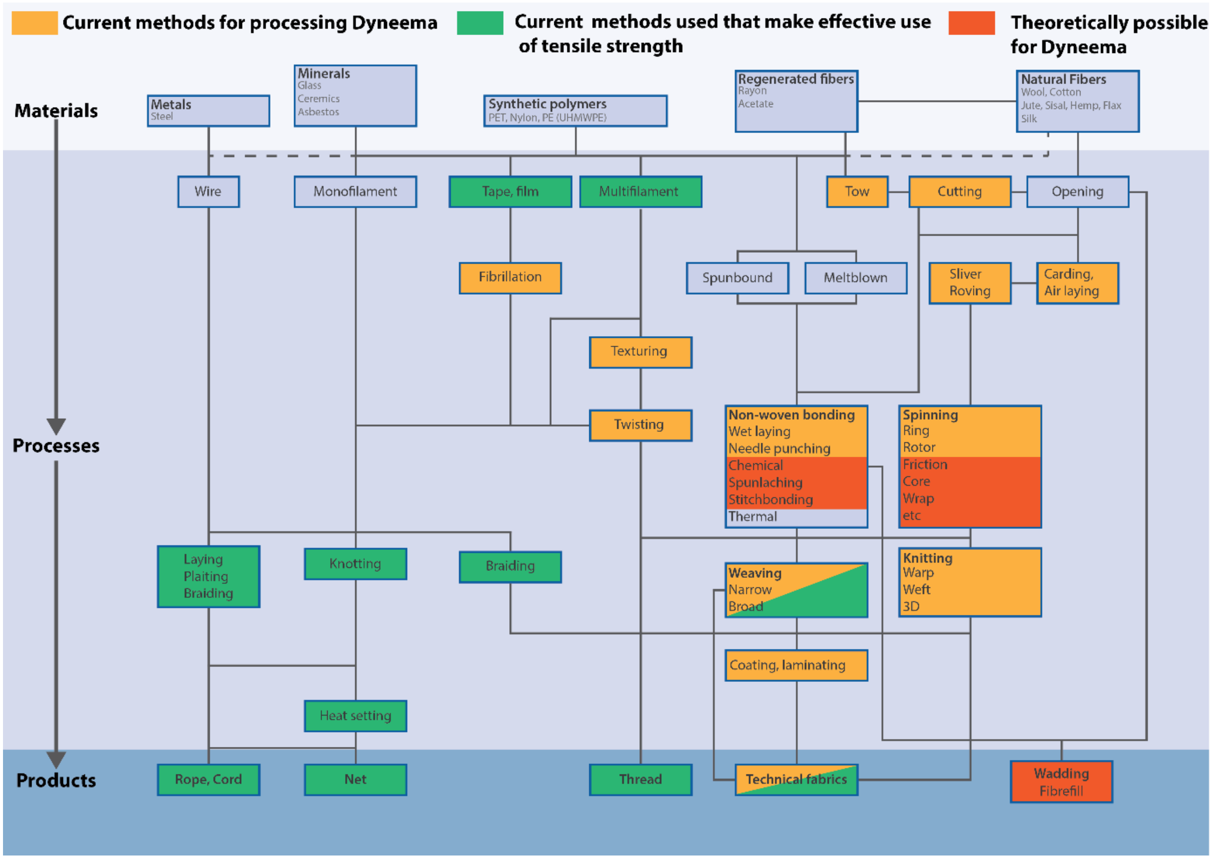


Graph 2.4. Creep properties of Dyneema® fiber. Source: Werff & Vlasblom. 2014.

DSM Dyneema BV has a good understanding of how creep will affect Dyneema® and which grade Dyneema® is suitable depending on the application, for example when Dyneema® is put under low loads, under 20 % breaking strength the creep will be only 1 % per year (Vlasblom M, & Bosman R, 2006). Knowing the effect of creep is essential for when choosing applications for Dyneema®.

Processing methods of Dyneema® fiber

DSM Dyneema BV sells Dyneema® fiber on bobbins to product manufactures, more on the product manufactures in chapter 2.2 and 2.4. These product producers make products from Dyneema® fiber with different processing methods. The processing methods have an effect on how effectively the properties of Dyneema® fiber are used. Not every production method is suitable for Dyneema® fiber. The suitable processing methods and the effect on the tensile strength are given below in figure 2.8. It was chosen to sort the processing methods by tensile strength because that is the most valuable property of Dyneema® fiber, see chapter 2.1.



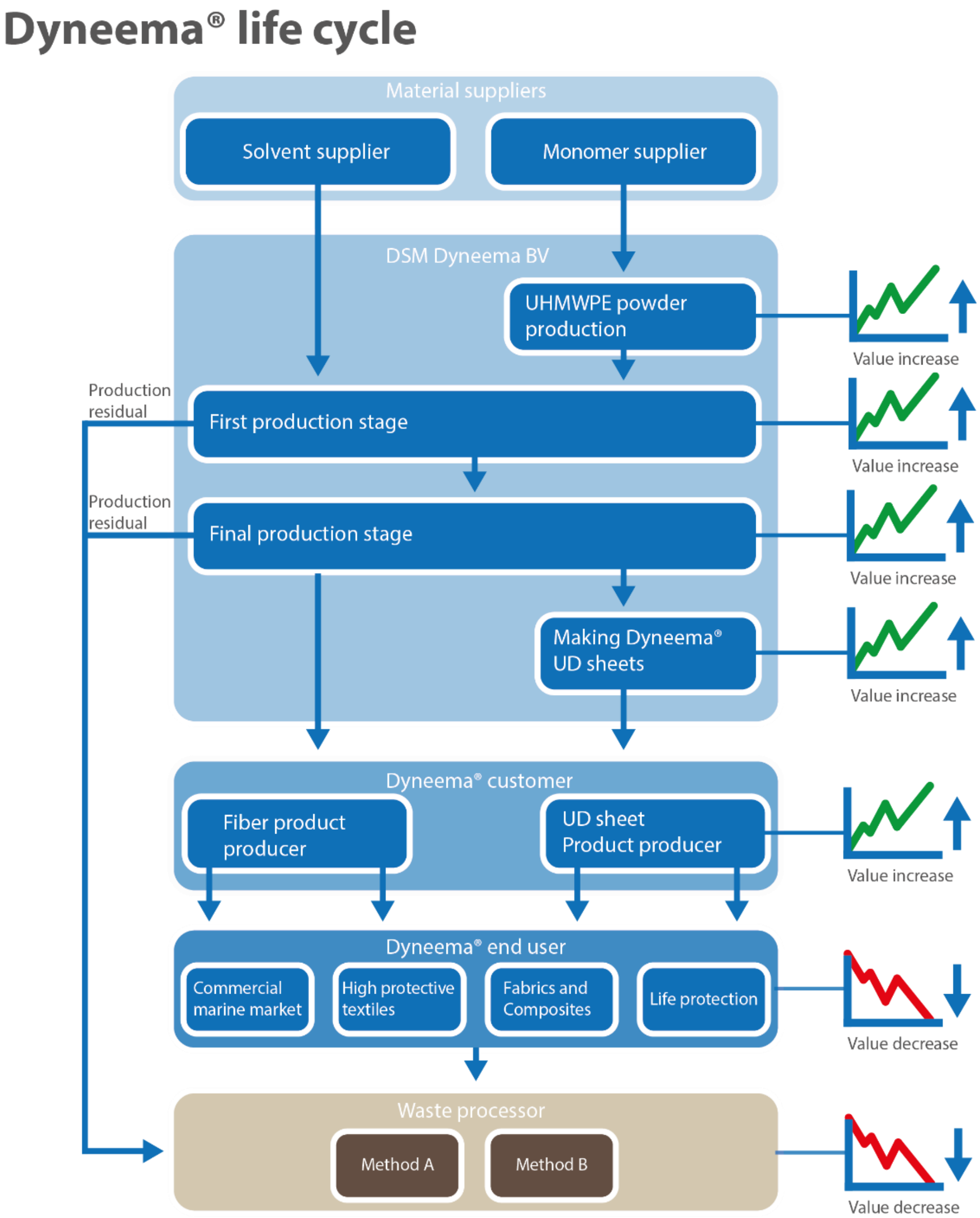
Graphic 2.8: An overview of the possible processing techniques for Dyneema® fiber. Source: Adaption on image from: Horocks, A, R. Handbook of Technical textiles. The textile institute, 2000. Based on information from (Vlasblom, 2018).

The different colors in graphic 2.8 show which processes are currently used for Dyneema®, which processes are currently used and use the tensile strength effectively and which methods are theoretically possible. This overview is made to see if Dyneema® is suited for applications and can be used to evaluate possible processing methods for EoU Dyneema®. The processing methods in graphic 2.8 are based on information from (Horocks, 2000), (Vlasbolm, 2018).

From the analysis of the processing methods of Dyneema® we learned that not all processing methods are possible and that the processing method influences the performance of the end products. The possible production methods should be taken into account when evaluating possible use applications.

2.2 DSM Dyneema markets

DSM Dyneema BV sells Dyneema® fiber to different markets across the world with the following production process, described in graphic 2.9. There are four different Dyneema® market categories, described in graphic 2.10. These four markets are analyzed to choose one market to focus on to explore a relative case for using EoU material.



Graphic 2.9: The life cycle of Dyneema® fiber. Source: self-made

By analyzing the Dyneema® life cycle, we learned that the product producers are the customers of *DSM Dyneema BV*. The different industries are the end user. It looks like that *DSM Dyneema BV* adds the most value to the Dyneema® product. This will be investigated further in chapter 2.5.

Focus on market

From the pros and cons in confidential appendix L, the commercial marine market is chosen to focus on in this graduation assignment. The commercial marine market is the best suited because the market has high volume (DSM, 2018). As we know from the challenges of the circular economy, chapter 1.2.2, a high volume is needed to make collection feasible. The Dyneema® fiber from the commercial marine market is considered the most recoverable compared to the products from the other markets, because ropes are a relatively pure form of Dyneema® fiber.

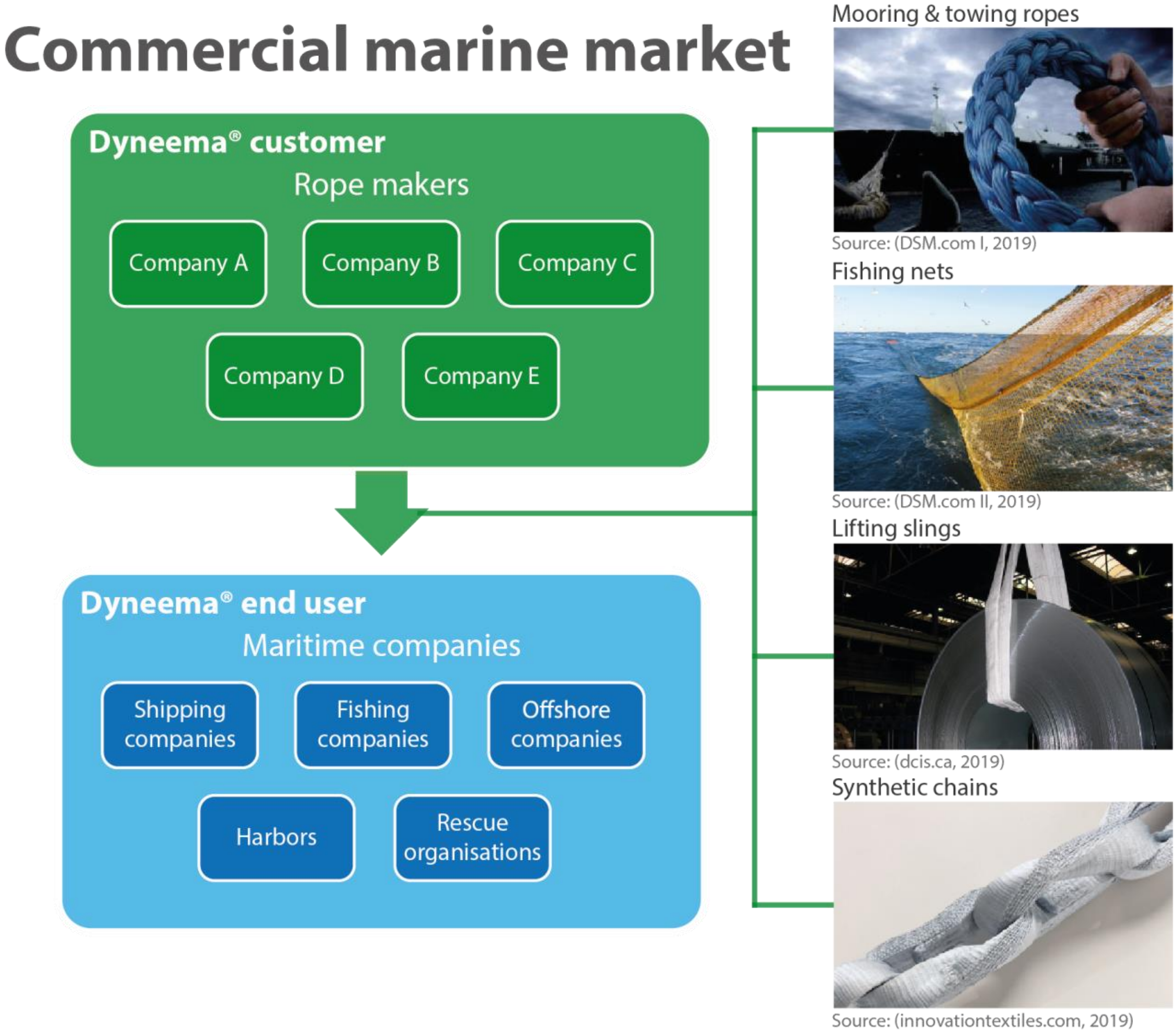
2.3 Commercial marine market

The commercial marine market consists of large industry shipping companies, off-shore companies and harbors. In this market, the Dyneema® is processed into ropes, nets and chains. The ropemakers are the Dyneema® customer, and the marine companies are the end users, see graphic 2.11.

Dyneema® has a competitive advantage in the commercial marine market over its competitors due to the following properties: High tensile strength for lightweight, no lubricants required, no water absorbing, abrasion & cutting resistance (DSM & Samson, 2018). In chapter 2.5 the way how, these properties create value is analyzed.

Commercial marine market segments

There are four market segments in the commercial marine market. Mooring & Towing ropes, fishing nets, lifting slings and synthetic chains, see graphic 2.11.



Graphic 2.11: Dyneema® in commercial marine market. Sources: self-made graphic.

Rope making

The Dyneema® customer buys Dyneema® multifilament fiber on bobbins from *DSM Dyneema BV.* The fibers are spun into yarns that are then braided or twisted into ropes, image 2.12. Some ropes get a braided Dyneema® shield, image 2.13. Nets are double knotted or heat set. Looking at graphic 2.7, it can be seen that the above processing methods make effective use of the tensile strength of Dyneema®.

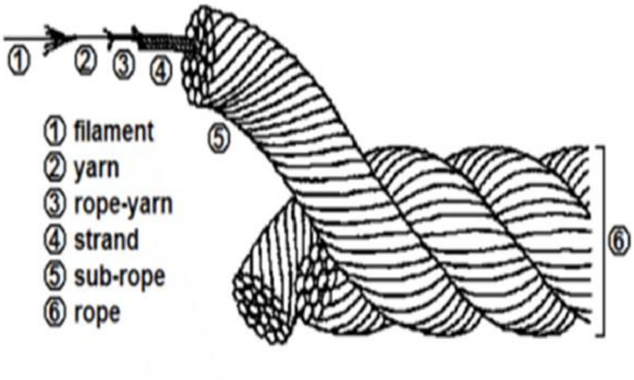


Image 2.12: The construction of a rope. Source: Aireen, 2016

Image 2.13: Dyneema® rope (grey) with a braided Dyneema® shield (red). Source: linysyntetyczne.pl, 2019.

Coating on ropes

One notable step the ropemakers do with the ropes made from Dyneema® fiber is the addition of a *coating A*, see confidential Appendix A. Coatings are applied to increases the durability of the material in the application (DSM, 2019).

It should be analyzed what effect(s) *coating A* has on value recovery possibilities of the EoU ropes, see chapter three. The circularity of the coating is investigated to explore if coating can be reused or otherwise recycled, also considering possible environmental concerns.

The coating used on the ropes made from Dyneema® fiber seems difficult to separate from the rope because of it being a thermoset. This makes recovery of Dyneema® ropes more difficult and potentially reduces the value of the rope material. Environmental concerns about the use of *Coating A* and similar coatings oblige more research for circular use of materials containing these types of coatings.

It is therefore concluded that the *coating A* is a possible barrier for the circularity of the ropes made from Dyneema® fiber from the commercial marine market. Chapter three elaborates more on this aspect.

2.3.1 Commercial marine End-of-Use material

EoU material from the commercial marine market is chosen as the source of EoU material for exploring reuse and remanufacturing possibilities. EoU material from the commercial marine market consist of ropes, netting, lifting slings and synthetic chains. It is chosen to use EoU ropes with a thickness of 32 mm to 44 mm, see confidential appendix B for the explanation.

From interviews it is known that the EoU ropes can be contaminated with grease, oil, sand and paint from use in industrial applications (Spijkers, 2019), image 2.14. The yarns of the EoU ropes from the commercial marine market can be stiff. The stiffness can be the result of the coating or the melting together of the fibers due to heat and pressure from abrasion (Spijkers, 2019). The strength of the EoU ropes is reduced due to damage of the ropes. The strength is theoretically reduced to an average of 40 % of the strength of new rope (McCorkle, 2003). To explore reuse and remanufacturing possibilities of EoU Dyneema® the EoU material should be analyzed. The goal of the analysis is to find out what the effect of damage is to the rope and what value is left in the material and possible ways of value recovery. In chapter three experiments are conducted to analyze the EoU material.

Image 2.14: A Dyneema® rope in use, the grey color on the ropes indicate contaminations on the rope. Source: (Dynamica-ropes.com, 2019).

2.3.2 Risk management

EoU material can be contaminated from use that means that there are risks involved in using the material. For companies it is important that potential risks are managed. When a contaminated material comes into contact with human skin, it could be a health risk. Health issues should be avoided at any cost. Furthermore, possible environmental concerns should be taken into account.

DSM Dyneema BV has a controlled production line and certifications to make sure new Dyneema® to meet all safety and performance requirements. Before the use of EoU Dyneema® has a good quality control risk could better be avoided. The EoU material will have to be cleaned to be entirely sure it will not be a risk for humans or the environment. Cleaning could be done with water, but for contact with human skin it should be cleaned more thoroughly this could be with chemicals, with high or freezing temperatures. The risk of pollution should also be managed when reusing or remanufacturing the EoU material.

Because of potential risk involved the materials used in the commercial marine markets must be certified. Certifications like *ASTM* and *DNV GL* provides the industry with a third-party demonstration of compliance to standards (ASTM, 2018). Currently certification for reused and recycled materials are not yet available.

From the above information it is concluded that EoU materials should be cleaned before reuse and the risk of pollution the environment should be checked. The requirement of certifications should be taken into account.

2.4 Stakeholder analysis

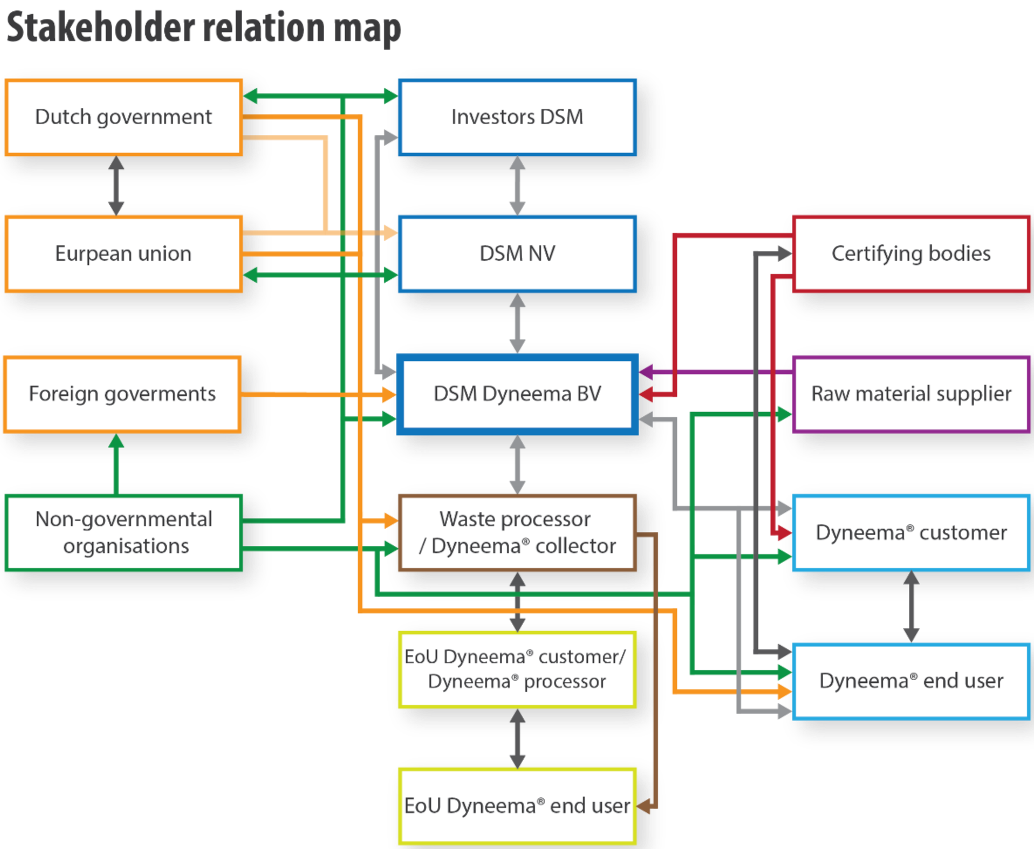
Stakeholders and the mutual relations between these stakeholders influence the circular strategy of *DSM Dyneema BV*. A stakeholder analysis on *DSM Dyneema BV* is done to analyze who are the key stakeholders, what the relations are between them what their role is to gain insights on how *DSM Dyneema BV* should approach the transition towards the circular economy. Here the process and the stakeholders are described briefly.

Process

The stakeholder mapping is done in collaboration with DSM employees. In a collaborative session with it was determined by discussions who the stakeholders are and why, see table 2.15, what are the relations between those stakeholders, see graphic 2.16, and their position on the stakeholder map, graphic 2.18. First, the stakeholders were positioned on the map for the linear situation and after that for a future circular situation. The assumption was that doing a collaborative session with DSM employees will give insights on how DSM thinks and approach circularity.

Table 2.15: Stakeholders	Overview with all the stakeholders of *DSM Dyneema BV*
Stakeholder	**Reason for being a stakeholder**
DSM NV	The mother organization of *DSM Dyneema BV*. Stakeholder because the board of directors from *DSM NV* take decisions for *DSM Dyneema BV* as well.
Investors in *DSM*	Investors in *DSM* are stakeholder because they can influence the direction of *DSM* goes towards business wise.
Dyneema® Customer	Is stakeholder because it makes products from Dyneema® fiber and is, therefore, part of the Dyneema® value chain.
EoU Dyneema® customer	Is a stakeholder in the circular situation because it makes products from the EoU material and is, therefore, part of the circular value chain.
Dyneema® end user	The end user of Dyneema® fiber is stakeholder because it uses and evaluates Dyneema® and is, therefore, part of the Dyneema® value chain.
EoU Dyneema® end user	The EoU Dyneema® customer is stakeholder because it will use the EoU products and play a role in the reception of the circular product.
EoU Dyneema® collector	The EoU Dyneema® collector is stakeholder because it will be an essential link in the circular value chain.
EoU Dyneema® processor	The EoU Dyneema® processor is stakeholder because it is part of the circular value chain.
Raw material supplier	The raw material supplier is stakeholder because it is part of the Dyneema® value chain.

European Union	The European Union is stakeholder because it can set up regulations that influence *DSM Dyneema BV*, their customers and end users.
Dutch government	The Dutch government is stakeholder because it can set up regulations that influence *DSM Dyneema BV*, their customers and end users.
Foreign Governments	The foreign government is stakeholder because it can set up regulations that influence *DSM Dyneema BV*, their customers and end users.
Non-governmental organizations	Non-governmental organizations are stakeholder because they can influence DSM customers and end users via public opinion.
Certifying bodies	Certifying bodies are stakeholder because they set up the regulations that *DSM Dyneema BV* should meet because of the customers and end-users demand it.
Waste Processor	The waste processor is stakeholder because it is part of the Dyneema® value chain.



Graphic 2.16: An overview of all the stakeholders and their relations. The colors indicate that stakeholders are related to each other. Source: self-made graphic.

Looking at the graphic 2.16 on the relations of the stakeholders led to the following insights

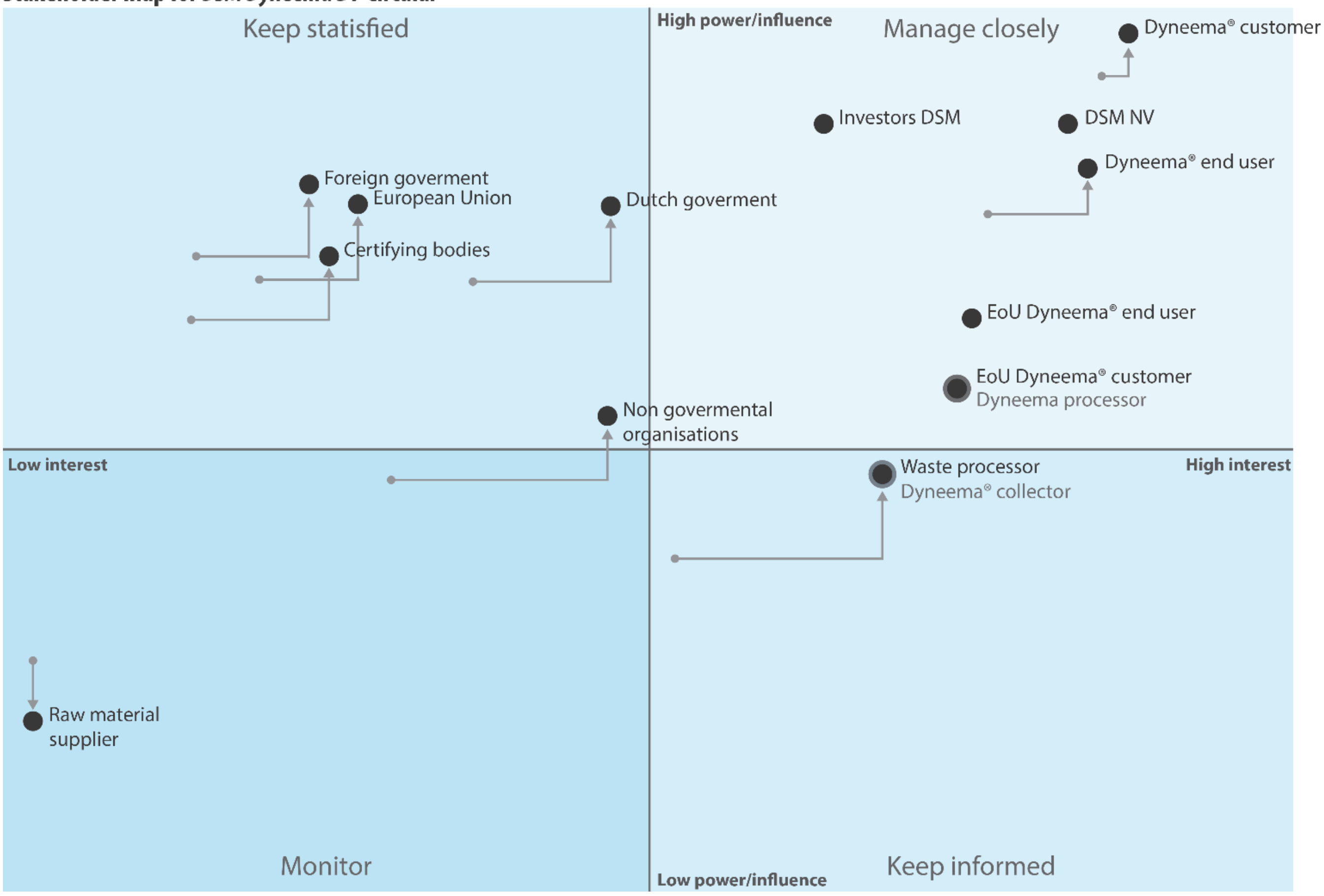
- The relations between the stakeholders gave insights on their importance.
- Stakeholders like the NGO's and the governments have both direct and indirect influence on *DSM Dyneema BV*. The indirect influence comes from the influence these stakeholders have on the Dyneema® customer and end-user.
- Regulations from the governments influence the waste processor.

Stakeholder map

The stakeholders are positioned on a stakeholder map by their relative power/influence and their interest in *DSM Dyneema BV*, see table 2.17. The power and influence of the stakeholder was determined by discussions in the collaborative sessions with DSM employees and on their expert opinion. The arrows indicate the shift of position from the linear to the circular situation.

Table 2.17		
Y-axis	**Power/influence**	The Y-axis represents the power the stakeholder has on *DSM Dyneema BV*. High power means that is has much control over *DSM Dyneema BV* low power means that the stakeholder has no control over *DSM Dyneema BV*.
X-axis	**Interest**	The X-axis represents the interest the stakeholder has in *DSM Dyneema BV.* High interest means that the stakeholder is very concerned with what happens to *DSM Dyneema BV.* Low interest means that there is no interest in what happens with *DSM Dyneema BV.*

Stakeholder map for *DSM Dyneema BV* Circular



Graphic 2.18: The stakeholder map showing the power and influence of the stakeholders. Source: self-made graphic, based on information from DSM.

The following insights were obtained from the stakeholder analysis map presented in Graphic 2.18.

- The most important stakeholders in both the circular and linear situation are the customer and end user of Dyneema® fiber.
- The most notable difference with the linear model is that almost all stakeholder became more important, especially the NGO's and the waste processor. The role of DSM towards these stakeholders has not changed.
  - The power and influence of the NGO's grew because it was estimated that in a circular situation these NGO's could influence the public opinion more.
  - The power and influence of the waste processor grew because it gets an additional role in the circular value chain.
    - That all the stakeholders became more important, led to the conclusion that to make the transition towards the circular economy DSM will have to collaborate more than they do now.
- The waste processor and the EoU product customer have a double role in the circular situation. This led to a discussion where it became clear that the circular value chain will differ for each product.
- The EoU end user is more important than the EoU customer which is the other way around compared to the new Dyneema® value chain. This again led to a discussion where is became clear that the circular value chain will differ for each product.
- DSM stated that they wanted to have a facilitating role in the circular value chain instead of full participation because they want to stay close to their core strengths.
- From doing the collaborative sessions it was discovered that DSM wants to make the transition but must be realistic because changes are not always easy to make in a large organization.
- From doing the collaborative sessions it was discovered that DSM is protective about the intellectual property rights of Dyneema®.

Implications for the graduation assignment

The insights presented above are informative for *DSM Dyneema BV* regarding the transition towards the circular economy. Not all points fit in the scope of my assignment and are therefore not further worked out but used in a recommendation in chapter 7. From the stakeholder analysis it was concluded that every value chain will differ, this will be further investigated in chapter 5.

2.5 Business model analysis

The business models from *DSM Dyneema BV* and a Dyneema® customer in the commercial marine sector are analyzed to gain insights on how value is created. Circular business models are investigated to discover what circular possibilities these models can offer for EoU Dyneema®. The canvasses are filled based on web search on the website of *company A* and interviews with DSM employees.

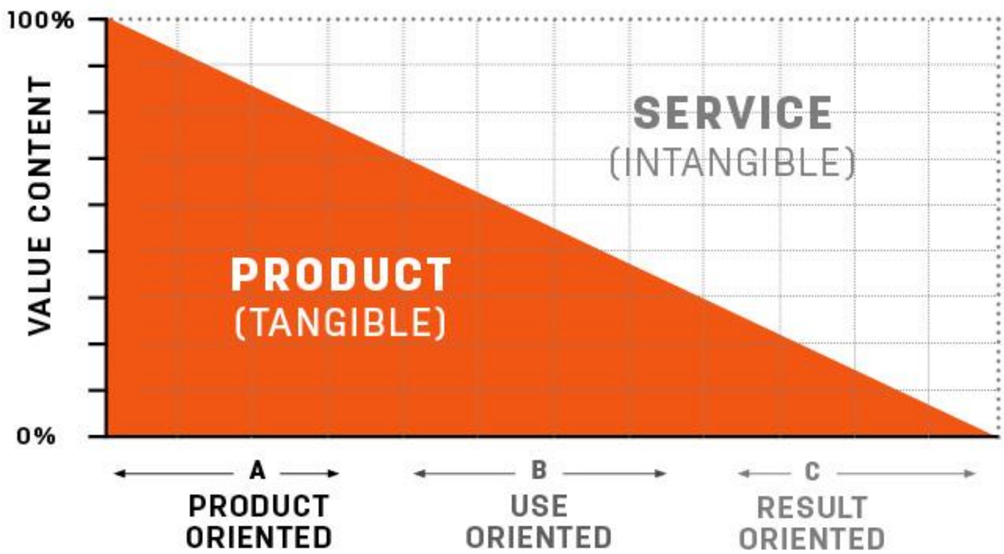
Circular business models

Circular business models fit the approach of slowing and closing of the resource loops (Bocken, 2016), in this case possibly expanding the Dyneema® product lifetime. Circular business models come in different forms: *Access and performance*, *extending product value*, *classic long life* and *encourage sufficiency, extending resource value and industrial symbiosis* (Bocken, 2016). For Dyneema® fiber the *access and performance*, *extending product value* and *encourage sufficiency* seem to be suitable.

The *access and performance* model provide the value proposition without ownership of the product, the responsibility for the maintenance and replacement of the product. The customer has access to the value from the product through a service rather than buying the product (Bocken, 2016), graphic 2.19. *Extending product value* are business models focused on extending the product lifetime beyond its first product use cycle by adapting strategies like reuse and remanufacturing (Bocken, 2016). *Encourage sufficiency* are models to reduce the need for new products by using principles as durability and service.

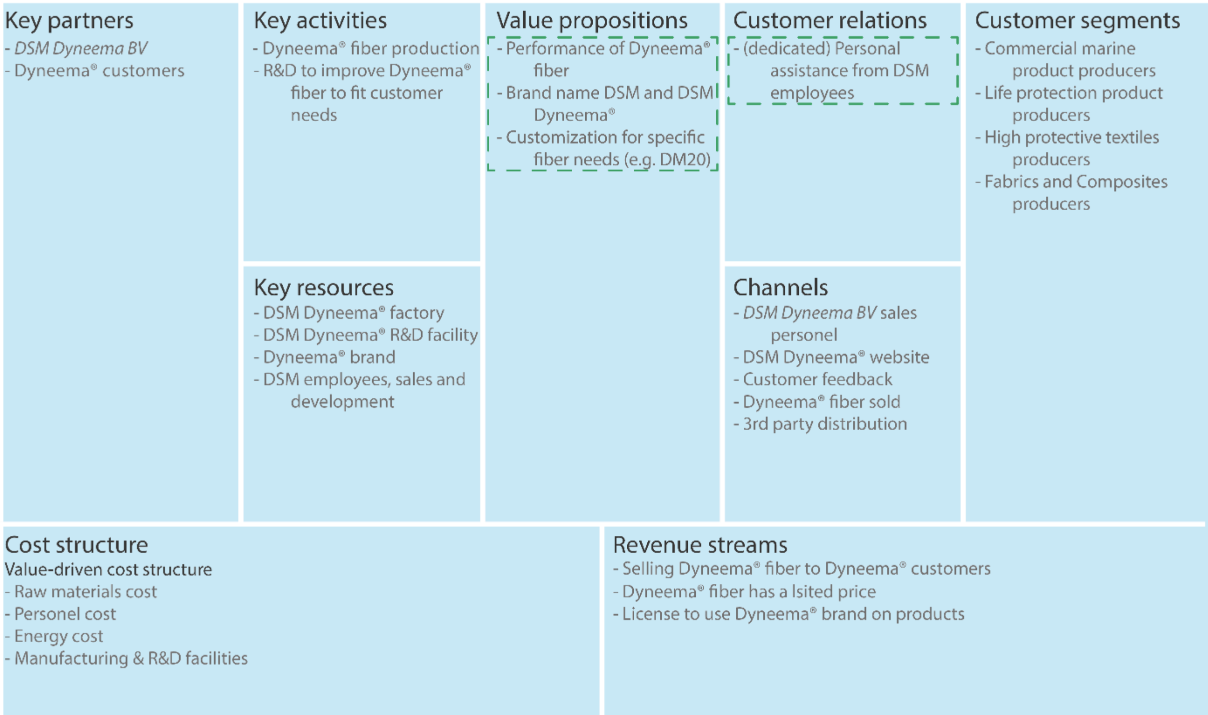
The three models mentioned above are interesting for Dyneema® because Dyneema® fiber, the value propositions of *DSM Dyneema BV* and *Customer A, graphic 2.20 & 2.21,* fulfill the descriptions of the *access and performance* and *encourage sufficiency* business models. The possibilities for *extending product value* model are explored in this assignment by looking at possibilities for value recovery through remanufacturing of the EoU material. The implementation of these business models falls outside of the scope of the graduation assignment.

For the circular opportunities of EoU Dyneema® the *access and performance* model can provide control over the quality of the EoU material because the service provider stays the owner of the products. It potentially makes Dyneema® fiber available to more customers, because of lower initial investments, increasing the volume of the market.



Graphic: 2.19: Graphic showing different ways of value creation. Source: Bakker, 2014.

***DSM Dyneema BV* business model canvas**



Graphic 2.20: The business model canvas of DSM Dyneema BV, the areas highlighted in green dotted lines are interesting for circular business models. Source: self-made graphic, based on information from DSM.

Dyneema product producer Company A

Graphic 2.21: Business model canvas of Company A, the areas highlighted by the blue dotted lines are interesting for circular business models. Source: self-made graphic, based on information from DSM.

Insights obtained by comparing business model canvasses of DSM Dyneema BV and company A

Analyzing the business model canvasses the value proposition of Dyneema® fiber was reviewed. The excellent strength for its weight is providing advantages over competing materials. For Dyneema® fiber end users the value proposition are the economic advantages of using Dyneema® fiber. Dyneema® fiber is not adding any possibilities but provides cost savings on the long run. Cost are reduced by savings in labor, maintenance, lubricants, upkeep, product lifetime and energy **(DSM & Samson, 2018) (DSM, 2018**). More safety and convenience are also a value by itself. It would be interesting to find out if EoU Dyneema® could offer the same sort of value on the long run. This is similar to *use* or *result-oriented* value creation, see image 2.19.

Both *DSM Dyneema BV* and *Company A* need each other to fulfill their business models. *DSM Dyneema BV* needs the customers of *company A* to create the market value of the fiber, which also depends on the performance of the end-product. *Company A* needs the unique properties of Dyneema® fiber for a competitive advantage in the market.

Both *DSM Dyneema BV* and *company A* use the Dyneema® brand name. The brand name is part of the value of the product produced by *company A.* For the marketing strategy of EoU material the permission for use of the Dyneema® brand name should be taken into account.

Some principles for circular business models are present in the value propositions, key activities and customer relations of *DSM Dyneema BV* and *Company A* their business models. Circular business models are an essential part of closing the material loops. However, *DSM Dyneema BV* does not sell the ropes, so collaboration with *company A* and possible remanufacturing parties and other will be needed to go to full circular business models. A recommendation for *DSM Dyneema BV* will be to prepare for more collaboration with business partners in the transition towards the circular economy.

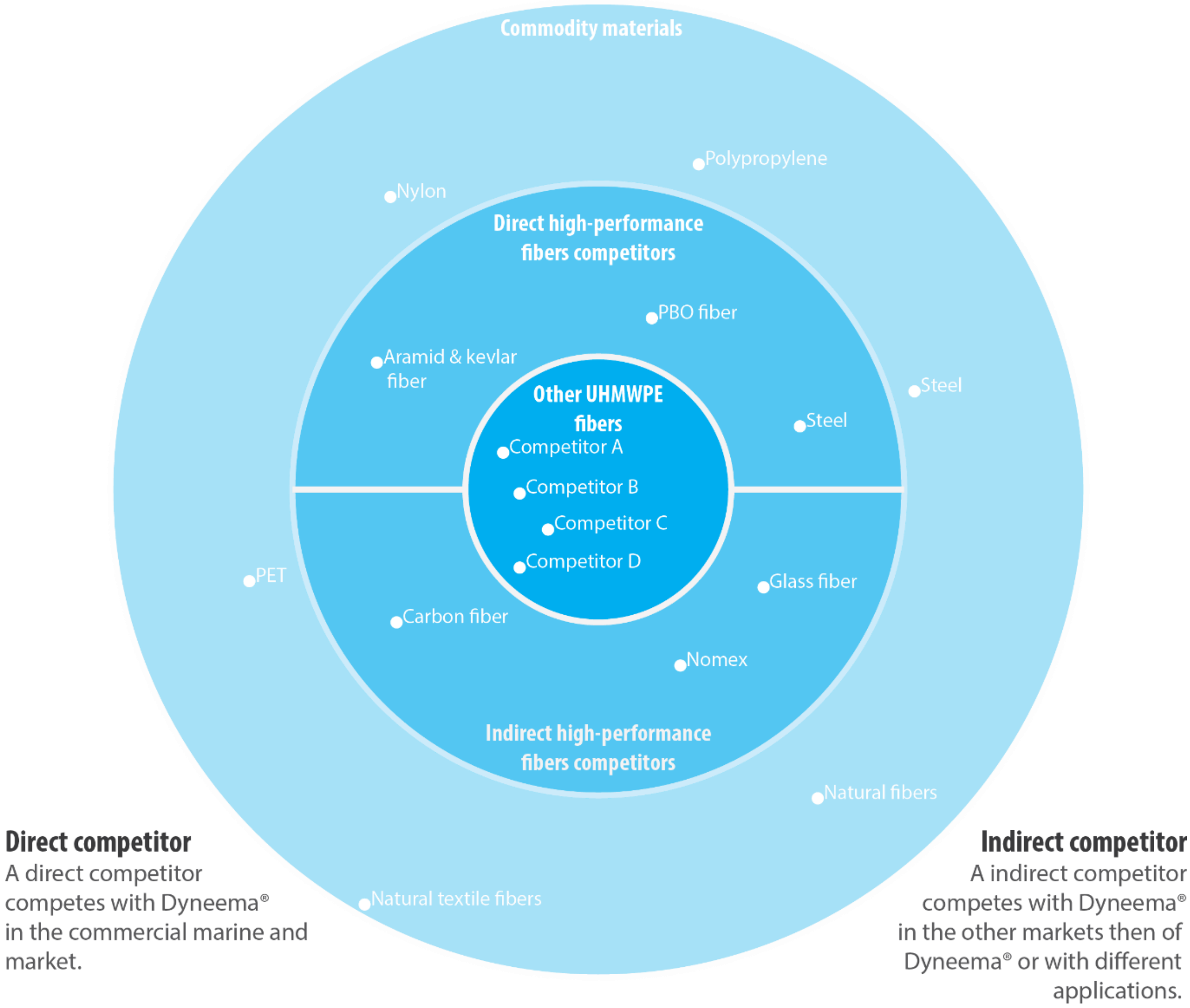
2.6 Competitor analysis

In this chapter, the competitors of *DSM Dyneema BV* are analyzed to gain insights on the value of EoU Dyneema® and find inspiration for circular possibilities. For the competitor analysis, the competitors in all markets are analyzed not only in the commercial marine market to gain more inspiration from the recycling of the competitors.

Who are the competitors?

The competitors of *DSM Dyneema BV* are divided into four groups and are mapped out to show how they compare to Dyneema® fiber. The more the competitor is in the middle of the circle in graphic 2.22 the more important the competitor is.

Dyneema® competitors



Graphic 2.22: Overview of the competitors of Dyneema® fiber, note that steel fits in two categories because it competes in two areas with Dyneema®. Source: self-made graphic, Based on information from DSM, See confidential appendix C.

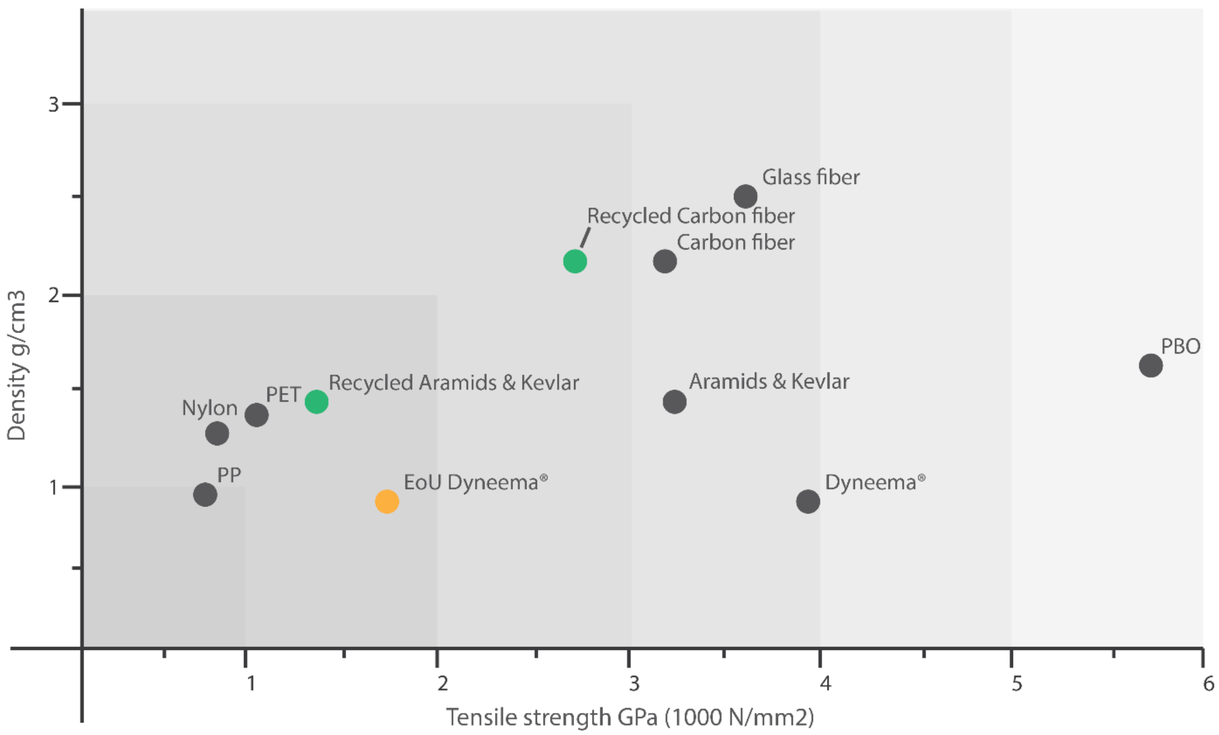
Focus

Web research on company websites and annual reports of the fiber producers, was used as the method to analyze the competitors. There was no information on the circularity of other UHMWPE fiber and *PBO fiber* to be found. To create focus, it was chosen to compare circularity of only the synthetic high-performance fiber competitors, Aramids & Kevlar, and Carbon fiber because information on these fibers could be found.

Competitors for circular Dyneema®

To obtain insights on how EoU Dyneema® competes, the residual strength of EoU Dyneema® is compared to other fibers. Table 2.23 and graphic 2.24 are to show how EoU Dyneema® compares to competing fibers in tensile strength and weight, this is done because these are important properties in the fiber industry.

Table 2.23 **Technical specifications of competitors**			
Source: (Bunsell, 2018)			
Material	**Strength GPa**	**Density g/cm3**	**The strength of recovered fiber**
Dyneema® (*SK75*)	3.95 GPa	0.96 g/cm3	40 % (1.58 GPa) EoU (McCorkle, 2003)
Aramids & Kevlar	3.25 GPa	1.45 g/cm3	40 % (1.3 GPa) (Marcuzzo, 2016)
Carbon fiber	3.2 GPa	2.2 g/cm3	85 % (2.7 GPa) (Pimenta, 2014)
PBO	5.8 GPa	1.56 g/cm3	-
Glass fiber	3.3 GPa	2.5 g/cm3	-
PET	1.11 GPa	1.38 g/cm3	-
Nylon	0.85 GPa	1.2 g/cm3	-
Polypropylene (PP)	0.65 GPa	0.95 g/cm3	-



Graph 2.24: The competitors of Dyneema® fiber and their residual strength after recycling. Source: self-made graph based on table 2.23.

The data presented in graphic 2.24 provided the following insights.

- The residual strength of EoU Dyneema® is theoretically higher than the strength of the commodity fibers.
    - Recycled Aramids and Carbon fiber are stronger than commodity fibers as well
    - The tensile strength affects the secondary properties, e.g. abrasion resistance. The assumption is that these secondary properties are also higher than the commodity fibers.

2.6.1 Circularity of competitors

An analysis on the circularity of the competing fibers will provide insights on how *DSM Dyneema BV* could close their material loops. It was chosen to compare to Aramids & Kevlar fiber and Carbon fiber. See appendix B for a more detailed analysis and sources for numbers in, graphic 2.26, 2.28. Information gathered on the recycling of competitors is done by web search on company websites and annual reports and interviews with *DSM Dyneema BV,* assumptions were made when no exact numbers where available. See Confidential appendix D for the circularity of Dyneema.

Criteria for evaluation

The competitors are analyzed on the following points, see table 2.25 for an overview.

- How much of the yearly production is being recycled?
- Is the material recycled in open or closed loop systems?
- What technologies are used for recycling?
- Who are recycling the fibers?
- What products are being made from the recycled fiber?
- What property of the fiber is used to provide value?

Table 2.25

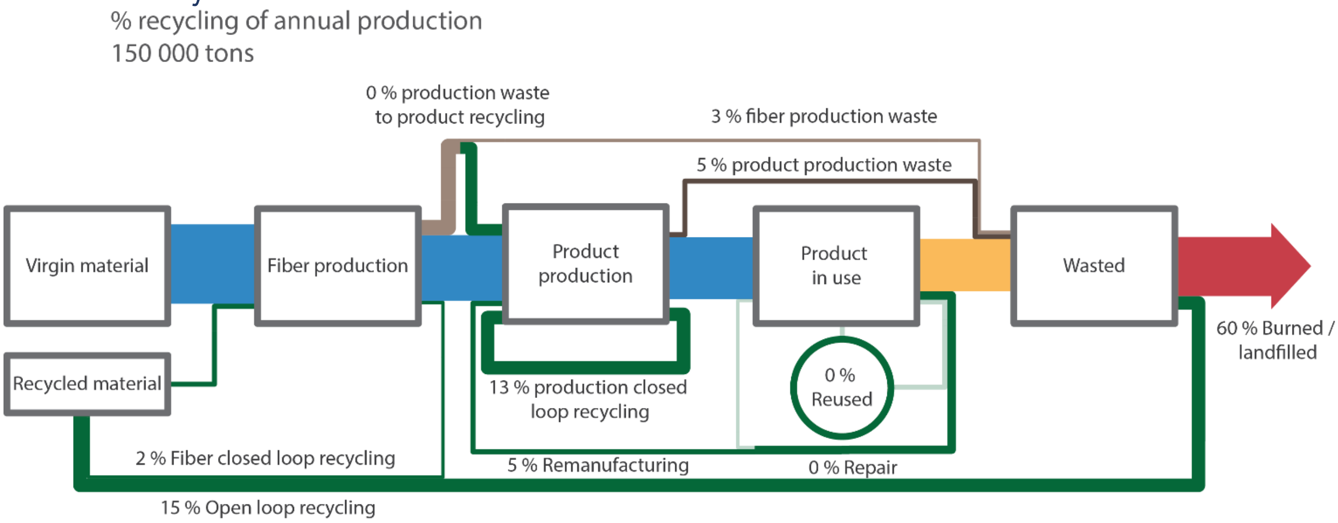
	Dyneema®	**Aramids & Kevlar**	**Carbon fiber**
Closed-loop recycling	Confidential Appendix D	10 %	15 %
Open-loop recycling	Confidential Appendix D	15 %	10 %
Recovery technology	Confidential Appendix D	Mechanical	Chemical & mechanical
Recyclers	Confidential Appendix D	TEIJIN and medium and small individual recyclers	ELG Carbon fiber Ltd. ROTH international, Product producers
Applications	Confidential Appendix D	Heat resistant material, Image 2.28	Polymer reinforcement, prototype parts, and mixes with virgin carbon fiber, image 2.30.
Property used	Confidential Appendix D	Heat resistance	Moderate strength for a reduced price

Competition as a business partner

To make the transition towards the circular economy methods for recollection, sorting, and processing of materials must be developed and set up. Not all materials and products are (currently) suitable for a circular economy because the volume of material flow is too small to create enough potential revenue to set up a value chain (Green Alliance, 2017).

Competitors have the same problem setting up a large enough value chain. When collaboration is considered, competitors can look at opportunities to set up a conjunct value chain. With collaborations, the transition to a circular economy is more feasible and both competitors can benefit from the circular economy opportunity (Ellen Macarthur foundation, 2013). For *DSM* it could be an opportunity to look for possible collaborations in the collection of EoU materials. For the feasibility of the conjunct value chain it might be needed to collect similar products or in similar markets.

2.6.2 Circularity Aramids & Kevlar



Graphic 2.26: An overview of the material flow of Aramids & Kevlar fiber. Source: self-made graphic.

In the graphic above, graphic 2.26, the Aramids & Kevlar material flow can be seen. Looking at the graphic led to the following insights.

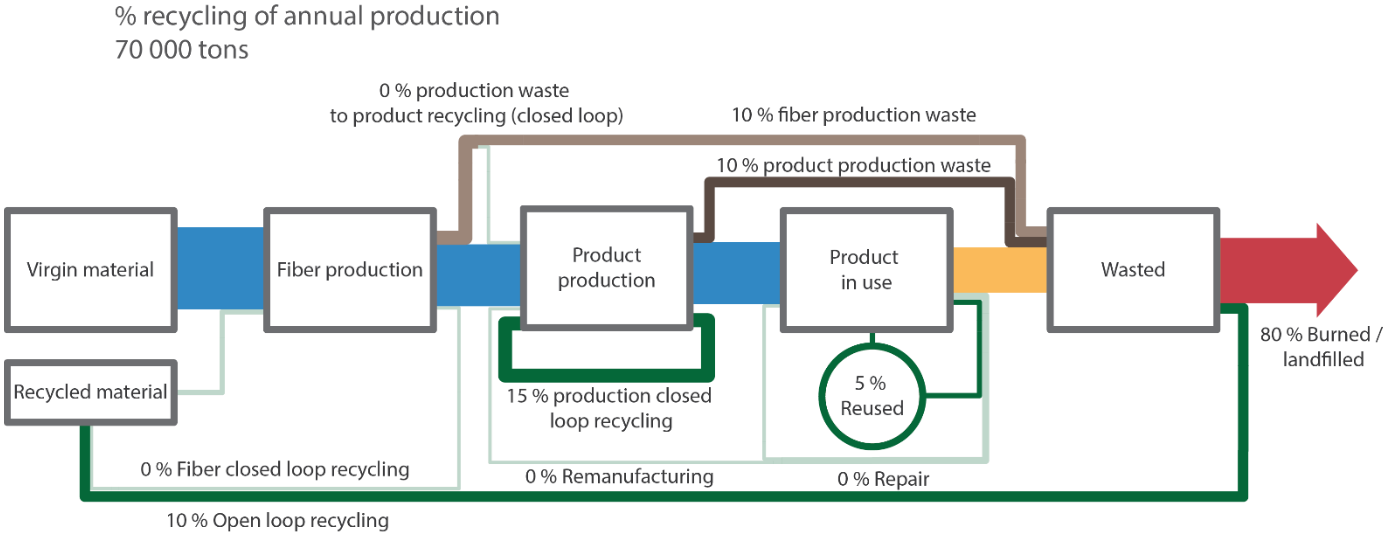
- Aramids & Kevlar are being recycled in both open & closed loop systems, but only part of all the material.
- The annual production is higher than that of Dyneema® fiber.

Other insights gained in analyzing circularity of Aramids & Kevlar fiber.

- Aramids & Kevlar are being downcycled because the value of the material is reduced in the recycling process (Rothe, 2017) see graphic 2.27 for product examples.
- *TEIJIN* has worked years on setting up a global open loop recycling collection system (Rothe, 2017). Interestingly is that Dyneema® products are quite like the products collected here, meaning that collaboration in the collection is possible.
- *TEIJIN*, the largest recycler of aramids has quality control and certification for their recycled material (Rothe, 2017).

Graphic 2.27. An overview of the new and recycled Aramid & Kevlar products. Source: self-made graphic.

2.6.3 Circularity Carbon fiber



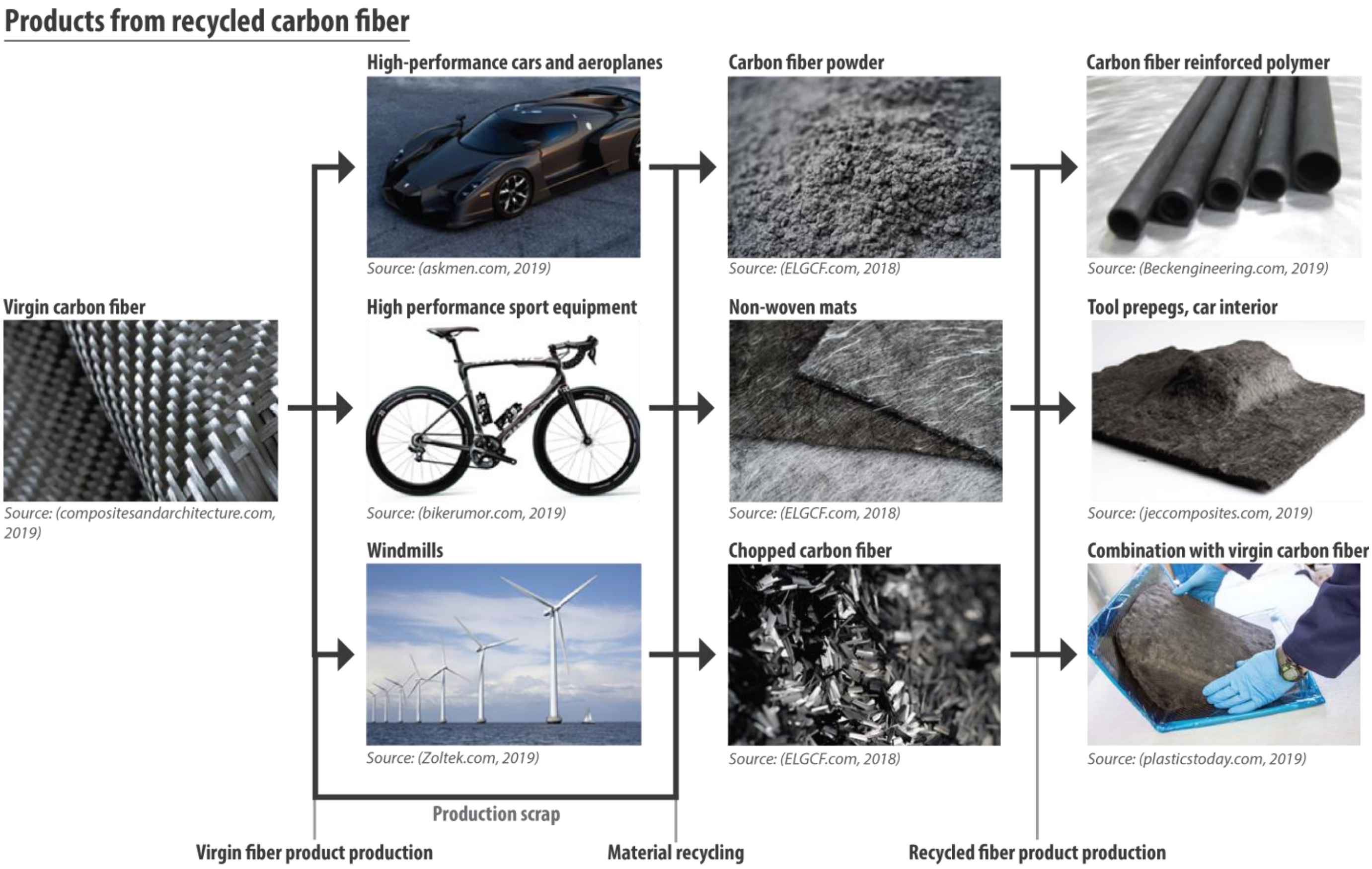
Graphic 2.28: An overview of the material flow of Carbon fiber. Source: self-made graphic.

In graphic 2.28, the Carbon fiber material flow can be seen, in graphic 2.30 the products from the recycled fiber can be seen. The following insight was obtained from looking at both these graphics.

- Carbon fiber is recycled in both open & closed loop systems, but only part of all the material.

Other insights gained in analyzing circularity of Carbon fiber.

- Carbon fiber recycling is downcycling because the value of the fiber is reduced in the recycling process (Materialsforengineering, 2018).
- A combination of chemical and mechanical recycling is used to recycle Carbon fiber (Materialsforengineering, 2018).
- The biggest challenge for the recyclers was to find a market for the recycled (CompositesUK, 2018).
- Some manufacturers are forced to recycle carbon fiber because carbon fiber production cannot meet the demands (Barnes, 2018).
- *ROTH international* takes apart large machines containing carbon fiber as a service (ROTH, 2018).
- Every product manufacturer has product residual.



Graphic 2.30: Recycled carbon fiber forms and products. Source: self-made image.

Conclusion competitor analysis

EoU Dyneema® theoretically has higher strength then commodity fibers, this can be an interesting opportunity. From the competitor analysis it was discovered that competition is downcycling their fiber. The biggest challenge was to find a market for their downcycled fiber. It is important to determine the valuable property of the recycled fiber in end-products for finding their specific uses and markets. Aramid producer *TEIJIN* has been working on a global collection system for the last years, *DSM Dyneema BV* could see this as an opportunity to work together in the collection.

2.7 Opportunities and challenges for *DSM Dyneema BV* from the transition towards the circular economy

In this chapter an understanding of the Dyneema® material and the commercial marine market was formed. This understanding was used to create focus and context needed to explore a design case in more detail.

Focus and context

In this chapter, it was chosen to focus on the EoU material from the commercial marine market for reuse. This choice was made to create a focus within the graduation project and because reuse and remanufacturing are an interesting strategy to close the material loop. It was decided that ropes with a thickness of 32 and 44 mm were chosen as the source of EoU material, chapter 2.3.1.

In this chapter the Dyneema® fiber properties, value proposition for Dyneema® customer and end user and the Dyneema® fiber processing methods gave insights on what would be criteria for finding an application where EoU Dyneema® could provide value. Further analysis of the business models is interesting for circularity but falls outside the scope of this graduation assignment.

From the stakeholder analysis, it was concluded that the circular value chain would differ for each specific market or application. Therefore, the choice is made to analyze one value chain further in the design case in chapter 5.

Opportunities

Collaboration with competitors in the collection of high-performance fiber EoU material seems promising. Circular business models could provide additional value, further analysis of this potential fall outside the scope of this graduation assignment.

From the competitor analysis we learned that, although EoU Dyneema® is theoretically less strong than new Dyneema® it is still stronger than commodity fibers, it would be interesting to investigate possibilities of competing with these fibers. Competing with these fibers will open up a large market, but it should not be forgotten that it comes with a price point challenge. Other high-performance recyclers have the similar challenges in the collection of the EoU material. Collaborations in the collection of the EoU material could be beneficial. Every product producer that works with high-performance fibers have production residual. High-performance fibers are very expensive and scarce, in the case of carbon fiber that was the driver for recycling. Meaning that the product producers would be eager to also develop a solution for their residuals. Collaboration with product producers is an opportunity here.

Challenges

The effect of creep must be taken into account when considering Dyneema® for applications where it endures continuous tension. From the stakeholder analysis and business model analysis it became clear that for the transition towards the circular economy, DSM could benefit from collaborative circular value chains. Also, DSM could think about how they share their information to their stakeholders, so that collaboration becomes easier. The value chain for the circular situation will be different for each EoU application. From the competitor analysis, the biggest challenge for the other high-performance fibers was to find a market for the recycled material. It was concluded that the coating on the ropes are a potential barrier for the circularity of the ropes from the commercial marine market, this will be further investigated in chapter three.

Chapter 3 - Analysis of End-of-Use Dyneema® from the commercial marine market.

In chapter three the EoU Dyneema® from the commercial marine market is analyzed with experiments to gain insights on the value and value recovery possibilities.

3.1 Method

The goal of the analysis presented in this chapter is to investigate the value of the EoU material and the possibilities of value recovery. EoU material from the commercial marine market is chosen as the source of EoU material. Tinkering and rapid prototyping are used to explore the value left in the material and possible ways of value recovery. An uncovered rope, image 3.1, and a covered rope, image 3.2, where analyzed. The EoU material was supplied by *DSM Dyneema BV,* the ropes are considered an example of the condition of all the EoU material from the commercial marine market. The following steps were taken in the analysis, time for each of these steps was tracked to get an idea of the required reprocessing time.

Steps taken in the experiments:

- The ropes were taken apart into individual yarns and sorted on condition, graphic 3.3, to get insights on the remaining value.
- The condition of the yarns was analyzed by taking a closer look with a microscope, image 3.4 to gain insights on the condition of the rope.
- Experiments were performed with the yarns to determine the steps needed to reprocess the yarns into new ropes and to gain insights on the possibilities for value recovery, graphic 3.9.

Image 3.1: An uncovered Dyneema® rope, fluffy fibers from abrasion damage and contamination from paint and oil can be seen here. Source: self-made picture.

Image 3.2: A covered Dyneema® rope, at first sight this rope looks less damaged and contaminated. Source: self-made picture.

3.2 Experiments

In this section the experiments to analyze the EoU material are shown.

Taking apart EoU rope

Uncovered EoU rope

Taking apart the rope into strands

Taking apart the strands into yarn

Sort the yarns on the amount of fluffy fibers

Graphic 3.3: The process of taking apart the uncovered EoU Dyneema® rope. The same process was done with the covered rope. Source: self-made image.

Taking apart the ropes

The uncovered rope is a 12-strand braided rope. The uncovered ropes needed to be unbraided to take apart. The unbraiding is an easy process as the strands do not stick to each other. The strands consist of yarns, the taking apart of the strands is also easy because the yarns are not braided. In the covered rope the yarns are held together by the cover and each other. The cover needed to be cut away which was not the easiest job with scissors. The taking apart the yarns was easy because the yarns where not stuck too each other.

Condition of the ropes

The EoU ropes where taken apart it was discovered that the individual yarns differ in condition. Therefore, the yarns where sorted on the amount of fluffy fibers, graphic 3.3. The yarns where sorted into three groups with group one being the best condition and group three the poorest condition. It was discovered that the individual yarns differ in condition. It is assumed that the fluffy fibers indicate broken fibers, graphic 3.4, broken fibers mean that the ropes are damaged. The assumption that the fluffy fiber indicate damage is confirmed from research on ropes made from Dyneema® fiber (McCorkle, 2003).

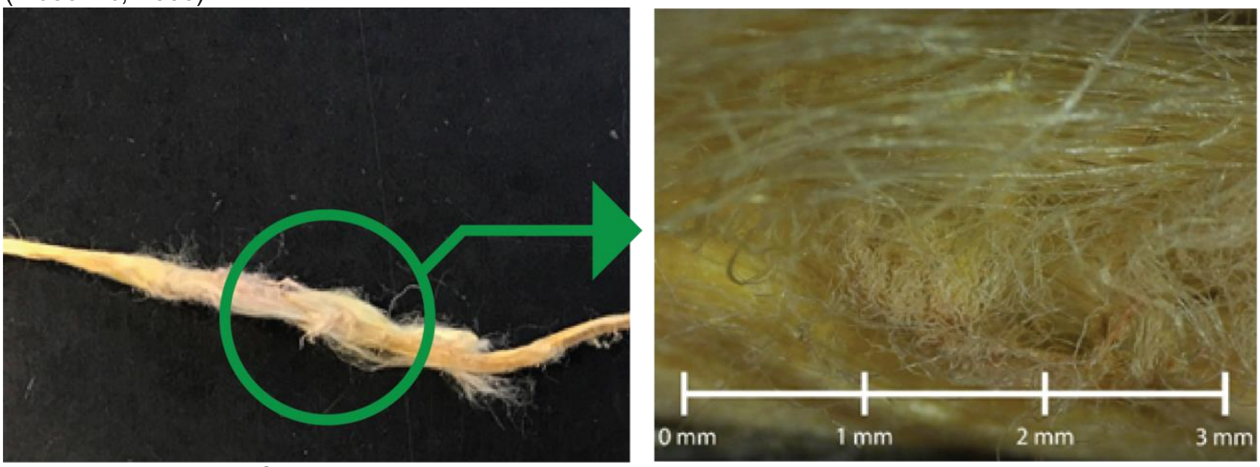


Image 3.4: An EoU Dyneema® yarn with fluffy loose fibers magnified by a microscope, the wrinkled fibers indicate broken fibers. From this it was assumed that fluffy fibers indicate damage to the rope. Source: self-made picture.

Contaminations on the ropes

It was investigated if there are contaminations on the surface of the rope. The purple color, image 3.2 is probably paint from a ship. It was discovered that small fibers came loose from the rope during the experiments. Furthermore, some sand was found inside the rope.

Image 3.5: After the experiments with the rope the table was covered with small fibers that came from the rope. Source: self-made image.

Findings from taking apart End-of-Use ropes made from Dyneema® fiber

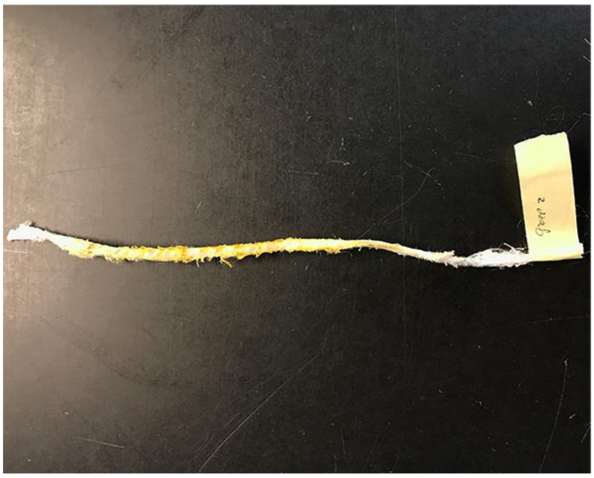
From taking apart the ropes, analyzing the yarns, softening the yarns and braiding experiments the following insights where gained.

- The condition of the EoU ropes differ along the length of the rope. The condition of the individual also yarns differs.
- The EoU ropes used in the experiments where contaminated with paint, oil and sand possibly inherent to industrial use, see also chapter 2.3.1.
- It was found that fibers could come loose from the rope during experiments. It seems recommendable to prevent these fibers from loosening regarding the risk of polluting the environment.

Stiffness of the yarns

When tinkering with the yarns the stiffness of the yarns stood out. Comparing the yarns from both the EoU ropes with a new Dyneema® yarns, it was discovered that the EoU ropes are noticeably stiffer. There may be two causes for the increased stiffness of the yarns, the first being the coating on the ropes and the second being the melting together of the fibers due to heat and pressure from abrasion, see chapter 2.3.1. Experiments were performed to investigate the effect of the increased stiffness on the value of the rope and if the stiffness could be reduced. To investigate the effect of the increased stiffness on the value of the yarns, experiments were performed on possibilities of processing the yarns into useable new ropes, graphic 3.6. These experiments provided evidence that the yarns were quite hard to work with. It is assumed that this will reduce the value.

Braiding experiment I



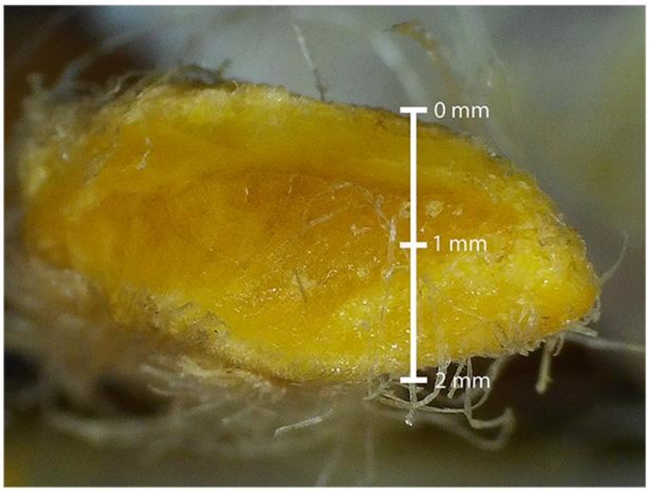
Graphic 3.6: The yarns where braided into ropes to test get an idea of how the yarns could be used, the rope was very poor quality due to the stiffness of the yarn. Source: self-made image.

Softening of the yarns

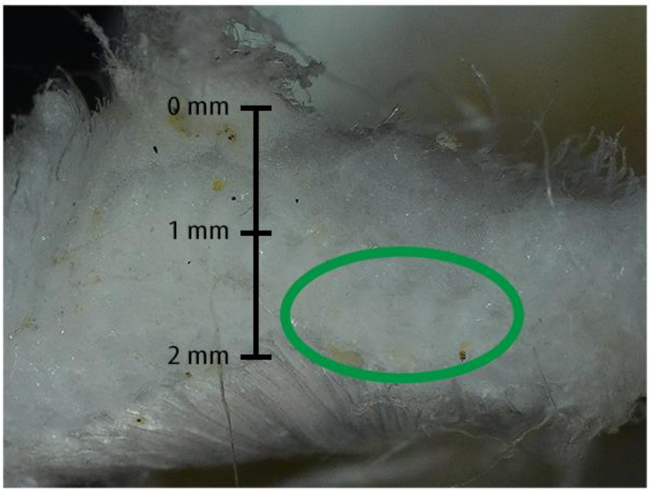
Before the stiffness of the yarns can be reduced it is required to find out the causes of the increased stiffness in the yarn. It is already known that this can be caused by either the coating or melting together of fibers due to heat and pressure from abrasion. Using a microscope, it was investigated if fibers in the yarn are molten together and if there is a coating on the yarn, graphic 3.7.

Yarn analysis

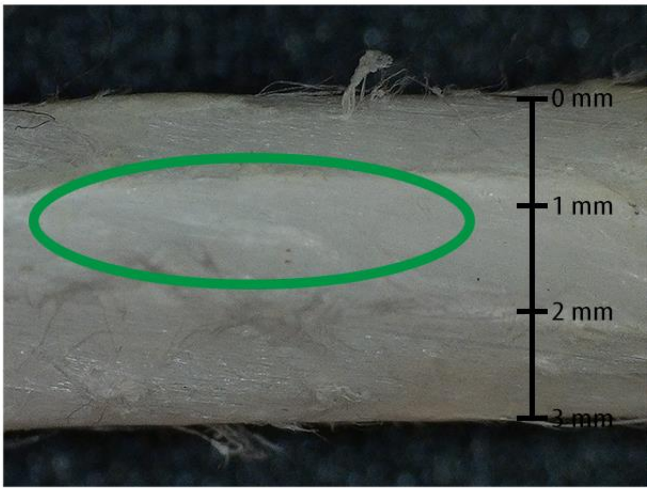
Yarn of the unshielded rope, the dark yellow indicates the precense of a coating. Also note the containminations that are present, see the black spots.



Yarn of the unshielded rope, the coating is inside of the yarn as well.



Yarn of the covered rope, the milky color indicates that fibers are molten together.



Yarn of the covered rope, the milky spots can be seen here as well.

Graphic 3.7: The yarns where analyzed with a microscope to look for the potential cause of the stiffness of the yarns. Source: self-made image.

By analyzing the yarns, it was found that there probably is coating material on the uncovered rope, as indicated by the yellow color. Increased stiffness of the yarns from the covered rope is probably due to fibers being molten together, as indicated by the milky white spots on the yarns, see graphic 3.7.

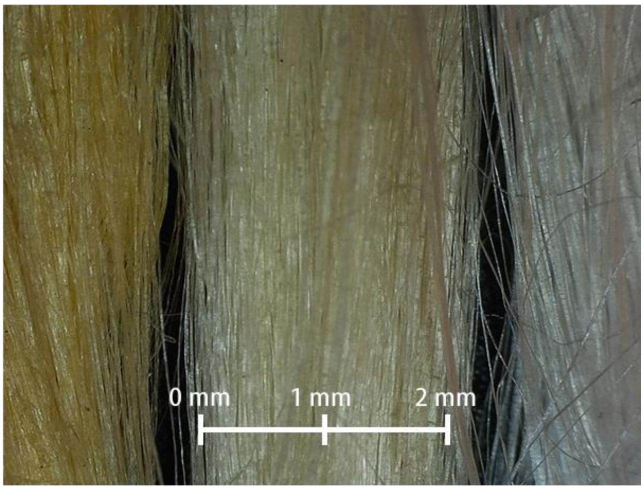
Experiments were conducted to soften up the yarns to investigate if the stiffness of the yarns could be reduced. If the assumption on the cause of the increased stiffness is correct, the yarn from the uncovered rope can likely be softened contrary to the yarn from the covered rope. Different methods for reducing stiffness were tried by tinkering with the material, graphic 3.8. It was discovered that the coating can be broken up and/or removed via mechanical and chemical methods, confidential appendix E. The softness of the yarns was evaluated by braiding new ropes from the yarns, graphic 3.9. Another experiment was to put the yarns in an oven in order to study the effect of temperature on the softening process. No effect of temperature was found.

Yarn softening experiments

Pulling the yarns through two rollers was found to be an effective way to soften the yarns.

Chemicals where used to remove the coating from the yarns.

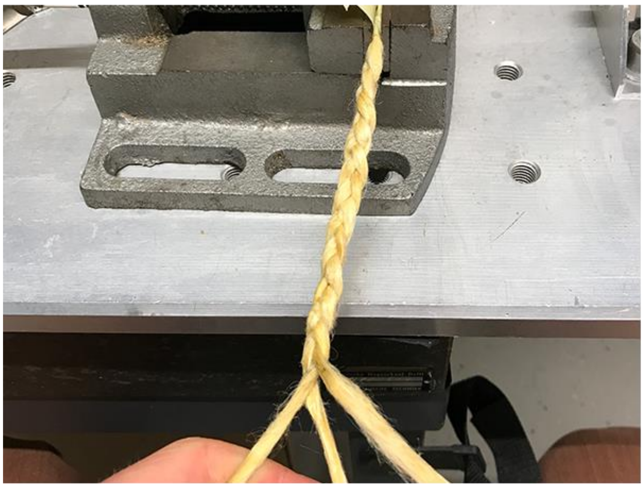
Evidence that part of the coating comes loose from the yarns onto the rollers.



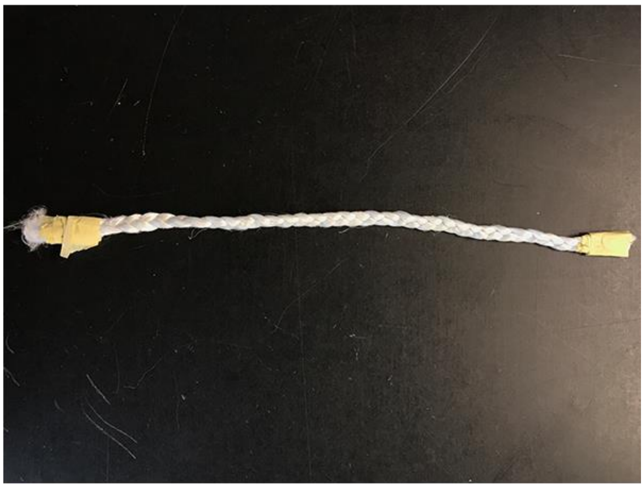
The yarns where analyzed with a microscope to see if the coating was removed by the chemicals.

Graphic 3.8: The mechanical and chemical method to soften the yarns. Source: self-made image.

Braiding experiment 2



Test setup used to braid ropes from the yarns.



A rope from new material was braided to be able to make an comparision.

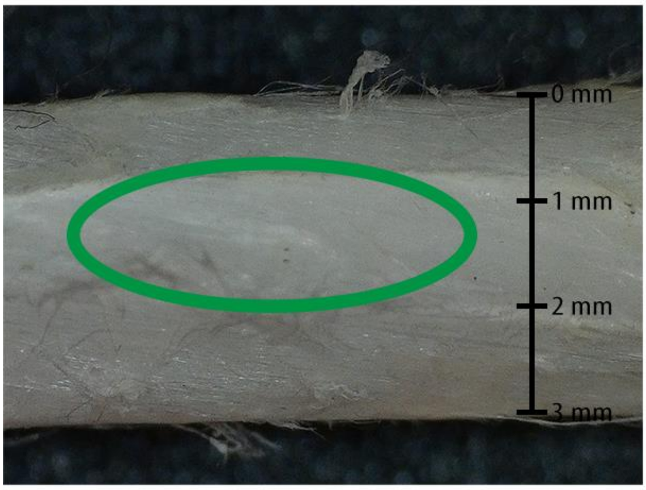
The softened rope from the uncovered rope was easy to to braid and is of similar quality compared to the new rope.

The yarn from the covered rope was still hard to braid and it resulted into a poor quality rope compared to the new rope.

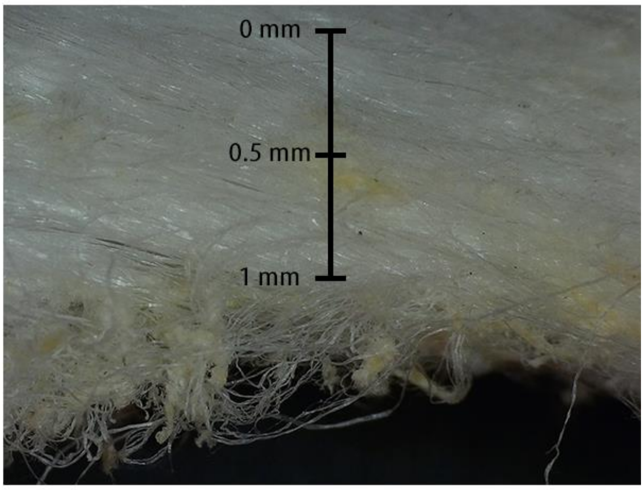
Graphic 3.9: Ropes where braided to get an idea of how easy the yarns could be processed. Source: self-made pictures.

As said earlier it was assumed that the yarn from the covered rope could not be softened because the fibers were molten together. To test this assumption the same softening process was done for yarns from both the uncovered and covered rope. The stiffness of the yarns from the covered rope could not be significantly reduced, the yarn looked different from new yarn, graphic 3.10. From these findings it is concluded that the assumption was correct. We can learn from this that some ropes or yarns can be damaged in a way that hinders reuse or remanufacturing, due to inability to reduce the increased stiffness of the yarn.

Covered rope analysis



Yarn of the covered rope, the area highlighted in green indicate molten together fibers. This yarn was rolled through rollers to try to soften this yarn.



The same yarn after rolling through rollers to soften. It can be seen that the molten together fibers are broken up. Resulting in the yarns becomer a bit softer.

graphic 3.10: The yarns from the covered rope where softened with the same process. On the right image, it can be seen that there is a lot of damage on the yarn due to the amount of wrinkled fibers. Source: self-made pictures.

Findings from the analysis of the yarns and softening experiments

- The coating was inside the yarns, not only on the outside.
- The individual Dyneema® fibers stuck to each other due to the coating. This made the yarns less slippery compared to new material.
  - Less slippery yarns could be potentially processed by methods different from the methods used for new Dyneema®, chapter 2.2.
- Yarns had increased stiffness, there are two possible causes for this.
  1. Increased stiffness could be caused by the coating.
  2. Increased stiffness could be caused by fibers being molted together likely due to heat and pressure from abrasion.
- No effect was found on the softening process of the yarns by temperature alone
- Yarns with the increased stiffness caused by the coating could be softened by mechanical and chemical methods.
- Yarns with the increased stiffness caused by molten together fibers resulting from heat and pressure of abrasion could not be softened.
- The yarns that could be softened could be braided easily into new ropes of similar quality to the ropes of new material.
- The yarns that could not be softened could not be braided easily into ropes, and the ropes were of inferior quality.

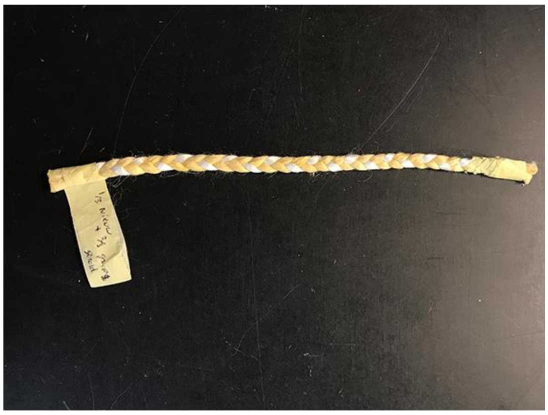
The last four findings resulted in the following conclusion: Ropes or yarns can be damaged in a way that hinders reuse or remanufacturing, due to the inability to reduce the increased stiffness.

Further reprocessing experiments

Further experiments where conducted to explore methods to improve value and circularity of the EoU material. Tinkering and rapid prototyping was used to explore possible ways to improve value and circularity, graphic 3.11.

Value increase experiment


Experiments to remove damaged fibers failed. No working method was discovered.


A rope braided from a combination of old and new material as a possible way to increase strength.


A rope braided from other ropes as a way to possibly reduce the time needed to take the ropes apart..

Three ropes of different quality. A is a rope made from poor condition EoU yarns. B is made from good condition EoU yarns. C is made from new yarns.

graphic 3.11: Possible ways to increase value and circularity where explored. Source: self-made pictures.

Insights obtained from value increase experiments

- No easy way was found to remove the damaged fibers from a yarn. This is likely due to the fact that the fibers stuck to each other too much.
- It is possible, and probably desirable, to combine new fibers with EoU fibers to potentially increase the strength of the rope and the value. Note that the EoU fibers are more grippy than the new fibers.
    - We recommend rope strength tests on ropes made from old and new fibers.
- There is a noticeable difference between the ropes of the best quality yarns (group 1) and the poorest quality yarns (group 3). It is assumed that removing the most damaged yarns could also have a positive effect on the strength of the rope and the value.
    - We recommend rope strength tests of ropes made without making use of the most damaged yarns.
- Different rope braiding methods could potentially have an effect on the time needed to take the ropes apart.
    - We recommend to further investigate this item.

Processing time

The taking apart of the rope is a required step of the remanufacturing process of EoU ropes. The time it took to take apart the ropes was tracked to get an idea of the investment needed for the value recovery. For this cost analysis the manual labor cost is estimated at € 17,5 p/ hour (Loonwijzer.nl, 2019). The uncovered and covered Dyneema® rope where 0.5 m long. The time needed to do the steps is multiplied by two to get the time per meter of rope. From the processing time it is concluded that the taking apart of EoU ropes is an interesting opportunity to investigate further, See confidential appendix F for more details. It was discovered that the type of rope, covered or uncovered, affects the processing time.

3.3 Summary and conclusion from analysis of End-of-Use material

Every rope and parts of the EoU ropes are of different quality. A sorting process will be required to filter out the ropes or yarns that are not suited for reuse or remanufacturing. Yarns with a lot of damage are considered unsuited because of the significant loss in strength due to heat and pressure from abrasion damage. It it seems recommendable to prevent fiber from loosening regarding the risk of polluting the environment. Damage to one spot on the rope could make the entire rope weaker, the useful length of the EoU ropes is therefore possibly reduced. It is likely long undamaged rope lengths are rare.

Yarns from the EoU ropes have increased stiffness which can be caused by two reasons, the first being the coating and the second being that fibers are molten together due to heat and pressure from abrasion. Yarns with increased stiffness caused by the coating can be softened, yarns with increased stiffness due to heat and pressure from abrasion cannot be softened. Resulting in the conclusion that ropes or yarns can be damaged in a way that hinders reuse or remanufacturing, due to the inability to reduce the increased stiffness. The EoU Dyneema® could be reprocessed into new ropes when the yarns are softened. The EoU fibers are less slippery compared to new fibers. Because of this, the EoU fibers could be potentially processed by methods different from the methods used for new fibers, chapter 2.2. In the design case in chapter 5 the processing for reuse and remanufacturing will be investigated further

Possible ways of increasing value were explored. There was no method found to remove only the damaged fibers from the yarns. Combinations with EoU yarns and new yarns are possible, strengths test are recommended for these ropes. It is assumed that removing the most damaged yarns could also have a positive effect on the strength of the rope and the value. Strength test are here also recommended. Different braiding methods was explored as a possible way to reduce time needed for taking apart the rope.

From exploration of the processing cost it was concluded that the taking apart of the ropes and sorting the yarns, is an opportunity worth investigating further.

In conclusion: EoU material can be recovered to extend lifetime to prevent obsolescence. Ropes or yarns can be damaged in a way that hinders reuse or remanufacturing, due to the inability to reduce the increased stiffness. The coating is a hinder for the circularity of the EoU material. The process of taking apart the ropes for value recovery is an interesting opportunity to investigate further.

Chapter 4 - Finding applications for a design case on End-of-Use Dyneema®

Chapter four is to find an application for a design case to evaluate possibilities or EoU Dyneema®. A list of criteria is set up to find, evaluate and choose the application. First, a trend analysis is done to look for potential upcoming markets.

4.1 Trend analysis and possible markets

To find possible future opportunities for EoU Dyneema® a trend analysis was conducted. Three most relative trends are explained more thoroughly and will be used in the list of criteria for finding possible applications. To find relative trends three trend reports were analyzed following the DEPEST method. The first report, *Global trends driving maritime innovation* (MESA, 2016) was analyzed for trends in the commercial marine markets. The second report, *The new sustainability Regeneration* (Tompson, 2018 I) was analyzed for potential interesting markets for the use of EoU material and trends regarding sustainability. The third report, *The future 100* (Thompson, 2018 II) was analyzed for its general overview of coming trends in 2019 to widen the search area.

Demographic

- Urbanization, more people will live in cities.

Ecological

- Global warming is changing the planet, more extreme weather conditions and droughts occur.
- Increasing plastic pollution is harming marine life and humans.
- Biodiversity loss is increasing.

Social

- The increasing importance of health and safety
- Good health and wellbeing are becoming more important
- People want transparency in businesses
- Food scarcity is rising

Technological

- Industry 4.0, IOT, AI and blockchain will change the maritime industry
- Manufacturing 2.0, Personalized products are introduced to the market
- Recycling technologies keep improving
- Green energy demand is rising
- New methods for energy production
- New methods for food production are developed
    - Vertical & urban farming
    - Aquafarming
    - Insect farming

Economics

- Growing global market increase waterborne trade and thus the Dyneema® market
- Resource prices are fluctuating
- There is a transition towards a circular economy

Political

- Regulations to reduce climate change, CO2 emissions, fuel and material use are becoming stricter.
- More regulations for the transition towards a circular economy are being instituted.
- More circular procurement incentives occur from public services to choose sustainable options.

Most interesting trends for *DSM Dyneema BV*

From the list of trends relative to Dyneema® the following three trends are chosen as the most interesting regarding EoU Dyneema® because of the connection to circularity and opportunity for business growth.

Regulations regarding climate change

Climate change is a growing concern and reducing our carbon footprint seem a necessity. Regulations are set in place to reduce this carbon footprint. Every business will have to adapt to regulations, it will be better to stay ahead of these regulations. From these necessities new businesses are arising that developing new ways to produce green energy (Tompson, 2018 I). Different types of energy production are being developed. Exploring the upcoming methods of energy production could create interesting opportunities for EoU Dyneema®.

The transition towards a circular economy

Besides regulations steering *DSM Dyneema BV* to explore circular business models, customers will seek for businesses offering these models. People will think better of a company that (re-)uses their by-products and EoU material (Tompson, 2018 II). Sustainability and circularity are becoming a value, and public opinion about this matter is becoming more important.

New methods for food production

Food scarcity demands new solutions for growing our food. These demands ask for the development of new technologies and businesses, but these are still in their starting phase. Examples of these business are: urban and vertical farming, fish and seaweed farms and insect farming. These markets provide a potential opportunity for growth, but as with any new market come with challenges as well (Tompson, 2018 I). It would be interesting to investigate the possibilities of using EoU Dyneema® as the choice material in these growing markets.

Conclusion

The trend analysis indicates that the trends in circular economy, climate change concerns and new methods of food production provide opportunities for *DSM Dyneema BV* to explore business activities with EoU material.

4.2 Applications for exploring possibilities of reuse of End-of-Use Dyneema®

To investigate circular possibilities for reuse and remanufacturing of EoU Dyneema® a design case on a possible application area will be conducted. A suitable application area is chosen from the list of criteria that is set up from research conducted in this graduation assignment.

Criteria for evaluating possible use applications

Table 4.1 shows an overview of the criteria's that will be used to find and evaluate possible applications areas for EoU Dyneema® from the commercial marine market sector. For further explanations the see relevant chapters. The design case will also provide insights on how to improve this list for future circular possibilities.

Table: 4.1: list of criteria			
Chapter	**Short description**	**Criteria**	**Reason**
Chapter 1.2	Lifetime extension	The use of the EoU Dyneema® should extend the product lifetime of the fiber	With lifetime extension the material is used more effectively
Chapter 1.2.2	Recoverability	The Dyneema® fiber should be recoverable from its application, preferably in a form suitable for further reuse.	When the fiber cannot be recovered it cannot be reused.
Chapter 1.2.2	EoU collection	The manufacturer of EoU Dyneema® products should preferably have an EoU collection system.	An EoU collection system is necessary to make the value chain fully circular.
Chapter 1.2, 1.2.2, 1.2.3	High-value loops	The use of EoU Dyneema® should preferably be in as high-value loops as possible, reuse before recycling.	Potentially the most resources and energy can be saved and it keeps the value of Dyneema® high.
Chapter 2.1	Constant tension	The EoU Dyneema® should not be under constant tension that it could evoke creep.	Creep could occur which will likely significantly reduce the product lifetime.
Chapter 2.1	Conventional processing methods	The use of EoU Dyneema® should be possible with currently used processing methods for Dyneema®.	For DSM and potential product manufactures it will reduce initial investments and time to market.
Chapter 2.1 & Chapter 2.6	Tensile strength	The use of EoU Dyneema® should make use of the high tensile strength of Dyneema.	Using the high tensile strength provides potential value over competitors of EoU Dyneema®.

Chapter 2.1 & Chapter 2.6	Strength relative to weight	The use of EoU Dyneema® should make use of its strength per weight unit.	Using the high strength for low weight provides further value over competitors for EoU Dyneema® besides strength only.
Chapter 2.3.2	Certifications	The use of EoU Dyneema® should not require certified material.	Recycled and reused materials likely cannot get certifications.
Chapter 2.3.2	Risk management	Applications, where the Dyneema® will be contact with skin, should preferably be avoided.	Potential risk involved with using EoU Dyneema® can be a risk of negatively influencing brand name.
Chapter 2.5	Value Proposition	Preferably, the use of EoU Dyneema® should provide value over the long run.	Value over the long run can provide value over competing materials that are hard to compete with on cost price alone.
Chapter 4.1	Market	The use of Dyneema® preferably in an upcoming market area and preferably Business to business.	large growth potential and the lack of a standard material for products in these markets, making it easier to introduce new materials.

Brainstorm on finding possible use applications

To find possible applications, a brainstorm session was conducted to use creative problem solving in this research project. For inspiration the following was used: The list of criteria, *The Handbook of technical Textiles (Horocks, 2000)* and web searches on the trends found chapter 4.1. Multiple brainstorm sessions where conducted personally with the following methods: *Braindump, mind maps, sketching and personal analogies,* see image 4.2 for one of the mind maps.

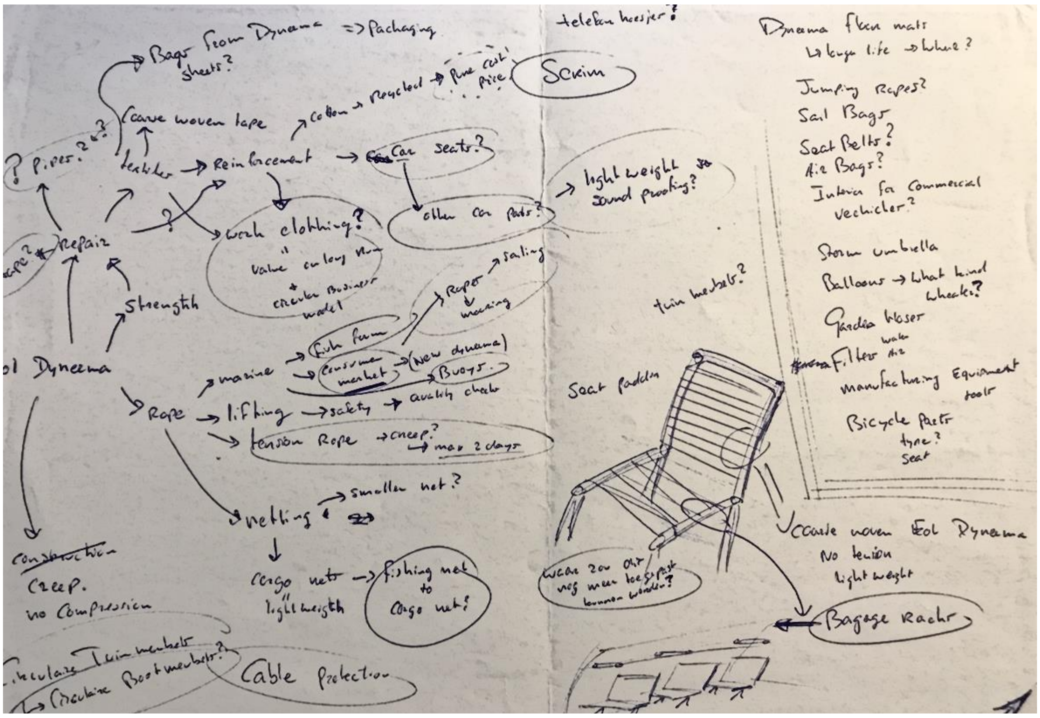


Image 4.2: Mind map resulted from one of the brainstorm sessions. Source: self-made picture.

4.3 Evaluation of possible use applications

Following from the brainstorm sessions mentioned in chapter 4.2, the three most promising application areas will be explained in more detail. These three applications were chosen by their fit with the list of criteria, circular potential and fit within the graduation assignment.

4.3.1 End-of-Use Dyneema® in Seaweed farming

Seaweed farming, also called kelp farming, is an upcoming technology which has the following applications for society: Source of food and healthy nutrients, natural fertilizer and animal food, biomass fuel and as a resource for bioplastics. In seaweed farming seaweed is grown on ropes placed underwater, image 4.3. The seaweed is harvested for its nutrients and energy value. Seaweed farming has been performed for a long time already, but usually at a small scale and mostly only for local food production. In the last five years, its potential and importance for an alternative source of sustainable food and energy for society is being investigated.

Fit criteria

- Dyneema® fiber is recoverable
- Dyneema® fiber is reused and/or remanufactured, which are a high value loops
- Makes use of the strength for low weight property of Dyneema®.
- Amount of processing required is low
- Seaweed farming on large scale is an upcoming market

Not fit criteria

- No EoU collection system is set up presently
- The ropes are under constant tension which potentially could evoke creep

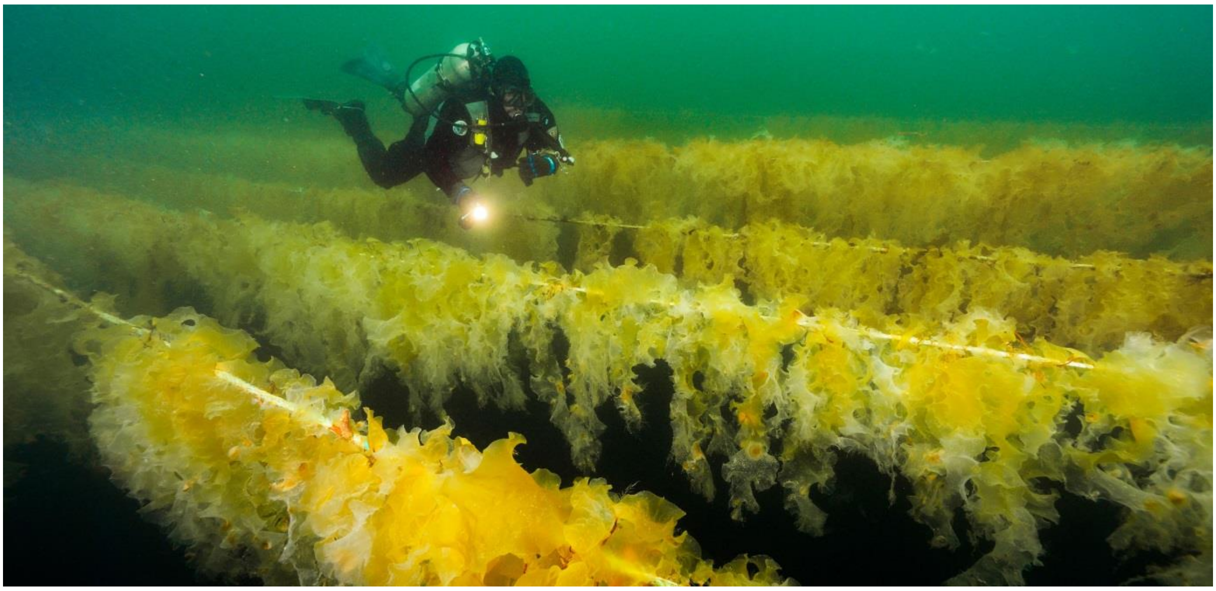


Image 4.3: Seaweed growing on ropes that are part of a seaweed farm. Source: Hakaimagazine.com, 2019

Opportunities for End-of-Use Dyneema® in seaweed farming

- Scale of farms
    - The strength of Dyneema® likely will be an important opportunity to scale op the seaweed farms to potentially better compete with conventional energy and food production. (Wouters, 2018).
- Cost structure
    - The value proposition and the lifetime of Dyneema® can contribute to increase the return on investment for the seaweed farms, which at the moment is a challenge (Wouters, 2018).
- Upcoming market

  The seaweed farming market is an upcoming market with a large growth potential (Karen, 2016). It is assumed that in this upcoming market there is not yet an established material. This could be an opportunity for (EoU) Dyneema® to become the material standard in this market and for DSM to expand business.

Challenges for End-of-Use Dyneema® in seaweed farming

- The creep
    - In a seaweed farm the construction lines endures constant tension. We learned that when Dyneema® is used in application where it endures constant tension the effect of creep should be taken into account.
- The certifications
    - In an interview with a farm builder it was indicated that there are certifications coming for the material of the construction lines (Schipper, 2019).

4.3.2 End-of-Use Dyneema® in Geotextiles

Geotextiles are used to reinforce the soil beneath construction works, image 4.4. The might be an opportunity for Dyneema® because soil has compression strength but no tensile strength and Dyneema® has the opposite. Underneath every road and buildings geotextiles are possibly creating a large. Because underneath every road and building geotextiles are used there might be a large market potential for the use of EoU Dyneema®.

Fit criteria

- The tensile strength of Dyneema® is used
- A possible value in the long run
- Conventional processing methods

Not fit criteria

- No EoU collection system
- Certifications could potentially become a problem
- Geotextiles are under constant tension which potentially could evoke creep in the material

Opportunities for End-of-Use Dyneema® in geotextiles

- Properties Dyneema®
    - Tensile strength, abrasion resistance, water absorption, and environmental resistance are all properties of Dyneema® that can provide value for geotextiles (Horrocks, 2000).

Challenges for End-of-Use Dyneema® in geotextiles

- Established market
    - The geotextile industry is an established market making it difficult to introduce new materials (TenCate, 2018).
- Cost price
    - It will be hard to compete on cost price with the commodity plastics used in the geotextiles market; the benefits of Dyneema® should outweigh the higher cost (TenCate, 2018).

Image 4.4: The white mats are geotextiles used to reinforce soil for construction. Source: dubaicompanieslist.com, 2019.

4.3.3 End-of-Use Dyneema® in (Technical) Textiles

Textiles can be found in two major markets, the clothing industry, and the technical textiles industry. Textiles in the clothing industry are used to make clothes for consumers or professionals and in the technical textiles industries to make fabrics for products. For some applications, textiles must be reinforced with synthetic materials to increase durability. Dyneema® is already used to reinforce textiles as shown by the example of the motorcycle jeans, image 4.5. It could be worth investigating if EoU Dyneema® could be the source of material for the reinforcement of textiles.

Fit criteria

- No certifications required
- A Possible value in the long run with textiles for professional workwear
- Creep is likely no problem

Not fit criteria

- Textiles used in clothing are a potential risk
- Dyneema® is possibly not recoverable

Opportunities for End-of-Use Dyneema® in technical textiles

- Possible value in the long run
    - When Dyneema® is used is to reinforce textiles in combination with a circular business model offer value in the long run can be gained.
- Extra protection
    - Clothes reinforced with Dyneema® could also offer extra protection besides the added durability
- Many different ideas possible
    - Textiles come in many forms and shapes. There are lots of different products ideas possible which means that there is possibly much to learn regarding reprocessing.

Challenges for End-of-Use Dyneema® in technical textiles

- Recovery of Dyneema® fiber is possibly difficult
    - When Dyneema® is woven into textiles, it will hard to recover the Dyneema® from the feedstock of material.
    - Contact with human skin, as stated in chapter 2.3.2, products that are in contact with human skin carry a potential health risk.

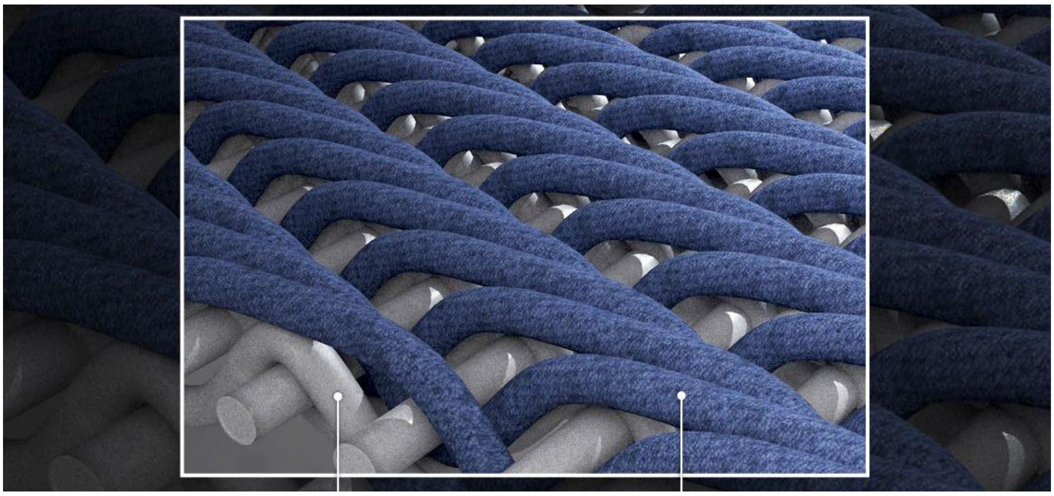


Image 4.5: Dyneema® fiber is used to reinforce motorcycle jeans as an example of using Dyneema® fiber in textiles. Source: trilobitemoto.cz, 2019

4.4 Choice of use application for further research

Out of the three most promising application areas one is chosen to analyze further in a design case. The choice of the application was made by evaluating the list of criteria, see table 4.6 (see also table 4.1), as well as by evaluating the circular potential and fit within the graduation project.

Circular potential

The application with the largest circular potential is seaweed farming. Since it is a combination of the technical and bio-cycle of the butterfly diagram, Image 1.1. The technical textiles & geotextiles are only circular in the technical cycle. Therefore, the choice for the application with the highest circular potential is seaweed farming.

Fit within the graduation project

The technical textiles application has the best fit within the graduation project because of the size of the products. For the embodiment of prototypes, it is possible to make full-size prototypes for technical textiles, not for the seaweed farm and geotextiles.

Table: 4.6: Evaluation using list of criteria

Criteria	Seaweed farming	Geotextiles	Technical textiles
Lifetime extension	++	++	+
Recoverability	+	-	--
EoU collection	--	--	-
High-value loops	++	+	+
Constant tension	-	-	++
Conventional processing methods	++	++	-
Tensile strength	++	++	+
Strength relative to weight	++	+	+
Certifications	-	--	++
Risk management	+	-	--
Value proposition	+	+	+
Market	++	++	+

Choice of application for design case on reuse possibilities of End-of-Use Dyneema®

Seaweed farming is the choice of application for the design case on reuse and remanufacturing of EoU Dyneema® from the commercial marine market since it fits the best within the given set of criteria and has the most circular potential. Concerning the fit within the present graduation project, the technical textiles scored better then seaweed farming, but the latter does fit within the project well enough.

Chapter 5 - Background information for a case study on using End-of-Use Dyneema® in seaweed farming.

Chapter five, a design case will be performed to investigate circular opportunities for EoU Dyneema® from the commercial marine market. The opportunities and barriers exposed by the design case will provide a recommendation for using EoU Dyneema® in general.

5.1 Research questions regarding using End-of-Use Dyneema® in seaweed farming

A case study is performed to gain insight in the possibilities of reuse and remanufacturing of EoU Dyneema® in seaweed farming. Therefore, the following research questions are formulated.

Research question regarding technical feasibility

- Can EoU Dyneema® from the commercial marine market be used for the construction of seaweed farms?

Research questions regarding economic feasibility

- What are the values EoU Dyneema® and *DSM Dyneema BV* could offer in the seaweed farming market?
- Are there incentives to use EoU Dyneema® over conventional materials used in seaweed farming?

Research question regarding circularity

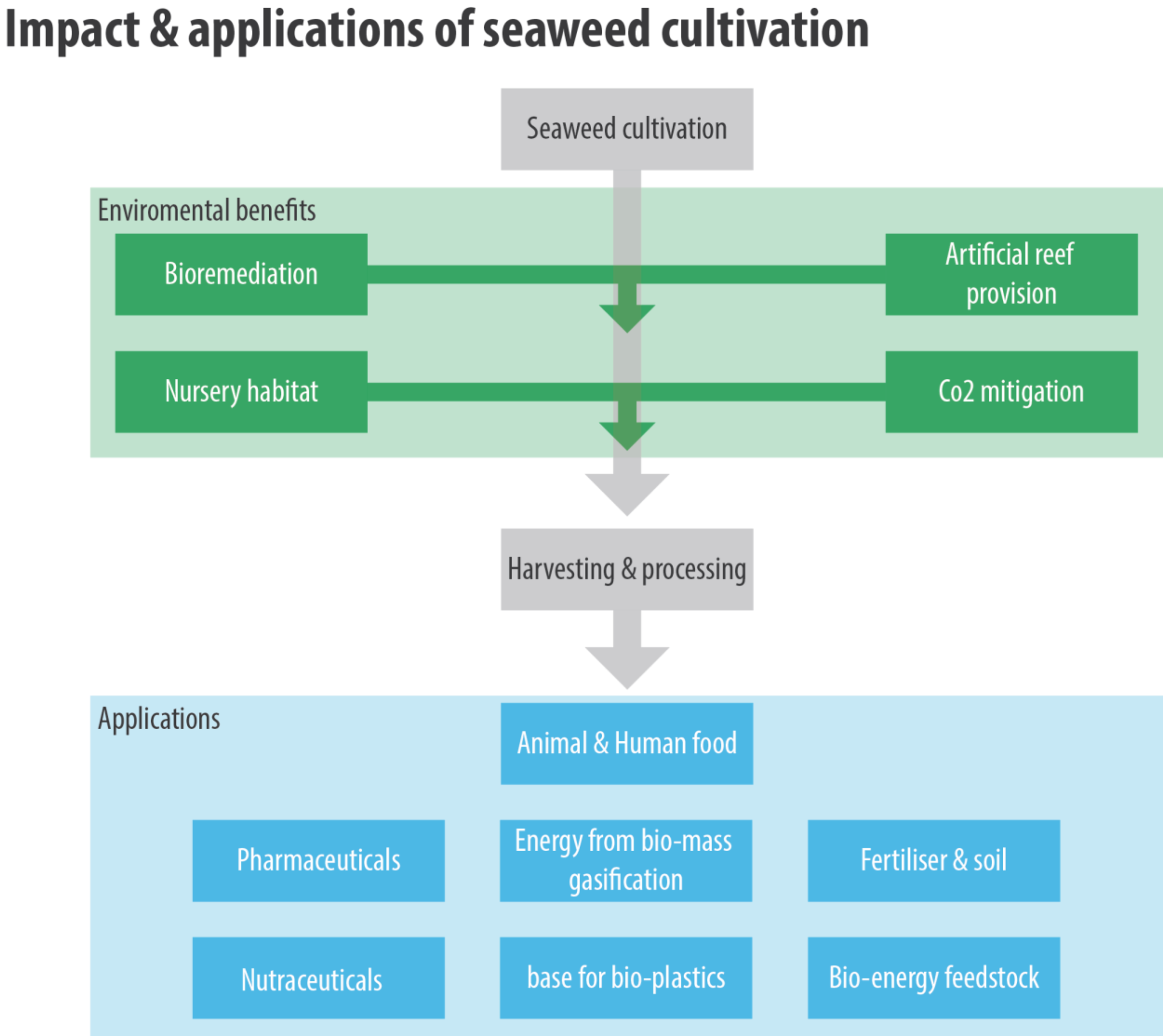
- Does using EoU Dyneema® in seaweed farms contribute to lifetime extension of EoU Dyneema® from the commercial marine market?

5.2 Background information Seaweed farming

Before answering the questions mentioned in chapter 5.1 some background information on the seaweed and its applications is given to provide context.

Applications for seaweed

Seaweed farming, also called kelp farming, at an industrial scale is an upcoming technology. Seaweed farming could provide society with food, energy, and bioplastics, see graphic 5.1. The challenge is to scale up the farms to be able to meet potential market size, see table 5.2, and compete with conventional energy and food sources (Correa, 2016).



Graphic 5.1: The different environmental benefits and applications of seaweed. Source: self-made graphic based on a graphic from Karen, 2016.

Table 5.2	Market potential seaweed farming	
Seaweed application	**Specific application**	**Estimated potential market size** **See appendix C for footnotes**
Food	Source of food and nutrients. Possible substitute for meat and vegetables and a source of food for animals and plants (Fleurence, 2018).	250 billion dollars (Grandview research, 2018 I)[1]
Medical	Pharmaceutical tablets, surgical applications, weight loss (Fleurence, 2018).	25 billion dollars (Grandviewreserach, 2018 II)[2]
Energy	Gasification of biomass (Schumacher, 2011).	2 trillion dollars (Wikipedia, 2018)[3]
Raw material	Bioplastics (Rajendran, 2012).	130 billion dollars (Grandviewreserach, 2018 III)[4]

The seaweed

For seaweed to grow, it needs a steady stream of nutrients, which occur in the sea naturally, CO2 and sunlight for photosynthesis (Karen, 2016). Nutrients could also be derived from (unnatural pollution) from fish farms or agriculture making combination between seaweed farms and fish farms a fascinating concept, image 5.3.

The seaweed grows on substrates, the surface the roots will hold onto, image 5.4. In a seaweed farm the lines, with a thickness of 12 to 14 mm, are the substrates. Depending on the type of seaweed the lines are placed on a depth between 2 to 20 meters. The seaweed is harvested by trimming the seaweed.

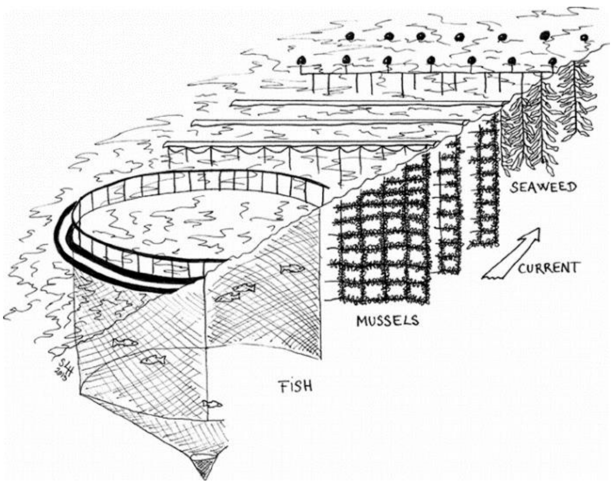


Image 5.3: A combination between a fish farm, mussel farm, and seaweed farm. Pollution from fish farms is a source of food for the mussels and seaweed farms. Source: Edwards, 2014.

Image 5.4: The rope where the seaweed grows on is called the substrate. Source: aquacultureNorthamerica.com, 2017.

The story of seaweed farming

Seaweed farming can play a role in the cultivation of food, nutrients, resources and energy for our society. Seaweed farming is an example of the bio-cycle from the butterfly diagram, image 1.1. When the farms could be built with circular materials the seaweed farming industry will be a combination between the bio- and technical cycle. This combination between the technical and bio-cycle is a promising opportunity to make the world a bit more circular.

Using EoU Dyneema® in seaweed farming can potentially provide circular values like the general circular values, *Sourcing value, Environmental value, Customer values* and *Informational value,* see chapter 1.2.2. Therefore, the use of EoU Dyneema® in seaweed farming is regarded as a circular opportunity for *DSM Dyneema BV.*

If the seaweed farming market will grow, it will potentially get attention, which could be a PR opportunity for *DSM Dyneema BV* once the NGO's pick up the story, as we learned from chapter 2.4. If DSM could help to grow this market, it will fulfill one of its core missions of creating a more sustainable world, chapter 1.1.

Using EoU Dyneema® in seaweed farms could extend the product lifetime of the lines made from Dyneema® fiber from the commercial marine market. With the extension of product lifetime *DSM Dyneema BV* is a step closer to becoming circular.

5.3 Seaweed farm construction

In this chapter, the design of the seaweed farms will be analyzed to provide more context. The user, the farm construction, the forces on the farm and cost are analyzed to gain the necessary knowledge to answer the question if EoU Dyneema® is suited for building seaweed farms.

User

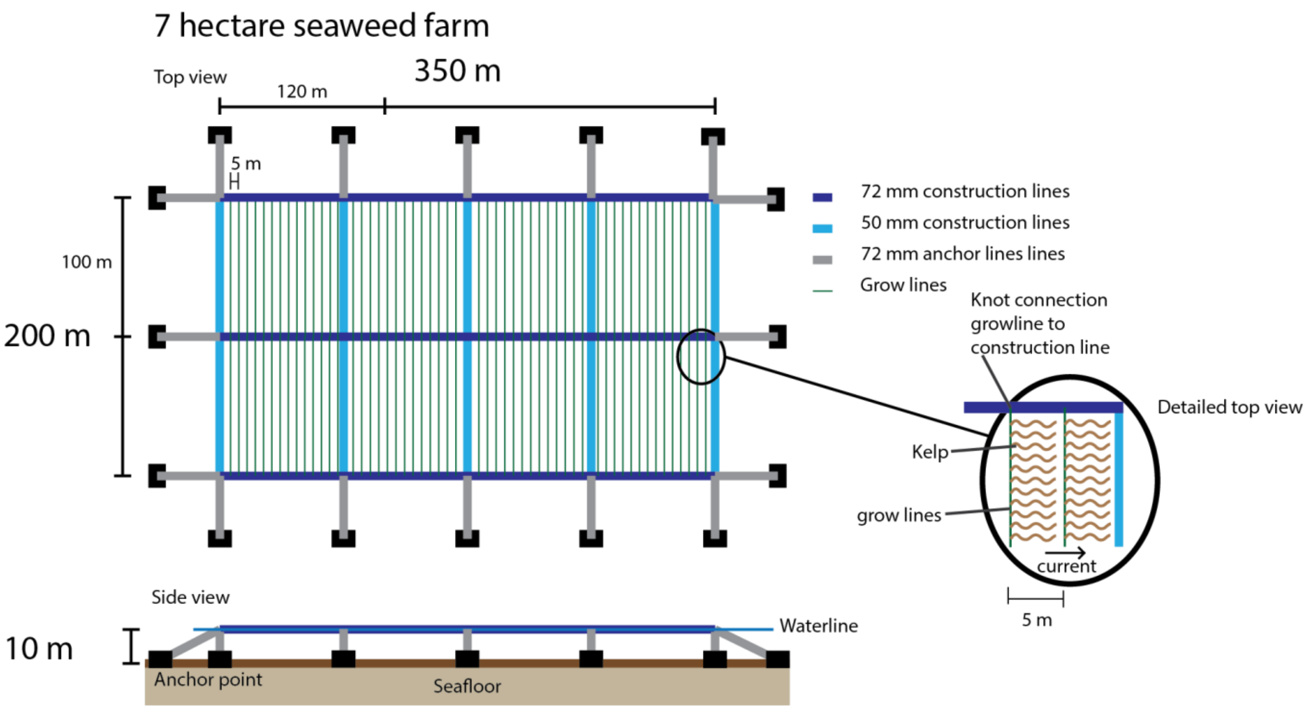
The users in this design case are the companies that build the seaweed farms and/or that use the seaweed farms. The companies that build these farms do not always cultivate and sell the seaweed themselves (Schippers, 2019). The use of circular materials in seaweed farms is preferred because of the desire to create a as sustainable way possible of producing food and energy (Wouters, 2018). Currently, the cost of materials is the most critical factor for the choice of material for the construction of the seaweed farms especially since profit margins are not high (Schippers, 2019).

Harvesting

To harvest the seaweed the plants are cut short. Currently, grow lines are damaged often requiring replacement. EoU Dyneema® is theoretically stronger and therefore provides a possible opportunity to reduce the need for replacing the grow lines. The replacement of the grow lines increases the maintenance cost considerably because of material and labor costs, see also chapter 5.5.

Farm construction

Graphic 5.5 shows an example of the design of a seaweed farm. The blue lines represent the construction lines which must withstand all forces that come from the drag of the current. The green lines represent the grow lines, the lines where the seaweed grows on, which are placed horizontally, see image 5.6.



Graphic 5.5: A drawing of a seaweed farm showing how a farm is constructed. Source: self-made image.

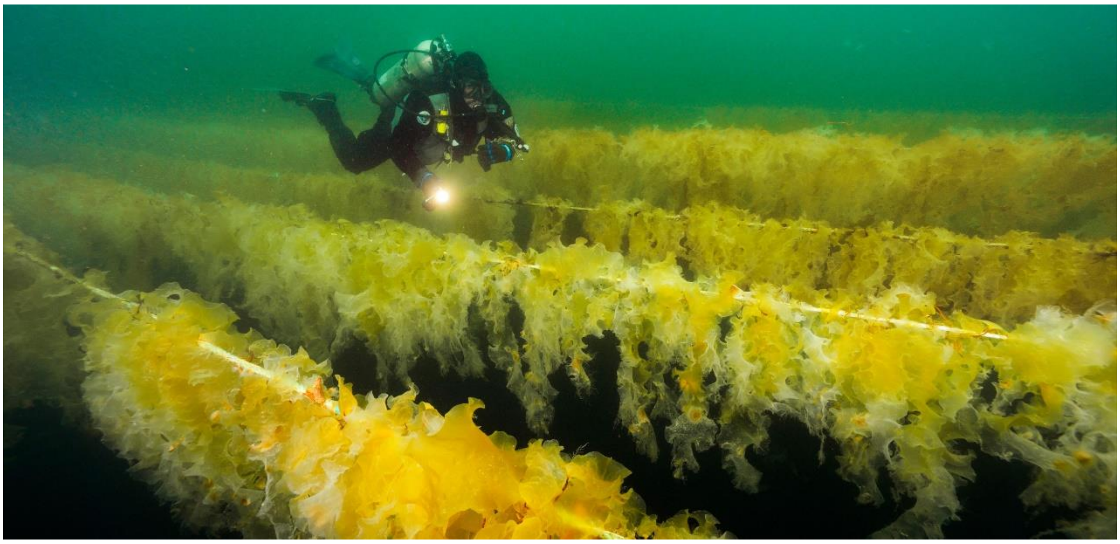


Image 5.6: The grow lines are placed horizontally underwater. Source: Hakaimagazine.com, 2019.

Construction lines

Currently, 72 mm thick nylon lines are used for the construction lines in seaweed farms, the blue lines in graphic 5.5. An assumption is that the for larger scale farm nylon and other commodity fibers would not be a viable option due to strength requirements according to (Wouters, 2018). Recycled commodity fibers are also not suited for use in seawater for the average lifetime of a seaweed farm (Wouters, 2018). In theory EoU Dyneema® is stronger than the nylon used in seaweed farms now, chapter 2.6, here lies the potential opportunity for EoU Dyneema® to have value over nylon. EoU Dyneema® could be a circular material that does fulfill the minimum material requirements.

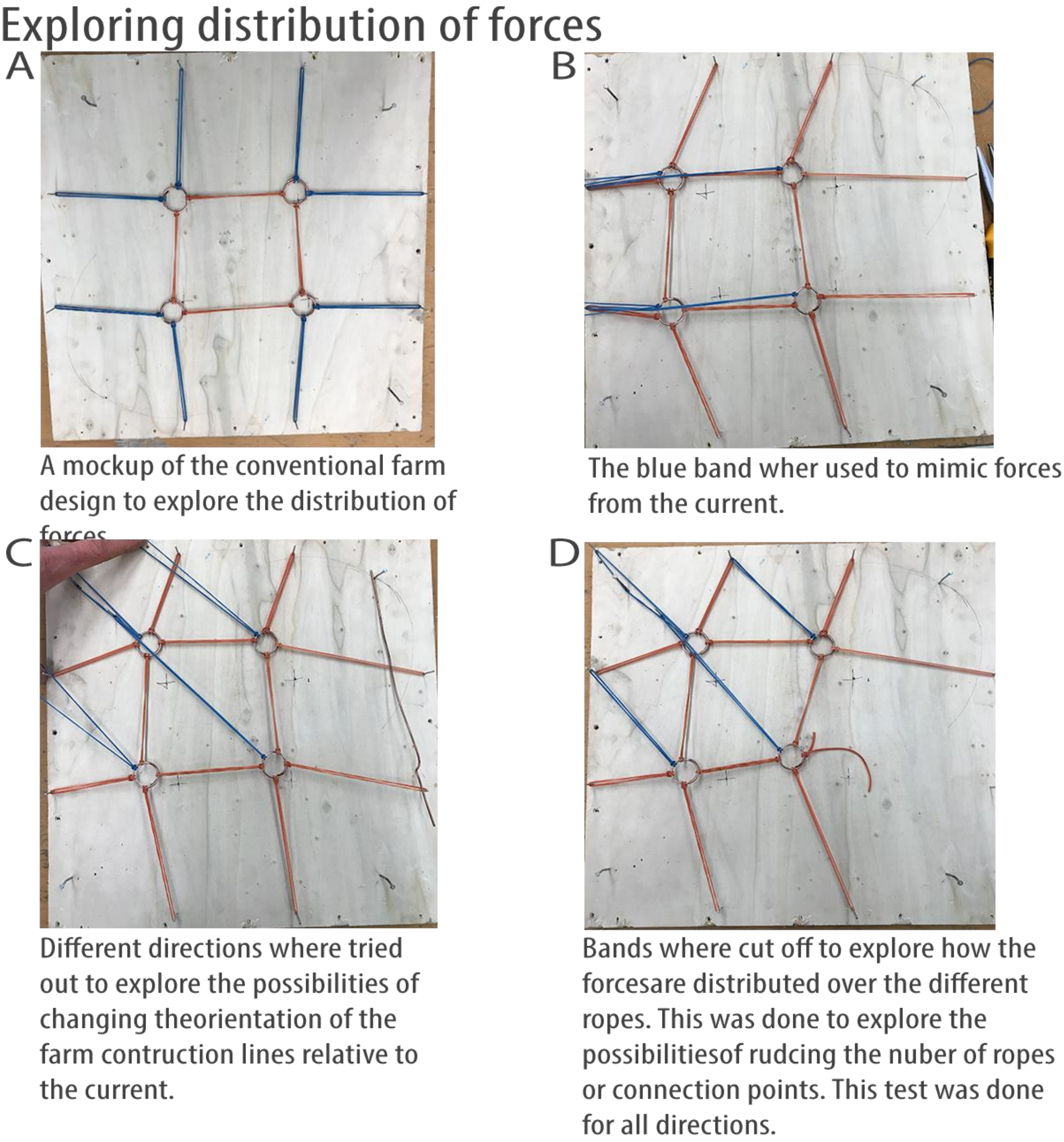
This conventional design is not optimal for the reuse of EoU lines because long rope lengths are needed. As we learned from chapter 3 the EoU Dyneema® lines are of lesser quality then new lines made from Dyneema® fiber due to industrial use, making it unlikely that long undamaged rope lengths are available. Another reason that long lines maybe unsuited for EoU Dyneema® is the risk of breakage. Dyneema® does not stretch much (Vlasblom, 2018) resulting in that sudden forces on the rope increase the change of breakage compared to lines made from commodity fibers (Spijkers, 2019). With the condition of EoU Dyneema® still uncertain it would be best to avoid long rope lengths and/or have a system to absorb sudden forces.

Construction of the seaweed farm

The lines in the farm are connected to other construction lines and the anchor points. Knots, splices and metal or plastics connecting constructions are possible. According to a guide for building seaweed farms knots are recommended (Karen, 2016). However, the recommendation for using knots is for using nylon lines. Knots significantly reduce the strength of lines made from Dyneema® fiber, splices are therefore recommended when using lines made from Dyneema® fiber (DSM, 2019).

Exploring distribution of forces using mock up prototypes

The way forces are distributed over the different lines in the seaweed farms was analyzed to gain insights on the possibilities of adapting the conventional design as seen in image 5.5. A mockup prototype was constructed to gain these insights. The forces on the lines where mimicked using rubbers bands that were put under tension, see graphic 5.7.



Graphic 5.7: Mockup prototypes used to explore the effect of the forces on the construction lines. Source: self-made pictures.

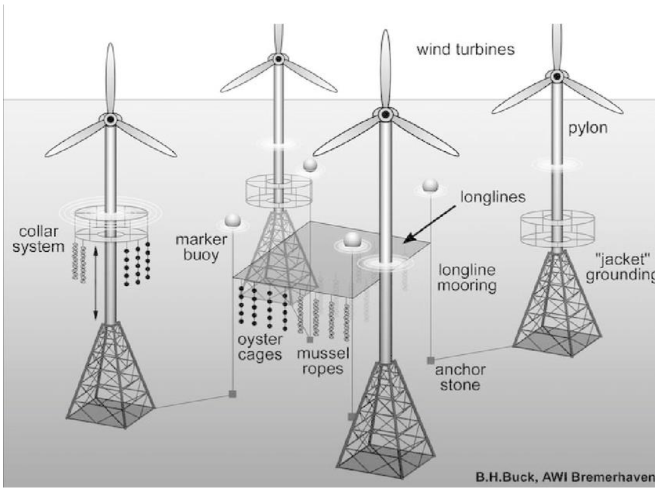
Insights gained from exploring the distribution of forces

- It is possible to change the direction of the lines relative to the direction of the current.
- When the lines are loaded at a 45 degree angle the forces are distributed evenly over 2 lines instead of one, graphic 5.7 section C.
- It would be best if the forces are distributed over at least four lines.

Anchor points

The construction lines are attached to the seafloor with anchor points. When building a seaweed farm, the anchor points should provide enough hold to prevent the farm from breaking loose. One future idea with high circular potential is to use the anchor points of wind farms to attach seaweed farms, graphic 5.8. Using the anchor points from wind farms could potentially save money and extend the lifetime of EoU windfarms and increase the efficiency of the structure (ECN, 2019).

The anchor points of the wind farms could be used to maximize circular potential and potentially reduce cost. The assumption is that these anchor points are strong enough for use as anchor points for the seaweed farm. Possibilities of using windfarms bases are investigated further in chapter 6.



graphic 5.8: A concept to show how wind farms could be co-used as anchor points for seaweed farms. Source: Buck, 2010.

Buoyancy needed in seaweed farms

The seaweed farm must float in the sea, buoyancy in the form of floaters is needed to let the farm float above the seafloor, see image 5.9. Dyneema® is lighter than water (Vlasblom, 2018) and will, therefore, float, resulting in the need for less buoyancy when Dyneema® is used. It is possible to use recycled plastics for the floaters (Meran, 2007) which would make the farm more circular.

The amount of buoyancy required determines the amount and size of the floaters; this will require more knowledge of buoyancy calculations, but this aspect will not be elaborated on in this graduation assignment.

Image 5.9: An example of floaters (yellow objects in the image), these floaters are currently used in an experimental farm. Source: Sioen.com, 2019

Forces on the construction lines

The drag of the seaweed from the current of 1 to 2 m/s causes forces to act upon the construction lines of the seaweed farm. Seaweed farm builder *Hortimare* has conducted simulations to determine the forces that act on the farms (Schipper, 2019). Simulation studies provided a maximum force of 300 kN on the construction lines, see Appendix D.

The grow lines in seaweed farms are made from nylon, polypropylene or natural fiber. The maximum force on these grow lines is 20 kN (Schippers, 2019), so the strength requirements are low compared to the construction lines. The other demand is that the seaweed will grow on these lines, which will be analyzed in chapter 5.4.

Tension on lines

The construction lines are put under tension to prevent the grow lines and seaweed to entangle. In the current farm design, the construction lines must be put under tension again after 2-3 years because of the stretch in the construction lines (Schippers, 2019). Putting the construction lines under tension again is a significant part of the farm maintenance costs. A possible opportunity for EoU Dyneema® over conventional materials would be to reduce the need for re-tensioning the lines, more on the costs of seaweed farms in chapter 5.5.4.

Design challenges from chapter 5.3

From the information in this chapter and chapter 5.2 the following design challenges came forth:

- Better distribution of forces
- Use of shorter lengths of lines
- A solution for line breakage due to sudden forces

5.4 Technical feasibility of using End-of-Use Dyneema® in seaweed farms

In this chapter questions regarding the technical feasibility of using EoU Dyneema® in seaweed farms will be answered. These questions must be answered to provide arguments for the technical possibilities of using EoU Dyneema® in seaweed farming.

Is there enough End-of-Use Dyneema® available?

It is assumed that there is enough EoU Dyneema® available, for the explanation see confidential appendix G.

Is End-of-Use Dyneema® strong enough?

From the competitor analysis, chapter 2.6, we learned that EoU Dyneema® is theoretically stronger than the commodity fibers that are currently used in seaweed farms. It is concluded that the EoU lines are strong enough for the farm in graphic 5.5 with a wide margin. Therefore, it is assumed that an increase in size of the farm is possible. See confidential appendix G for the calculation to confirm that EoU Dyneema® is strong enough

Creep & stretch

From chapter 5.3 we know that the construction lines in a seaweed farm are under constant tension & from chapter 2.1 we know that creep should be taken into account when Dyneema® is under tension for long periods of time. From chapter 5.3 we learned that elongation or stretch will influence the maintenance cost of a seaweed farm.

To get an idea of the effect of creep when using Dyneema® a calculation is done, see confidential appendix I. It was concluded that the 44 mm rope will be able to withstand the creep elongation. With an 7 % elongation the creep will not cause the farm to fail and maintenance does stays within conventional standards (Schippers, J. 2019).

In all types lines, there is some elongation under tension, also known as stretch and rope connections could increase the amount of stretch. Dyneema® does have low stretch (Vlasblom, 2018). Just as with the creep, the stretch should be accounted for. To make sure creep (for other rope diameters) and stretch will not be a problem for the cost and strength of the farm, the following design challenge is added: The seaweed farm re-design should have a way to re-tension the construction lines.

Does seaweed grow on Dyneema®?

Two factors play a role in the growing of seaweed on lines. The first being the structure of the rope itself and the second the molecular bonding of the rope material (Schippers, 2019) Taking these two factors into account, seaweed will grow on EoU Dyneema® when a polar coating is applied, see appendix F. Though the coating currently used is polar, an alternative should be found because the presently used coating hinders the circularity as stated in chapter 3.

Conclusion technical feasibility

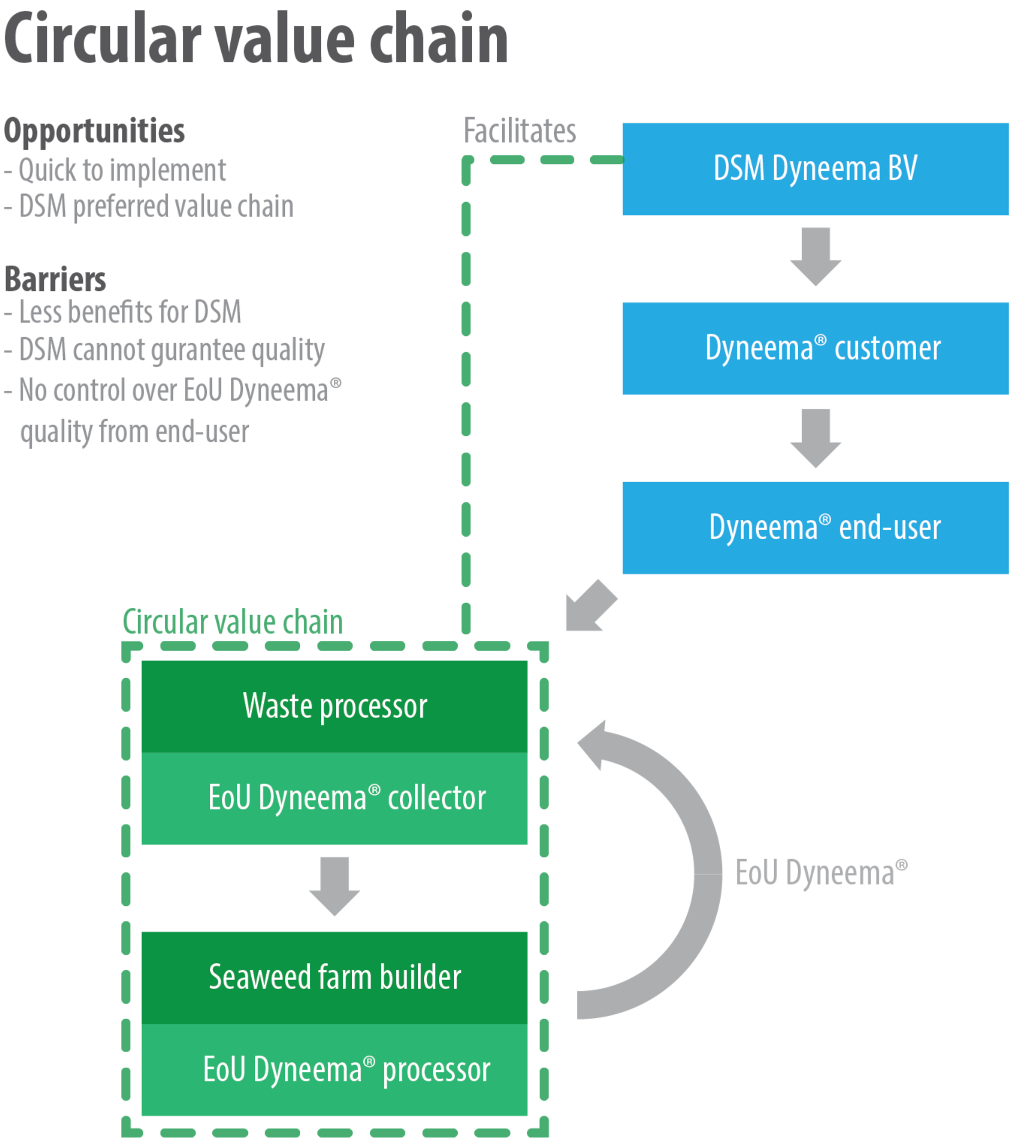
From the information provided in this chapter, it is concluded that there is enough material available, the EoU Dyneema® is strong enough, creep can be handled, and seaweed will grow on lines made from Dyneema® fiber if a coating is applied. Now the technical feasibility of using EoU Dyneema® in seaweed farms has been explored the business case will be explored in the coming section.

5.5 Business case for the use of End-of-Use Dyneema® in seaweed farming

In this chapter, the economic feasibility of using EoU Dyneema® in seaweed farms will be investigated. First, the specific circular value chain will be analyzed. Secondly, the value that EoU Dyneema® could offer and thirdly the EoU material processing time is analyzed. These three points will give the necessary economic arguments for the possibilities of using EoU Dyneema® is seaweed farms.

5.5.1 Circular value chain

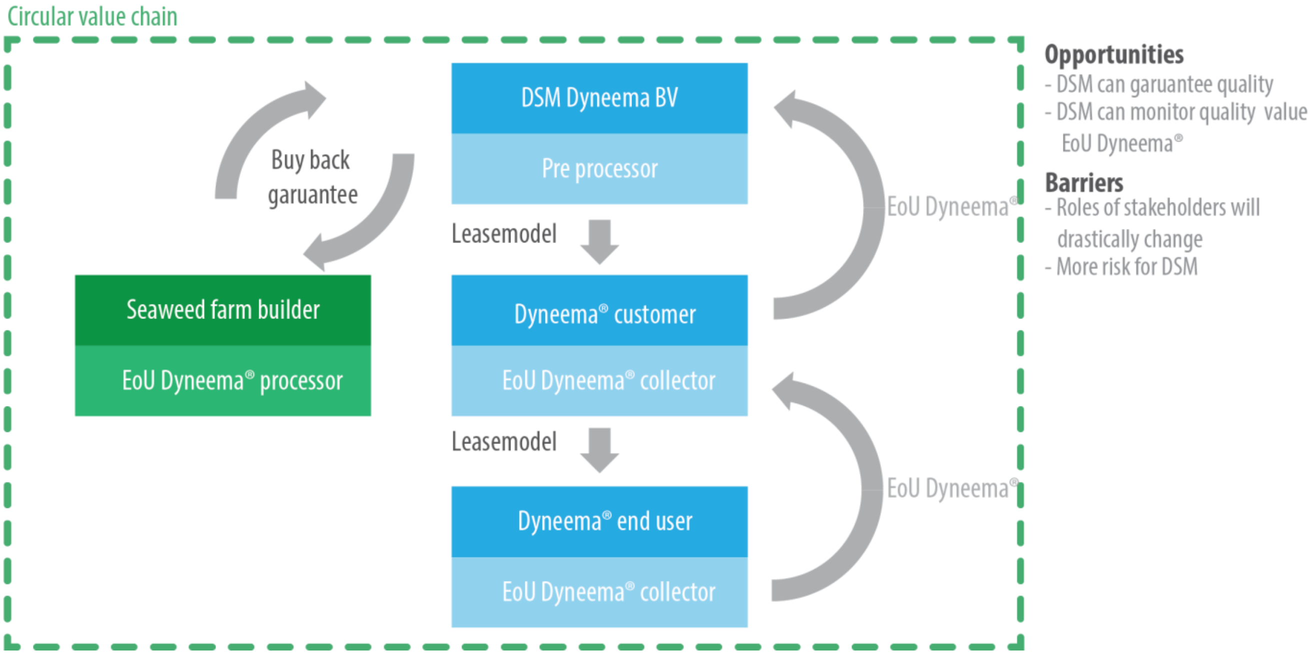
We learned in chapter 2.4 that the circular value chain would be different for each specific market. In this chapter two possible circular value chains and the effect on the use of EoU material is explained.



Graphic 5.10: The circular value chain where DSM Dyneema BV is a facilitator of a separate circular value chain. Source: self-made graphic.

In the value chain in graphic 5.10 *DSM Dyneema BV* facilitates a circular value chain that is separate from the Dyneema® value chain, DSM stated that they desire this role, chapter 2.4. In this value chain, most roles of the stakeholders stay the same which keeps the value chain simple and possibly faster to implement.

Circular value chain II



Graphic 5.11: The circular value chain where DSM Dyneema BV is part of an integrated circular value chain. Source: self-made graphic.

In the value chain presented in graphic 5.11, *DSM Dyneema BV* and the most important stakeholders are part of the value chain. Besides the addition of stakeholders, the roles of the most important stakeholders will change. Advantages are possibilities of circular business models in the entire value chain which will give more control over the material, see chapter 2.5. It was concluded in chapter 2.4 that the Dyneema® customer is the most important stakeholder, which means that changing the role of this stakeholder will not be an easy task and could be a risk for the business of *DSM Dyneema BV*.

Impact on design case

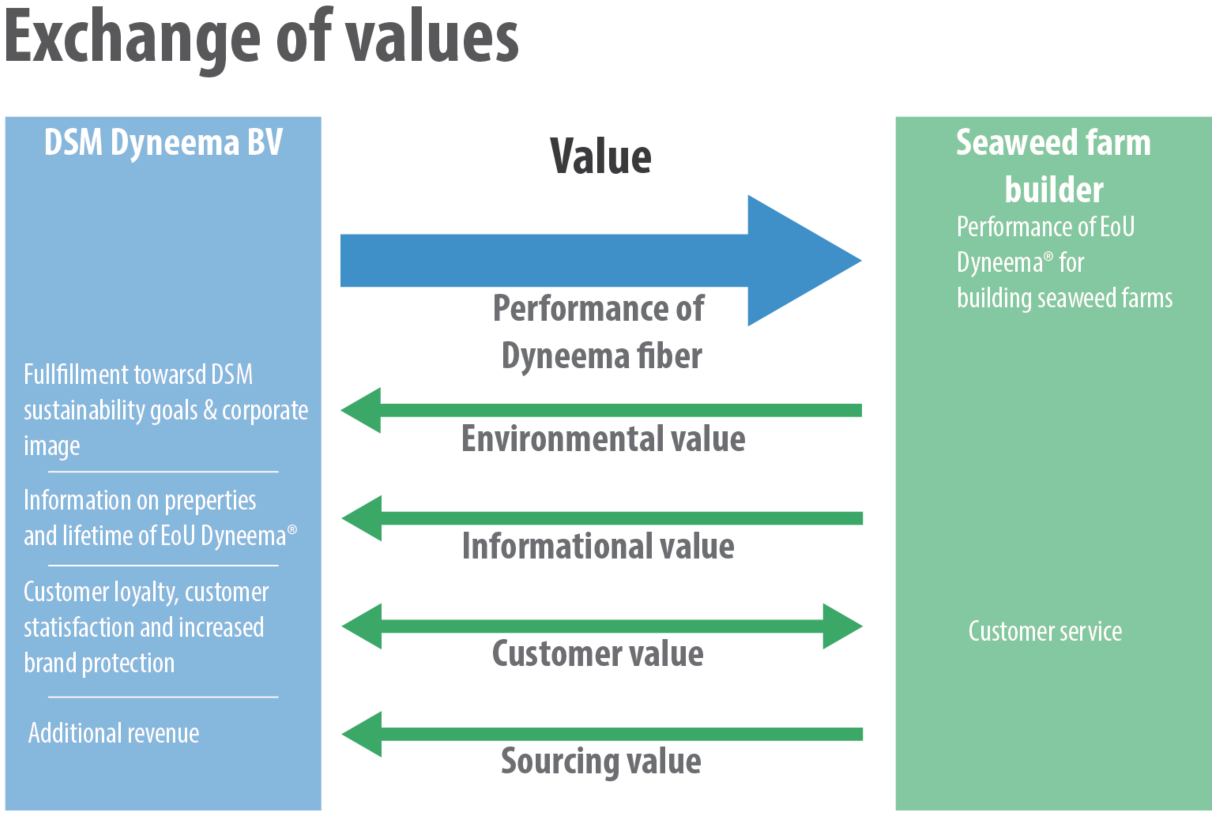
Both value chains, graphic 5.10 & 5.11, provide challenges and opportunities that must be solved before the final decision can be made of which value chain is the best suited. Choosing which of the two models would be the best is a time-consuming process which can only be finalized when the entire business case is analyzed further.

When EoU Dyneema® will be reused or remanufactured there should be a collection system for collecting the material after the first and second product life cycle. This has to be integrated in the circular value chain.

The choice for the best model does not affect the design of the seaweed farm. Therefore, the following decision is made: The value chain will not be analyzed further because it does not affect the use of EoU material in the re-design.

5.5.2 Circular values from End-of-Use Dyneema®

To investigate viable business case opportunities an analysis of the exchange of values is done to show the extra value that circular business could offer to *DSM Dyneema BV* or the third party that will be the EoU material supplier to the farm builder. From chapter 1.2.1 we learned that the transition to the circular economy in general could provide the following additional values: *Sourcing value, Environmental value, Customer value* and *Informational value.* Graphic 5.12 shows values applicable to the seaweed farm case.



Graphic 5.12: Exchange of values for Dyneema® customers. Source: self-made graphic.

Graphic 5.12 shows how the general additional values from the circular economy could provide business opportunities for either DSM as the material supplier. It is concluded that for both DSM there are potential additional values to gain from the circularity of Dyneema® in the seaweed farming market. The values DSM gets from the circularity of Dyneema® could possibly also be values for a third party as the material supplier if DSM does not want to be an active part of the value chain.

5.5.3 Certifications and risk

In the coming years, certifications will become required for seaweed farm construction (Schippers, 2019). Certifications are to provide third-party demonstration of compliance of standards, in the case of seaweed farming the standard is that the construction lines do not break and cause damages to other maritime industries. The certifications are only required for the construction lines because breakage of the construction lines could cause trouble contrary the breakage of the grow lines. There are currently no certifications for using EoU material. The requirement of certifications will not be a problem for using EoU material due to the following reasons.

- When minimum strength requirements are met exceptions can be made to regulations for pilot projects.
- A possible combination of new and old Dyneema® could offer a solution here. New Dyneema® could be used for the construction lines where certifications are needed.

5.5.4 Processing of End-of-Use Dyneema®

The EoU material must be processed in order to use it in seaweed farms. The costs of this reprocessing process mostly determine the material costs. The number of steps needed to process the material is used to analyze the effect on the processing costs. The time required for the processing steps are based on experiments with EoU Dyneema® in chapter three.

It is chosen to analyze the possibilities of reuse and remanufacturing of EoU material for the construction lines and grow lines to get an idea of the potential and barriers of remanufacturing of EoU Dyneema®. Processing steps needed for the reuse are presented in table 5.13. Processing steps needed for remanufacturing are presented in table 5.14. See confidential appendix J for processing times and costs. Note that the reuse case, table 5.13, is based on a future scenario where a different coating is used that does not have to be removed for concerns regarding circularity.

Table 5.13

#	Processing step	Reason
1	Sort lines on quality	Not every EoU rope is of sufficient quality
2	Cleaning the lines	The effect of contaminations is unknown no risk should be taken
3	Cut lines to length	Processing step needed for constructing a farm
4	Test lines on strength	To fulfill certification requirements
5	Add a new layer of circular coating	To protect Dyneema®, to prevent possible contamination to the environment and make rope polar for the growing of seaweed

- The rough estimation on the processing costs on the reuse of EoU lines gave the insight that it would be interesting to analyze reuse further, see confidential appendix J.

Table 5.14

#	Processing step	Reason
1	Sort lines on quality	Not all EoU material is of sufficient quality.
2	Take lines apart	Step needed for remanufacturing
3	Sort yarns on quality	Not all yarns are of sufficient quality
4	Cleaning the yarns	The effect of contaminations is unknown, so no risk should be taken
5	Remove coating	Hinder to circularity
6	Cut lines to length	Processing step needed for constructing a farm
7	Remove coating	Processing step needed for braiding new lines with EoU Dyneema®
8	Braid new lines	Remanufacturing step
9	Add a new layer of circular coating	To protect Dyneema®, to prevent possible contamination to the environment and make rope polar for the growing of seaweed

- The rough estimation on the processing costs of remanufacturing EoU lines are significantly higher than the costs for reuse. Based on this rough estimation the costs of remanufacturing compared to the price of new Dyneema® is still interesting to investigate further. The removing of the coating is the most time-consuming step.

5.5.4 Costs of seaweed farms

As indicated in chapter 5.3 using EoU Dyneema® provides two opportunities that potentially will reduce the maintenance costs of the seaweed farm. The first is the reduction of the need to replace grow lines, the second is the reduction for the need of re-tensioning the construction lines.

For the evaluation of the costs of EoU Dyneema® in seaweed farming a paper on the economic assessment of seaweed farming is used as an example (Correa, 2016). From this research we learned that the running costs are the most significant cost of a seaweed farm. The running costs are 87 % of the farm costs (Correa, 2016). As show in table 5.15, the maintenance costs are main part of the running costs. From chapter 2.5 on the analysis of the value proposition of Dyneema®, we know that the economic value of Dyneema® lies in the reduction of costs over its lifetime compared to the use of commodity plastics.

From the economic assessment of seaweed farming it was concluded the larger the farm the better the return of investment. Earlier the higher strength of EoU Dyneema® was regarded as an opportunity to increase the size of the farms. Therefore, the increase in farm size is a design challenge in chapter six.

Table 5.15 on next page, shows an overview of the costs of a seaweed farm. The labor cost and the equipment cost are the most significant cost factors. Equipment are the boats and diving gear needed for seaweed cultivation. Other cost includes, license for farm site, fuel & seeding.

Table 5.15: 10-acre farm costs			
Construction part	**Fixed costs**	**Running costs**	**Yearly costs**
Anchor points	€ 45 000	Repairs and maintenance	€ 33 000
Material cost	€ 60 000	Labor	€ 12 000
Labor cost	€ 40 000	Kelp plants	€ 8000
		Equipment	€ 24 000
		Harvest	€ 10 000
		Other	€ 9000
Total	€ 145 000		€ 96 000
Costs per acre	+/- € 14 500		+/- € 9600
Source: *(Correa, 2016)*			

The data in table 5.15 provides the following insights

- Looking at the fixed costs for building a seaweed farm the reuse case, table 5.13, is an interesting case analyze further. From looking at this specific case the remanufacturing of EoU Dyneema® does not seem an interesting opportunity, see confidential appendix K for the costs price estimations.
- Reducing the maintenance costs seems to be an opportunity to increase the return of investment of a seaweed farm.
    - EoU Dyneema® could potentially reduce the maintenance costs making it a potential interesting choice of material over commodity plastics.

Conclusion cost analysis

Rough estimations on the required processing time and costs for reusing and remanufacturing EoU Dyneema® gave the following insights:

- Compared to costs of new Dyneema® the reuse and remanufacturing case is interesting to analyze further
- Compared to conventional materials used in seaweed farming only the reuse of Dyneema® is interesting to analyze further.

The use of EoU Dyneema® is seen as a potential opportunity to increase return of investment by reducing the maintenance costs. This opportunity is regarded as quite interesting to investigate further. Therefore, reducing maintenance costs is a design challenge in chapter six.

Conclusion chapter 5

The following answers can be given to the research questions given in chapter 5.1.

Research question and answer regarding technical feasibility

Can EoU Dyneema® from the commercial marine market be used for the construction of seaweed farms?

- The technical analysis on using EoU Dyneema® indicates that it can be used for the construction of seaweed farms.

Research questions and answers regarding economic feasibility

What are the values EoU Dyneema® and *DSM Dyneema BV* could offer in the seaweed farming market?

- EoU Dyneema® can offer the farm user a circular material for the construction of the farm. For the material supplier (DSM or third-party) there are additional values from the circular economy to be gained, 5.5.2.

Are there incentives to use EoU Dyneema® over conventional materials used in seaweed farming?

- The incentive is that the value created from reuse are potentially higher than the costs. There are potential opportunities from to use of EoU Dyneema® to reduce the maintenance cost of seaweed farms. If the maintenance costs can be reduced this will provide an interesting design case for the use of EoU Dyneema® is seaweed farming. More investigation is needed to evaluate this potential.

Research question and answer regarding circularity

Does using EoU Dyneema® in seaweed farms contribute to lifetime extension of EoU Dyneema® from the commercial marine market?

- The use of EoU lines in seaweed farming is a possible way to extend the lifetime of the lines from the commercial marine sector. The lifetime is extended with approximately the lifetime of a seaweed farm, which is 10 to 15 years.

Design challenges

Besides the research questions some design challenges came forth that will be attended to in chapter six. To design a seaweed farm that is suited for the use of EoU Dyneema® the following design challenges came forth:

- Better distribution of forces
- Use of shorter lengths of rope
- A solution for rope breakage due to sudden forces
- There should be a method to re-tension the construction lines
- Investigate possibilities to increase in size of the farm
- Investigate possibilities to farm maintenance costs

Chapter 6 - Re-design for a case study on using End-of-Use Dyneema® in seaweed farming.

From the information on seaweed farming in general, the technical and business analysis a farm re-design is made. In this chapter the design challenges are tackled for using EoU material in seaweed farms.

6.1 Farm re-design

In this chapter, the insights from chapter 5 are used to make a seaweed farm re-design were the use of EoU Dyneema® is possible.

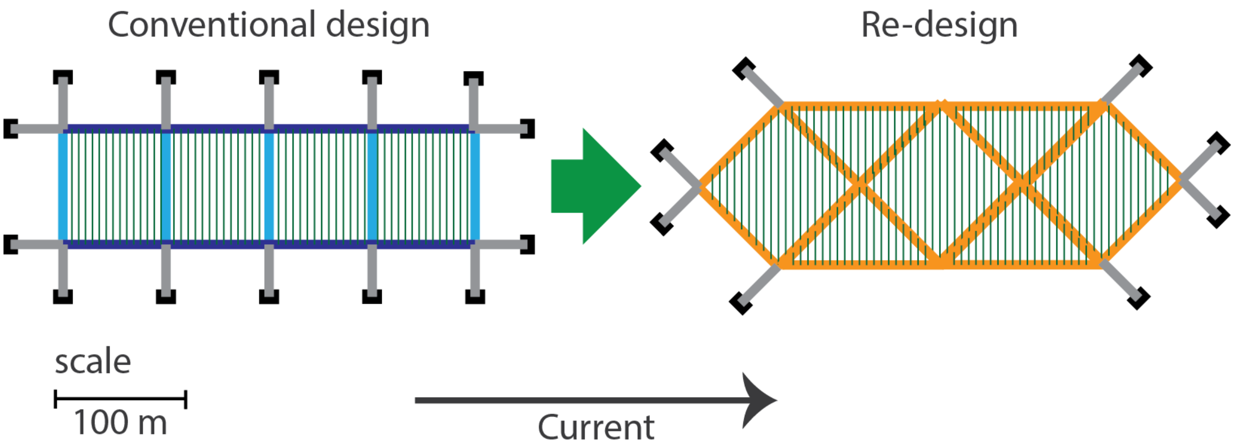
Design challenges

From the information in chapter and chapter 5. the following design challenges were set up.

- Better distribution of forces
- Use of shorter lengths of rope
- A solution for rope breakage due to sudden forces
- There should be a method to re-tension the construction lines
- Investigate possibilities to increase in size of the farm
- Investigate possibilities to farm maintenance costs

Distribution of forces

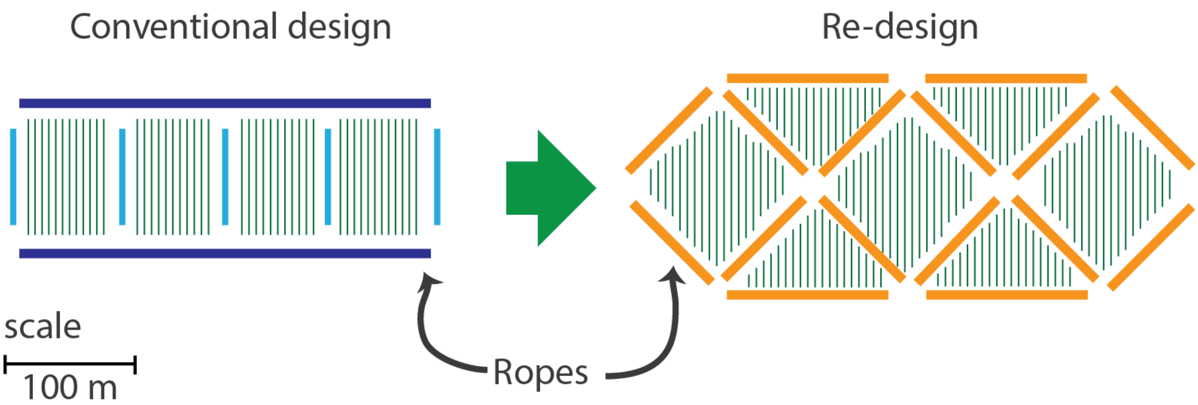
To distribute the forces over the construction lines. The construction lines are constructed differently to the direction of the current, see graphic 6.1. From chapter 5.3 we know that it is possible to change the direction of the lines relative to the direction of the current. Because by changing the direction, the forces are divided more evenly over the lines.



Graphic 6.1: The adaption of the design to better distribute the forces. Source: self-made graphic.

Use of shorter rope lengths

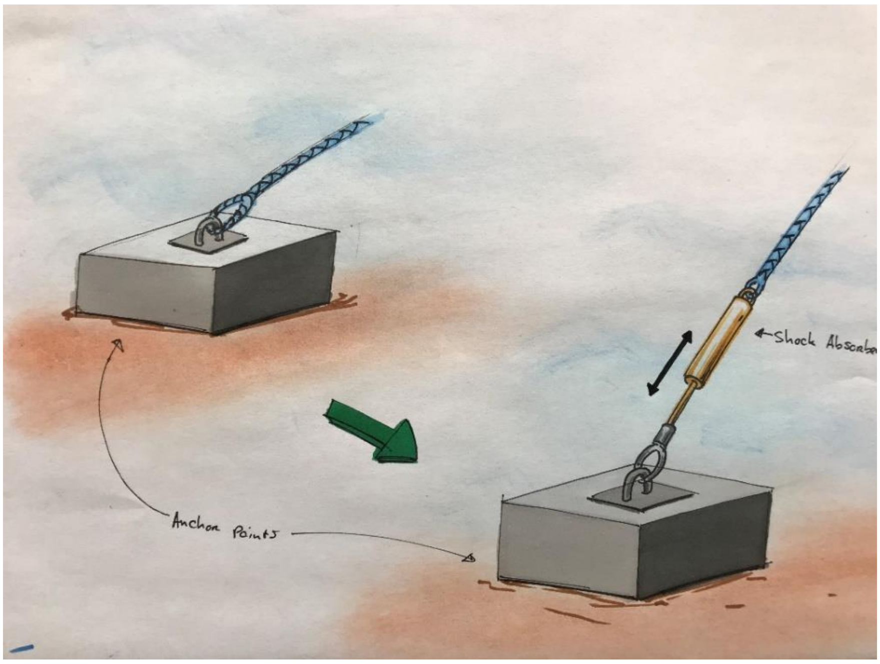
From the analysis of the distribution of forces it is learned that it would be best if the forces are divided over four lines, graphic 5.6. A re-design is made that will make the use of shorter rope lengths possible and make the farm potentially easier to repair and cheaper due to the shorter rope lengths that must be replaced, see graphic 6.2.



Graphic 6.2: The adaption on the design to make use of shorter rope lengths. Source: self-made image.

Possible solution for rope breakage

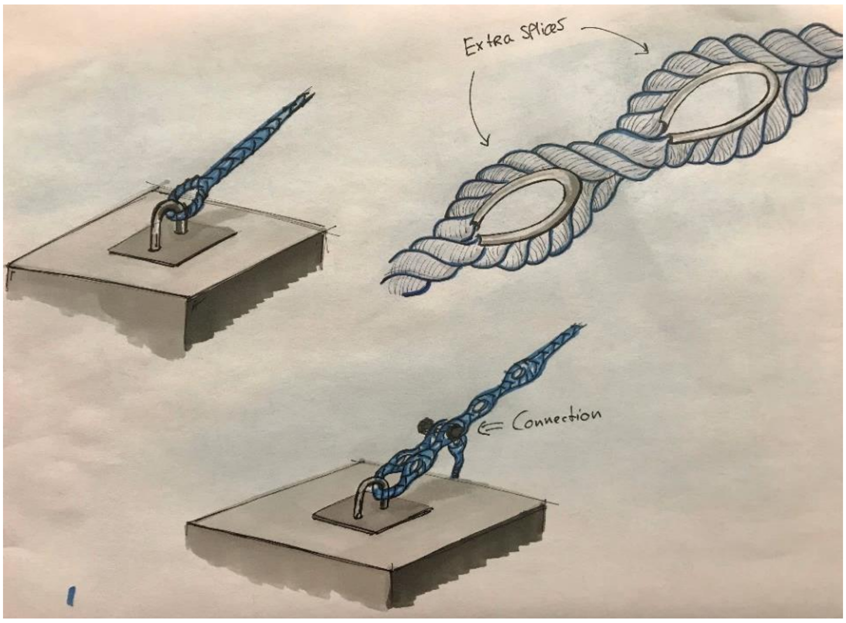
To provide a potential solution for the design challenge on rope breakage the lines of the seaweed farm are connected to the anchor point via a shock absorber, graphic 6.3. This shock absorber will absorb sudden forces and reduce the risk of breakage. Shock absorbers are used in maritime environments (Hlw, 2019)



Graphic 6.3: A shock absorber will absorb shocks from sudden forces reducing the changes of breakages. Source: self-made image.

The solution for creep, stretch & reduction in maintenance cost

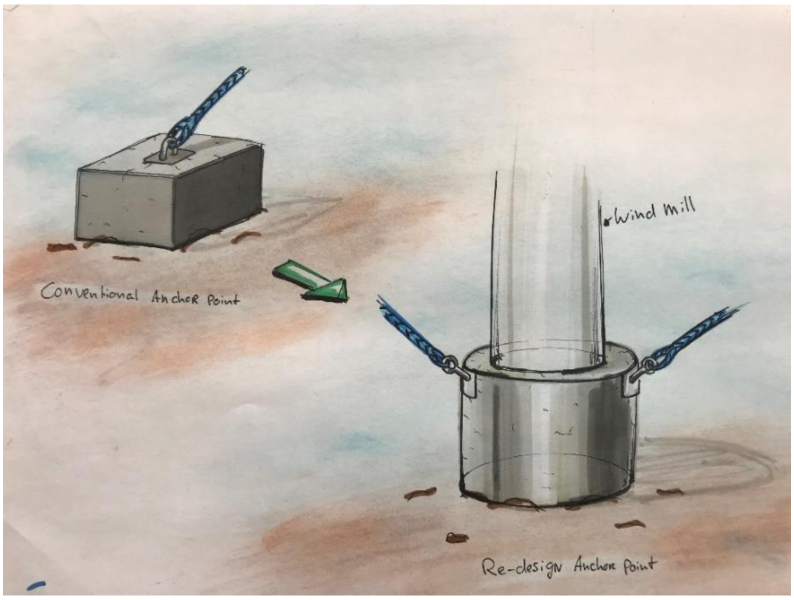
To prevent creep and stretch being a problem an adjustable connection is used. The adjustable connection could also provide possible maintenance costs savings. Costs are saved by reducing the time needed for re-tensioning the lines.



Graphic 6.4: An adjustable connection so that the maintenance costs due to creep or stretch can be reduced. Source: self-made graphic.

Reduction of farm construction costs & increase in size

In chapter 5 the use of windfarm bases as anchor points for seaweed farms was established as a potential opportunity. The use of the basis of the windfarms could potentially reduce the cost of building anchor points. The strength of EoU Dyneema® ropes was also seen as an opportunity to increase the size of the farm. With the use of the windfarm bases the farm size has also increased, see graphic 6.7.

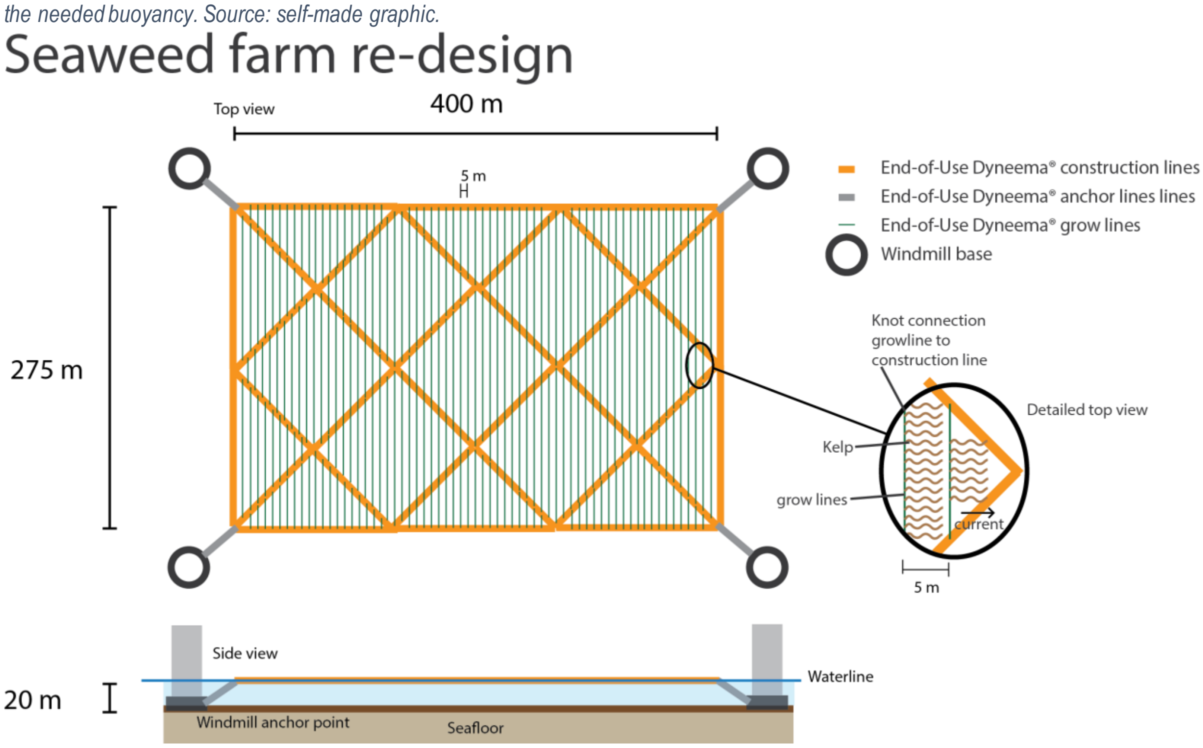


Graphic 6.5: Seaweed farm re-design, the anchor points are the base of windmills. Source: self-made graphic.

6.2 Final re-design

The final re-design is a seaweed farm where all the above solutions of the design challenges are used, the farm can be seen in image 6.6 & 6.7.

Graphic 6.6: The final re-design, the seaweed farm is positioned between windmills that double as anchor points. The buoys, in red, are for the needed buoyancy. Source: self-made graphic.



Graphic 6.7: The dimensions of the final re-design. Source: self-made graphic.

The farm re-design

The final farm re-design has all the possible solutions integrated in the design. The use of EoU material is optimized by making it possible to use shorter ropes lengths for both the construction and the grow lines, image 6.2. The possible effect of creep and stretch has been taken into account by using shock absorbers and re-tensioning connections to the anchor points, image 6.3 & 6.4. The farm size has increased to make optimal use of the higher strength, compared to nylon, of EoU Dyneema®.

The maintenance costs are likely reduced due to the stronger EoU Dyneema® groe lines that need less replacing. The re-tensioning could be done quicker to also save cost. Anchor points from windfarms will give a possible reduction in the construction cost.

With the use of EoU Dyneema® the lifetime of the Dyneema® fiber could be extended by 10 years, the average lifetime of a seaweed farm. The lifetime of this seaweed farm could potentially be even longer due to the better performance of Dyneema®.

When the seaweed farm has reached the end of its product life cycle, the materials will be taken back by the material processor. The condition of the EoU Dyneema® shall be evaluated to determine its next life cycle.

6.3 Discussion for using End-of-Use Dyneema® in seaweed farming

This discussion will be based on the findings described in chapter five and six. First, the opportunities for using EoU material are given followed by the barriers for using EoU Dyneema® in seaweed farming.

Opportunities

The market potential, table 5.2, the environmental benefits, graphic 5.1 and the fit with the corporate strategy of *DSM Dyneema BV* makes seaweed farming a market where the circular goals of *DSM Dyneema BV* could be fulfilled. The fulfillment of the corporate goals can be a value for DSM.

In theory EoU Dyneema® is stronger than commodity fibers, chapter 2.6, this is an interesting opportunity to make the seaweed farm bigger, which will increase profit. Also, the use of Dyneema® provides a potential opportunity to reduce the costs of maintenance.

Rough estimations on the required processing time and costs for reusing and remanufacturing EoU Dyneema® gave the following insights:

- Compared to costs of new Dyneema® the reuse and remanufacturing case is interesting to analyze further
- Compared to conventional materials used in seaweed farming only the reuse of Dyneema® is interesting to analyze further.

Barriers

Both value chains, graphic 5.10 & 5.11, provide challenges and opportunities that must be solved before the final decision can be made of which value chain is the best suited. Choosing which of the two models would be the best is a time-consuming process which can only be finalized when the entire business case is analyzed further.

The processing of EoU material into smaller grow lines is possible but the processing time is long compared to the value of the grow lines. The process of making small line form thick EoU Dyneema® lines should be optimized. Another option is to actively collect smaller Dyneema® lines or just use thick lines instead.

The biggest cost savers in the re-design are also suited for other materials. Meaning that the cost reduction does not come from the material. The only value EoU Dyneema® offer over commodity plastics is that it is slightly stronger and is circular. The concern is that this would not be enough to convince a farm builder to invest a lot of money in developing a farm specifically for EoU Dyneema®.

Discussion

In my opinion the most promising opportunity is that the costs of reusing EoU Dyneema® lines can potentially compete with commodity plastics in seaweed farming. To realize this opportunity the coating on the lines should be optimized for circular use. The biggest barrier is the condition of the Dyneema® lines. The strength of the EoU lines is theoretically higher then commodity plastics. However, in practice damages to the rope will determine if a rope is strong enough for a specific case. The amount and severity of the damages are still quite uncertain due to the lack of personal experience with the EoU material. More investigation on the condition of EoU Dyneema® is needed to draw a final conclusion on the strength of EoU Dyneema® and the possibility of using it in seaweed farming. The use of EoU Dyneema® in seaweed farming comes with both opportunities and barriers that need further investigation. Because of the environmental and circular benefit of the seaweed farming market. I do recommend further investigating the use of EoU Dyneema in seaweed farming.

6.4 Lessons learned from the design case on using End-of-Use Dyneema® in seaweed farming

To gain insights on the use of EoU Dyneema® in general a design case on seaweed was conducted. In this section lessons learned from chapter five and six are mentioned.

The design of a seaweed farm should be adapted so that shorter lines lengths could be used, sudden forces are absorbed, and the lines can be re-tensioned more easily. From this was learned that adjusting the design of the application/product is required for optimal use of EoU materials. Besides challenges using EoU materials could also provide advantages for both the seaweed farming business, such as maintenance cost reduction, and the material supplier, like the additional circular values. Adapting the design for optimal use of EoU materials could often be a challenge but will often be worthwhile.

Usually knots are recommended to connect the lines in seaweed farming. However, it was noted by DSM that knots are undesirable when using Dyneema® lines due to the effect of knots on the strength of the lines. Splices are the recommended type of connection for Dyneema® lines. From this was learned that when using EoU material the designer should be well aware of all the properties of the material. Also, properties EoU material can differ from the original material. Therefore, it is recommended to not only have knowledge of the properties of new material, but also of the properties of the EoU material.

From the design case it was learned that the coating is that is needed for the use of the lines, constructed of Dyneema® fiber, in the commercial marine market is a hinder for the circular use of the Dyneema® fiber.

Chapter 7 - Recommendations for circular possibilities of *DSM Dyneema BV*

This chapter discusses the opportunities and barriers for the transition towards the circular economy of *DSM Dyneema BV*. Personal recommendations are included.

7.1 Circular opportunities for *DSM Dyneema BV*

In circular economy collaboration is a key feature. For *DSM Dyneema BV* there are opportunities for collaborations in the value chain. From the stakeholder analysis, the business model analysis and the competitor analysis we learned that more collaboration is likely needed. Collaborations could provide opportunities from circular business models. Circular business models could provide additional circular values like, *Informational value, Environmental value, Customer value* and *Sourcing value.* Also, collaboration with competitors in similar markets could be an interesting opportunity to cope with the challenge of collecting EoU products back from the market.

The analysis concerning the competitors it became clear that every product producer that works with high-performance fibers has production residual. High-performance fibers are expensive and scarce, meaning that the product producers would be eager to develop a solution for their residuals. Sacristy can the driver for recycling, such as is the case for carbon fiber. A collaboration with other product manufacturer could be an opportunity to make Dyneema® fiber circular.

From the experiments with the EoU Dyneema® it was concluded that the taking apart of EoU ropes is an interesting opportunity to recover valuable material. Value recovery could be done by removing damaged strand or yarns from the EoU ropes or by combining EoU Dyneema® fibers with new fibers. Removing damaged yarns could increase the strength and thus the value of the recovered rope. I was that combinations of EoU Dyneema® and new Dyneema® could also improve rope strength, but I recommend strength tests to prove the impact of the value recovery methods. The theoretical residual strength of EoU Dyneema® ropes suggest that the strength of the EoU ropes is reduced but could be be competitive with ropes made from commodity plastics.

In the design case it was concluded that reuse of EoU Dyneema® is an interesting opportunity to investigate further. However, for optimal reuse it is advised that reuse demands are already taken into account when producing the products from Dyneema® fiber.

From the design case it was concluded that the use of EoU Dyneema® in seaweed farming could contribute to the extension of product lifetime of lines made from Dyneema® fiber. The use of EoU Dyneema® in seaweed farming comes with opportunities as well as barriers that both need further investigation. Because of the environmental and circular benefit of the seaweed farming market, I recommend further investigating on the use of EoU Dyneema® in seaweed farming. The investigations for the use of EoU Dyneema® could also provide knowledge for other applications of EoU Dyneema®.

7.2 Barriers for *DSM Dyneema BV* regarding the transition towards a circular economy

The coating used on the ropes made from Dyneema® fiber seems difficult to separate from the rope because of it being a thermoset. This makes recovery of Dyneema® ropes more difficult and potentially reduces the value of the rope material. Environmental concerns about the use of *Coating A* and similar coatings oblige more research for circular use of materials containing these types of coatings.

DSM Dyneema BV is protective of the intellectual property rights of Dyneema® fiber, which is completely understandable for any business. Protection of intellectual property rights could be a barrier to find possible business partners that collaborate to explore circular possibilities with EoU Dyneema®. It would an advantage if legal processes would not be a hinder for first explorations of circular opportunities of EoU Dyneema® with business partners.

Certifications like *ASTM* and *DNV GL* provides the industry with a third-party demonstration of compliance to standards (ASTM, 2018). Currently there are no certifications for reused and recycled materials. It was discovered during the design case that seaweed farming, a relatively new industry, certifications are also required. It will be likely that most applications in which EoU Dyneema® could be used require certification of some sort. Lack of a certification for EoU Dyneema® could be a hinder for finding possible applications for EoU Dyneema®.

7.3 Recommendations for *DSM Dyneema BV*

The most valuable insights on the possibilities of reusing EoU Dyneema® as described in this graduation assignment were gained by the experiments and prototyping with the material. From the design case it was learned that it is recommendable to obtain knowledge on the properties of EoU material besides the knowledge of the new material. To obtain knowledge on the properties of the EoU material prototyping seems an interesting opportunity. The prototyping could be done by DSM or by a collaboration with a product manufacturer.

The coating on the ropes recovered from the commercial marine market appear to be a hinder for the reuse of the ropes. For optimal circular use it could be considered to adjust the coating on the ropes. In general, it should be considered that other ways to construct ropes are considered so that the need for the coating could be avoided altogether. For example, using covered ropes instead of the uncovered ropes.

Considering using EoU materials in a product or application, alterations in the entire product design should be considered in order to optimize the use of EoU materials. To investigate possibilities of using EoU Dyneema®, I recommend the making of prototypes to discover the need for alterations in the design. The making of these prototypes could be done in collaboration with a product manufacturer. My recommendation is to investigate product possibilities in a market in which the product can be evaluated by customers rather quickly, like for example the textile industry. This way, specific knowledge concerning circularity and production for more complicated or advanced applications can be gained with lower investments of time and money.

Collaboration appears to be an interesting opportunity for the circularity of Dyneema® fiber. Creative facilitation and co-creation are good opportunities to find yet unknown possible applications. As I learned from my teacher in creative facilitation H. van der Meer, who facilitated creative sessions for finding applications for high performance materials. In these sessions the most interesting and unexpected outcomes seemed the most interesting opportunities for some materials. Therefore, to find potential business partners, I recommend co-creating session in which potential product producers could freely experiment with the EoU material.

Chapter 8 - Evaluation

In this chapter the graduation assignment is evaluated. First the choices and assumptions made in the process are evaluated followed by an evaluation on the process of the project and how that affected the outcome.

8.1 Evaluation on the choices and assumptions

Choice to change the research question

The initial assignment from DSM was a more strategic design focused project. As an Integrated product design student this graduation project could not be a fully strategic design project. This made the project a combination of the two. Due to my lack of experience on the strategic part I made it myself very difficult but a very good learning experience.

At the beginning of the project the research question given by *DSM Dyneema BV* was changed to fit my masters program, personal ambitions and DSM its wishes. The choice of adapting the research question was a good one. The research question that was set up was maybe a bit too difficult. The research question made it very hard for me to do where I am good at, keep a steady focus and work methodically. I made it too difficult for myself.

Focus on commercial marine market

The choice of looking at one market instead of four was a good choice regarding time. The choice of the commercial marine market was a good one due to the impact the findings can have due to the size of the market. What was difficult is the size of the EoU material. Lines sold in the commercial marine market could be hundreds of meters long and nets can be hundreds of square meters. Other markets like the life protection would have been an easier fit within this graduation project due to the size of the EoU material.

End-of-Use material

In chapter 2.3.1 an assumption was made that the two lines that where analyzed represented how all the EoU material would look like. Still the assumption is there that the lines do represent the condition of a rope that would have been thrown away. It would have been good to see where the lines failed. The choice to not analyze a fishing net was due to the lack of availability of an EoU fishing net.

Focus on using End-of-Use material from the commercial marine market

In this assignment the decision was made to focus on the EoU material from the commercial marine market instead of following the initial assignment from DSM to look at the production residual. This choice was made on the amount of waste available and the circular challenge of collection. Towards the end of the project it was discovered that there was way more production residual than initially stated. This means that there was no need to look at EoU material for the circular challenge of collection. However, the analysis of the EoU material was not a bad choice due to the amount of interesting insights gained.

List of criteria

In chapter four, a list of criteria was set up to find an evaluate possible use applications for a design case on using EoU Dyneema®. This list was made from prior research and literature studies that were done at the beginning of the graduation project. After doing the design case this list could be improved. The list could mainly be improved in not steering towards applications that require high strength too much. Also, for evaluating application the list was good, but for finding the applications the list was too restrictive.

Choice of application

In chapter four there was chosen for seaweed farming out of three applications that seemed the most interesting after the brainstorm.

Textile reinforcement with EoU fiber is not as easy as it seems due to the coating because even when soaked in *chemical A* the fibers still stick to each other a bit. A new way of using fiber to reinforce textiles will have to be developed. The same problem with the coating can be said for the geotextiles.

The making of the geotextiles is not suited for sticky fibers. Here also a new way of making the textiles must be developed. This is not different from seaweed farming as it also had its challenges. The challenges are the interesting design problems. Due to the fit within the graduation project I think that the technical textiles would have been a better fit when looking back.

Design case

In the design case I could not do the things I wanted to do when I choose seaweed farming, partly my fault and partly that of the restrictions from DSM. I should have seen that there were restrictions to who I could involve in the graduation process. If I realized that sooner, I would have chosen for the technical textiles industry instead. The technical textiles industry would have been a better fit for the graduation assignment.

What I should have done differently in the seaweed farming design case was: In the design case the choice was made to look at only the farm itself, not the whole concept. This limited how much I could change and really design.

8.2 Evaluation on the process

The main point of evaluation is that I did not work methodically enough to do such a complicated and broad research assignment.

Working with the End-of-Use material

I should have started experimenting with the EoU material sooner because it gave the most interesting insights but too little and too late. I started too late with this because I let to be guided too much by the wishes of *DSM Dyneema BV*.

I waited too long to make definitive decisions on the structure of my report. This led to a very large amount of information without proper focus. There was focus in my head, but it would have been way better if there was more focus on paper as well to firstly communicate the direction I was going and secondly not losing the focus by an overload of information. This also prevented me to inform my mentors properly on what I was doing. Also, my long-term planning changed too much to properly plan the steps that needed to be taken.

My approach to design is to run around looking at much as possible information and try out lots of different little approaches. To eventually find an interesting idea. The problem was that this project was too complicated for the blindly running around.

The intended method of this project was to do a research by design project. However, it become too much a sort of consultancy research project. At the beginning of the project I was led too much by research papers instead of design methodology. The moment I wanted to go towards more design practice I kept working too long on the research.

The process was too ambitious for time that was available for a graduation project. I wanted to answer the question where Dyneema® could be reused. I wanted to find the value of Dyneema® and where it all could be used for, just like the green alliance paper. This was way too much to do on my own in a graduation project. I should have used the basic market analysis tools and way sooner have moved on to working with the material itself.

I had a focus on outcomes of what DSM **should** do with Dyneema®, instead of just giving valuable insights, inspiration and recommendations on what **could** have been done. This goal was a bit too ambitious and made me less objective.

List of requirements

In chapter 3.4 A list of requirements was set up for finding and evaluating possible use applications with all the knowledge and findings I had at that moment. When I looked at the list later in the project, long after the design case was done, I noticed that the list could be improved a lot. Insights for improvements did come from the design case as well, making that serve its purpose. With the updated list a better choice for an application could be made.

A direction of thought was that the high tensile strength applications would be best suited for Dyneema® because that is where the value of Dyneema® can come forth, this should be reviewed because I think this is not that simple.

In evaluation possible application for the reuse and remanufacturing of EoU Dyneema® one of the evaluation criteria was the possible fit within the graduation project. I made the choice to not take the fit within the graduation assignment as the most important factor, looking back it would have been better for my graduation result if I had done that.

The scoring with the list of criteria was not chooses to choose the application but only to communicate my choice, this was good. But maybe I should have left it out of the occasion completely.

From the insights I got from the experiments with the EoU material I should have used prototyping and experimentation with EoU material for finding a suitable application area.

Brainstorm

When I started this graduation project, I had the idea to use creative facilitation and co-creation for finding possible use applications for EoU Dyneema®. This was even recommended by a professor that is specialized in materials. Because I did not follow my plan, I did not go through with this. A proper brainstorm session with multiple people would have given more interesting directions, just like the little co-creation session on the stakeholders. I think that insights from a proper co-creation session would have been a lot better result than I have now with the design case.

Insights and conclusions

Because of the uncertainty of the results there I felt the need for finding and writing down more insights and conclusions. This resulted in that it became quantity over quality. Considering that quality is actually more important when it comes to insights this is a remark for the future.

Sources

(Aireen, 2016) Aireen, N. Image from: *Review on Polyester Mooring lines of offshore structures.* Reserachgate.net. October 2016.
(Ad.nl) Image from: https://www.ad.nl/binnenland/meerderheid-voor-afschaffen-statiegeld-plastic-flessen~a6fb93c1/. Conducted on: April 2019.
(Askmen.com, 2019) Image from website: https://www.askmen.com/entertainment/guy_gear/carbon-fiber-products/. Conducted on April 2019.
(Altex.de, 2018) Website *altex*: https://www.altex.de/en/textil-recycling/products/aramid-fibre-nonwoven-and-fabric. Conducted on: December 2018.
(Astm, 2018) *Certification and declaration programs: The safety equipment institute.* From: https://www.astm.org/CERTIFICATION/. Conducted on: November 2018
(AquacultureNorthamerica.com, 2017) Image from: https://www.aquaculturenorthamerica.com/news/pioneering-offshore-mussel-farm-scores-another-industry-first-1780. Conducted on: March 2019.
(Bakker, 2014) Bakker, C., M, Den Hollander, E. van Hinte and Y. Zijlstra. *Products that last: Product design for circular business models.* TU Delft library. Delft 2014.
(Bakker, 2014) Bakker, C., Products that go round: exploring product life extension through design. Journal of cleaner production. 2014.
(Barnes, 2018) Barnes, F. *Recycled carbon fiber: Its time has come.* From: https://www.compositesworld.com/columns/recycled-carbon-fiber-its-time-has-come-. Conducted on: December 2018.
(Beckengineering.com, 2019) Image from website*:* http://www.beckengineering.com/store/p5/Carbon_Fiber_Reinforced_Polymer_%28CFRP%29_Structural_Tubes.html. Conducted on: April 2019.
(Be sustainable, 2017) Be sustainable. *Recycled textile fibers and textile recycling.* December 2017.
(Bikerumor.com, 2019) Image from website: https://bikerumor.com/2012/12/05/3d-woven-braided-carbon-fiber-concept-road-bike-by-jacob-haim/. Conducted on April 2019.
(Bocken, 2016) Nancy M. P. Bocken, I. de Pauw, C. Bakker & B. van der Grinten. *Product design and business model strategies for a circular economy.* Journal of Industrial and product Engineering. 2016.
(Brentindustries.com, 2018) Website*:* https://brentindustries.com/products/aramid/. Conducted on: December 2018.
(Buck, B.H. 2010) Buck, B.H. Mussel cultivation as a co-use in offshore windfarms: potential and economic feasibility. 11-2010.
(Bunsell, 2018) Bunsell, A.R. *Handbook of Properties of Textile and technical fibres.* Woodhead publishing, January 2018.
(Chembid.com, 2018) Website: https://www.chembid.com/suppliers/100703/shandong-xingye-environmental-technology-corp/. Conducted on: December 2018.
(Chemtrust, 2015) *Circular economy and chemicals: Creating a clean and sustainable circle.* Chemtrust. 2015.
(Chmcomposites.com, 2019) Website & image from website: http://chmcomposites.com/recycled-fibres/. Conducted on: April 2019.
(Compositesandarchitecture.com, 2019) Image from website *compositesandarchitecture:* http://compositesandarchitecture.com/?p=4976. Conducted on April 2019.
(CompositesUK, 2018) *Delivering UK growth through the multi-sector application of composites.* The 2016 UK composites strategy. Composites UK. 2016.
(Correa, 2016) Correa, T. *Production and economic assessment of giant kelp Macrocystis pyrifera cultivation for abalone feed in south of Chile*. Aquaculture research. 2016.
(Dcis.com, 2019) Image from: https://www.dcis.ca/store/index.php?main_page=product_info&cPath=6_351&products_id=1226. Conducted on: March 2019.
(DSM, 2014) *Brighter living solutions: Measurably better impact on the planet and people.* Corporate strategy from DSM N.V. 2014.

(DSM, 2018) Interviews with DSM employees: Interviews conducted in 2018.
(DSM, 2018 II) Website *DSM Dyneema BV:* https://www.dsm.com/products/dyneema/en_GB/home.html. Conducted on: October2018.
(DSM & Samson, 2018) *Total cost of ownership.* Webinar from DSM & Samson ropes. From: https://www.dsm.com/content/dam/dsm/dyneema/en_GB/Downloads/Presentations/Total_Cost_of_Ownership_WorkBoat_Webinar_2018.pdf
(DSM.com I, 2019) Image from: https://www.dsm.com/products/dyneema/en_GB/industries/maritime.html. Conducted on: March 2019.
(DSM.com II, 2019) Image from: https://www.dsm.com/products/dyneema/en_US/industries/commercial-fishing.html. Conducted on: March 2019.
(Dubaicompanieslist.com, 2019) Image from: http://dubaicompanieslist.ae/companies-dubai/geotextiles-dubai/. Conducted on: March 2019.
(Dynamica-ropes.com, 2019) Image from: https://dynamica-ropes.com/mooring-rope/. Conducted on: April 2019.
(ECN, 2019) *Seaweed cultivation pilot at windfarms.* Ecofys. From: https://www.ecn.nl/nl/nieuwsbrief/engels/2012/march/seaweed-cultivation-pilot-at-wind-farms/. Conducted on: March 2019.
(ELGCF.com, 2018) Image from: http://www.elgcf.com/. Conducted on: December 2018.
(Ellen MacArthur foundation, 2013) [Ellen MacArthur foundation. Towards the circular economy, vol.1. 2013.]
(EU, 2018) *Circular economy: new rules will make EU global front-runner in waste management and recycling.* Conducted on: 22-05-2018. From: http://europa.eu/rapid/press-release_IP-18-3846_en.htm
(EU, 2017) *Study for the strategy for a non-toxic environment of the 7th Environment Action Programme.* From: http://ec.europa.eu/environment/chemicals/non-toxic/pdf/NTE%20main%20report%20final.pdf. Conducted on: April 2019.
(EPA.gov, 2019) Image from website: https://www.epa.gov/smm/sustainable-materials-management-non-hazardous-materials-and-waste-management-hierarchy. Conducted on: 18-3-2019.
(Fiberbrokers.com, 2018) Website *fiberbrokers*: http://www.fiberbrokers.com/. Conducted on: December 2018.
(Fleurence, 2018) Fluerence, J. Seaweed proteins. University of Nantes, France. 2018.
(Green Alliance, 2017) Green Alliance., *Getting it right from the start Developing a circular economy for novel materials.* The Green alliance, 2017.
(Grandviewreserach, 2018 I) Argiculturere global market report 2018. Grandview research Inc. From: https://www.prnewswire.com/news-releases/agriculture-global-market-report-2018-300602763.html. Conducted on: December 2018.
(Grandviewreserach, 2018 II) Dietary supplements Market size Worth 278 billion by 2024. Grand view Research Inc. From: https://www.grandviewresearch.com/press-release/global-dietary-supplements-market. Conducted on: December 2018.
(Grandviewreserach 2018 III) Plastics market worth 654 billion by 2020. Grandview research Inc. From: https://www.prnewswire.com/news-releases/plastics-market-worth-65438-billion-by-2020-grand-view-research-inc-511720541.html. Conducted on: December 2018.
(Hakaimagazine.com, 2019) Image from: https://www.hakaimagazine.com/news/chemical-cues-prompt-farmed-seaweed-to-protect-itself/. Conducted on: April 2019.
(Harmonyrecycling.com, 2018) Website *Harmon recycling*: http://www.harmonyrecycling.com/. Conducted on: December 2018.
(Hlw, 2019) Website *Health land & water:* https://hlw.org.au/project/environmentally-friendly-moorings/. Conducted on: March 2019.
(Hollander, 2017) den Hollander, M. C., Bakker, C. A., & Hultink, E. J. (2017). *Product Design in a circular Economy: Development of a Typology of Key Concepts and Terms.* Journal of industrial Ecology, 21(3), 517-525.

(Horrocks, 2000) Horrocks, A.R. & Anand, S.C. *Handbook of technical textiles.* Woodhead publishing limited. 2000.
(Huysman, 2015) Huysman, S. The recyclability benefit rate of closed-loop and open-loop systems: A case study on plastics recycling in Flanders. Journal of: Resources, Conservation and recycling. January 2015.
(Indiamart.com, 2019) Image from website: https://www.indiamart.com/proddetail/aramid-yarn-for-optical-fiber-cable-and-rubber-hose-6905459255.html. Conducted on: April 2019.
(Innovationintextiles.com, 2019) Image from: https://www.innovationintextiles.com/fibres-yarns-fabrics/load-solutions-as-launches-lightweight-tycan-chains-made-with-dyneema/. Conducted on: March 2019.
(Jeccomposites.com, 2019) Image from website: http://www.jeccomposites.com/knowledge/international-composites-news/recycled-pyrolysis-carbon-fibre-mat-industrial-use. Conducted on: April 2019.
(Karen, 2016) Karen, M. *Best practice guidelines for seaweed cultivation and analysis.* 2016.
(Kett-rope.com, 2019) Image from website: http://www.kett-rope.com/kevlar-aramid-rope-15.html. Conducted on April 2019.
(Loonwijzer.nl, 2019) Website: https://loonwijzer.nl/eigenbaaswijzer/uurtarieven-in-50-beroepen-zzpers-vergeleken-met-werknemers. Conducted on: April 2019.
(linysyntetyczne.pl, 2019) Image from website: https://www.linysyntetyczne.pl/overbraided-dyneema-12mm Conducted on: March 2019.
(Marcuzzo, 2016) Marcuzzo, J, *S. Study of Aramid Fiber/Polychloroprene Recycling Process by Thermal*
(Materialsforengineering, 2018) Bakewell, J. *Recycling Carbon Fiber.* From Website: http://www.materialsforengineering.co.uk/engineering-materials-features/recycling-carbon-fibre/160324/. Conducted on: December 2018.
(Mbtautomotive.co, 2019) Image from website: http://www.mbtautomotive.co.za/introducing-kevlar-friction-material/. Conducted on April 2019.
(McCorkle, 2003) McCorkle, M. *Abrasion and residual strength of Fiber tuglines.* DSM Dyneema BV & Samson Rope technologies. 2003.
(Meran, 2007) Meran, C. Examination of the possibility of recycling and utilizing recycled polyethylene and polypropylene. Elsevier. 2007.
(MESA, 2016) *Global trends driving maritime innovation.* Maritime Europe Strategy Action. 2016.
(Naqvi, 2018) Naqvi, S.R. *A critical review on recycling of end-of-life carbon fibre/glass fibre reinforced composites waste using pyrolysis towards a circular economy.* Elsevier. September 2018.
(Ourworldindata.org, 2018) *FAQ's on plastics.* From: https://ourworldindata.org/faq-on-plastics#how-much-plastic-and-waste-do-we-produce. conducted on: December 2018.
(PEACOCK FIBERS, 2018) Website: https://peacockfibres.co.uk/aramid-fibre-recycling-4-c.asp. Conducted on: Decemeber 2018.
(Pimenta, 2014) Pimenta, S, & Pinho, S, T. *Recycling of carbon fiber.* Handbook of recycling. 2014.
(Plastictoday.com, 2019) Image from website: https://www.plasticstoday.com/recycling/recycled-carbon-fiber-key-mass-market-applications/7344798259925. Conducted on: April 2019.
(Polyvel.nl, 2018) Website: http://www.polyvel.nl/en/milled-aramid-fibres/. Conducted on: December 2018.
(Prnewswire.com, 2018): *Global and China Aramid fiber industry report 2015-2018.* From: https://www.prnewswire.com/news-releases/global-and-china-aramid-fiber-industry-report-2015-2018-300187807.html. Conducted on: December 2018.
(Rajendran, 2012) Rajendran, N. Seaweeds can be a new source for bioplastics. Journal of Pharmacy research. 25-01-2012.
(Rijksoverheid, 2016) *Nederland circulair in 2050: Rijks breed programma circulaire economie.* September 2016.
(Rmintl.com, 2018) Website: http://rmintl.com/. Conducted on: December 2018
(Rothe, 2017) Rothe, J. *Recycling @ TEIJIN Aramid.* Teijin aramid. 2017.

(ROTH, 2018) Website: https://www.roth-international.de/en/stripping-down/stripping-down-cfrp-gfrp/. Conducted on: December 2018.
(Samson, 2016) *Guide to rope selection, handling, inspection and retirement.* Samson ropes. 2016.
(Schenkel et al. 2015) Schenkel, M. *Understanding value creation in closed loop supply chains – Past findings and future directions.* Journal of manufacturing systems p. 735-737. 2015
(Schippers, 2019) Interview with: Schippers, J. 2019. Hortimare BV. Interview with J. Schippers, Business development advisor at Hortimare BV.
(Schumacher, 2011) Schumacher, M. Hydrothermal conversion of seaweeds in a batch autoclave. Elsevier. August 2011.
(Sioen.com, 2019) Image from: https://sioen.com/nl/nieuws/at-sea-sleutel-op-de-deur-zeewierboerderijen. Conducted on April 2019.
(Smithsonianmag.com, 2019) Image from: https://www.smithsonianmag.com/science-nature/recycling-you-may-be-doing-it-wrong-180951192/. Conducted on April 2019.
(Stahel, 1981) Stahel, W. *Jobs for tomorrow: The potential for substituting manpower for energy.* January 1981.
(Spijkers, 2018) Spijkers, J. Interviews with J. Spijkers, Application manager at DSM Dyneema BV. Interview conducted on: October 2018.
(Spijkers, 2019). Spijkers, J. Interviews with J. Spijkers, Application manager at DSM Dyneema BV. Interview conducted on: 04-02-2019.
(Spijkers, 2019 II) Calculations performed by DSM employee Spijkers, J. 6-2-2019.
(Teijin, 2018) Article on website Teijin, *Recycling*: https://www.teijinaramid.com/en/about-us/sustainability/recycling/. Conducted on: December 2018.
(TenCate, 2018) Interview with *Tencate Geosynthetics Netherlands BV*. Interview conducted on: 22-November-2018.
(Thomasnet.com, 2018) Website: https://www.thomasnet.com/products/kevlar-recycling-services-97007339-1.html. Conducted on: December 2018.
(Ties-necktie.com, 2019) Image from website: https://www.ties-necktie.com/Aramid.html. Conducted on April 2019.
(Tompson, 2018 I) Thompson, J. W. *The new sustainability regeneration*. Innovation group. 2018.
(Tompson, 2018 II) Thompson, J. W. *The future 100*. Innovation group. 2018
(Trends.directindustry.com, 2019) Image from website: http://trends.directindustry.com/ningguo-bst-thermal-products-co-ltd/project-113675-158836.html. Conducted on April 2019.
(Trilobitemoto.com, 2019) Image from: https://www.trilobitemoto.cz/index.php/technologies-trilobite/item/354-dyneema-material. Conducted on: March 2019.
(Vlasblom, 2018) Vlasblom, M. *The manufacture, properties, and applications of high-strength, high-modulus polyethylene fibers*. Handbook of Properties of Textile and Technical Fibres, CH18. 2018.
(Vlasblom M, Bosman R, 2006) Vlasblom, M, Bosman, R: Predicting the creep lifetime of HMPE mooring rope applications, Boston, 2006, Oceans MTS/IEEE.
(Werff & Vlasblom. 2014) Werff, Harm & Vlasblom*. New Developments of the Dyneema® Ultra High Molecular Weight Polyethylene Fiber.* 2014.
(Werff, 2018) *Werf, H, vd. High performance polymer fibers.* College TU Delft Lucht & Ruimtevaart. 13 September 2018.
(Wikipedia, 2018) World energy consumption. Wikipedia: https://en.wikipedia.org/wiki/World_energy_consumption. Conducted on: December 2018.
(Wouters, 2018) Interview with: Wouters, J. Founder of: *TheSeaweedCompany*. Interview conducted on 2-11-2018.
(Zoltek.com, 2019) Image from: http://zoltek.com/applications/wind-energy/. Conducted on April 2019.