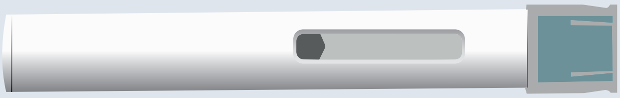
2023

THE ROAD TOWARDS A CIRCULAR AUTOINJECTOR



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PREFACE

Dear reader,

This thesis is the final work of my Masters Strategic Product Design. The result of six and a half joyful years at the TU Delft coming to an end. During my masters, I believe that have developed a lot of new knowledge, skills, connections, and experiences that shape the strategic designer that I am today.

For this thesis, I had the opportunity to combine three domains that I find very interesting and relevant namely, sustainability, health care, and strategic entrepreneurship. Doing this project made me feel socially and sustainably involved. I felt empowered as a strategic designer and I got the chance to help make an impact, and for that I am grateful.

First and foremost, I want to acknowledge and thank my supervisory team that has helped me during the past five months.
Dear Margreet, I want to thank you for our weekly sessions in which you were able to assure me where needed, and help me remind whenever I unconsciously mentioned something important. Your feedback was always helpful to me and I felt truly supported throughout the entire process.

Dear JC, I want to thank you for the support you gave in many different forms. From the connections, you so easily trusted me with to the private coaching sessions in which you helped me to structure the web of information I had gathered. I have enjoyed the meetings that we had because there was always something to laugh about.

I also want to thank Alliance to Zero, specifically Marion and Sebastian, for the opportunity to learn from their experiences and for giving me the freedom to ask any question that I had. I felt very welcome during my trip to Dublin and I enjoyed working together.

And lastly, I want to thank my support team which consists of my family and friends who looked after me, listened patiently to my ideas or struggles, gave advice, or just accompanied me on the many coffee breaks. On that note, to anyone taking the effort to read my thesis, best of luck and I hope it will inspire you.

Enjoy reading!

Meike Schuringa

EXECUTIVE SUMMARY

This thesis is the result of a research question set up by the non-profit Alliance to Zero. They were curious to know if their product, the Ypsomate autoinjector, and specifically its emissions caused by the raw materials used in the production of the device, could be reduced through mechanical or chemical recycling, and if through recycling they could make the materials of the autoinjector circular.

The product exists of many materials that have different disinfection needs and all have the ability to be mechanically recycled. Mechanical recycling of a single material stream is an established form of recycling, that has the best ability to reduce emissions, and has the preference of experts.
In contrast, chemical recycling of which the most desirable sub-process called depolymerisation, only has the ability to recycle three plastics that reside within the product. Therefore, chemical recycling cannot be used as the sole process to recycle the materials of the autoinjector.

From four scenarios that were presented to Alliance to Zero was confirmed that mechanical recycling of single material streams had the preference. In addition, the single material streams should be obtained through the disassembly of the product and the early separation of its components.

These conclusions were used to construct a value chain that further explained which routes materials had to follow in order to get them to a recycler.
Developing the value chain requires resources such as machinery and a physical space. However, due to the expected growth in production and therefore collection numbers of the autoinjector, some machines were suggested to switch towards a more industrialized process later on in the strategy.

In addition, the amount of value captured through this process was optimized by looking at the recyclability of the materials. During this exploration, the polymers PA and POM were defined as plastics that are difficult to recycle. As a result, based on polymer-specific properties, it was suggested that the PA component (5) could also be made with the polymer PBT, and the components made from POM (4, 7, 9, 10) with PC.

Additionally, the plastic supplier and recycler Sabic was highlighted as an important partner in both returning plastic components to be entered into mechanical recycling, and helping increase the use of mechanically recycled plastic in the production of new devices. As a result, a partially closed loop was obtained.

To aid in the realization of the value chain, a strategic and material specific roadmap and a sustainable business model that communicate the strategic and entrepreneurial decisions were provided.
Realizing the value chain resulted in 76,9 to 100 % of the autoinjectors materials being recycled and 39,03 to 51,17 % of its materials being circular.
Consequently, value was created through a decrease in emissions of 32,21 to 46,17 g CO_2 during the production of each autoinjector and the reuse of its valuable materials.

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1. LIST OF ABBREVIATIONS

CO2 eq.	Carbon dioxide equivalent
Downcycling	The recycling of a product or a material whereafter its value is lower than the original
Recycling	The collecting and processing of materials to turn them into new products
Reuse	To use a product or component again
EOL	End-of-life
EPR	Extended Producer Responsibilities
GHG	Green House Gasses
Mixed stream	A stream that exists of multiple components made from different materials
Mono stream	A stream that exists of multiple components made from the same material
PCR	Post Consumer Recyclate
Raw materials	Materials that are used within the primary production of goods
Supply chain	The process between producing and distributing the product
Value chain	Set of activities done by the company to increase competitive advantage

PA 60% GF	Polyamide with 60% Glass Fibres
PBT 30% GF	Polybutylene Terephthalate wit 30% Glass Fibres
PC	Polycarbonate
PC/10% ABS	Polycarbonate mixed with 10% Acrylonitrile Butadiene Styrene
PET	Polyethylene Terephthalate
PP	Polypropylene
POM	Polyoxymethylene

2. PRODUCT COMPONENTS

Throughout this thesis references will be made towards certain components displayed in the picture below (Figure 1).

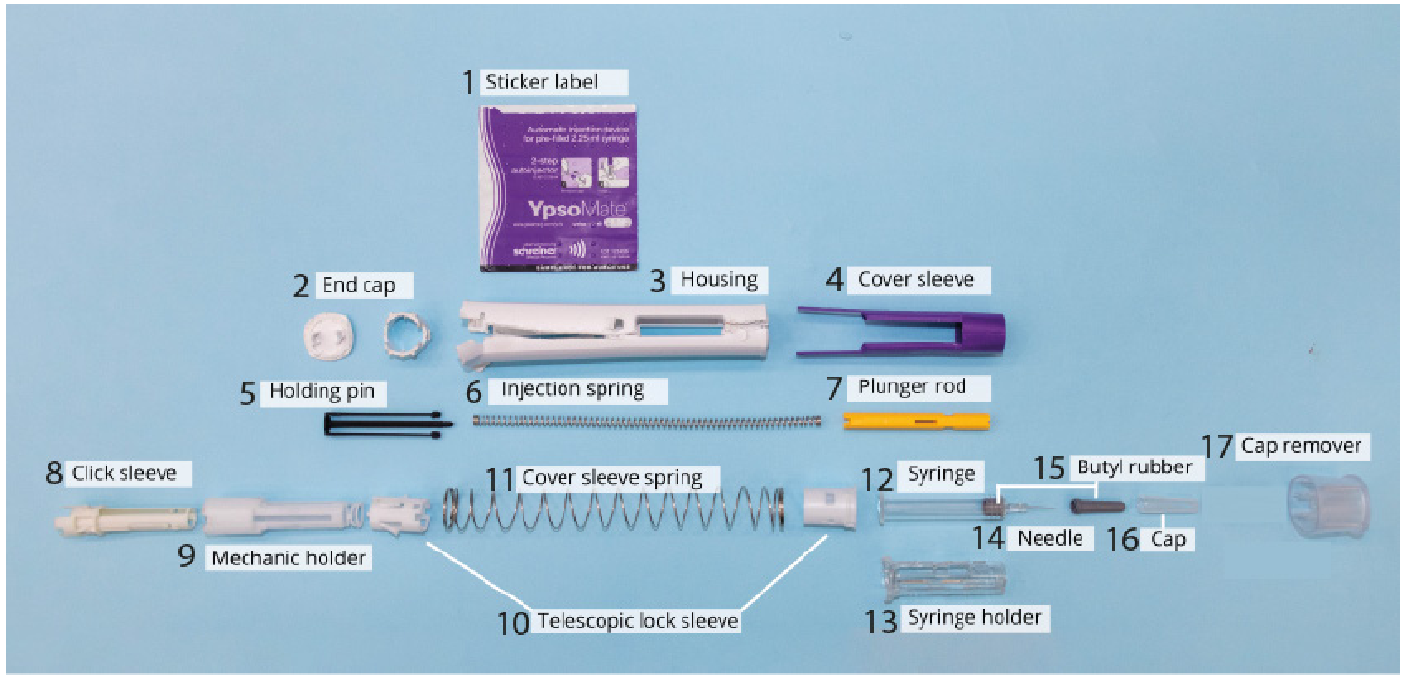


Figure 1
Exploded view of components in the Ypsomed autoinjector 2.25 ml

3. INTRODUCTION

In this thesis, the circular ability of an autoinjector is discussed. To increase the circular ability and reduce the environmental impact of this product through the recycling of its materials, more information and knowledge were needed. Therefore, this thesis aims to explore the circular potential of the materials in the autoinjector.

In the first part of this report, an introduction is given on why this thesis is relevant. Continuing with an exploration of the product, and the environment to which it belongs. Highlighting the necessity for it to become more circular and defining the disinfection needs of each component. The two types of recycling that could enable this increase in circularity are discussed, and some factors influencing the future of a more sustainable autoinjector are elaborated on.

Using these factors, a possible future vision for Alliance to Zero is described. Other insights obtained during the previous phase are highlighted and translated into scenarios that were discussed with Alliance to Zero. Their feedback was used to compose a value chain that could enable the reuse of valuable materials.

Continuing with a defined process, the resources that are needed to realize this value chain are elaborated on. Whereafter the recyclability of the product is further explored for all the materials. Suggestions are given on possible plastic replacements and future partnerships, aiming at increasing the recyclability and circularity of the autoinjector.

The last phase of this thesis is focused on combining and communicating these insights into a strategy and a business model that will aid Alliance to Zero in future decisions for the autoinjector. The strategy will exist of a material specific and strategic roadmap that includes links to chapters of this research. Lastly, a conclusion and a discussion are provided.

4. STRUCTURE

The structure of this thesis was inspired by the double diamond model (Figure 2). The double diamond method exists of four phases where a diverging and converging phase succeed each other twice. A linear process at first glance, however, it does require the researcher to iterate on earlier decisions and found information.

Discovering the environment

In this first phase, broad research is conducted. Discovering the assignment, the product, the recycling field, and what future developments will play a role.

Defining the value chain

Insights gathered in the previous phase are highlighted and used to construct multiple scenarios and a future vision. The drawn conclusions are thereafter used to define the process that can help capture material value.

Develop the value chain

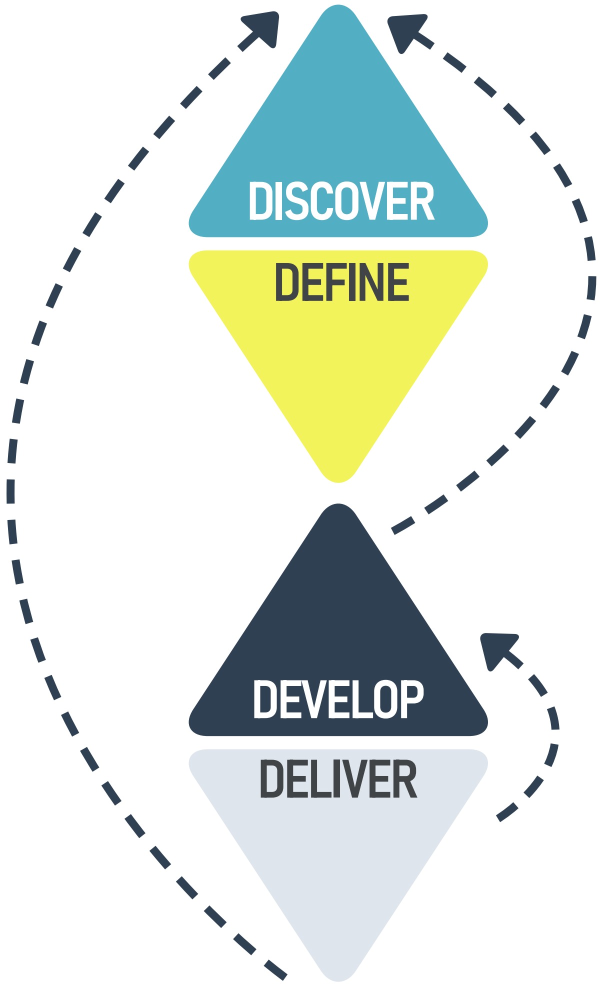
Developing the value chain requires resources such as machinery and a physical space where the machinery can be stationed.
Additionally, the value that can be created through this process should be explored and maximized to allow for circular potential to be obtained.

Deliver guidance towards a more sustainable future

In the last phase of the double diamond, all information gathered is translated into a strategy. Throughout the report, links will be made with decisions that are displayed in the roadmap and communicate the strategy. Moreover, to show the new business model in which Alliance to Zero will operate, the sustainable business model canvas is used and discussed.

Conclusion

In the last section, the conclusions needed to answer the research questions are discussed and evaluated. Whereafter a discussion is provided and options for further research are elaborated on.



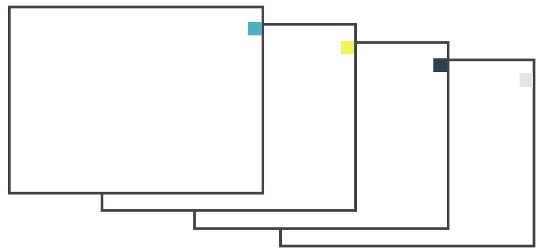


Figure 2
The Double Diamond method & reporting of phases

5.

DISCOVERING THE ENVIRONMENT

Project brief.

The pharmaceutical industry is responsible for 52 mega tons of CO_2 eq. (Belkhir & Elmeligi, 2019). The founders of Alliance to Zero saw that the need for reduction of this footprint is shared amongst key role players in this supply chain of pharmaceutical products.
Yet, change is not happening fast enough to effectively decrease the carbon footprint. Therefore, the founders recognised the need for these key role players including component suppliers, machine suppliers, assembly or manufacturing service providers, primary and secondary packaging to final device assembly and even collection after use, to collaborate and share responsibility (Alliance to Zero, 2021).

The autoinjector, a device that aids in self-administration of medication, is a product that belongs to this specific sector and emits 164 gr CO_2 eq per unit originating from raw materials used in its production (Appendix B). Most of these devices end up in landfill or are incinerated after a single use, causing the supply chain to be linear and therefore wasteful. In order to decrease the carbon footprint of the raw materials of the autoinjector, a more circular approach is needed. In other words, making use of the materials that are left after use instead of discarding them.

Each phase in the supply chain of the autoinjector is responsible for some emissions. However, during this thesis the focus will be on the emissions made in the first phase of the supply chain where raw materials are needed to manufacture the autoinjector (Figure 3).
Therefore this thesis will focus on the following research question:

Can we reduce the environmental impact of the autoinjector through increasing the circularity of the raw materials used in the product by recycling them?

Two sub-questions that will influence the answer of the main research question are:

What are the developments in mechanical and chemical recycling (which one is more sustainable). And which is best applicable to the plastics used in the autoinjector?

Open or closed loop? Which one is best applicable to the autoinjector considering the outcome of the first sub-question?

Translated to Roadmap
- Working towards a more circular future
- Value created through reduction of emissions

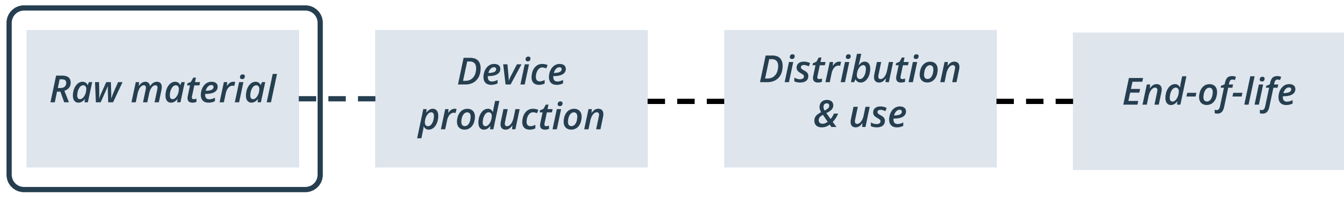


Figure 3
Current value chain of the autoinjector

The Ypsomate autoinjector.

The product

An autoinjector (Figure 4) (Ypsomate 1 ml) is a medical device that aids patients in safe self-administration of medication at home whereafter the product is usually discarded of. The device made its debut in the 1980s and is often used to treat conditions such as seizures, migraines, rheumatoid arthritis, diabetes, and other chronic diseases (Figure 5) (Simpson, 2020). In addition, a device such as this provides benefits for the patients such as safety, efficacy, and ease of use (Roy et al., 2021).

The market

This thesis will be focused on the European market. The European autoinjector market is driven by countries such as Germany, Italy, UK, France and Spain (Market Data Forecast, 2022). According to Roy et al. (2021), today there are about 80 different autoinjectors that have been developed by 20 pharmaceutical companies. As a result, 50 different drugs have been developed to be administered through these autoinjectors. The market is driven by factors such as the development of more enhanced technology, the growth of the biologics industry and the increase in the number of people with chronic diseases and allergies.
Therefore, researchers expect the autoinjector European market size to grow with a CAGR (Compounded Annual Growth Rate) of 16.32% within the period of 2022 to 2027. As a result, the current market of 0.83 billion USD is expected to reach 1.76 billion USD in the year 2027 (Market Data Forecast, 2022).

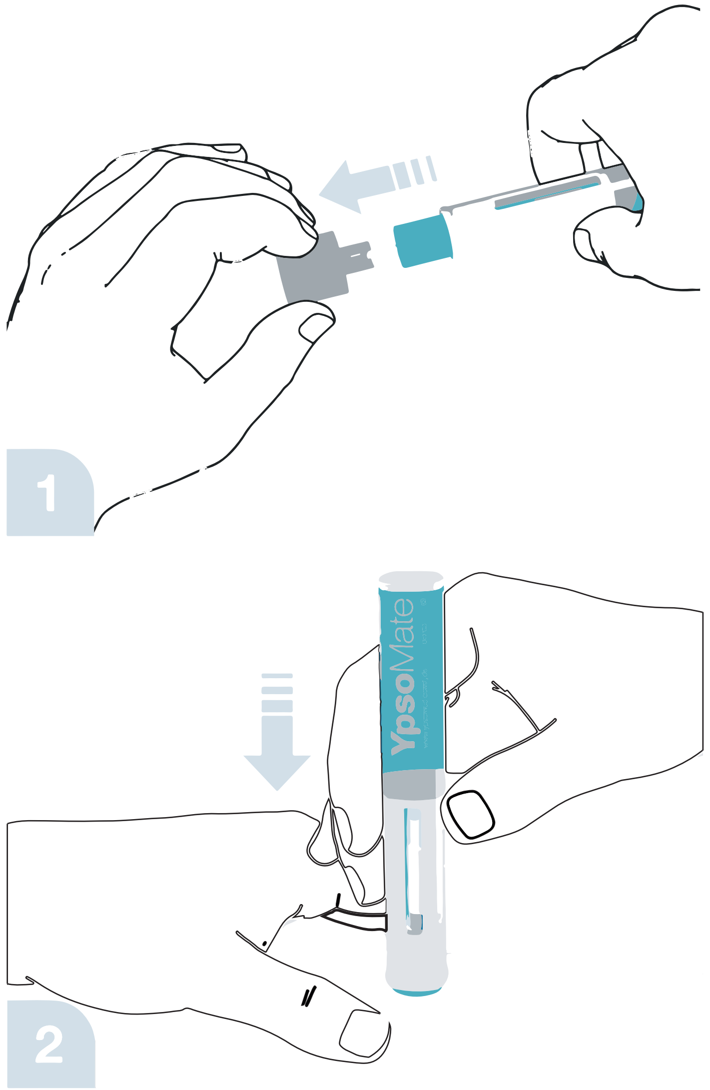


Figure 4
1: Removing the cap remover, 2: injection

5.2

According to Gerner from Ypsomed (Appendix G), Ypsomed has a market share estimated at 50%. In other words, Ypsomed produces about half of all the autoinjectors in the world. This year their production numbers amount to twenty million autoinjectors (1ml, 2.25 ml). In the year 2025, they expect to have increased its production up to a hundred million devices. Whereafter, in 2027 the latest expectation lies at a production volume of a XXX million autoinjectors with an equal division between the 1ml and 2.25 ml versions of the product (Table 1).

According to a market report done by Future Market Insights on Auto-Injectors Market (2022), the distribution channel that will benefit the most from this growth are online pharmacies. The easy availability, the low time intensity, and the possibility of discounts make this route is preferable to the consumer.

The competition

The members of Alliance to Zero are not the only ones who have noticed the need for change in the pharmaceutical supply chain (Phillips Medisize, 2021).
For example, Phillips with their new product, the Aria smart autoinjector. A semi-reusable autoinjector that was developed to tackle the emissions made in the pharmaceutical sector.
In addition, Novo Nordisk launched a recycling programme for pre-filled injection pens in the UK in 2022 (Taylor, 2019). They can recycle 85% of the materials, yet in order to do so the pens need to be returned to their facility in Denmark through the same boat that delivers them to the UK.
Some companies also try to lower their carbon emissions by investing in renewable energy or buying carbon offsets. However, according to the blog post by Phillips Medisize (2021) one might argue this to be ‘green washing’.

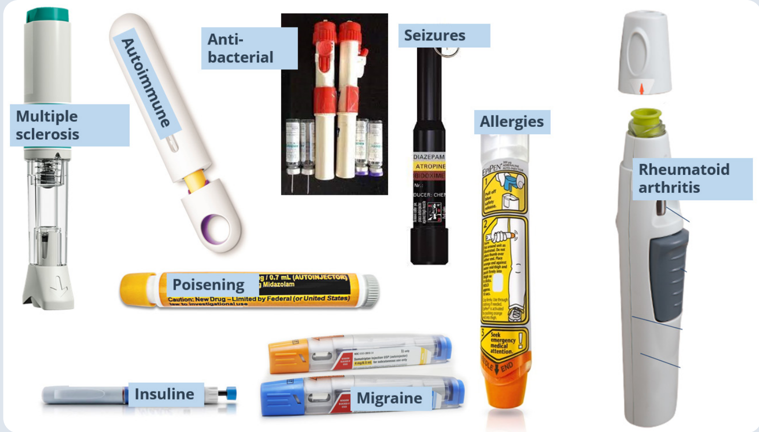


Figure 5
Self-injectables on the market

Ypsomed expected production

2023	20 million
2025	100 million
2027	500 million

Table 1
Expected production numbers Ypsomed

The materials

Comparing the autoinjector to a simple syringe, one of the bigger differences is the number of different materials that are used to perform the same act (Figure 6). These additional materials are needed to provide extra user safety and ease of use however, they also increase the amount of waste with each injection (Phillips Medisize, 2021).

The injection device exists of plastics, rubber, glass and metals. Most of the plastics, which represent 70% of all the materials in the product, are engineering plastics which are often used for their heat resistance, chemical resistance, impact, flame retardance and mechanical strength (Figure 7) (Yildizhan, 2021). This type of plastic is considered more effective than commodity plastics which are cheaper and are produced on a bigger scale. However, the mechanical properties of commodity plastics are also weaker compared to those of engineering plastics. Therefore, engineering plastics are considered ideal for products that need engineering to design.

Table 2 describes which specific materials exist in the autoinjector. They are listed from the material with the most weight to the least and are accompanied by the emissions that belong to their production from raw materials.
Therefore, it is easy to see that the plastics PC/ABS and POM contribute most to the product and together represent almost half of its weight. However, if the ranking of table 2 were done according to the CO2 emissions, the stainless steel springs would come second to the PC/ABS components instead of POM.
Also, the medical syringe, a component that scores third when it comes to weight, yet if ranked on emissions it would come second last. In other words, a very present component but limited in value.

Figure 6
Ypsomate autoinjector (left) and ordinary syringe (right)

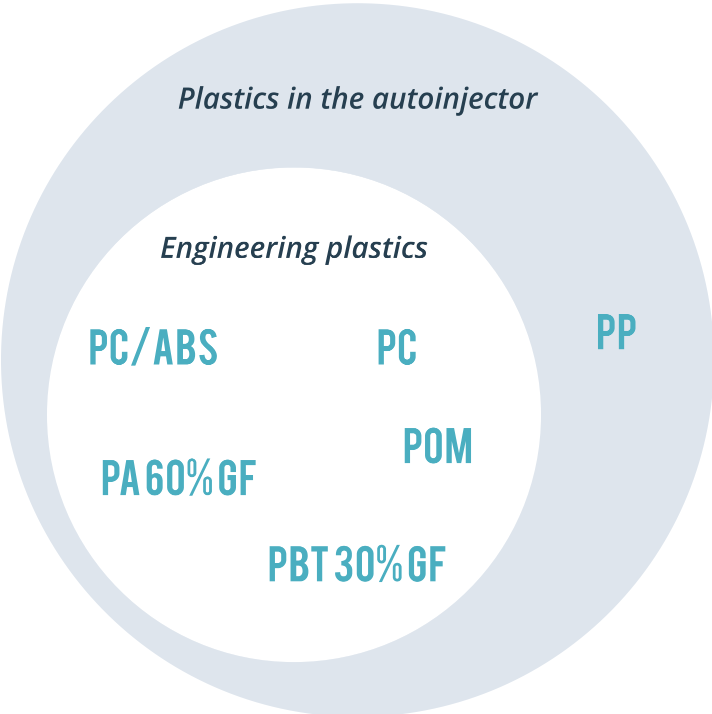


Figure 7
Plastics within the autoinjector

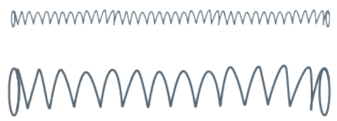
Material	Component	Weight (gr.)	%	g CO2 eq.
PC / ABS 10%		11,87	28,6	66
POM		8,27	20	24
Medical syringe		8	19,3	3,3
Stainless Steel		4,88	11,7	27
PC		4,49	10,8	21
PA 60% GF		1,3	3,1	6
PBT 30% GF		1,26	3	6
PP		0,876	2,1	3
Rubber		0,6	1,3	7
PP laminated paper		0,01	0,1	1
		41,55	100%	164,3

Table 2
Component material overview

The granulate

Until now at the end of its life, the product is shredded as a whole. This results in a stream of cut-up little pieces of ten different materials, also called a mixed stream (Figure 8.5). As opposed to a single or mono stream, where the stream only exists of a single type of material. The mixed granulate is sterilized and sent to the incinerator.

Noticeable from this mixture is that often the sticker label remains attached to different components (Figure 8.1). This could possibly complicate the sorting process.
Furthermore, some parts of the housing are compressed together with parts of the components that reside inside the housing (Figure 8.2). They are mended together in such a way that it is hard to imagine that they can be separated through a separation process.
In contrast, the rubber components and the end cap are easy to detect and are never attached to another component (Figure 8.3, 8.4).
And lastly, the shredded material does not only exist of big pieces of components but also very fine material (Figure 8.6). A lot of fine glass exists in the mixture, which will complicate the separation process of glass and increases the chances of a contaminated stream. A stream that exists of a single material yet also unintendedly contains small pieces of a different material.

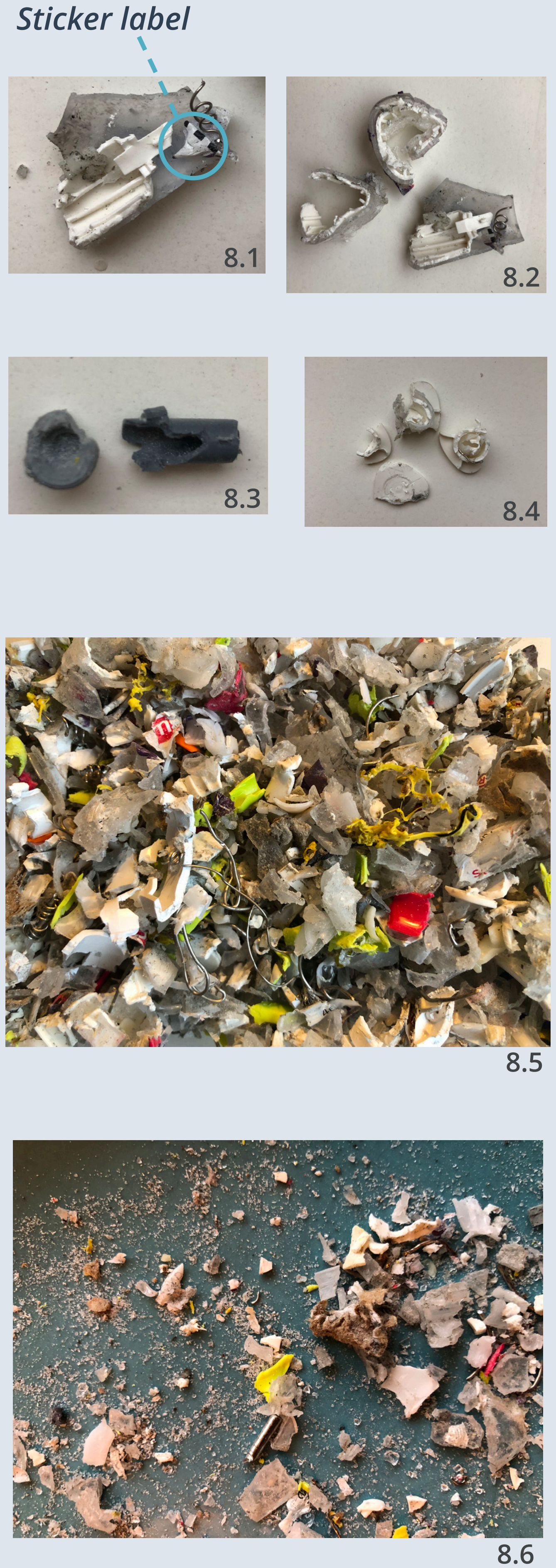


Figure 8
Granules after shredding of autoinjectors

The circular economy.

A model that combines a business model and the creation of value within a product's lifespan is the Value Hill (Figure 9). The model is designed to aid businesses in putting their strategy and value chain in a circular context and encourages them to have more control over their resources (Inchainge, 2022).

The hill is divided into three phases, pre-use, use, and post-use. The value of a product is at its highest after purchase in its use phase. However, with the decrease of the product its usability, its position on the hill will lower. Yet, the value of the product can be retained through a circular strategy.
A circular strategy that is based on this model strives to maintain product value in the post-use phase by remaining high on the value hill. In other words, the strategy that retains the most value within this model is reuse and redistribute. The last step on the hill is recycling, the last process that can close the loop and ensure that the post-use materials will be used to produce new products.

Currently, none of the circular strategies are used on the autoinjector and its process remains linear.
However, during this thesis, the potential of the recycling strategy of the circular economy will be explored and a conclusion on how much material value can be retained through this strategy is given.

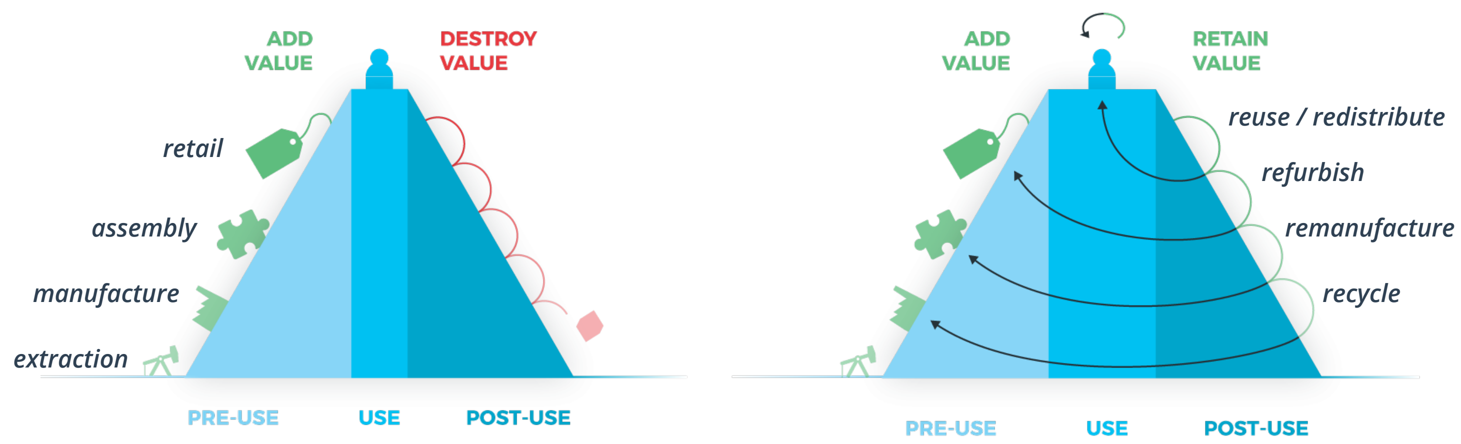


Figure 9
The Value Hill

Collection

The first important step that aids in increasing the circularity of the autoinjector, is the collection of the product (Safe Returns, n.d.). Janssen, a Belgium pharmaceutical company has developed a service where used prefilled syringes can be safely returned by post. This way, an easy and safe way to reduce the amount of medical waste and its CO_2 emissions can be realized.

In a webinar on medical waste by Geysel (2022), an employee of Janssen highlights that this process has already been realised in the United States and Switzerland, and they plan on including six more European Countries. In addition, he elaborates on an important quality of this process namely, ensuring that they only get their product returned. As a result, assurance is given that only the materials used in their products and production processes are collected, decreasing the chances of contamination through sort-like materials but from a different manufacturer to end up in the mono-material stream.

Another initiative that has realised the collection of autoinjectors today is by HealthBeacon (Appendix V). HealthBeacon is a start-up located in both Ireland and the United States. They design devices that are part of a product service system that enables the safe return of autoinjectors (Joyce, 2021). Furthermore, it aids the patient to take their medication on schedule.
HealthBeacon is also a company that is a part of Alliance to Zero. In a conversation with HealthBeacon, a range of 15-25% was given that should be considered when wanting to know how many devices they expect to have returned in the following years (Table 3).

Translated to Roadmap
- Production volumes
- Take-back volumes
- Implementation of collection routes

Year	Ypsomed production	Take-back range 15 - 25%
2023	20 million	3 - 5 million
2025	100 million	15 - 25 million
2027	500 million	75 - 125 million

Table 3
Number of returned autoinjectors

Sterilization.

The autoinjector is a medical product, therefore, before sending the materials towards a recycling facility the materials should be sterilized.
Most medical devices must be sterilized, due to their contact with either sterile tissue or mucous membranes. The patient that comes in contact with the medical product might carry microbes that could lead to the infection of others through touch.
Therefore, if a post-use medical product is not properly sterilised, it may lead to the contamination of another person (Rutala & Weber, 2013).

Components of medical devices or products can be divided into three groups, namely, critical, semi-critical, and non-critical items (Table 4).

Critical items are items that enter sterile tissue or the vascular system and are therefore at high risk of contamination. Critical labelled components usually need the highest level of disinfection, namely sterilization.

Semi-critical items are items that come into contact with the mucous membranes of the body or nonintact skin. These components should eventually be free of all microorganisms and should therefore require high-level disinfection.

And lastly, non-critical items. These items make contact with the outer skin and should only be decontaminated. They are labelled non-critical because according to Rutala and Weber (2013), human skin acts as a barrier to microorganisms and therefore the sterility of the item touching the human skin is not important.

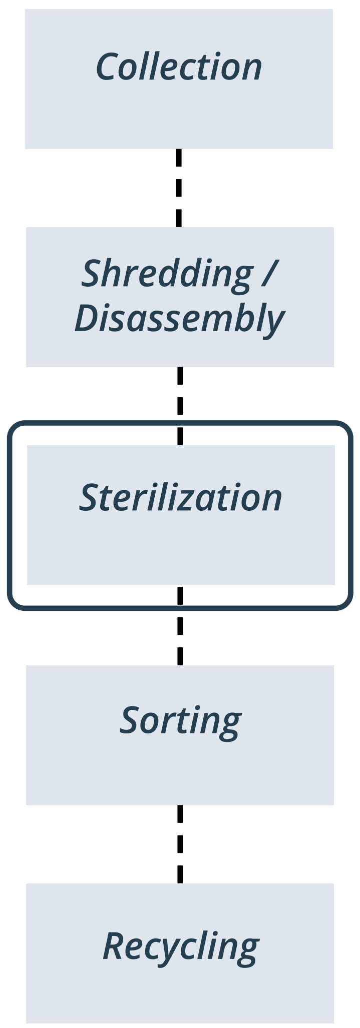


Figure 10
Place of sterilization in the value chain

Critical	*Sterilization*
Semi-critical	*High level of disinfection*
Non-critical	*Low level of disinfection*
No disinfection needed	-

Table 4
Disinfection classification

Considering this classification, figure 11 shows what effect this would have on the Ypsomate components. The parts that have been listed as critical and therefore in need of sterilization, are the syringe that carries the medicine, and the needle that enters the human body.

Both the plunger and the cover sleeve have been highlighted as semi-critical. This is due to the possible contact of the plunger with the medicine when it is pushing the substance out of the syringe. In addition, the cover sleeve might touch intact human skin when put onto a limb when using the product. Whereafter, there are the non-critical items, these are the components that represent the outer layer of the product and are therefore touched by the user with their hands. Meaning that intact skin could have possibly been in contact with these components.

And lastly, the components that remain inside the product during use and that do not come in contact with the medicine in the syringe. These components are not in need of disinfection according to the ranking of Rutala & Weber (2013).

Currently, the product as a whole enters an autoclave that first shreds the product into granulate and thereafter the granules are sterilized through steam sterilization. Meaning that if this type of sterilization is used on the whole product, granules need to be separated from each other before being sent to a recycling company. However, figure 8.5 displays what this mixture looks like at the end of the sterilization process and discussed which aspects of the granulate might hamper the sorting process.

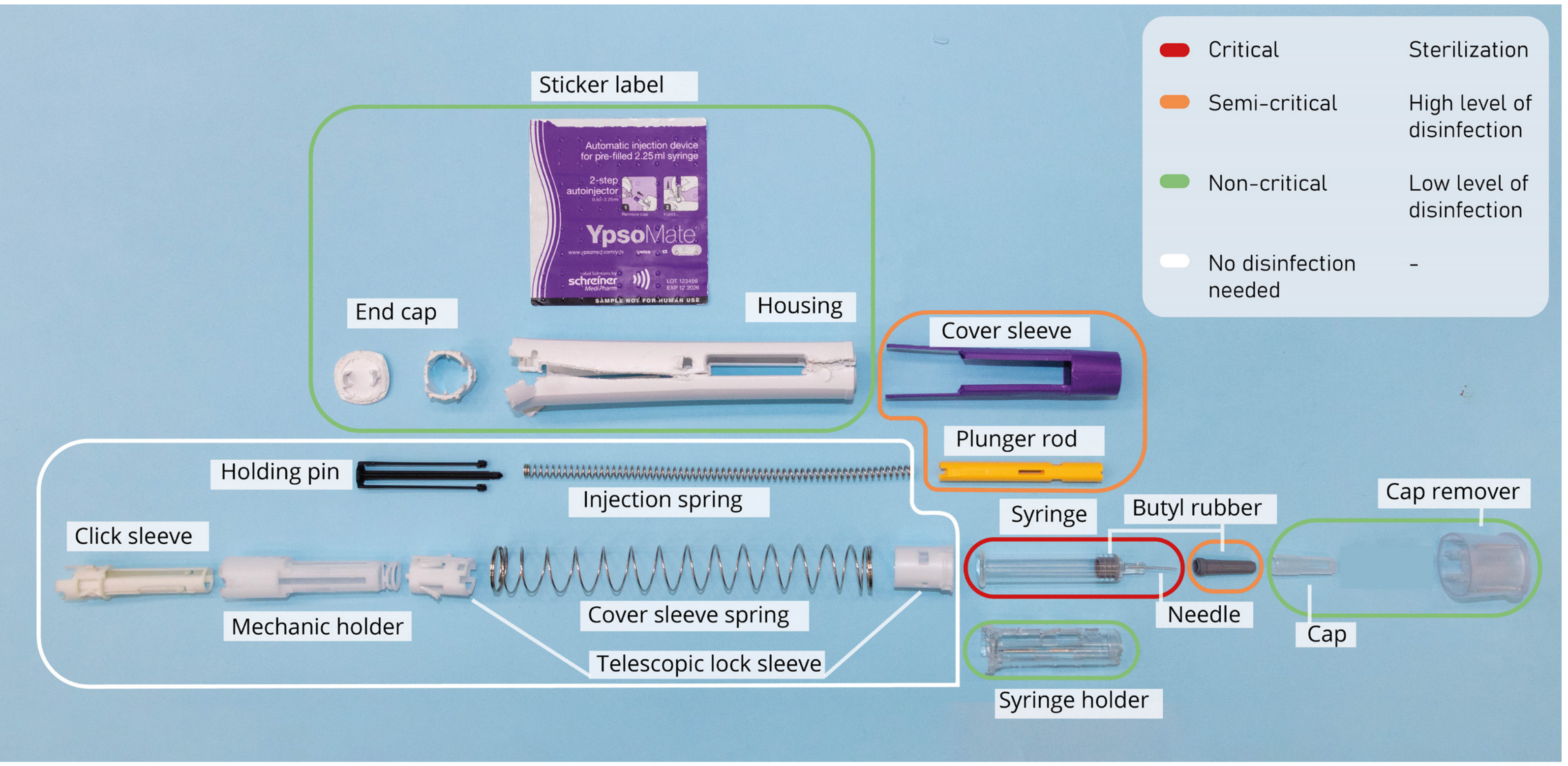


Figure 11
Component disinfection overview

Additionally, using the classifications of Rutala & Weber (2013), it can be concluded that only the syringe and the needle are in need of this type of sterilization and should enter this process. In other words, the components that are in need of sterilization should be removed from the product and treated in the autoclave whereafter the glass and metal are sorted and ready for recycling. This avoids having to separate a more complicated mixture existing of all the materials in the product.
Important to highlight is that due to safety reasons human touch of the needle and glass parts should be avoided both before and after the autoclave.
Subsequently, a calculation of the weight that these two components will represent in the coming years can be made, using the earlier discussed production numbers and collection correction (Table 5).

Production period	Amount of waste per year (kg/year)	Amount of waste per day (kg/day)
2023 - 2025	2.400 - 40.000	10 - 15
2025 - 2027	120.000 - 200.000	460 - 770
2027 - 2030	600.000 - 1 million	2.310 - 3.850

* amount of waste calculated with a take-back range of 15-25%
*assumption was made that there are 260 working days in a year (waste per year / 260 = waste per day

Table 5
Expected waste from medicinal syringe

Recycling.

Recycling enables the reuse of the raw materials in the production process (Devasahayam et al., 2019). Through this process, manufacturers can save on resources and emissions and save the materials from ending up in landfill or the incinerator. It represents the last option on the Value hill that enables circularity (Inchainge, 2022).
According to Plastic Recyclers Europe (2019), recycling of plastic parts reduces the environmental footprint. Additionally, it is an important element of the waste hierarchy and a crucial process that answers to an ever-growing market and demand of new plastics. During this research, two types of recycling will be discussed namely, (1) mechanical recycling displayed in blue, and (2) chemical recycling displayed in yellow (Figure, 12).

Mechanical recycling

Mechanical recycling is currently the most common type of recycling (Davidson et al., 2021). During mechanical recycling materials are collected, sorted, washed and grinded, eventually with granulate as an end product (Figure 13) (Ragaert et al., 2017). This form of recycling requires a well sorted and cleaned waste stream, ensuring the best environmental benefits (Devasahayam, 2019).

However, the downside of this process is that often the plastics degrade under the action of recycling, causing the plastics to not be infinitely recyclable (Ragaert et al., 2017). According to Folkersma and Jager (Appendix F), depending on the plastic, the maximum recycle cycles a plastic can withstand lie between four to five cycles.
Yet, the properties lost during the recycling process can be recovered by mixing the plastic recyclate with virgin plastic (Cestari, 2021). In other words, the polymer

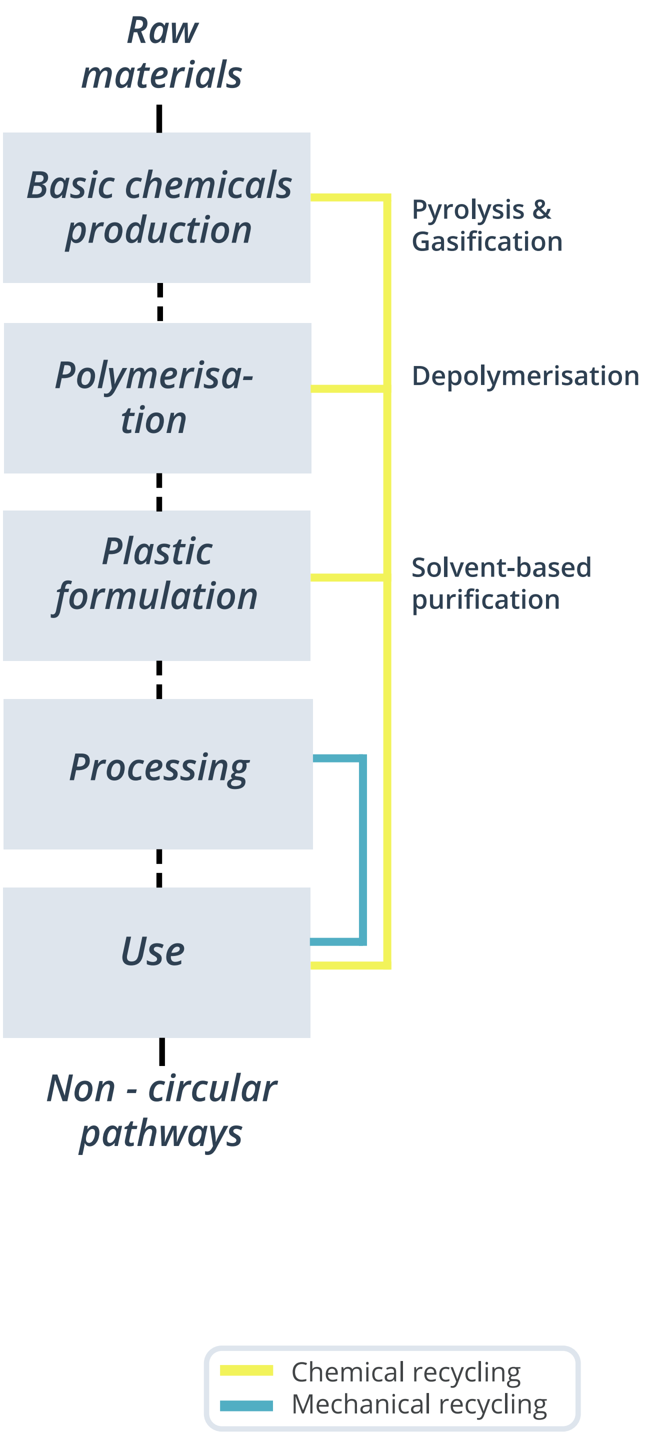


Figure 12
Plastic production process and recycling methods

compound would then exist of for example 30% recycled plastic and 70% virgin plastic. Because even though most polymers are 100% recyclable, due to the degradation of the plastic that takes place during the recycling process, a polymer compound existing of a 100% recyclate is not desired.

Mechanical recycling can be done with both a mixed stream of plastics or a stream of just one plastic, also called mono stream (Ragaert et al., 2019). However, the mixing of multiple different plastics results in lower quality of mechanically recycled polymers, also called downcycling (Crippa et al., 2019; Davidson et al., 2021). In addition, in an interview with Folkersma & Jager (Appendix F), Folkersma confirms this distinction by mentioning that recycling mechanically with one plastic (as opposed to with a mix of plastics) is the ideal situation.
As a result, the properties of the plastic are preserved, whereas with a mixture of plastics (and therefore mixed properties) causes degradation of the plastic.

According to Broeren et al. (2022), the quality of the recycled plastic is determined by the impurities that it contains and whether these are removed or not. If these impurities are taken along in the mechanical recycling process degradation of the material will take place.

Yet, according to Crippa et al. (2019), it is the increase in the amount of different plastics that creates a complex landscape to work in. This results in challenges for collection, sorting and recycling of used plastics, as can be seen in the autoinjector. Plastics are mixed with different percentages of glass fibres or a different plastic. This increases the number of plastics that can be used and the sorting steps that need to be taken.

However, if a product were to be shredded in its entirety, meaning that multiple autoinjectors would be thrown into a machine that cuts them into tiny pieces, the residue would be small parts of different materials as shown in figure 8.5. The sorting of such a mixed stream of materials is more difficult and complex (Ragaert et al. 2017).
Due to the mixing of different materials, including plastics and their possible impurities it is hard to tell the one material from the other. In order to treat such mixed streams, improvement on sorting techniques are needed first (Jager & Folkersma Appendix F).
Therefore, a well sorted and cleaned waste stream with as few materials as possible is most desired.

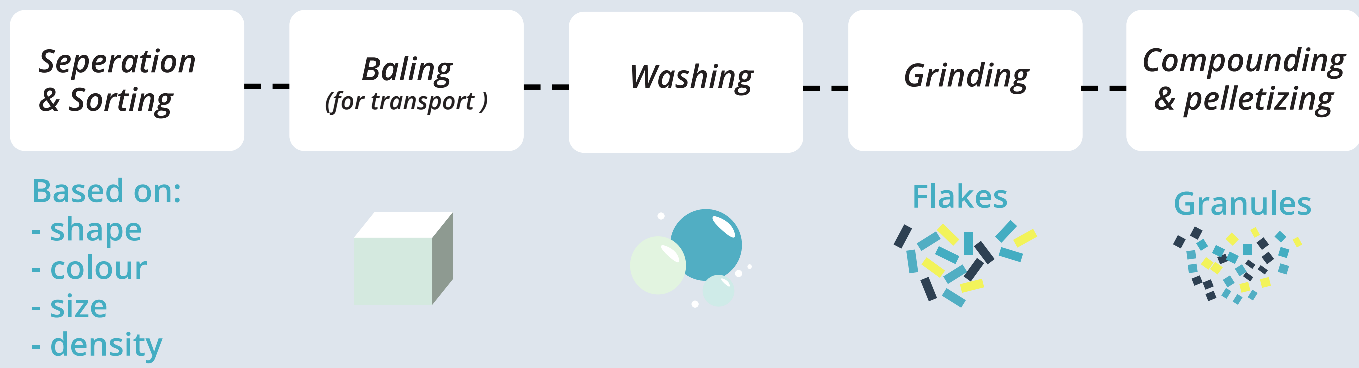


Figure 13
Mechanical recyling process

Chemical recycling

In an interview with Balkendende (Appendix D), chemical recycling is described as the least used method for recycling and is often only carried out in pilot form. This method of recycling is built around the idea of bringing the polymer back to its monomer or feedstock form (Ragaert et al., 2017; Joseph et al., 2021; Davidson et al., 2021).

The opinions about how good of a solution this form of recycling is, are divided. According to research from the American climate organisation GAIA (2020), chemical recycling releases toxic chemicals into the environment, has a large footprint and does not fit in a circular economy. In addition, as mentioned earlier, the method is still in its developing phase and is not yet energy efficient (Crippa et al., 2019).
However, Geert Bergsma from the research facility CE Delft argues during an interview that there are different types of chemical recycling (Appendix E). Chemical recycling is an umbrella term for a number of methods (Broeren et al., 2022), of which four will be discussed in this research, namely solvent-based purification, depolymerisation, pyrolysis, and gasification (Figure 14).

Solvent-based purification is a method that produces near-virgin-grade polymers (Crippa et al., 2019). The method enables the removal of additives or contaminants in the polymer, meanwhile, the structure of the polymer remains intact and can be remade into plastics.

Depolymerisation is a method that is used to bring polymers back to their monomer form. During this process, polymer chemistry is used to break the polymer bonds into monomers, the original building blocks of a polymer. As a result, these depolymerized monomers, sometimes blended with virgin monomers, can be used to produce new polymers (Crippa et al., 2019; Davidson et al., 2021).

Pyrolysis is the method that is used when it is desired to return the polymer back to its feedstock form. It is commonly used with plastic packaging waste that is difficult to mechanically recycle or chemically depolymerize (e.g. PET). During this process, in the absence of oxygen, the polymers are heated to temperatures of 500 degrees and higher in order to break the polymer bonds and create solid, liquid and gaseous hydrocarbon products (Davidson et al., 2021; Ragaert et al., 2017).

Gasification is a process which through controlled steam is able to produce syngas, a gaseous mixture of hydrogen and carbon monoxide. This process requires temperatures of 1000 – 1500 degrees, and a limited presence of oxygen (Crippa et al., 2019; Davidson et al., 2021).

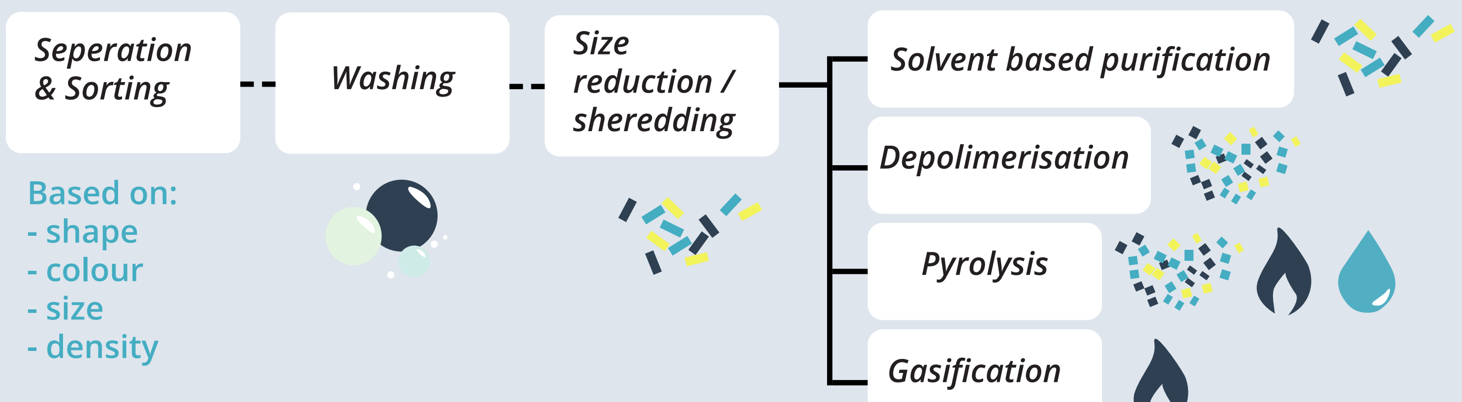


Figure 14
Chemical recycling process

When deciding between the four chemical recycling processes, certain properties that distinguish the different processes mentioned earlier, could play a role in the decision-making process. A summary of relevant properties can be found in table 6, where the four different chemical recycling processes are compared against mechanical recycling.

Waste stream

Generally, recycling can be done with a mixed or mono stream of material. Chemical recycling is often advocated as a recycling method with the ability to treat mixed material streams without downcycling the material. However, this process property is actually only true for pyrolysis and gasification (Broeren et al., 2022). As a result, if one were to choose solvent-based purification or depolymerisation, materials should be separated first.

Plastic-to-plastic yield

Another property that should be highlighted is the 'plastic-to-plastic yield'. This yield is determined by how much plastic is conserved from the beginning to the end of the recycling process. In other words, the amount of plastic that leaves the recycling process is often lower compared to how much plastic has entered the process, this ratio is described with the 'plastic-to-plastic yield'. The percentages corresponding with this yield describe the amount of new plastic that can be produced from the plastics that have entered the process (Broeren et al., 2022).
In a research done by Broeren et al. (2022), it is argued that not every method of chemical recycling conserves the same amount of plastic during the process. A clear distinction between the methods can be seen. Whereas the upper two processes (solvolysis & depolymerisation) present yields close to a hundred, and the latter two (pyrolysis & gasification) score less than fifty percent. In other words, one could argue that more material is lost during the latter two processes and that therefore solvent-based purification and depolymerisation are preferred.

Recycling process	Waste stream *(Broeren et al., 2022)*	End product *(Crippa et al., 2019)*	Value of end product (euro) *(Li et al., 2022)*	Plastic-to-plastic Yield *(Broeren et al., 2022)*	Polymers	Toxins *(Ragaert et al., 2017; Gaia, 2020)*	CO2 eq. reduction compared to incineration (kg CO2 eq. / kg plastic waste) *(Broeren et al., 2022)*
Mechanical	mono & mixed	Plastic compounds	600 - 2000 / ton	89 - 100 %	Addition & condensation		2 - 3,5
Chemical							
Solvent-based purification	mono	Polymers	1380 - 2800 / ton	100 %	Condensation		3
Depolymerisation	mono	Monomers	1380 - 2800 / ton	97 %	Condensation		3
Pyrolysis	mono & mixed	Hydrocarbons & petrochemicals	1380 - 2800 / ton	49 %	Addition & condensation	HCN, CO, CO2	1,5
Gasification	mono & mixed	Hydrocarbons & petrochemicals	150 - 450 / ton	34 %	Addition & condensation	NOx, CO, CO2	1 - 1,5

Table 6
Recycling method specific properties

Polymer type

Another difference that can define which chemical process is useful or not is the type of polymer which each process is able to treat. In an interview conducted with Folkersma & Jager (Appendix F), Folkersma clearly describes the differences between addition and condensation polymers.
Addition polymers are polymers that are harder to break, and in order to break them into monomers, high temperatures are required. They require an environment of 600 to 700 degrees, and therefore a lot of energy.
Condensation polymers are easier to break and are therefore less energy intensive to break into monomers.
Three materials used within the autoinjectors belong to the addition polymer group namely, polypropylene (PP), acrylonitrile-butadiene styrene (ABS), and rubber. Meaning that if they were to be chemically recycled they could fit into either pyrolysis or gasification.

Toxics

As mentioned earlier in this chapter it is argued that chemical recycling releases toxic chemicals and is therefore not environmentally friendly. However in table 6 one can see that this only includes pyrolysis and gasification. These methods produce products that contain toxics such as carbon monoxide (CO) and hydrogen cyanide (HCN) (Ragaert et al., 2017). This property makes pyrolysis and gasification less desirable compared to the other processes.

Ability to reduce emissions

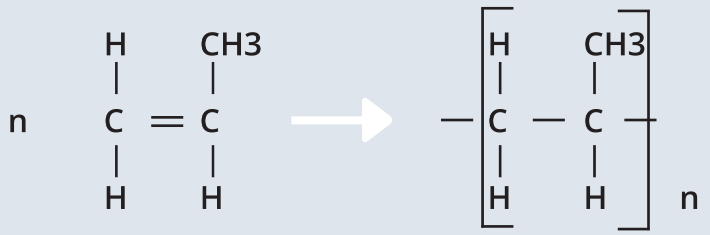
The last property in table 6 displays the ability of each process to emit less CO_2 compared to the emissions that are made when they are incinerated. According to Broeren et al. (2022), when it comes to decreasing the carbon footprint, mechanical recycling remains the most desirable process. This technology is then followed by solvent-based purification and depolymerisation. And finally, pyrolysis and gasification with the lowest ability to reduce the carbon footprint compared to incineration.

Using these properties the conclusion can be drawn that depolymerisation is the most favourable chemical process to use in the case of the autoinjector.

Chemistry

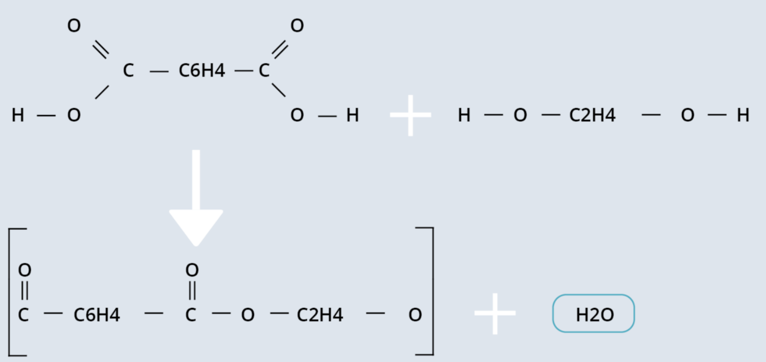
Addition polymerisation

The monomer of an addition polymer has a double bond between its two carbon molecules. During polymerisation of this monomer, the double bond opens up and enables the link with another monomer. No additional molecules or by products are needed during this polymerisation.



Condensation polymerisation

During the polymerisation reaction of a condensation polymer a by product is made. This is done through the linking of two different monomers. This by product could for example be H2O, also known as water.



Expert interviews

In order to get different perspectives on both mechanical and chemical recycling, five people with knowledge of recycling were interviewed (Appendix D, E, F, K, L). The people interviewed ranged from employees of a recycling company, research experts, and professors at different institutions. The aim of these conversations was to get their perspective on both recycling methods. Which method would they generally prefer, and which possibilities are there for the materials of the autoinjector after its use?

Interesting to see was that many of the interviewed agreed that mechanical recycling is the preferred method if the material would allow it.

"Mechanical recycling first if possible"
– Bergsma G.

"I expect that the plastics that can be recycled mechanically right now, will never go into chemical recycling"
- Employee Morssinkhof recycling

"Mechanical recycling is always preferred, economically and in terms of energy intensity"
- Jager & Folkersma

However, according to Balkenende, it depends on what one wishes to do with the material after recycling.
Recycling entails that the material keeps a certain value, with mechanical recycling this value is partially lost, meanwhile with chemical recycling this value is kept depending on which process is used. He highlighted that a distinction should be made between the different processes that reside under the method of chemical recycling, and only depolymerisation has the ability to retain the value of the material. A process distinction on which Jager and Folkersma agreed on:

"Well see I think you have to make a distinction in pyrolysis, of that I know people think critically."
– Jager & Folkersma

Moreover, they elaborated on the types of plastics within the autoinjector that could possibly enter the chemical depolymerisation process.

"PC is possible, PBT and PA as well."
– Balkenende

"Under high pressure and high temperatures one could depolymerise polycarbonate (PC). But it should be a pure stream."
– Jager & Folkersma

Additionally, value is only seen in the post-use materials of this product when they are separated from each other.

"Actually, you can only recycle these things (the components) properly if you can separate them at a very early stage."
- Bergsma

"But if you have parts that are a single material which can be composites such as PBT with glass, then it is advantageous to be able to separate them already at the component level."
– Bergsma

"But it does depend on how polluted your stream is, because if you are going to recycle mechanically, you need to wash and sort properly."
- Folkersma & Jager

In conclusion, if a material stream can be recycled mechanically, this process will remain preferred to chemical recycling. Even if a distinction is made between the different processes of chemical recycling, more specifically depolymerisation which is effective with three plastics from the autoinjector, mechanical recycling remains favoured. However, mechanical recycling will only be valuable if single material streams can be obtained, preferably before the shredding of the product.

Subconclusion

To conclude, looking at both the literature and the opinions of experts it can be concluded that mechanical recycling with a single material stream remains the most desired method.

Mechanical recycling is currently the most common and universally executed method that can reduce emissions. Only if a material is not able to be recycled mechanically one should look further to chemical recycling. Additionally, research indicates that chemical depolymerisation, the preferred chemical process, is often used with commodity plastics (Table 7). In fact, according to experts, chemical depolymerisation is only able to treat three of the autoinjectors' plastics (PC, PBT, PA). As a result, chemical recycling cannot be used as a sole process to recycle the materials of the autoinjector.

To put this in perspective, a desirability scale is composed (Table 8). This scale shows that mechanical recycling with a single plastic remains the most desired form of recycling. Using this subconclusion, a table can be composed that summarizes important findings (Table 9).

Research paper	*Polymer(s) used in depolymerisation & solvent-based purification*
Ragaert er al., 2017	PET, PE
Davidson et al., 2021	PET
Gaia, 2020	PET, PLA, HDPE, LDPE, PS, PVS, PU
Crippa et al., 2019	PET, PE, PMMA, PS
Broeren et al., 2022	PET, PS

Table 7
Depolymerised polymers in research

Desirability of recycling processes

1. *Mechanical mono stream*
2. *Depolymerisation*
3. *Solvent-based purification*
4. *Mechanical mixed stream*
5. *Pyrolysis*
6. *Gasification*

Table 8
Desirability scale for recycling methods

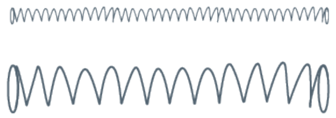
Material	Weight (gr.)	Weight %	g CO2 eq.	Mechanical / Chemical (* depolymeriastion)	Sterilization
PC / ABS 10% 	*11,87*	*28,6*	*66*	M	*Low Level Disinfection*
POM 	*8,27*	*20*	*24*	M	*High Level Disinfection (purple and yellow piece)*
Medical syringe	*8*	*19,3*	*3,3*	M	*Sterilization*
Stainless Steel 	*4,88*	*11,7*	*27*	M	-
PC 	*4,49*	*10,8*	*21*	M / C	*Low level disinfection*
PA 60% GF 	*1,3*	*3,1*	*6*	M / C	-
PBT 30% GF 	*1,26*	*3*	*6*	M / C	-
PP 	*0,876*	*2,1*	*3*	M	*Low level disinfection*
Rubber 	*0,6*	*1,3*	*7*	M	*High-level disinfection*
PP laminated paper 	*0,01*	*0,1*	*1*	M	*Low Level disinfection*
	41,55	*100%*	*164,3*		

Table 9
Ypsomate 1ml summary

Trends.

Knowing which developments are going to play a role in the future is important when creating a strategy. Therefore, a few trends in different areas that are expected to shape the future environment of the autoinjector have been described.

Self-injectables

According to a market size report on Injectable Drug Delivery (2022), the market of self-injectables is expected to grow. This growth is a partial response to the COVID-19 pandemic. Due to the overburdened hospitals and the risks of getting infected, there was an increase in interest in self-injection devices. This caused a transition of care from the hospitals to the patients at home (Roy, 2022).

Growing mechanical recycling market for engineering plastics

Besides packaging (39.9%) and building and construction materials (19.8%), engineering plastics represent the third most widely used material (EuRic, 2020). They represent about 16% of the total EU material demand. The use of these types of plastics has been growing (Plastic Recyclers Europe, 2019). These plastics are popular because they are light, more durable, provide safety, and have an environmental performance that scores better compared to other materials. However, the progress in the recycling of these plastics will rely on better collaboration and coordination of manufacturers, sorting centres, waste managers and recyclers.

Sustainable supply chain

According to a trend report done by Beale et al. (2020), investing in setting up the right infrastructure whilst you have the opportunity, could be favourable in the near future and win over customers. Ensuring resilience through the collaboration between innovative technologies such as AI and the Internet of Things. Additionally, for many companies the supply chain represents a large part of their environmental impact (Gatley, 2021). Benefits of a sustainable supply chain could be less costs, better continuity of supply, and future resilience. Building such a supply chain involves practices such as creating a circular supply chain and the engagement of suppliers.

EPR, Extended Producer Responsibility

A regulatory trend is the Extended Producer Responsibility, in short EPR. Extended Producer Responsibility is a framework that is designed to accelerate the transition towards a circular economy, and is included in the EU's circular economy and waste management policy (Dimitropoulos et al., 2021).
According to Bergsma et al. (2022), in order to reach the recycling targets set for the future, policies such as Extended Producer Responsibility are needed. Rules that for example ensure a mandatory percentage of recyclate being used in the production of new products. Introducing EPR in more sectors, especially those in the recycling chain, could ensure an increase in the recycling of plastics in Europe.

Translated to Roadmap
- Use 30% recyclate in the production of the autoinjector

AI for sorting

A technological trend is Artificial Intelligence driven sorting. According to Pahl (2020), machine learning and robotic sorting could solve the inefficiencies of material sorting. They have been found to work twice as fast as humans, and have the ability to reduce health risks of the employees. Furthermore, due to the use of cameras and technology they are able to identify various colours, shapes, textures and sizes, making it easier to sort the waste. As a result, the sorted streams of plastic are less contaminated and will lead to a higher quality plastic stream.
A company that is currently realizing this technology is AMP Robotics (2021). According to them, object recognition goes as far as hundreds of categories of papers, plastics, metals and other materials (personal communication, 18 dec. 2022).

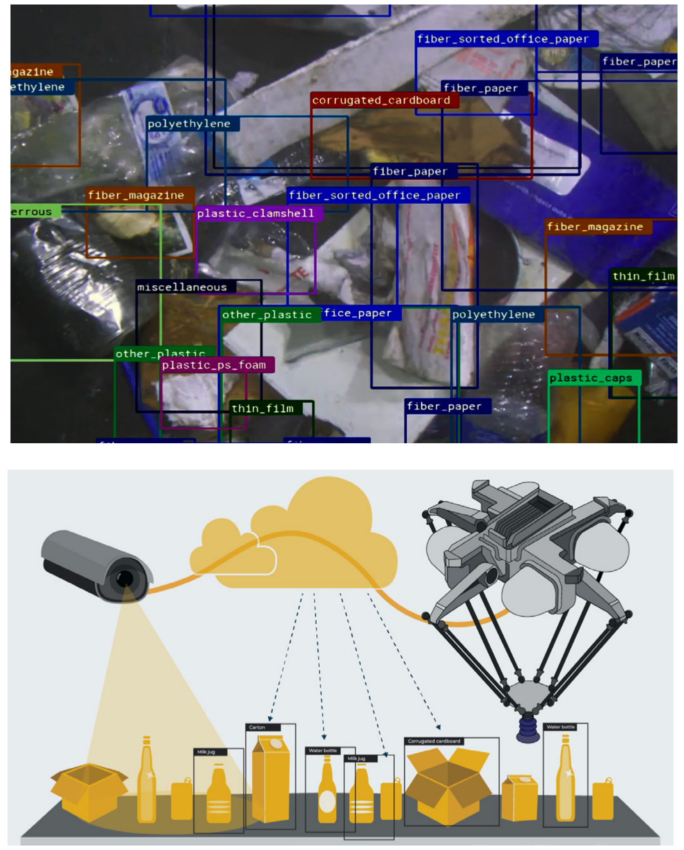


Figure 15
AMP Robotics (2021), AI driven sorting system

6.

DEFINING THE VALUE CHAIN

Future vision.

Based upon trends that have been discussed in the earlier paragraph, a future for Alliance to Zero can be sketched. The future vision functions as a destination, showing how the future of Alliance to Zero could be. To make this future more tangible, personality characteristics were distilled from the earlier described trends.

Firstly, an explorer, in order to reach the ability to be circular, tests should be performed continuously on materials, components, and processes. Furthermore, the field of ever-developing technological solutions will continue to grow, another reason why exploration is needed.

Secondly, an entrepreneur, reaching a net zero carbon footprint in the pharmaceutical supply chain cannot be realised alone. Valuable partnerships and connections are needed to create a cross-pollination of knowledge that sustains growth and innovation.

And lastly, a teacher, due to a combination of sharing knowledge and carrying responsibility.

In summary, Alliance to Zero, a laboratorial facility where the circular potential of pharmaceutical products is explored. Through valuable partnerships, Alliance to Zero has the ability to create circular medical materials and share knowledge in order to realize net zero pharmaceutical products.

Translated to Roadmap
- The future vision at the end of the roadmap

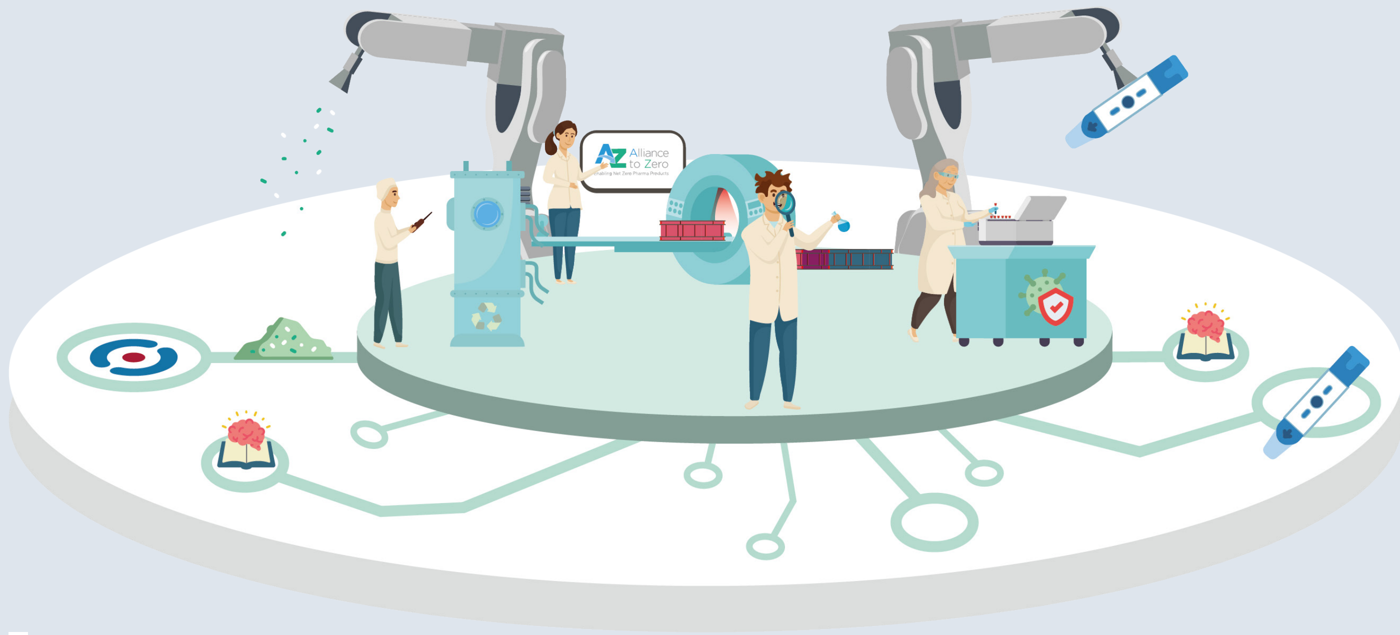


Figure 16
Future vision Alliance to Zero

Main insights. 6.2

Decreasing the emissions that come with the production of the autoinjector requires a more circular approach. In order to enable this approach collection of the device should be put into place.
Subsequently, an increase of circularity for the autoinjector can be realised through recycling. Recycling enables the reuse of raw materials in the production process and saves them from ending up in landfill or the incinerator (Devasahayam et al., 2019). There are two types of recycling namely mechanical and chemical recycling.

If the autoinjector were to be recycled, mechanical recycling of one single material would be most desirable. Mechanical recycling is currently the most common type of recycling and is the preferred process of experts in the area. It can be done with a mixed and mono stream of plastic. However, the mechanical recycling of a mixed stream is considered downcycling, and mechanical recycling of one single plastic is the most desirable. To obtain such a stream one can either shred the product as a whole and then separate, or disassemble the product into components and then sort. However, the sorting of a mix of different small plastics tends to be difficult, resulting in a preference for the disassembly of the product first.

Even though mechanical recycling is most desired, and chemical processes are not conducted with most plastics, chemical recycling could potentially be an option for some plastics, namely polycarbonate (PC). Depolymerisation is a type of chemical recycling that has the most promising process characteristics to be considered as a recycling method for the plastics inside the autoinjector. The process has a high yield, has the ability to reduce the amount of CO_2 compared to incineration, and produces no toxins. Yet, according to earlier findings in chapter 6.5, only three polymers have the ability to be recycled through this method and therefore chemical recycling cannot be used a sole process to recycle the post-use materials in the autoinjector.

Before recycling, some parts of the product should also be sterilized. The medicinal syringe and attached needle require this type of disinfection due to its contact with sterile tissue and human membranes. Sterilization is the highest order of disinfection methods, followed by high level, and low level disinfection. The other components of the autoinjector are either in need of low level, high level, or even no disinfection.

Translated to Roadmap
- Value horizon 1: creation of mono material streams

Scenarios. 6.3

Based on the information collected during chapter 5, four scenarios were created. There are two specific points in the process of recycling the autoinjector that will define the value chain.
First, the way the autoinjector is treated after collection, will it be shredded as a whole or will it be disassembled?
Second, will chemical recycling be included next to mechanical recycling?
As a result the scenarios are made using the following variables (Figure 17):

1. Shredding, or disassembly
2. Mechanical, or mechanical and chemical recycling

Both variables influence the circular ability of the process, and together four scenarios are created. The scenarios were discussed with employees of Alliance to Zero in order to obtain concrete feedback on the possibility of the described situations.
The detailed scenarios can be found in appendix O.

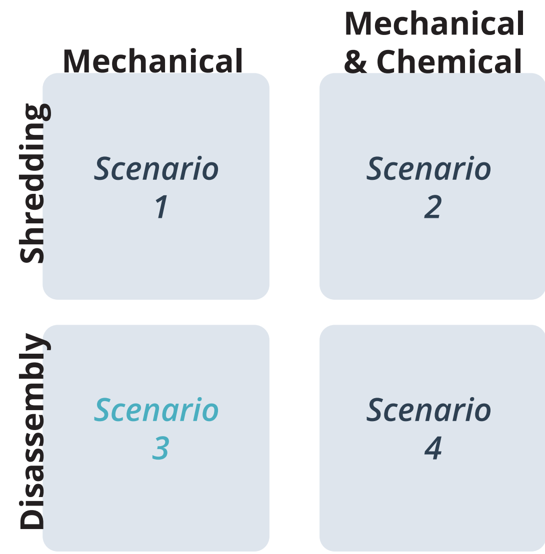


Figure 17
Scenario creation 2x2

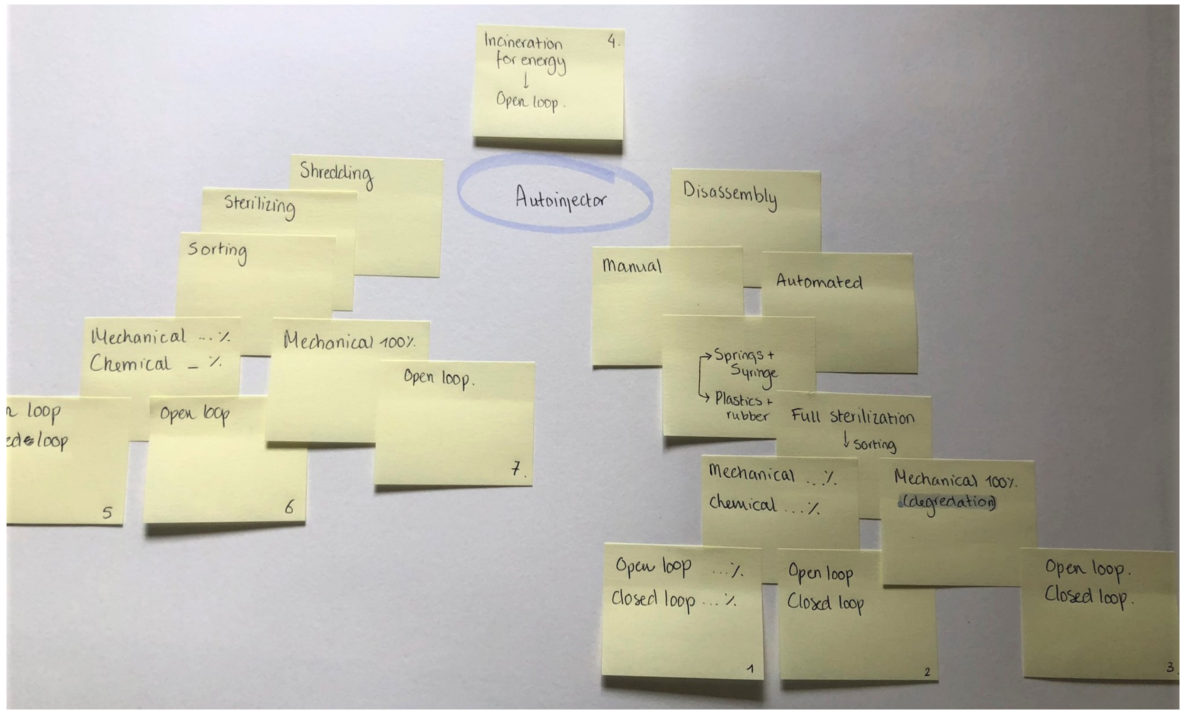


Figure 18
Scenario mapping

Shredding - Disassembly

An important consideration in setting up the value chain is the decision between the shredding or disassembly of the product. This is due to the value that is seen within the different end products of both processes.

If the product were to be shredded as a whole this would result in a mix of all the materials that reside in the autoinjector. The chances of obtaining a single material stream, which is required by many recyclers, from this mixture are low.
However, if the product is disassembled into components through a disassembly machine, the separation of the components into single material streams would be easier.

This desire for disassembly was confirmed during the discussion with employees of Alliance to Zero, they saw no future in the scenarios where shredding took place. If the product were to be shredded as a whole the mixture would be considered less valuable compared to when it would be disassembled. The pieces of components that remain after the shredding process tend to stick together as shown in chapter 5.2. After sorting this would result in contaminated material streams and a recyclate with low market value.
Furthermore, during this meeting Alliance to Zero elaborated on the fact that they themselves have been working on a disassembly machine, which they hope to have finished by 2025.

Mechanical - Mechanical + Chemical

Due to the inability of chemical recycling to treat most of the plastics in the autoinjector, chemical recycling alone could not be an option. Therefore, scenarios were created where Alliance to Zero would test with chemical recycling alongside the main route of mechanical recycling.
Moreover, this chemical side of the process was placed in-house because there are currently no facilities at hand that are focussing enough on the plastics used in the autoinjector. However, whilst discussing the scenarios, the employees of Alliance to Zero highlighted that setting up the chemical recycling process would not be something they are interested in due to high investment costs. As a result, two mechanical recycling scenarios were left.

To conclude, using the insights gained on the four presented scenarios during the meeting with Alliance to Zero, results in the continuation with scenario 3, where the product is disassembled and the components are mechanically recycled.

Translated to Roadmap
- Acquisition and implementation of disassembly machine

- Value horizon 2: Mechanical recycling

The optimal scenario

Another scenario that was presented to the members of Alliance to Zero is the optimal scenario. The optimal scenario is based on the upper strategy of the Value Hill namely, reuse (Inchainge, 2022). Using this strategy will save the most resources.

Within this scenario, the inner assembly of the medicinal syringe could function like the cartridge from a printer and the autoinjector could become a refillable device.
After removing and collecting the medicinal syringe with the needle, they would be shredded, sterilized and separated. The then shredded glass would be returned to the manufacturer of the syringes to be reused in production. This would leave the needle as the only component that is not able to enter the closed loop. Due to its high risk of contamination and fragility, it is not recommended to recycle or reuse it.
However, some hurdles do exist to this scenario;

- A redesign is required where replacement and refill of the medicinal syringe is taken into account

- Designing a safe way to insert the medicinal syringe into the reusable housing of the product

- Keeping the medicinal syringe and needle sterile whilst inserting it into the reusable housing

- Keeping the needle in tact whilst inserting the medicinal syringe into the reusable housing

- Testing the number of use cycles it can withstand

Given these hurdles, and also the implementation time of getting to a scenario as described above, this research will continue with the current design of the autoinjector.

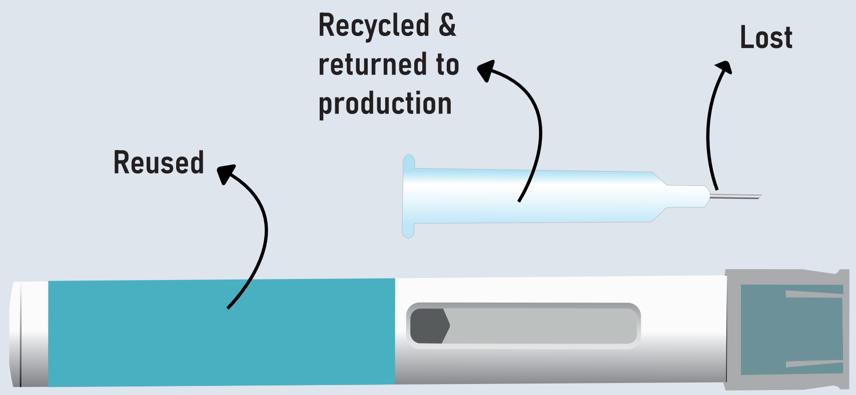


Figure 19
Reusable scenario

Conclusion.

Considering the conclusion that disassembly with mechanical recycling is currently the most desired route, and the main insights from the earlier paragraphs, a value chain can be constructed (Figure 20). The value chain includes actions that are needed to enable the reuse of valuable materials of the autoinjector.

The value chain starts with the collection of the products, a crucial step to enable a more circular supply chain for the autoinjector. Using the expected production numbers of Ypsomed, and a take-back range prediction of 15-25 % from HealthBeacon, results in the volumes mentioned earlier in table 3.
Subsequently, conclusions from previous paragraphs are used to determine the next step; disassembly. The autoinjector is to be taken apart by a machine, whereafter one is left with a mixture of components that consist of their own diffent material.

Next, the sorting of components on material level is done through a sorting machine, resulting in single material streams. From here, the glass syringe with the needle still attached, goes its separate way towards sterilization. After sterilization the metals and glass pieces will be separated from each other and transported towards their End-of-life phase.

The materials that do not require sterilization, are split into groups that either don't or do need disinfection. Afterwards, these materials are also transported towards their End-of-life phase.
To return to the conclusion reached during the discussion of the scenarios, this last phase would be mechanical recycling if the materials lend themselves to it.

Accordingly, what happens in this last phase, whether that is the mechanical recycling of materials or not, influences how much the of emissions originating from the End-of-life phase are decreased.
However, the focus of this research lies not at the End-of-life phase but at the beginning, where raw materials are needed to manufacture components used to produce the autoinjector. Yet, the conclusion of whether the materials end up in mechanical recycling or not does influence the circular potential of the product and therefore the impact that can be made in the first phase of the supply chain. In other words, if the materials are not recycled, there is no chance of them returning to production and aiding in the decrease of emissions originating from raw material production.

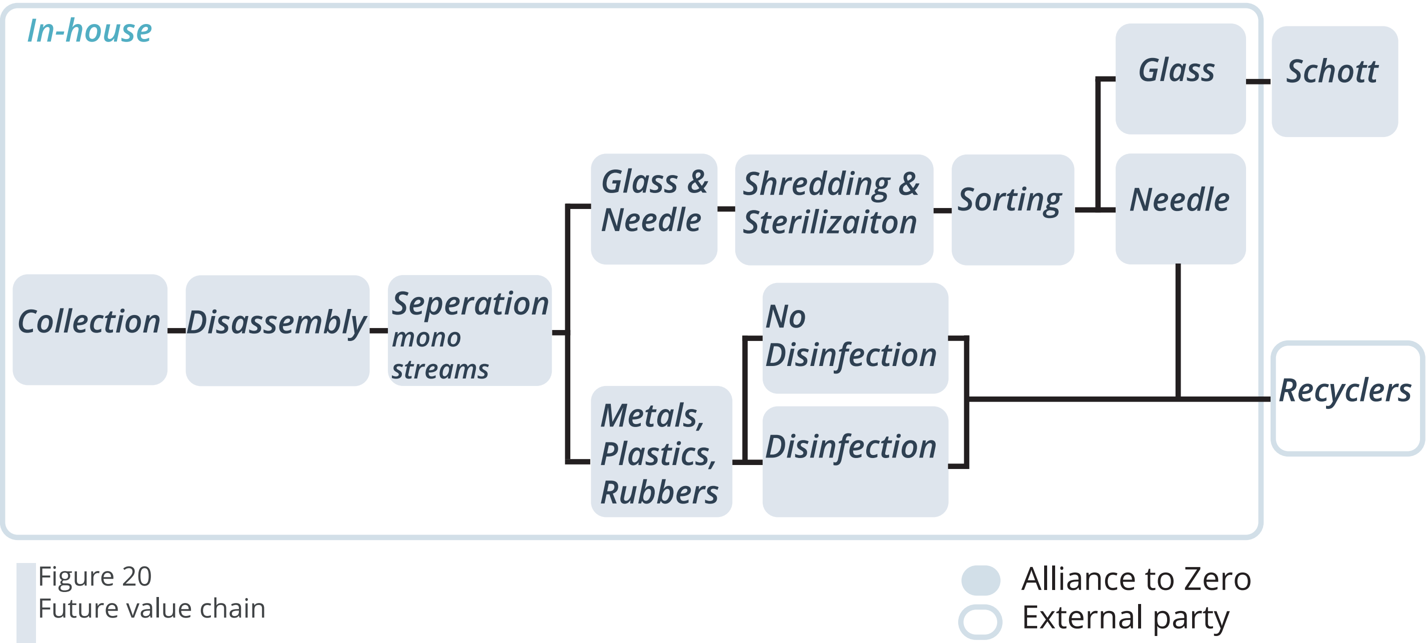


Figure 20
Future value chain

7.

7.1 RESOURCES
7.2 DESIGN FOR RECYCLING

DEVELOP THE VALUE CHAIN

Resources.

In order to realize the in chapter 6.4 set value chain, some resources are required. Resources that can influence how well recyclable a material stream is, and therefore the ability to reduce emissions.

Warehouse

The earlier discussed value chain describes which processes happen in-house, suggesting that a physical space is needed to execute the desired activities that enable the recycling of the materials.
The current supply chain of the autoinjector is mainly divided over the countries Germany, Belgium, and Switzerland (Figure 21). Proximity of the warehouse to the other companies in the supply chain is important because it allows for materials such as the glass to be easily returned to the manufacturer and used again in the production of the syringe.
According to a report done by Plastic Recyclers Europe (2022), in the year 2020 Germany had the most plastic recycling capacity of Europe. Followed by countries such as Italy, Spain, UK, and France (Figure 21).
Considering both the location of the supply chain companies and the concentration of recycling facilities, a suggestion can be made for the allocation of a physical space where the in-house activities can be carried out. As a result, no unnecessary emissions are made due to the transport of the post-use materials.

Germany

The warehouse should therefore be located in Germany, close to Schott (Figure 21, number 2). An indication of the area that could be beneficial is given with the turquoise highlighted area on the map. This way the warehouse remains close to the key role players in the supply chain and close to many different recyclers.

Number of warehouses

According to Cornwell (2016), one central warehouse location would result in less complicated inventory and economy of scale is reached more easily. However, it also means that larger distances will have to be covered. Choosing a truly central location is often a success factor in such cases.
Multiple warehouses will therefore mean shorter routes, and quicker pickups. Yet, it is also accompanied with more complex inventory. Moreover, considering the machinery needed in the value chain of the autoinjector, every new warehouse is therefore accompanied with additional investment costs due to new machinery that should be bought.
Therefore, according to Cornwell (2016), for growing companies it is important to start with a central location where Alliance to Zero can optimize their operations before expanding to more locations.

Translated to Roadmap
- Acquisition and implementation of a warehouse in Germany

- Optimizing for efficiency of the warehouse
- New hub in the last horizon after optimization

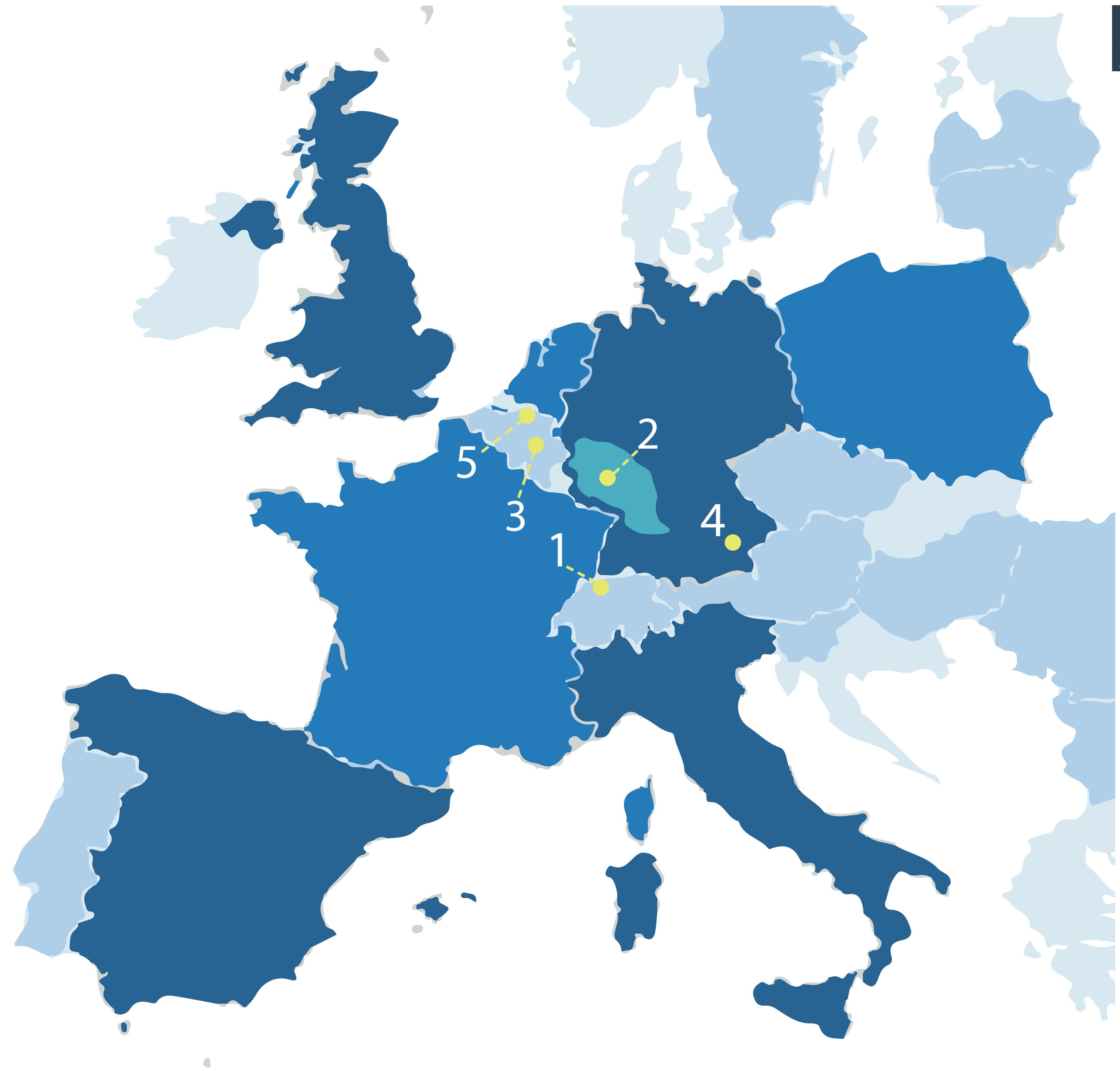


Figure 21
Warehouse allocation

Sorting

As mentioned earlier the sorting step in the recycling process is critical. It determines the quality of the material stream and therefore the recycled plastic.
According to Prajapati et al. (2021), manual sorting is the most commonly used sorting method. However, this type of sorting is time-consuming and employees could be exposed to pathogenic and toxic contaminants. As a result, there is a growing need for automated sorting methods.

Automated technologies that could be useful are for example eddy current-based sorting, LIBS, X-ray-based sorting, optical-based sorting, and spectral imaging (Figure 22). Ideally, to increase the efficiency of these processes they would be combined with artificial intelligence (Prajapati et al., 2021).

Artificial intelligence, a recent trend in the sorting industry, requires human intelligence such as visual perception and follow-up decision making (Taylor, 2019). With this new technology, companies hope to increase the quality of the materials streams after sorting and decrease labour costs through automation.
The sorting system has the ability to store data and learn, therefore constantly improving itself (Pahl, 2020).
Additionally, it is able to recognize items on shape, colour, and opacity to increase detection accuracy (Figure 24) (AI, 2022).
However, the main downside of such a machine compared to manual sorting are the purchase costs, and the costs due to its energy consumption.

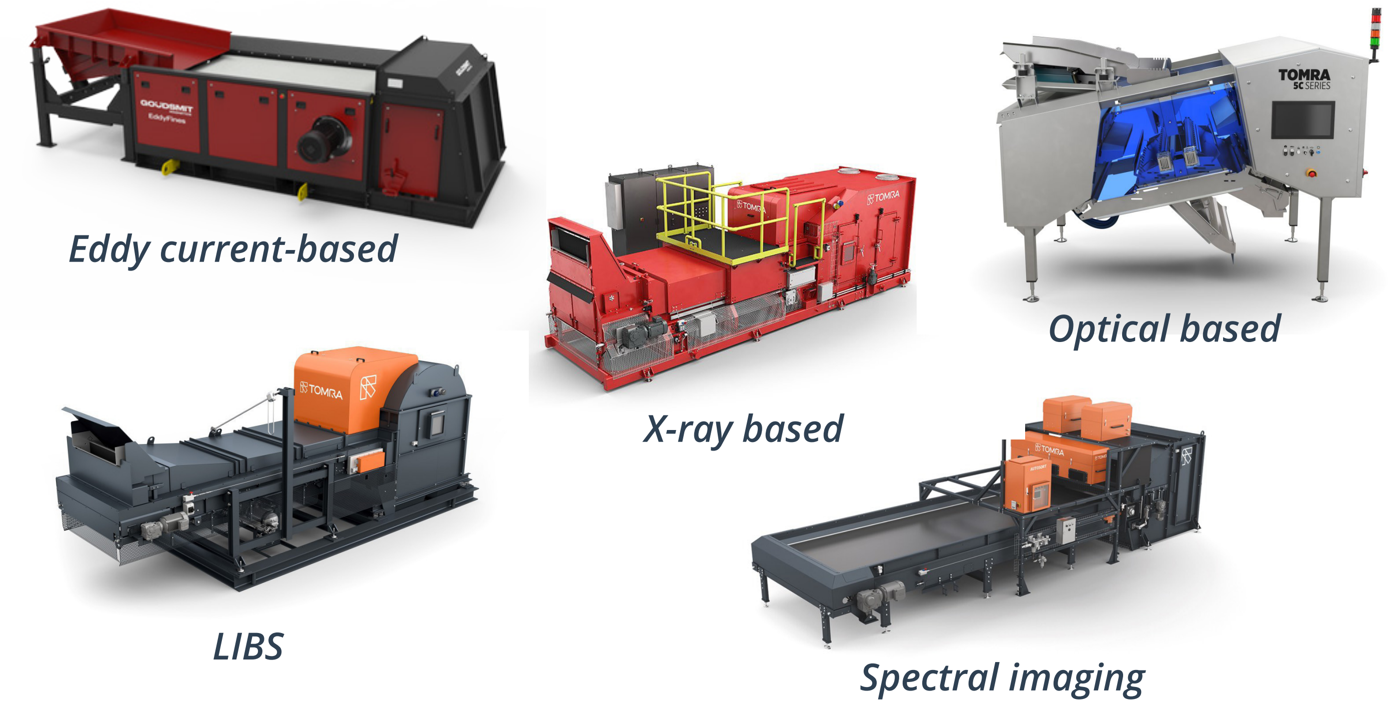


Figure 22
Industrial sorting machines

Within the described value chain in chapter 6.4, after sterilization separation of the needle from the glass is to take place. At this point the glass and needle are a shredded mixture and separation can happen through a magnet. Considering that the needles are the tiniest part of the autoinjector a manual magnet could be of use. An example of such a magnet is shown in figure 23, from Bel Air finishing (Magnetic Separators, n.d.). This seems to be an easy and fast way to separate the needles from the glass without having to touch any of the parts.

Figure 23
Manual magnet, Bel Air

Translated to Roadmap
- Acquisition and implementation of sorting magnet

- Acquisition and implementation of AI driven sorting machine

Figure 24
AI driven sorting machine

Methods to disinfect

Earlier in chapter 5.4, a distinction was made between the disinfection or sterilization of components in the autoinjector. In this chapter, different methods are discussed which can be used to obtain the proper amount of disinfection.

Sterilization

According to Zeus (2005), common sterilization methods for medical devices are microwave sterilization, autoclaving, irradiation, and chemical disinfection.

Chemical disinfection eliminates bacteria through the use of various gaseous chemicals. Most plastics remain unaffected by this process. However, the gas that is used in the process is considered flammable and explosive.

There are two types of irradiation, gamma and E-beam. Both methods have high capital costs due to the equipment needed for the process. Furthermore, it is argued that the plastics that enter the process change in the polymer structure.

Autoclaving is based on the idea of steam that penetrates into a product. However, due to the temperatures (121 degrees) used for autoclaving, some materials will lose their structural integrity.

And lastly there is microwave sterilisation. According to Zimmerman (2017), there are two types of microwave sterilization namely, conventional and sophisticated. However, only the latter one is argued to be suited for biohazardous waste. In addition, the method is argued to be more environmentally friendly compared to autoclaving.

Currently, Alliance to Zero, specifically HealthBeacon uses an autoclave to sterilize the autoinjectors they have collected (Figure 25). This autoclave shreds the devices and then uses steam to sterilize the components. The autoclave belongs to the company Tesalys, a France-based manufacturer of equipment for the treatment of infectious waste (Tesalys, n.d.).
With this machine, the shredding of the material is combined with sterilization. The sterilization is done at a temperature of 135 degrees for a period of ten minutes.
The company has three types of machines which have the ability to handle different volumes of waste ranging from 5-20 kg/h. In other words, these machines could be useful when handling smaller collection volumes of autoinjectors.

Figure 25
Tesalys autoclave

However, if those collection volumes tend to increase, larger operations are needed to treat the infectious waste. A company that produces larger sterilization machines is Ecosteryl. In an interview conducted with Mouchati (Appendix L), an employee of Ecosteryl, Mouchati highlights three phases of its sophisticated microwave sterilization process namely , shredding, sterilizing, and sorting (Figure 26). During the second phase, ovens are used to sterilize the materials. The ovens are preheated at a temperature of 100 degrees, an environment in which the materials should remain for an hour. According to Mouchati, no degradation occurs during this phase because the temperature remains below 130 degrees. This process has the ability to treat materials such as glass, metals, aluminium, plastics etc., and sort them into their homogeneous material stream after sterilizing.

The installation does not use any additional water, making this process a more favourable option than the other alternatives. These specific ovens are easy to upscale: if a client wishes to expand, the company has the ability to link additional ovens to the process, resulting in an increase in the amount of treatable waste.
However, the installations are large and are able to handle a quarter of a ton to 7 tons a day. To put in perspective, 75 to 300 kg per hour. Therefore, if Alliance to Zero only wishes to sterilize the needle and glass, the machine of Ecosteryl would be too large in the first years considering the take-back numbers discussed in chapter 5.4.
However, this machine becomes interesting with the production numbers from the year 2030. Moreover, the Tesalys machines would not be able to handle such an amount of waste (Calculation 1). Therefore, a switch during the coming years towards a more automated and industrialized process might be favourable.

Figure 26
Ecosteryl sterilization process

Machine related production capabilities

Tesalys autoclave

20 kg x 8 hours per work day x 260 working days = 41.600 kg / year

Ecosteryl

75 kg x 8 hours per work day x 260 working days = 156.000 kg / year

Expected waste from the syringe (table 5)

2023 - 2025

8 gr. (20 million x 0.15) =	2.400 kg	(glass & needle) / year
8 gr. (20 million x 0.25) =	40.000 kg	(glass & needle) / year

2030

8 gr. (500 million x 0.15) =	600.000 kg	(glass & needle) / year
8 gr. (500 million x 0.25) =	1 million kg	(glass & needle) / year

* amount of waste calculated with a take-back range of 15-25%
* assumption was made that there are 260 working days in a year (waster per year / 260 = waste per day)

Calculation 1
Waste in need of sterilization

Disinfection

For the other components that need disinfection, a solution could be the device of Watter (Sustainable disinfection, n.d.). This machine displayed in figure 27, was developed to offer a sustainable disinfection solution using water, salt, and electricity. The type of disinfection belongs to high-level disinfection (see chapter 5.4) and could therefore treat the other components that are in need of high- and low-level disinfection. The substance used to disinfect the components is biologically degradable, leaves no residue behind, and is not harmful. According to a conversation with a microbiologist from Watter (Appendix R), the components would have to reside in the substance for 10 minutes in order to achieve the desired disinfection. The machine would deliver the substance, whereafter a pump transfers the liquids in a bath in which the components reside for the required amount of time.

Translated to Roadmap
- Acquisition of Tesalys autoclave
- Acquisition and implementation of Ecosteryl machine
- Acquisition and implementation of Watter disinfection machine

Figure 27
Watter disinfection machine

Machine related investments

This paragraph summarizes which machines are needed to realize the value chain described in chapter 6.4, whereafter an estimation of their costs is provided.

First, the disassembly machine, a process on which HealthBeacon is working and will hopefully have realised by 2025. However, because they themselves are working on it, no estimate of these costs have been included.
Second, the machine that has to separate the materials after the product has been disassembled. This machine is an important step in the supply chain, because it is the step that should realize single material streams. Failing to do so influences whether recyclers are going to accept the post-use materials. As a result, if the recyclers would accept the contaminated material stream, the quality of the recycled material would be negatively influenced.

Third, the disinfection machine. Because not all components need sterilisation a lower-level of disinfection method is chosen. However, this does mean an additional machine to invest in, but again a step in the process that might influence whether the recyclers accept the material that Alliance to Zero has to offer. Because the product is a medical product, recyclers do ask manufacturers to disinfect the material before shipping it to the recycler.
Fourth, another autoclave; if Alliance to Zero were to expand into hubs around Europe, an additional autoclave is needed. This autoclave is a machine that Alliance to Zero currently uses at the HealthBeacon hub in Ireland. This machine shreds the material whereafter it is sterilized.

And last, a device that aids in the separation of the needle from the glass. After the sterilization process, one is left with a shredded mix of needles and glass. In order to safely remove the needle from the glass a magnet should be used, whereafter both can be transported to their designated End-of-life phase.

From this chapter it can be concluded that the initial investments that come with the machinery needed for the value chain are estimated at roughly 700.000 to 900.000 euros.

Machine	Purchase of 1 machine (euros)	Source
Sorting (AI driven)	**300.000 - 400.000**	Appendix S
Disinfection (Watter)	**35.000**	Appendix R
Autoclave (Tesalys)	**5.0000**	
Sorting (Magnet)	**500**	Appendix T
Sterilization (Ecosteryl)	**356.000 - 400.000**	Appendix U
TOTAL	**696.500 - 896.500**	

** the price of the autoclave was estimated based on prices of other autoclaves*

Table 10
Purchase costs of machinery

Conclusion

In conclusion, to realize the recycling of the materials used in the autoinjector some resources are needed first. According to the in chapter 6.4 set value chain a disassembly, sorting and disinfection machines are needed.
However, the sorting step takes place at two locations in the process, after disassembly and after the sterilization of the glass and needles. As a result, the process requires two different sorting machines of different sizes.
In addition, as a result of the classification in disinfection needs, two different disinfection processes are required to treat the components. Also, due to the possible increase of demand for the self-injectables, a process such as sterilization needs a second larger machine to handle the expected waste stream in 2030.
This results in extra purchase costs for Alliance to Zero that could lie between 700.000 to 900.000 euros.

Design for recycling.

This chapter is aimed at optimizing the amount of value that is captured within the previously set value chain (Chapter 6.4). In other words, increasing the amount of material that ends up in mechanical recycling.
This is done through an exploration of the recyclability of the materials within the autoinjector, optimizing the autoinjector's recyclability through the replacement of plastics, and the creation of valuable partnerships as part of a sustainable supply chain.

Material recyclability

This chapter aims to investigate more specifically how well recyclable the materials of the autoinjector are. According to Plastic Recyclers Europe (2022), plastic recycling starts with design. For a plastic to be considered recyclable it should meet the following conditions:

- The plastic that is collected for recycling should, have a market value, meaning that potential buyers see value in the recycled material.
- The plastic should be sorted into a defined and existing stream for recycling. In other words, are there already companies out there that recycle this stream?
- The plastic should be recycled with commercial recycling processes, do different established processes for the recycling of this stream exist?
- The plastic should become a raw material used in production of new items. Meaning that this recycled plastic is desired to be used in the manufacturing of new products and/or components.

Generally, the autoinjector counts six different plastics out of which three are filled with either glass fibres or a different plastic. In addition, five plastics are considered an engineering plastic (PC/ABS, POM, PC, PA60%GF, PBT30%GF) (Yildizhan, 2021). The demand for engineering plastics has been growing. In a market research on Engineering Plastic Recycling Market (2021), they address the expectancy of this market to grow during the period of 2022-2027. This will result in an increased market value of the engineering plastics and therefore the first recyclability criteria for five materials.

Yet, the product also contains some metals, rubber, and glass. All of which are considered well recyclable. Therefore, in the assessment of the recyclability of the materials all types are discussed separately on the four conditions mentioned before. The four below the material name show which conditions have been met (blue circle), or not (white circle).

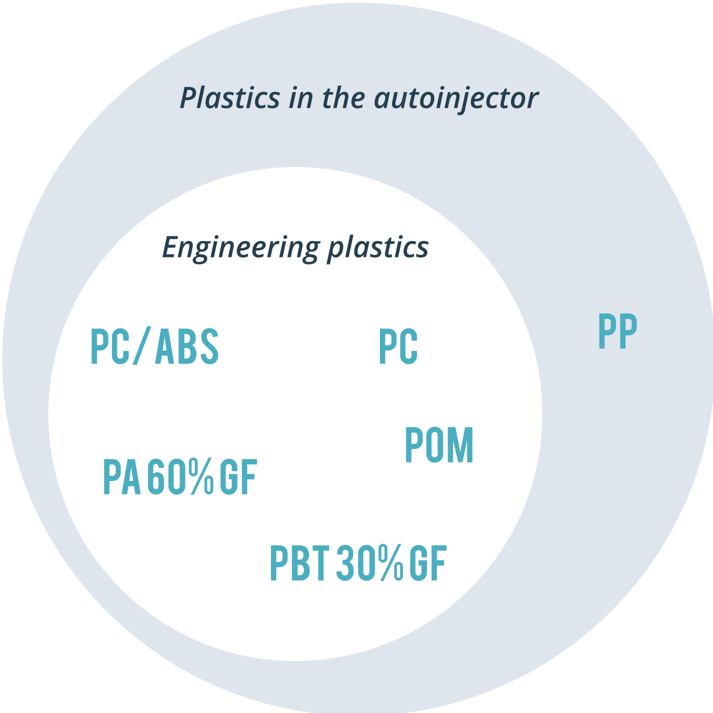


Figure 28
Plastics within the autoinjector

PC/ 10% ABS

Polycarbonate mixed with 10% Acrylonitrile Butadiene Styrene

This blend of polymers is often used in electrical equipment and housings (Liang & Gupta, 2002). Generally, PC is mixed ABS to improve its processability. In addition, according to MGG Polymers (2019), a PC/ABS polymer is very suitable for the mechanical recycling process. Besides, both MGG and Sabic, two recycling companies, have an established mechanical recycling process for this polymer and makes new products from the recyclate. Both companies are proof that PC/ABS is a common stream and that that process of recycling it is established.

The recycled polymer is often used as a raw material in the automotive, appliance, and electronics industry (PC/ABS Resin Market Size, 2022; MGG Polymers, 2019). Additionally, both the companies Sabic and MGG polymers have commercialized the recycling process of this polymer and produce new products or granules from the recyclate.

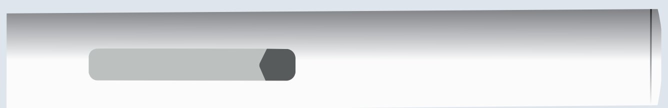


Figure 29
Components 2 (End cap), 3 (Housing)

POM

Polyoxymethylene

POM is a material commonly used to produce precision parts (Recycled POM, n.d.). The material is a valuable engineering plastic with properties such as chemical resistance and low water absorption, and is therefore often used in medical engineering. POM is a fine candidate for mechanical recycling. The most important properties of POM are maintained during the recycling process. Moreover, once recycled the plastic lends itself to be used in the automotive and electronics industry within precision parts.

One of the few companys that engages in the recycling of POM is Plastic Expert located in the UK (POM plastic, n.d.). In conclusion, The polymer POM is a desired plastic that has an existing stream for mechanical recycling and is used as a raw material within the production of new components within other materials. However, since not that many recyclers can be found that recycle this plastic, the criteria of a commercial recycling process remains open.

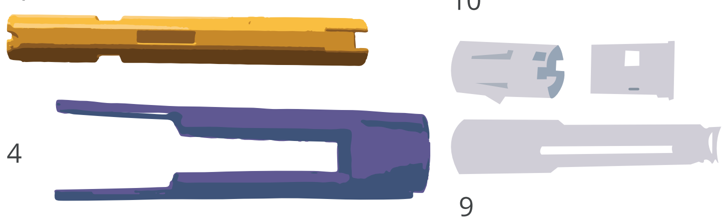


Figure 30
Components 4 (Cover sleeve), 7 (Plunger rod), 9 (Mechanic holder),10 (Telescopic lock sleeve)

Glass syringe

According to Kloke (Appendix H), the glass syringe is made from a special composition that should not be mixed with other compositions because the material would lose important properties as a result. Therefore, a clean stream of this material is very important. Two aspects of the value chain, being take-back schemes and a disassembly machine, should allow for the glass stream to remain clean and therefore the recycling of the glass syringes seems feasible. In addition, the mechanical recycling of this component is desirable because glass has no memory.

"That is the great thing about glass, you just erase the history and recombine the element. With plastics you take along the history"

- Kloke

This is referring to the forms of degradation that the plastics undergo during production after recycling. Nowadays, Schott is testing the reuse of production scraps in the production of new glass. The recycling of the glass is definitely feasible, however only if it can be guaranteed that it is the same glass as used in the production of Schott.

Moreover, if the glass is not returned to Schott, there still is a large glass recycling market because of its high recyclability. The recycled glass is often reproduced into bottles, jars, or glass wool insulation (How is glass recycled?, n.d.).

To summarize, the glass that originates from Schott is of high value when during collection no mixture with other glass takes place. The stream already exists yet more research is needed to realize the inhouse recycling process. When this process is finalized the recycled glass could thereafter be used in the production of new glass ampules.
However, the glass can also be recycled within more common mechanical recycling processes. This would mean that the glass sent to common recyclers is mixed with other glass and therefore not desired to return to production. Yet, it would be used as a raw material in other products.

Translated to Roadmap
- Set up of glass syringe recycling with Schott
- Use of recycled glass in production

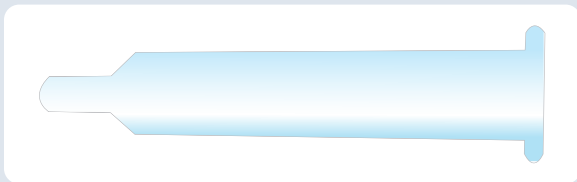


Figure 31
Component 12 (Syringe)

The needle

Steel

In figure 32 the needle, a component that is produced by a sub-supplier, is still glued to the glass syringe. Needles used in syringes are considered hazardous objects and should therefore be disposed of properly in order to prevent contamination and injuring of others (Bennet, 2015). Due to its contact with the vascular system this part is considered critical according to the classification discussed earlier by Rutala & Weber (2013). The high risk of transmission of diseases due to the contact with the vascular system causes them to not be taken back and remelted into new needles (Bennet, 2015). They are often disposed and collected in a sharps bin to prevent sharps injuries (Health and Safety Authority, 2014). What should happen with that bin differs per EU country (Meds disposal, 2020).

Reuse of the needles is not a desired option. According to Shuman & Chenoweth (2012), syringes and needles are truly intended for single use. This is mostly due to two reasons. First, during the disassembly of the autoinjector, it was observed that this component is very fragile. The component easily bends, hampering the possibility of reuse.

Furthermore, according to Kloke (Appendix H), an employee of Schott (the glass manufacturer), sterilizing and reshaping the component is hard to imagine as a financially viable process because that requires a lot of steps.

Yet, often after the sharps bin has been collected the sharps are sent to an autoclave where they are sterilized, making them safe to be sent towards a landfill (Brenner, 2021). But, if they are sent to an autoclave and therefore sterilized, the risk of possible contamination is avoided and the waste is seen as regular municipal waste (Stericycle, 2020). Meaning that the metal could be mechanically recycled at a metal recycler.
The recycling group MGG is experienced in steel recycling, has an existing stream and an established process. After the mechanical recycling the material will be used in production of new products. However, since it is a very small and low weight part, chances could be that they see now value in the recycling of this material stream.

Translated to Roadmap
- Recycling of the needle together with other metals at MGG

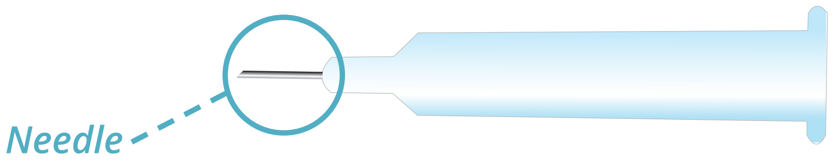


Figure 32
Component 14 (Needle)

Stainless Steel

In an interview with Bergsma (Appendix E), the metals used in the production of the springs are discussed. He explains that once this metal is put into mechanical recycling, the metal will never become a spring again. Therefore, the reuse of this material is preferred and recycling would be seen as downcycling. Moreover, this means that if the springs were to be recycled the recyclate cannot be used in production again.

Often the steel used for making springs is of higher quality compared to more common steel. This is due to the many extra treatment steps that the steel needs in order to become a spring. Therefore, Bergsma says, direct reuse of these springs is better compared to remelting them.

However, this research is aimed at the scenario of recycling. According to the recycling group MGG (n.d.), stainless steel recycling is an activity that has existed for some years now and is economically viable. MGG sources stainless steel because the material is fully recyclable. Recycled steel can thereafter be used in many different applications. Showing that the recycling of this material is common, the process is established and the material has value. Also, the recyclate would be used as a raw material in production, yet not in our product.

Translated to Roadmap
- Stainless steel recycling with MGG

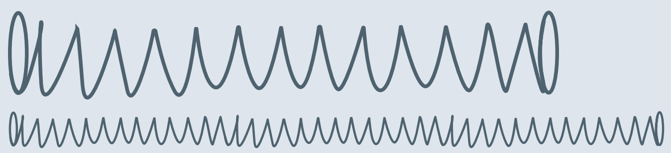


Figure 33
Components 6 (Injection spring), 11 (Cover sleeve spring)

PC

Polycarbonate

PC is a durable plastic that is commonly used due to its transparency (Recycled PC, n.d.). Recycled PC should be able to be mechanically recycled into the same product as virgin material. The transparency of the material can be maintained during the recycling process. However, if impurities exist in the waste stream this optical property might get lost. Moreover, the company Sabic already has a commercial recycling process for PC. With the recycled polymer, they make new polymers that contain a percentage of recycled PC in the blend. The polymer is thereafter often used as a raw material to produce windows, traffic lights or other appliances.

Translated to Roadmap
- PC recycling with Sabic

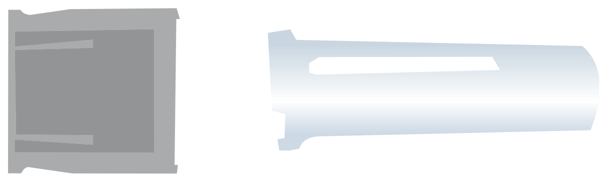


Figure 34
Components 13 (Cap remover), 17 (Syringe holder)

Composites

PA, Polyamide & PBT, Polybutylene Terephtalate with glass fibres

Composites are plastics that are reinforced with fibres of a different material (Drogt, 2017). In the case of the autoinjector two components (Holding pin, 5 and the click sleeve, 8) are reinforced with glass fibres. Here, the plastics act as a binding material for the strong glass fibres. Due to this reinforcement, their technical lifespan is longer and they require almost no upkeep, causing them to be a good candidate for reuse and mechanical recycling.

The waste stream of these components tends to be limited and reuse of composite components is suggested. Moreover, mechanical recycling of these polymer types is the preferred method, however commercial recycling routes have yet to be developed and market potential remains low (Drogt, 2017; Bica, 2017).
However Sabic, a plastic compound supplier of the Alliance to Zero, is interested in performing test with the PBT polymer to thereafter use the recyclate in other products.

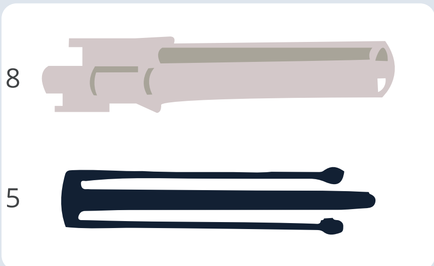


Figure 35
Components 8 (Click sleeve), 5 (Holding pin)

PP

Polypropylene

A valuable plastic that is commonly recycled and made from the propene (or propylene) monomer (Recycled PP, n.d). A polymer that is often chosen for its superior strength usually in engineering applications. Depending on the way the polymer is produced the material can either be hard or soft, opaque or transparent, light or heavy, insulating or conductive. Recycling of this plastic is possible both mechanically and chemically (pyrolysis) according to an employee of Sabic, where they excute both. The recycled polymer is thereafter used as a raw material in applications such as plant pots, containers, home storage, automotive parts, etc. (Recycled PP, n.d.).

Figure 36
Component 16 (Needle cover)

The label

PP laminated paper

The label of the autoinjector is made from paper laminated with PP (Appendix W). According to Collins (2022), this mixture does not seem to be recyclable due to the need for the separation of the two materials.
However, there is a company called Terracycle that is able to provide a “zero waste pallet” in which the labels can be collected (Terracycle, n.d.). This full pallet is returned to them and they have the ability to recycle the pp coated paper. From this recyclate Terracycle makes various objects ranging from plant pots and water cans to bracelets and frisbees.

Translated to Roadmap
- Label recycling with Terracycle

Figure 37
Component 1(Sticker label)

Rubber

Butyl rubber

The rubber used inside the autoinjector is called butyl rubber. This type of rubber is useful in the autoinjector because of its resistance to chemicals (Ridderflex, n.d.). Furthermore, it is resistant to ozone, sunlight and oxidation, making it a very durable material.

All types of rubber are mechanically recyclable through many established processes and most of their input comes from tyres (Recycling inside, n.d.). The collection and repurposing of this material costs less energy intensive compared to the virgin production of rubber, making it a very valuable product to recycle. Recycled rubber is used as a raw material in shoes, tires, or carpets for example (Recycled Rubber Uses, n.d.).
However, according to a research done by Carnstone (Appendix W), the rubber components in the product are coated with a solvent. And as mentioned earlier in chapter 5.5, if not washed properly, this impurity could cause for material degradation during recycling and therefore a decrease in its value.

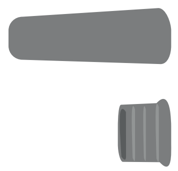


Figure 38
Component 15 (Rubbers)

Subconclusion

In conclusion, using the above described criteria on both the plastics and the other materials in the autoinjector, a table can be composed showing the recyclability of the materials (Table 11).
Using this table it can be concluded that the polymer PA with glass fibres has the lowest recyclability. Therefore, if the recyclability of the product is desired to increase a first look should be taken at the replacement of the PA plastic.

Material	Market value	Existing stream	Commercial mechanical recycling process (mono stream)	Recyclate of mono stream is used as raw material
PC/ABS	YES	YES	YES	YES
POM	YES	YES	NO	YES
Glass	YES	YES	YES	YES
Needle	NO	YES	NO	YES
Stainless steel	YES	YES	YES	YES
PC	YES	YES	YES	YES
PA 60% GF	NO	NO	NO	NO
PBT 30% GF	NO	YES	NO	NO
PP	YES	YES	YES	YES
Paper with PP laminate	NO	YES	NO	YES
Rubber	NO	YES	YES	YES

Table 11
Recyclability of the materials in the autoinjector

Replacing Plastics

Decreasing the number of different materials that the autoinjector contains has two main benefits, namely (1) less different recyclers and (2) increased amount of material delivered to that recycler. For example, if the components that are made from POM were to be produced with PC/ABS, not six but five material streams would exist. Consequently, more weight of PC/ABS would be delivered to a recycler, increasing the chances of that recycler accepting the material stream. Resulting in less different recycling routes and fewer emissions due to a simpler supply chain (Figure 39).

However, since the device is a medical product, specific requirements have to be met. During this paragraph only plastics have been considered for replacement because they represent the largest material group within the autoinjector. Some plastics might have been chosen to ensure the safety of the product.
Additionally, for medical products properties such as durability, chemical resistance, and heat resistance are important (Medical Grade Plastics, 2022). Properties as such make the product suitable for sterilization and transport of medicine. Specifically the polymers PP, ABS, and PC are highlighted as plastics with good chemical resistance, toughness and sterilizability.

Moreover, the components that are manufactured from these polymers are not desired to be replaced within the product. According to Gerner, the PP needle cap (Component 16) and the rubbers (Component 15) in the autoinjector are produced by a sub-supplier and delivered as a sub-assembly to Sharp in Belgium where the final assembly takes place. Therefore, Alliance to Zero has no influence on these components.

Furthermore, Gerner mentions that the components made from polycarbonate (Components 13, 18) have to remain transparent, and therefore made from PC. This is due to tests that must be done with the autoinjector to assess its safety. Additionally, as will be discussed in the next paragraph, PC and PC/ABS are plastics that are desired in the mechanical recycling industry and therefore not desirable to be replaced. Also, the PBT polymer is a desired polymer to further test mechanical recycling possibilities with and should therefore remain within the autoinjector.

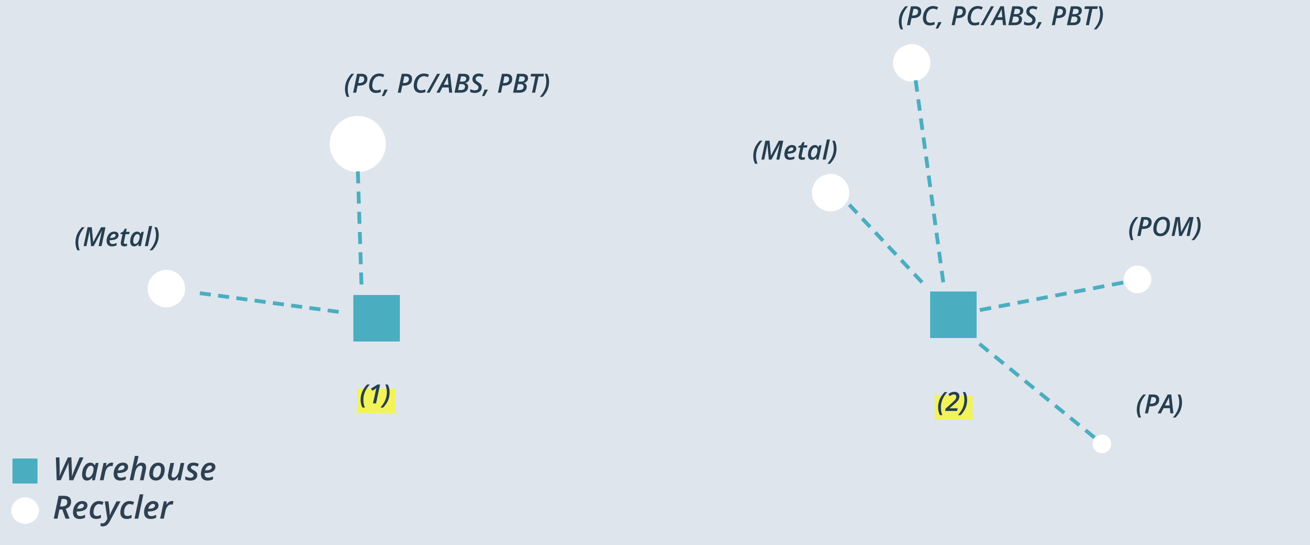


Figure 39
Recycling partner distribution scenarios

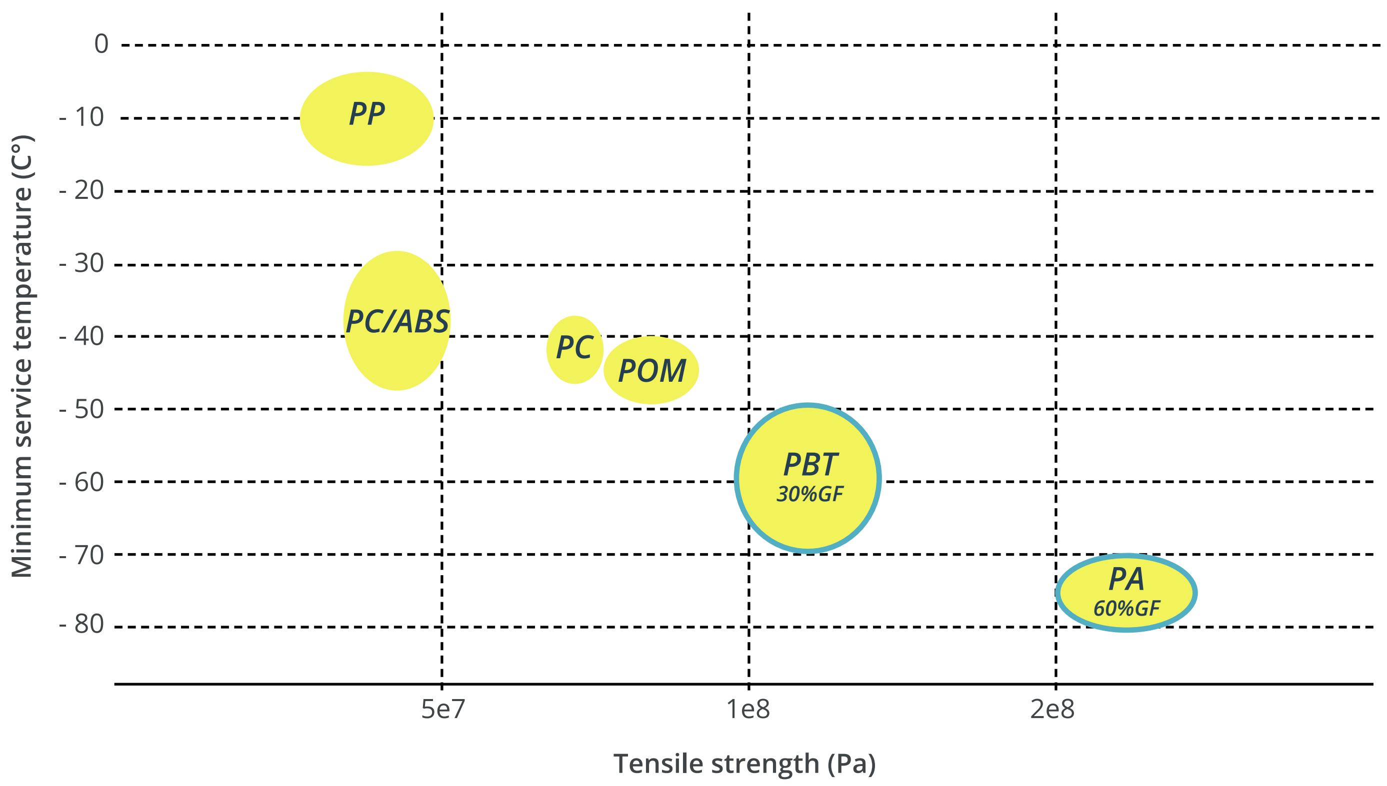


Figure 40
Tensile strength, minimum service temperature, CES edupack 2022

As a result, the remaining polymers, POM, and PA are further discussed as options for replacement. Returning to the previous table 11, from chapter 7.2, PA with glass fibres is considered to have the lowest recyclability and is therefore most desired to replace.

The polymer PA is often chosen for its toughness at low temperatures (CES edupack, 2022). A material its toughness is also described as its ability to absorb energy and plastically deform without breaking.

Continuing, a plot (Figure 40) was composed of the plastics within the autoinjector to analyse whether the same properties can be found within other plastics. On the x-axis, one can find the toughness of the materials expressed as Tensile strength in Pascale (Pa). On the y-axis, the temperature within which the polymers are able to function, is displayed in degrees (C°). In other words, the graph now shows the properties for which the polymer PA is often chosen.

Looking at the graph one can see that PA (right corner), is able to function at low temperatures and is the toughest plastic in the autoinjector. The polymer whose properties are closest to PA is PBT. Indicating that if PA was chosen for the properties displayed in the graph, tests could be performed to see whether component (5) functions as desired whilst made from the PBT polymer.

The other polymer that remained and has little commercial mechanical recycling routes according to the earlier paragraph is POM. The polymer is often chosen because of its high dimensional stability and wear behaviour (Recycled POM, n.d.).
Dimensional stability is the ability to maintain the same size under different environmental circumstances (Ensinger, n.d.). This property is defined by low water absorption and low thermal expansion of the plastic. Table 12 displays the values of these properties for each of the plastics in the autoinjector. Whereas POM, a polymer that is chosen for its dimensional stability is almost equal to

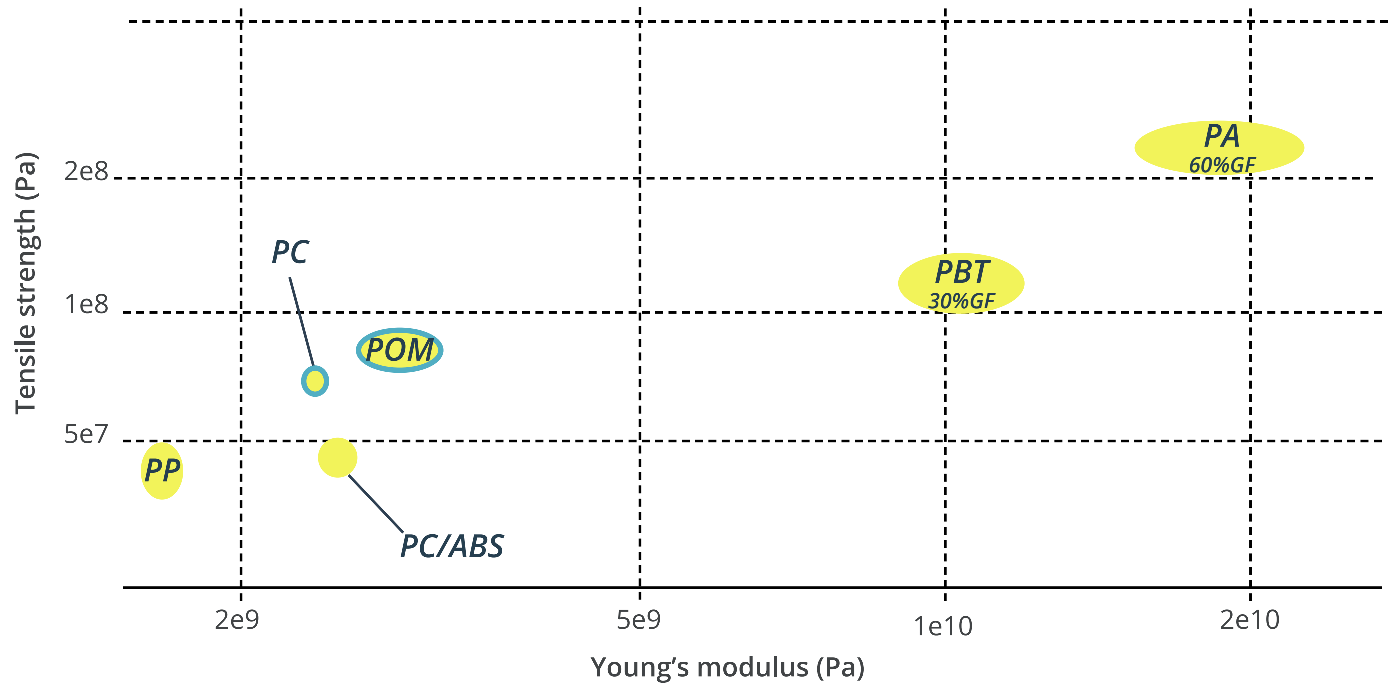


Figure 41
Young's modulus, Tensile strength, CES edupack 2022

the polymers PC/ABS and PC. Furthermore the polymer PP seems to score best on this property.
POM is also often chosen for its wear behaviour (Recycled POM, n.d.). Wear behaviour is determined by the elastic behaviour of a polymer, expressed in the Young's modulus on the x-axis, and its toughness which is expressed in Tensile strength on the y-axis (Parsi, 2022).
And so, the graph displayed in figure 41, indicates that PC and POM might behave the same when it comes to their wear behaviour.

Material	Water absorbtion (weight gained in 24 h) (%)	Thermal expansion coefficient (strain%/ degrees)
POM	0,2 - 0,22	1,1e-4 - 1,98e-4
PBT	0,06 - 0,08	2e-5 - 1,3e-4
PA	0,36 - 0,52	2e-5 - 2,7e-4
PP	0,02 - 0,021	8,1e-5 - 1,9e-4
PC/ABS	0,15 - 0,24	1,1e-4 - 1,71e-4
PC	0,14 - 0,16	1,2e-4 - 1,25e-4

Table 12
Dimensional stability properties

Subconclusion

In conclusion, looking at the properties for which certain plastics might have been chosen. Some options present themselves to look into further and test for possible replacement.
Preferably replacement with plastics that already exist in the product, because the aim of this action is to create less different materials streams. Based on the graphs and properties shown above tests can be performed to see how the PA part (5) works when made from PBT, and the POM parts (4, 7, 9, 10) made from PC.

Translated to Roadmap
- Reduce number of materials in the autoinjector
- PA becomes PBT
- POM becomes PC

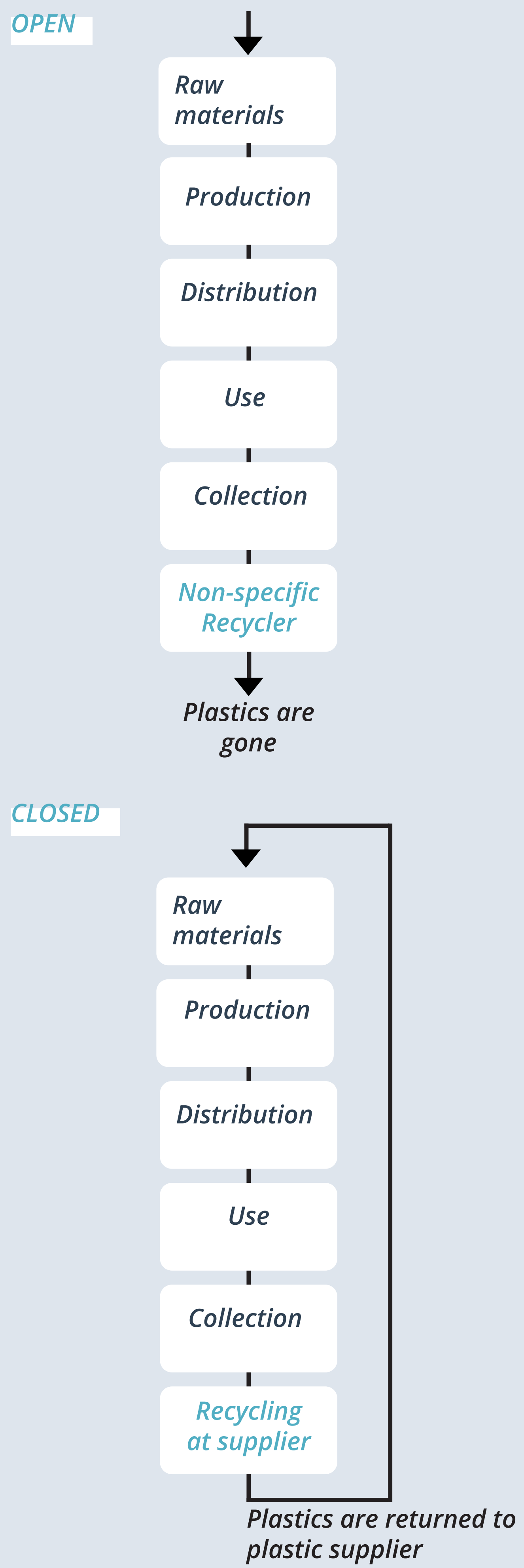


Figure 42
Open and closed loop supply chain

Closed loop partnership

In order to meet in chapter 5.6 discussed Extended Producer Responsibilities that might be set in the near future, resulting in manufacturers having to use a mandatory amount of recyclate in their production, some partnerships could be formed to aid in meeting these requirements for the autoinjector.

A current supplier of plastics used in the autoinjector is Sabic. This company engages in activities that address the production of more sustainable materials in the pharmaceutical industry (Fix & Brouwer, 2020). Sabic does not only produce plastics, it also has the ability to recycle them. Additionally, they aim to develop innovative opportunities in collaboration with their clients, which makes them an interesting partner in the future of the autoinjector.

To give an indication of what this partnership could mean to Alliance to Zero two scenarios are displayed and discussed (Figure 42).

1. *Open supply chain*: In the first scenario Alliance to Zero buys plastic from a supplier, which could be Sabic, to produce some of its parts. After the collection and separation of used materials, these plastics are delivered to a non-specific recycler. This recycler is able to make new products (not the autoinjector) from the recyclate or will sell the recyclate to other manufacturers. Leaving the supply chain open.

2. *Closed supply chain*: Alternatively, Alliance to Zero tries to close this supply chain by returning the plastics that were sourced from this supplier. The supplier, in this case Sabic, then has the ability to recycle their plastics and use the recyclate in the production of new compounds. This compound that partially exists of recyclate is thereafter bought by different customers, including Alliance to Zero.

In other words, in both scenarios the post-use materials are recycled, however, in the second one the plastics are returned to the supplier and there is a possibility that the plastic originating from the autoinjector is returned to its production.
This will create a closed supply chain for some of the plastics within the autoinjector, a characteristic of the in chapter 4.6 discussed sustainable supply chain.

Currently, Sabic is the supplier of the three plastics that exist in the autoinjector namely, polycarbonate (PC), Polycarbonate mixed with 10% Acrylonitrile Butadiene Styrene (PC/ABS) and polybutylene terephthalate with 30% glass fibres (PBT).
In two conversations with two employees of Sabic the possibility of closing the supply chain was discussed (Figure 42, scenario 2) (Appendix, M). This resulted in the following future options:

1. They were interested in receiving the plastics PC and PC/ABS that they supply to the autoinjector to use in their mechanical recycling process.

2. They are interested in getting the polymer PBT back, and together discover the mechanical recycling possibilities whereafter the polymer finds a new purpose in another product.

3. They were also interested in mechanically recycling other plastics that do not originate from their production such as polypropylene (PP).

4. They were interested to discuss the possibility of switching to plastic compounds that contain a percentage of recyclate. Meaning that if these compounds were to be used in production, and returned to be recycled by Sabic, somewhat of a closed material loop would exist.
In other words, the at Sabic recycled plastics originating from the autoinjector would be used to manufacture a new plastic compound by mixing it with virgin plastic from Sabic. This compound would thereafter be used in the production of the autoinjector again.

Weight per material per year in tons

	2023	2025	2027
PC/ABS	59,35	296,75	593,5
PC	22,45	112,25	561,25
PBT	6,3	31,5	157,5
PP	4,38	21,9	109,5

Table 13
Contribution of weight per plastic

Continuing with future option 1, 2, and 3 means that after use the polymers PC/ABS, PC, and PP would be sent to Sabic for mechanical recycling. And that PBT can also be sent to test with mechanical recycling.

The three polymers (PC, PC/ABS and PP) that are recycled account for 41,5 % of the total weight, meaning that almost half of the product would be recycled at one company through implementing future options 1 to 3. However, during this conversation they referred to a minimal input of ten tons (10.000 kg) per plastics. And even more input is expected when it comes to the polymer PP. Therefore, a calculation was made to show what that means for the plastics that they are interested in. Table 13 shows that the weight of the polymers PC/ABS and PC that can be used in the mechanical recycling of Sabic is enough during the first time period. Meanwhile, PP will get interesting for them between the year of 2027 to 2030.

Continuing with the last future option, as mentioned earlier Sabic also produces plastic compounds that contain post-consumer recyclate (PCR).

After the last conversation with them, Sabic did some research into its compounds to see which are best applicable to use within the autoinjector. Their suggestions included a compound of PC/ABS containing 46% PCR and a PC compound containing 61% PCR (Appendix N) . Because these compounds contain PCR, using them in the production of new autoinjectors will cause an increase in the amount of recyclate in the autoinjector, and therefore a decrease in the emissions due to the use of less raw materials. According to the calculation shown in calculation 2, the replacement of the two PCR containing plastics compounds would cause an increase of 19,74 % of recycled plastic in the autoinjector.

In addition, if the suggested plastic replacements of the previous paragraph that resulted in an increase of the polymers PC and PBT are taken along in this calculation, more recycled plastic would reside in the product (Calculation 3). Specifically due to the increase in the contribution of the polymer PC the percentage of recycled plastic would grow 31,87 %.

Recycled plastic in product (no plastic replacement)

PC/ABS (46% PCR)	11,87 g x 0,46 =	5,46 g
PC (61% PCR)	4,49 g x 0,61 =	2,74 g
total of 8,20 grams		
Percentage of total weight	(8,20 / 41,55) x 100% =	19,74%

Calculation 2
Recycled plastic in product production

Recycled plastic in product (with plastic replacement)

PC/ABS (46% PCR)	11,87 g x 0,46 =	5,46 g
PC (61% PCR)	12,76 g x 0,61 =	7,78 g
total of 13,24 grams		
Percentage of total weight	(13,24/ 41,55) x 100% =	31,87%

Calculation 3
Recycled plastic in product production after plastic replacement

Subconclusion

To conclude, partnering with Sabic would enable for the PC/ABS, PC, and PP polymers (41,5 %, with material replacement 60,28%) of the autoinjector to be recycled.
In addition, a closed loop for the two polymers PC/ABS and PC can be obtained. Doing so through switching to the plastic compounds of Sabic that are used in production and contain PCR mixed with raw material, resulting in an increase of 19,74 % (with material replacement 31,87 %) recycled plastic in the autoinjector.

This closed loop for two polymers within the autoinjector its supply chain is an aspect of a sustainable supply chain (chapter 5.6), and therefore beneficial to Alliance to Zero.

Translated to Roadmap
- Partnership with Sabic
- Recycle PC/ABS and PC at Sabic

- Test PBT recycling
- Test with PCR in plastic components

- Increase contribution PBT and PC through replacements
- Switch to PCR in component production

- PP recycling from the year 2027

Conclusion

To conclude, improvements can be made on the material level to increase the recyclability of the product.
First, the materials are judged on their recyclability, showing that the polymer PA is difficult to recycle and could be considered for replacement with a different material.
Second, leaving out the polymers that have a specific use or interest from recyclers leaves the polymers PA and POM to consider for replacement. The properties on which these polymers are often chosen are plotted into graphs showing that the PA component (5) could be tested when made from PBT, and the POM components (4, 7, 9, 10) tested when made from PC.

Lastly, a partnership with the current supplier Sabic is suggested to close the supply chain loop of the polymer PC/ABS and PC, recycle the polymer PP, and test recycling with the polymer PBT.
These actions could result in 41,5 % (with plastic replacement 60,28 %) of the autoinjector materials being recycled after use and 19,74 % (with plastic replacement 31,87 %) of the materials used in the production of a new autoinjector to contain PCR.

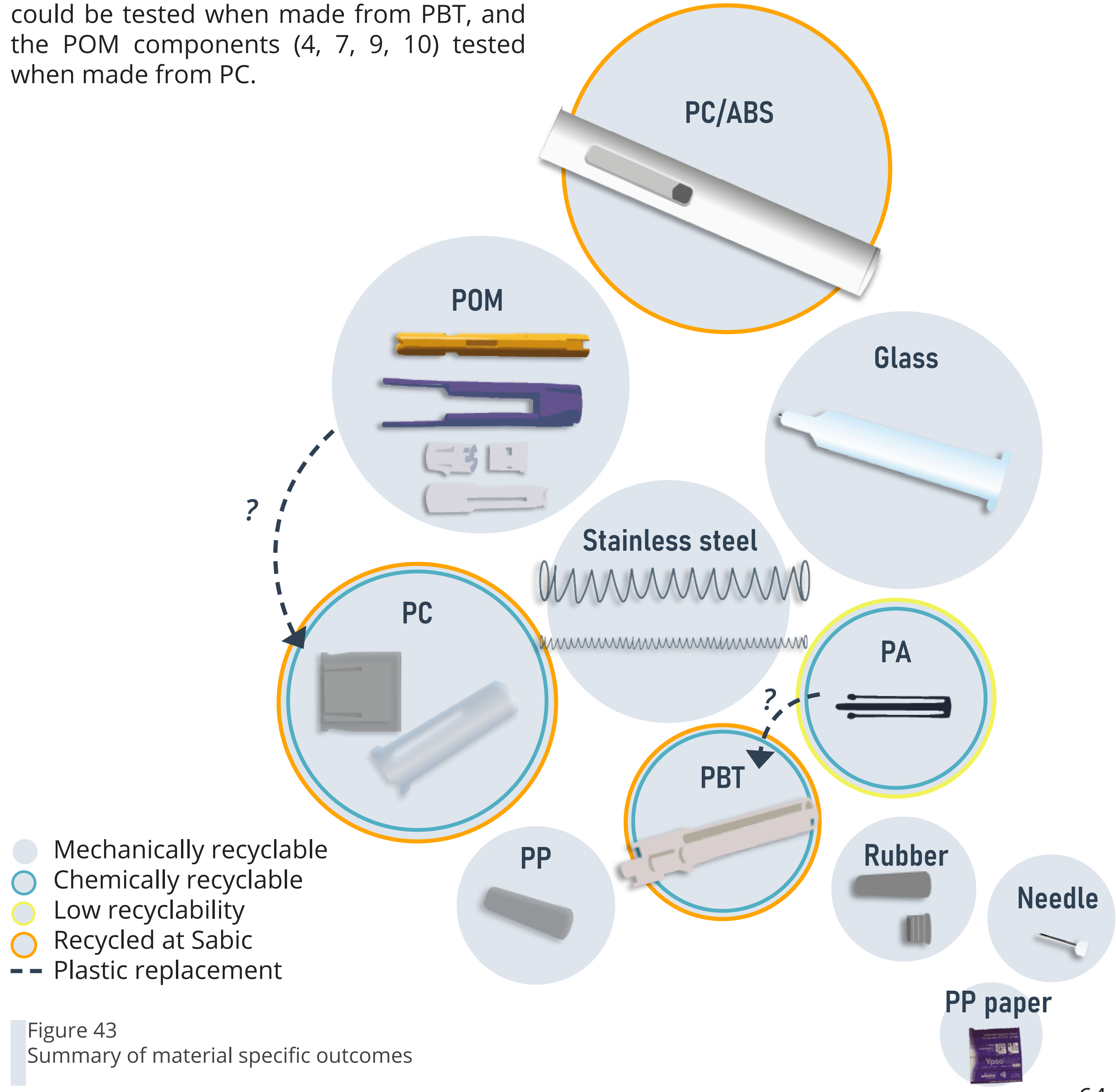


Figure 43
Summary of material specific outcomes

8.

DELIVER GUIDANCE TOWARDS A MORE CIRCULAR FUTURE

The roadmap.

The strategic roadmap

The strategic roadmap is divided into a beginning, middle, and end, called horizons (Figure 44). Each horizon has a different purpose and value proposition, the choices made within the roadmap are connected with this purpose. The three phases are working towards the future of Alliance to Zero, this future was described earlier in chapter 6.1. In this future,

Alliance to Zero, functions as a laboratorial facility where the circular potential of pharmaceutical products is explored. Through valuable partnerships Alliance to Zero has the ability to create circular medical materials and share knowledge in order to realize net zero pharmaceutical products.

The time pacing of the horizons was based on a presentation given by Alliance to Zero, where their ambitions towards net zero emissions were communicated in three phases working towards the year 2030. Basing the year spacing of the strategic roadmap on their vision should increase the ease with which the strategy is implemented.

The three horizons are focussed on creating value yet through different actions, each horizon acts as a gate towards the next horizon. In other words, if the value of horizon 1 is not obtained it will most likely cause that little value will be captured in horizon 2 or 3 as well. Therefore, the values described in each horizon describe the main goal of that period in the strategic roadmap. Anticipating the future environment of the autoinjector, trends and opportunities are communicated and linked to certain actions that should be performed. This anticipation on the future should enable future resilience of the company.

To clearly show the expected increase in the number of autoinjectors produced and therefore collected, the production and take-back volumes are included.
Whereafter, the most important steps that are needed to make the future of the autoinjector more circular through recycling are communicated and divided into three subjects namely, Design for recycling, Warehouses, and Machinery. For some of these steps, a link is made to a possible partner that can aid in the completion of this step.

At the bottom of each horizon, the amount of material that can be recycled and emissions saved due to the decreased dependency on raw materials are communicated.
In summary, the strategic roadmap links important aspects of the autoinjectors current and future environment and capabilities to clearly describe the path that should be taken in order to decrease CO2 emissions through the act of recycling.

Material specific roadmap

Thus far the strategic roadmap has included only a few materials that were linked with important partners. However, a strategy exists for every material of the autoinjector (Figure 45), this roadmap displays the most important steps that should be taken with each material within the time limits of the strategic roadmap. Every step displayed in this roadmap is based on the idea of creating value through the act of recycling.

Horizon 1 : Unlock material value

The first period of the roadmap ranges from 2023 to 2025 and is focused on the unlocking of valuable post-use materials. Whilst in the autoinjector, the materials are already of high value however, in the eye of the recycler, the materials only have value if they are sorted into mono streams.
With the increased market demand for the recycling of engineering plastics, recyclers will be interested in our plastics. Yet, if these mono streams are not obtained the material loses value in the eye of the recycler, or they are downcycled. Therefore, the value of the materials within the autoinjector should first be 'unlocked'.

An implementation step that covers all horizons is the creation of collection routes. This is a crucial step that allows for the autoinjectors to be collected. It continues throughout all three horizons because new clients should be obtained every year. Therefore, the routes through which the autoinjectors are collected are dynamic and will evolve over time.

The next two crucial processes that are needed to create the desired mono streams, are the disassembly of the product and sorting of the components.
Disassembly of the product will result in a mixture of components. These components are made from their own specific material, and if sorted properly are valuable and attractive to recyclers.
Accordingly, the machinery required to sort these components into mono material streams is to be implemented next. As a result, mono streams are acquired and can be sent to possible partners for recycling.

These potential partners should be explored in the first horizon. This could be relationships with recyclers, suppliers or both. Having these relationships set in the first horizon allows for experimentation in the next horizon. Testing with the plastic compounds of the supplier and/or the recycler to explore where the opportunities lie to improve the circularity of the autoinjector.
Additionally, to execute all the activities described above, a warehouse is needed. Therefore, the suggested hub in Germany should be acquired. Continuing with the purchase of the disassembly, sorting, sterilization, and disinfection machines to set up the value creation process.

During this first horizon, no recyclate is used in production and no cuts in the emissions of the raw materials are made yet. Therefore, no closed loop exists, however, some material groups might get recycled through the first partnerships that will be made during this first phase. Resulting in a recycling potential of 52,5 %.

Disassembly

Sorting

52,5 %
Recycled material

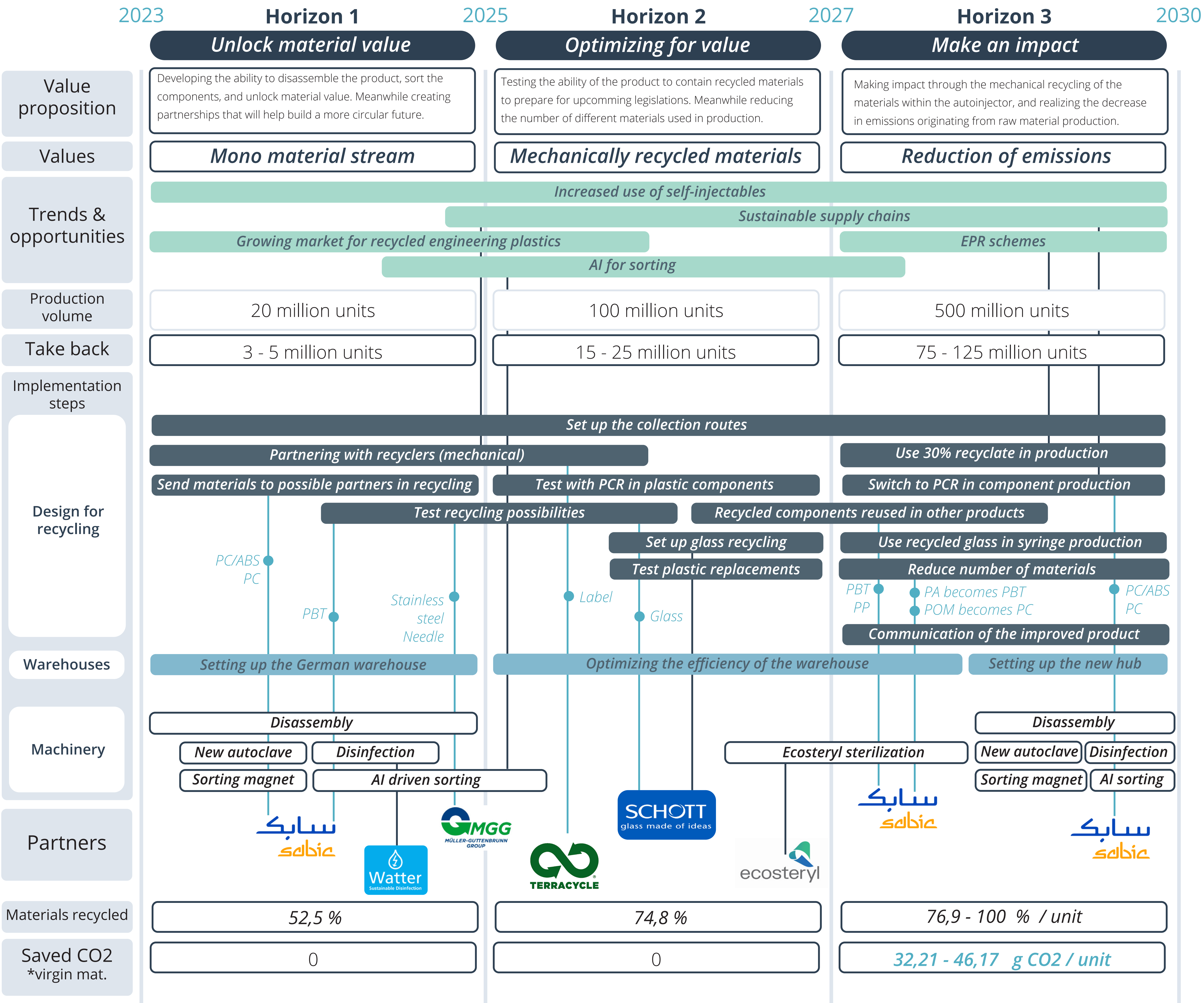
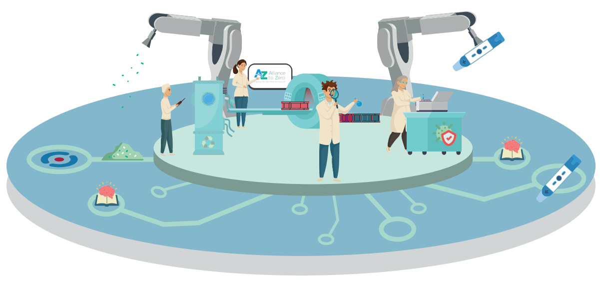


Figure 44
Strategic roadmap

Towards a circular Future.



Building a future where through the exploration of possibillities, a entrpreneurial mindset, and the sharing of knowledge reductions in the emmisions of the pharmaceutical sector can be realized.

	2023 – Horizon 1 – 2025 *Enabling material value*	2025 – Horizon 2 – 2027 *Optimizing for value*	2027 – Horizon 3 – 2030 *Make an impact*
PC/10%ABS	Send to Sabic for recycling	Test with PCR in compound	Switch to components with PCR
POM		Test component with PC polymer	Switch to better polymer & recycle
GLASS	Set up return route to Schott	Test with recycled glass	Use PCR glass in production
Stainless Steel	Send to a steel recycler	Recyclate used in other products	
PC	Send to Sabic for recycling	Test wit PCR in compound	Switch to components with PCR
PA 60% GF		Test component with PBT polymer	Switch to better polymer & recycle
PBT 30% GF	Send to Sabic for testing	Recyclate used in other products	
PP			Send to Sabic for recycling
PP laminated paper		Partnership with Terracycle	Recyclate used in other products
RUBBER	Send to rubber recycler	Recyclate used in other products	
Needle	Send to steel recycler	Recyclate used in other products	

Figure 45
Material specific roadmap

Horizon 2 : Optimizing for value

The second period of the roadmap ranges from 2025 to 2027 and is focused on the optimization of value that can be created through the mechanical recycling of the post-use materials and the efficiency of the value-capturing process.
If the materials cannot be recycled, no reductions in the emissions originating from the raw materials used in the autoinjector can be obtained. Moreover, the process that has been set up in the first horizon should be optimized before expanding to other areas of Europe.

The first optimization of the circular potential of the autoinjector is done through the use of post-consumer recyclate (PCR) in the production of new plastic components. This improvement is enabled through a partnership with Sabic, in collaboration with them a switch can be made to plastics that contain a percentage of PCR. Using plastic compounds with PCR can cause a reduction in the emissions made through the use of raw materials.

The second optimization of the circular potential of the autoinjector is done through the replacement of the plastics PA and POM. Switching these plastics to other plastics that have higher recyclability and already exist within the product causes (1) a decrease in the number of materials, (2) fewer different routes to be driven towards different recyclers, and (3) more weight of the replacing plastic to be sent to a recycler.

However, before these changes can be executed, tests should be performed on both optimizations to assess if the product remains safe for transport, use, and disposal.

Additionally, tests should be performed with the recycled glass. During the third horizon, an important step is to use PCR glass in the production of new syringes. Due to the high recyclability of the glass, the syringe can be manufactured with 100% recycled glass. Together with Schott, the supplier of the glass syringes, the return, recycling and manufacturing of this component should be executed whereafter tests can be performed to determine if the component can be used in the production of new syringes. The use of PCR glass in the manufacture of the syringe will also cause for decrease in the emissions that originate from the use of raw materials.

In summary, before performing the optimization steps three types of tests should be performed to determine whether these optimization suggestions are feasible.

1. Tests with components containing a percentage of post-consumer recycled plastic.

2. Tests with components made from PA and POM produced with a different plastic.

3. Tests with the syringe made from post-consumer recycled glass.

Testing of optimizations

Value chain efficiency

74,8 % Recycled material

Horizon 3 : Make an impact

The last period will be from 2027 to 2030. This horizon is focused on the realization of the circular potential of the autoinjector. Realizing the reductions in emissions due to less dependency on raw materials and the use of mechanical recycled materials. The preparation of the previous horizon has created a new autoinjector that will contain recycled materials.

As a result of the collective exploration of both Alliance to Zero and its partners, optimizations in the product have been made and an impact can be calculated.
This results in the mechanical recycling of 76,9% of the autoinjectors materials and decreases the emissions that belong to the End-of-life phase. The remaining 23,1% originates from the materials PA and POM. The polymer PA is not included due to its low recyclability, and POM because fruitful recycling routes have yet to be found. However, if replacement of both plastics happens as suggested in chapter 7.2, finding a recycler for both polymers might be a waste of effort. In addition, replacing both polymers with a plastic that already exist within the autoinjector, raises the earlier recycling percentage to 100%.

The recycling of the materials allows for their reuse within the production of new components. Specifically, the glass, PC/ABS, and PC polymers aid in the creation of a more circular device. As a result 39,04 % of the materials used in the production of new autoinjectors are recycled and therefore circular. Replacing the PA and POM polymer increases this percentage to 51,17 %. Both percentages answer the in chapter 5.6 discussed Extended Producer Responsibilities.

As a result of a percentage of the materials being circular, reductions in the emissions that originate from production with raw materials are realized. The in chapter 5.1 decribed emissions of 164 gr CO2 eq. are decreased with a precentage of 19,6 to 28,10 % per autoinjector.

As a part of making an impact, a start should be made with the procurement of a second warehouse and machinery. Smoothly expanding the reach that Alliance to Zero has, will cause the impact that they can make to grow.

76,9 - 100 % Recycled material

39,04 - 51,17 % Circular materials

CO2 eq. ***19,6 - 28,10 % Emission saved per unit***

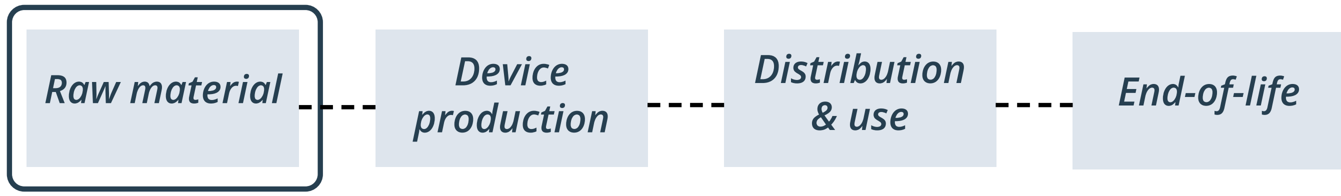


Figure 46
Current value chain of the autoinjector

Recycling partners

In order to make the autoinjector more circular, recycling partners are essential. Within the proposed strategy Sabic is an important partnership because they have the ability to aid Alliance to Zero with both the recycling of materials and supply of PCR containing plastic compounds.

Other partnerships that have been included included are recyclers such as MGG and Terracycle, because MGG has the ability to mechanically recycle more than one material originating from the autoinjector, and Terracycle is one of the few recycling programmes that accept the PP laminated paper stream and therefore unique and important to highlight. In addition, all three partners have a favourable location near the supply chain of the autoinjector shown in figure 47.

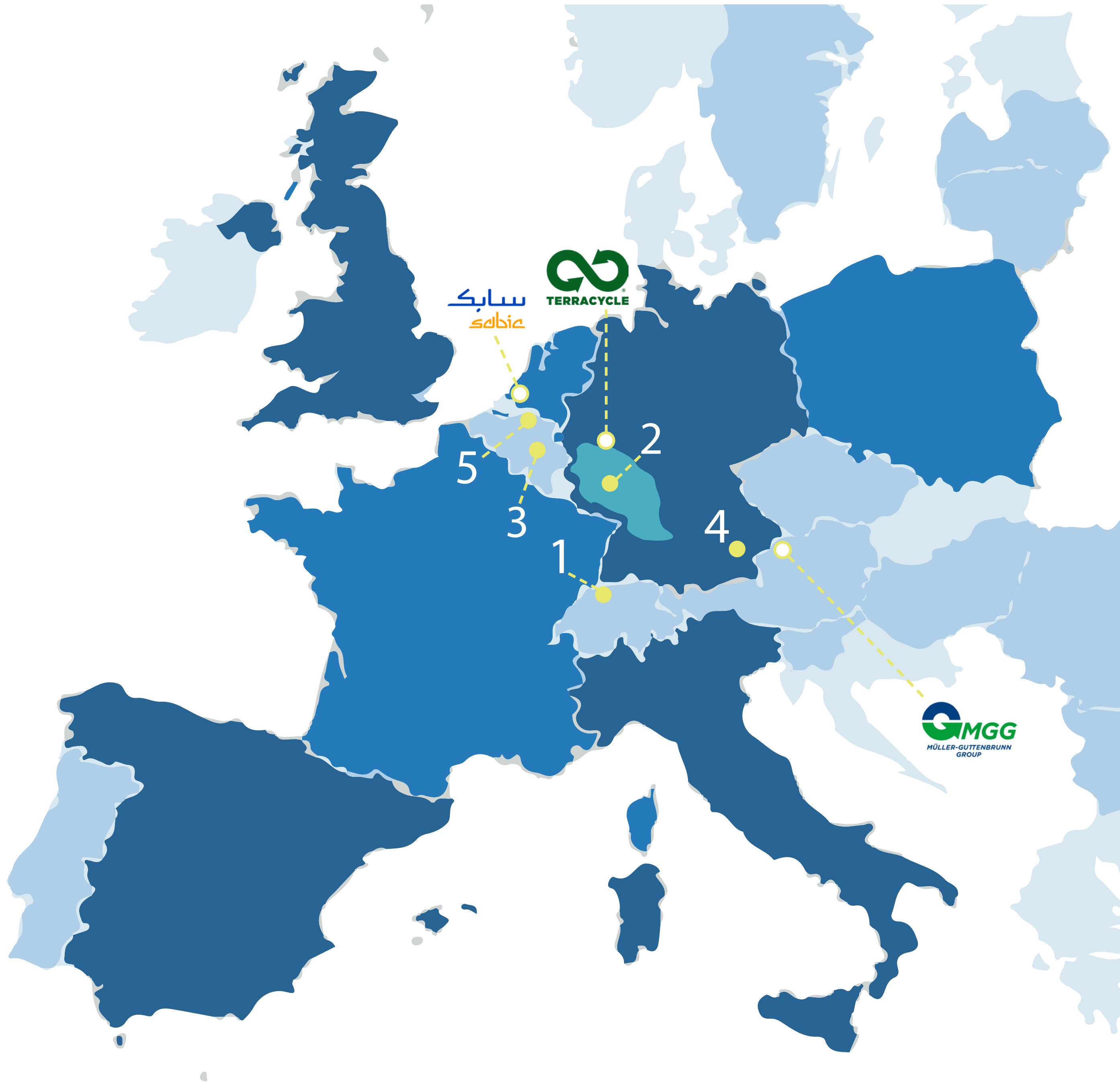
Yet, as a result, the materials POM, PA, and the rubbers have not been paired with a specific recycler. However, the plastics POM and PA are materials that are replaced later on in the strategy whereafter they would be replaced with materials that already have a recycling route. Meaning that it might be inefficient to invest energy time and money into creating a partnership for two difficult to recycle plastics that are replaced in a few years' time.
Moreover, rubber recycling is a very common type of recycling and many recyclers can be found within the area of the supply chain of the autoinjector. Therefore, finding a company that is willing to recycle the rubber of the autoinjector should not be difficult. However, careful consideration should be taken whether adding another recycling route for a low weight and small amount of material is desirable.

Closed loop or open loop

The circularity of materials is mostly obtained through the partnerships with Sabic and Schott. Both partners have the ability to supply materials for production as well as the recycling of materials, as a result a partial closed loop exists within the supply chain of the autoinjector (Figure 48).

A fully closed loop would be obtained when all the materials of the autoinjector are recycled and returned to the production of a new autoinjector. During the production of this new autoinjector no additional raw materials would be needed and the device would exist of 100% recycled material. However, currently there is only one material that can be fully recycled namely, glass.

Technically, plastics are also 100% recyclable however, as described in chapter 5.5, if the quality of the plastics is to be maintained after recycling, the mechanically recycled material should be mixed with raw materials. In other words, 100% mechanically recycled plastic is not desirable.
Additionally, the recycling of stainless steel springs is also called downcycling. After the recycling of these springs it is most likely that they will never become springs again therefore, the chances of this material to be returned to the production of a new autoinjector are low.
Also according to Sabic, the recycling of PBT components is possible. However, the recyclate would be repurposed into other products because the properties of the material will not remain the same after recycling and the material is not desired to be reused within production of the autoinjector.



Density of plastic recyclers

- > 1mt
- between 0.5 and 1 mt
- between 0.25 and 0.5 mt
- < 0.25 mt

Area of interest for the warehouse

Supply chain of the autoinjector

1. Ypsomed (Berdorg, Switserland) - plastic component production

2. Schott (Mainz, Germany) - Glass syringe production and assembly needle

3. Datwyler (Alken, Belgium) - Production of the rubbers and the PP needle cap

4. Schreiner (Oberschleisheim, Germany) - Production of the label

5. Sharp (Hamont-Achel, Belgium) - Final assembly of all sub-assemblies

Figure 47
Partnership locations

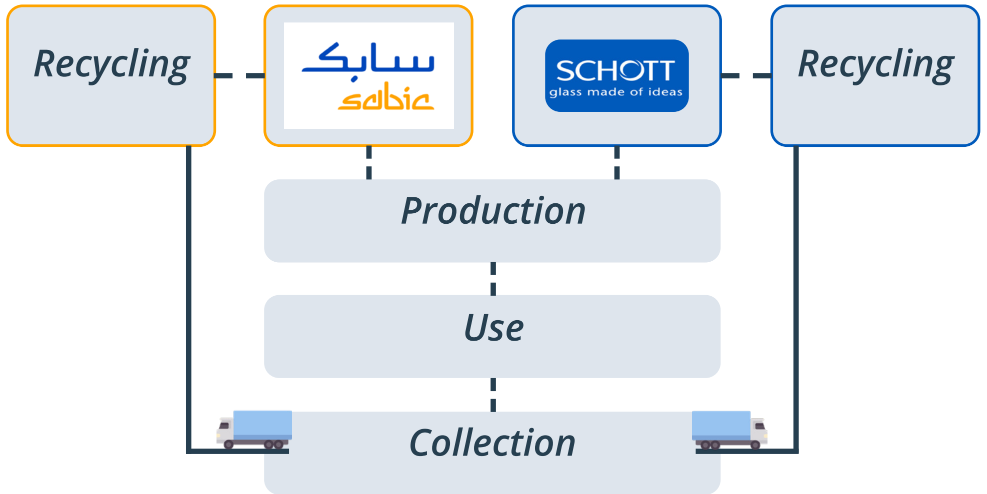


Figure 48
Closed supplier spupply chain

Therefore, the only circularity of this strategy exists within the partnership with Sabic and Schott.
By returning the material streams that they have supplied, mechanically recycling the mono streams, and reusing the glass (100% recycled) and plastic (mixed with virgin) in the manufacture of new components, 39,03 to 51,17 % of material circularity is obtained depending on the replacement of POM and PA. Therefore, the answer to the question whether the autoinjector can become closed or open loop would be partially closed loop.

In summary, the autoinjector has a circular potential of 39,03 to 51,17 % due to the use of recycled glass and plastic in the production of new autoinjectors, and is held back by plastics that cannot be recycled with a 100% yield, materials that are not able to be returned to production after recycling, and metals that are downcycled.

Recycled material *without* plastic repalcement

19, 73 %	recycled plastic
19,3 %	recycled glass

39,03 % total circular materials

Recycled material *with* plastic repalcement

31,87 %	recycled plastic
19,3 %	recycled glass

51,17 % total circular materials

Figure 49
Circular material percentage

Emission savings

As a result of the circularity of some of the materials, fewer emissions will be produced during the production of the autoinjector.
Throughout all three horizons is communicated how much emissions originating from the production with raw materials are saved, yet in the first two horizons, little reductions are made. It is not until the last horizon that the activities of the earlier two phases will pay off their efforts. Both recycling the plastics and using recycled plastic in production should cause a decrease in the total emissions of the autoinjector.

However, the reduction in emissions due to the recycling of the materials after use will cut into the emissions of the End-of-life phase. Whereas the reductions due to using recycled plastic in production will cause a decrease in emissions that are due to the use of raw materials, the focus of this thesis. Therefore, only the latter one is included in the strategic roadmap.

Often, the production of recycled plastics requires only 30% and glass 70% of the emissions compared to production with raw materials (Table 14). Therefore, if the earlier discussed 15,40% recycled plastic and 19,3% recycled glass were to be used in the manufacture of a new product , a reduction of 32,21 g CO2 eq. per autoinjector would be encountered (Calculation 4). To put in perspective, the emissions of the autoinjector that are linked to the use of raw materials would be decreased by 19,6 %.

These numbers do not include the replacement of plastic materials that were suggested in chapter 7.2, doing so would result in 46,16 g CO2 to be saved per autoinjector, and decrease the emissions originally made through the use of raw materials with 28,10% (Calculation 5).

Moreover, if those emissions are multiplied by the expected amount of autoinjector that are collected a range of 2.4 to 4 million kg of CO2 would be saved in the year 2030 (with plastic replacement 3.46 to 5.77 million kg CO2).

Expected CO2 savings 2030 (kg/year)	
NO component materials replaced	2.4 - 4 million
WITH component material replacement	3.46 - 5.77 million

Table 15
Expected savings of emissions in 2030

Material	CO2 footprint primary production (CO2 kg/kg)	CO2 footprint as consequence of mechanical recycling (kg CO2/kg)	CO2 mechanical recycling / CO2 primary production (%)
PC/ABS	4,63 - 5,11	1,57 - 1,74	34
POM	3,04 - 3,36	1 - 1,14	32
PC	5,62 - 6,2	1,91 - 2,11	34
PP	1,85 - 2,04	0,636 - 0,7	34
Glass	1,67 - 1,84	1,17 - 1,29	70

Table 14
Emissions originating from material production, CES edupack

Saved emissions originating from use of PCR (no plastic replacement)

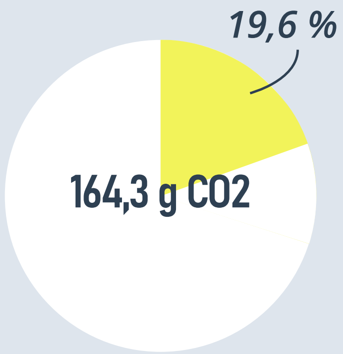
19,73 % recycled plastic (see chapter 7.2) = 32,43 g CO2

32,43 x 0,30 (see table 14) = 9,73 g CO2
32,43 - 9,73 = *22,7 g CO2* (saved due to the use of recycled plastic)

19,3 % recycled glass = 31,7 g CO2

31,7 x 0,70 (see table 14) = 22,19 g CO2
31,7 - 22,19 = *9,51 g CO2* (saved due to the use of recycled glass)

TOTAL **32,21 g CO2 (per unit)**



Calculation 4
Emissions saved originating from use of PCR

Additionally, if the material replacements are implemented according to chapter 7.2 more emissions are saved.

Saved emissions originating from use of PCR (with plastic replacement)

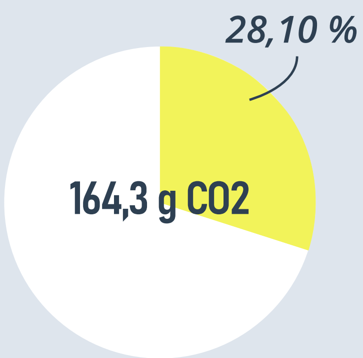
31,87 % recycled plastic (see chapter 7.2) = 52,36 g CO2

52,36 x 0,30 (see table 14) = 15,70 g CO2
52,36 - 15,70 = *36,66 g CO2* (saved due to the use of recycled plastic)

19,3 % recycled glass = 31,7 g CO2

31,7 x 0,70 (see table 14) = 22,19 g CO2
31,7 - 22,19 = *9,51 g CO2* (saved due to the use of recycled glass)

TOTAL **46,17 g CO2 (per unit)**



Calculation 5
Emissions saved originating from use of PCR, with plastic replacement

Sustainable business model.

A business model canvas originally exists of nine segments (Hoekstra, 2022). These segments usually are the key partners, key activities, key resources, value proposition, customer relationships, channels, customer segments, cost structure and revenue streams.
The impact entrepreneur Bar, gave a sustainable twist to this canvas by adding the segments of Eco-social costs and Eco-social benefits, creating the sustainable business canvas (Figure 50) (n.d.). By including these two segments, the business owner is asked what the business its negative and positive impact is on the environment. Filling out this canvas can give a good indication of where the business is and which steps have yet to be taken (Hoekstra, 2022), it plots the costs and benefits against each other, intuitively showing where change is needed.

Value proposition

Through this renewed product Alliance to Zero is offering still the safety, reliability, and ease of use that it has brought the past years. Yet, a new part of their value proposition is to include doing better for the planet as well. Doing so with well-considered partnerships and collective responsibility.

Key partners

According to the in chapter 5.6 discussed trends, setting up a sustainable supply chain requires collaboration. Partners that can aid Alliance to Zero in the implementation of the value chain and creating a more circular future for the autoinjector. For Alliance to Zero this means partners in recycling and disinfection who are willing to collaborate and share knowledge in order to come the best imaginable solutions.

Key activities

The main activities to realize the value chain discussed in chapter 6.4 are collection, disassembly, sorting and disinfection. Very concrete and important activities that should be performed to get the post-use materials of the autoinjector recycled. However, those activities can eventually be automated and optimized. Therefore, less concrete activities are derived from the future vision in chapter 6.1. The three activities of exploring, connecting, and teaching are circled around the idea that Alliance to Zero will always focus doing better together.
Implementing these activities will help Alliance to Zero to improve itself and build resilience.

Key resources

This block describes the physical and human resources needed to perform the activities and uphold the partnerships. Many of these resources have been discussed in chapter 7.2 however, resources are also needed in the form of employees and more graduates or phd'ers willing to further investigate the different routes towards a more sustainable future.

Customer relationships

Channels through which Alliance to Zero builds a relationship with the pharmacies, hospitals and the user of the product. These relationships could be built and maintained through the collection service as well as seminars and webinars where knowledge is exchanged.

Sustainable Business Model Canvas

Key partners

- The Alliance to Zero Partners
- Sabic
- Watter disinfection
- Ecosteryl sterilization
- MGG
- Terra cycle
- Collection service partner

Key activities

- Collection
- Disassembly
- Sorting
- Disinfection

- Explore
- Connect
- Teach

Key resources

- Warehouse
- Disinfection machine
- Sterilization machines
- Sorting machines

- Employees
- Graduates
- PHD'ers

Value proposition

- Safety
- Reliability
- Ease of use

- Best for people and planet
- Responsibility
- Good cooperative relations

Customer relationship

- Collection service
- Knowledge and expertise sharing

Channels

- Pharmacies
- General practicioners
- Instructions on the device

Customer segment

- EU self injectable market

Cost structure

Fixed
- costs of procurement of machinery
- costs of warehouse (electricity, rent)
- costs of employees
- costs of collection and supply
- costs of patents

Variable unforseen costs

Revenue streams

- Investors
- Government grants

Eco-social costs

- Extra CO_2 emissions due to machinery
- Extra CO_2 emissions due to transport between warehouse & value chain
- Disposal of the needle

Eco-social benefits

- Recycling of materials
- Reduction of virgin materials used in production

Figure 50
Sustainable business model

To highlight, customer relations with the user are important to stimulate them to return the product. Knowledge of Alliance to Zero, its purpose, and how the user can easily aid them or be a part of this journey is a first step. The second step would be thinking of where the behavioural intervention should take place in order to ensure that the return of the product becomes part of their behaviour.

Channels

Channels through which customers (patients) are reached are for example pharmacies, general practitioners, and the instruction manual that comes with the device itself.
According to a nurse practitioner specialized in diabetes, the prescription of medicine is often done in consultation with the patient (Appendix J). The person prescribing the medicine merely gives information on the options and the patient makes the final decision. Often the patient chooses the cheap or easiest to use product, convenience and price are very important to the patient.

Whenever the nurse practitioner advises a patient on medication she does highlight when there is a more sustainable option to obtain. However, according to a personal conversation with a general practitioner, sustainability is not on the agenda of most medically qualified drug prescribers.
Yet both agree that when a sustainable option is more costly than a medicine with the same convenience, the patient will most often go with the cheaper option.
Additionally, on an instruction manual or packaging of the device a user can be informed of the collection service that Alliance to Zero provides. Potentially causing an increase in the number of autoinjectors collected.

Customer segment

As described in the project brief, this thesis focussed on the European market of the autoinjector. Therefore, the customer segment is the European autoinjector customers. Direct customers are (online) pharmacies and hospitals, and indirect customers are the patients using the autoinjector.

Costs vs revenue

The costs represent which predictable and unpredictable expenses need to be made. The fixed costs can be one-time payments fo which some were discussed in chapter 7.1, and monthly dues. Examples of variable costs can be costs due to inefficiencies of the machinery or their processes. Something that is very likely to happen since most of the processes used in the value chain have yet to be set up.
Opposed to the revenue area, how is Alliance to Zero going to pay for the expenses made in the neighbouring block?

Eco-social costs and benefits

A trade-off that should be considered carefully is that between costs and benefits on the environment when implementing the process of recycling. Saving of the emissions is central to the research question at hand however, emissions are made by setting up the value chain, running the machines, collecting the autoinjectors and delivering the post-use materials to the recyclers. Quantification of these emissions should be made to assess whether they weigh out the benefits gained through the act of recycling. If operating the process of recycling the autoinjector costs more than it saves, then the route of recycling is not profitable.

9.

CONCLUSION

Emission reductions

As a result of the mechanical recycling of 76,9 to 100 % of the separated materials that exist within the autoinjector, a material circularity exists of 39,03 to 51,17 %. This circularity causes less dependency on raw materials and a decrease of 32,21 to 46,17 g CO_2 in the emissions made during the production of one autoinjector (corresponding with a 19,6 to 28,10 percentual decrease).

Mechanical recycling

Mechanical recycling of a single material stream, the method that is able to recycle the materials from the autoinjector, is the most desired method. It is an established form of recycling, that has the best ability to reduce emissions, and has the preference of experts. Yet, it is only most desired if single material streams can be provided.

A single material stream is obtained through the disassembly of the product and the early separation of the components of the product.
However, mechanical recycling alone will only cause a decrease in emissions that originate from the End-of-life phase. For a decrease in the emissions made in the phase where raw materials are used during the production of the autoinjector, recycled materials should be returned to the production of the autoinjector. In other words, a closed loop is needed.

Partially closed loop

This closed loop is created through a partnership with Sabic and Schott. A closed loop partnership entails that the material suppliers have the ability to take back their materials, recycle them, and thereafter return them to the production of the product. However, for the autoinjector, full circularity will not be obtained through the act of recycling. This is mainly due to the inability of some materials to be returned to the production process, the unlikeliness of a recycled plastic compound to contain 100% of recycled plastic, and the downcycling of metals.

Moreover, the ranges that exist within the earlier given percentages are due to the possible changes that can be made on a material level. More specifically, the polymers PA and POM should be replaced to decrease the number of materials in the autoinjector and increase the amount of recycled and circular materials. As a result, the reductions that can be made are optimized and the highest values within the earlier given ranges are obtained.

To conclude, this research has explored the recyclability of a specific product, the autoinjector. However, materials that are used in this product are also commonly used in the appliance, automotive, and medical sector. Therefore, the information discussed in this study could be beneficial for other products that Alliance to Zero wishes to make more sustainable and for manufacturers in those product areas.
Additionally, this thesis has provided a holistic overview of mechanical and chemical recycling and discussed important considerations that play a role when deciding between the two recycling methods. This information should aid Alliance to Zero in deciding the circular future of the autoinjector and other possible products that belong to the pharmaceutical sector.
However, the most important conclusion remains that, the impact of the autoinjector can be significantly reduced by making the materials more circular through mechanical recycling.

10.

DISCUSSION

The purpose of this section is to provide a more critical perspective on the process and results that have been collected during this thesis. Therefore, limitations that have been encountered are discussed. Additionally, as a result of this thesis, further research areas are suggested.

Limitations.

1ml and 2.25 ml

As mentioned earlier in this report, there are two versions of the Ypsomed autoinjector. However, only one (1ml) has been used during this thesis. As a result, the calculations made are based on the weight and emissions that originate from a 1 ml version. Yet, according to Gerner (Appendix, G), the ratio of both versions in 2030 is expected to be 50/50. Therefore, the emissions that are saved could be higher than expected.

Collection

During this thesis, the assumption was made that the autoinjectors are collected with a take-back range of 15 to 25%. However, due to different regulations per country in Europe (Meds disposal, 2020), the compliance of a country with the collection system might not be a given. This will result in a lower number of collected autoinjectors and therefore the amount of materials sent to a recycler will also decrease and cause less impact to be made.

Disassembly

At the time of this research, the assumption was made that a disassembly machine would be provided by the employees of HealthBeacon in the year 2025, this should allow for the disassembly of all components. However, two difficulties arise with this assumption that are worth mentioning. First, the label (component 1), a sticker that is attached to the housing of the device, and a component that is easy to remove manually. However, if the process were to be automated it is difficult to foresee how a machine will remove a component that sticks to its surface and requires some precision to be removed.
Second, the rubber (component 15) that after injection remains inside the glass syringe (component 12). Again, a component that is simple when removed manually, however in order to get it out of the syringe automatically without fracturing the glass seems hardly possible. This thesis has not considered the limitations that these two components provide in the process of disassembly.

Sorting machine

After the disassembly of the device and the creation of loose components, the separation into mono material streams should happen with a sorting machine. This thesis provides a brief explanation of the difference between manual and automatic sorting and the different industrial sorting machines that exist. It is concluded that the sorting machine that is aided by artificial intelligence will be helpful in the future, and what this machine could mean for the autoinjector should be explored.

However, the assumption is made that the components are successfully sorted into mono material streams without any errors. Yet, in reality, a process as such might not be as efficient and error proof at the start of implementation, especially since the idea behind artificial intelligence is that the system learns by doing. Consequently, the amount of material that was used in the calculations can be lower than anticipated.

Testing of plastic replacement

Increasing the recyclability of the materials within the autoinjector requires the substitution of some of the materials. During this research suggestions based on research have been provided however, due to the limited amount of time no further validation of these suggestions could have been provided. Yet, these suggestions do influence the results of the saved emissions and circularity of the materials.
Therefore, a range is given with the concluding numbers of the saved emissions and recycled materials.

Estimated investments

In chapter 7.1, an estimation is provided on the purchase costs of the machines that are required to develop the value chain. Most price estimates are based on conversations with employees of the companies to which the machine belongs.
However, the estimation of the price of the autoclave is based on the prices of other autoclaves and might not be as realistic. In addition, the estimation only includes purchase costs therefore, one should consider that the realistic costs that come with the implementation of the machinery will be higher than this estimation.

Future research.

Recycling a temporary solution

Recycling, as opposed to other circular strategies that can retain value (Inchainge, 2022), has been the focus of this thesis. And as a result, mechanical recycling has been chosen to help reduce the emissions originating from raw material production and increase the circularity of the materials within the autoinjector.
However, it is also seen as a temporary solution because a material only has a limited number of recycling cycles that it can go through (Folkersma & Jager, appendix F). In other words, after a material has exhausted its maximum number of cycles the material is still lost.
Therefore, research into strategies higher up the Value hill should be researched and compared.

Emission balance

The focus of this thesis is on the savings that are made in the emissions of the material production phase.
However, the implementation of the value chain and the processes required to get the post-use materials recycled are polluting processes. Therefore, research into the emissions that they require is needed and a balance should be composed to assess whether the implementation of this process remains desirable.

Contaminations

The research that was used to determine which materials reside within the autoinjector did not disclose specifications on the contaminations that they might contain. Contaminated plastics could hamper the acceptance of the post-use materials by recyclers. Chemical recycling, specifically solvent-based purification can pose a solution here. As mentioned in chapter 5.5, according to Crippa et al. (2019) this type of recycling removes additives or contaminants from the polymers meanwhile, the structure of the polymer remains intact. Therefore, more research could be done to see if solvent-based purification can be used as a cleaning step before recycling if needed. Making chemical recycling a supporting process of mechanical recycling.

The patient and the prescriber

This thesis discusses many stakeholders, however to test the desirability of the product more research into the patient, the medication prescriber, and the health insurers should be conducted. Making the autoinjector more sustainable makes the device better for the planet and its people. However, sustainability is also a product characteristic that could function as a unique selling point to health insurers, medical staff, and patients.
Yet, according to a personal conversation with a general practitioner, sustainability is not a criterium that many pharmacists include in their decision making process when prescribing medication to their patients. Moreover, the chances of a patient choosing the more sustainable Ypsomed autoinjector will increase if it is covered by health insurance, because most people are likely to choose the cheapest option (Appendix J).
Therefore, future research into the market implementation of the product is required, specifically looking at the health insurers, medication prescribers, and the medication user.

11.

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Appendix.

Appendix A: Project brief

Personal Project Brief - IDE Master Graduation

TU Delft

Increasing the circularity of the autoinjector — project title

Please state the title of your graduation project (above) and the start date and end date (below). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

start date 20 - 09 - 2022 — 13 - 02 - 2023 end date

INTRODUCTION **

Please describe, the context of your project, and address the main stakeholders (interests) within this context in a concise yet complete manner. Who are involved, what do they value and how do they currently operate within the given context? What are the main opportunities and limitations you are currently aware of (cultural- and social norms, resources (time, money,...), technology, ...).

Alliance to Zero is a nonprofit organization who represents the pharmaceutical supply chain. The founders of Alliance to Zero saw that the need for reduction of the footprint in the pharmaceutical world is shared amongst key role players in this supply chain. However change is not happening fast enough to effectively decrease the emissions footprint.
Therefore, the founders of Alliance to Zero recognised the need for these key role players, including component suppliers, machine suppliers, assembly or manufacturing service providers, primary and secondary packaging to final device assembly and even collection after use, to collaborate and share responsibility (Alliance to Zero, 2021). These companies now represent the founding companies of Alliance to Zero, and together they strive towards a net zero carbon footprint in the pharmaceutical regulated market.

A product that belongs to this market is the autoinjector. The single use autoinjectors made their debut in 1980's and were used even more when they became useful to manage chronic diseases in 2006 (Simpson, 2020). The autoinjectors were designed to aid patients to safely and effectively self-administer their prescribed medication. As a result a small portion of the care that usually was given through clinics and hospitals is reorganized towards the patient and the care givers.
The consumer need for autoinjectors that are used for self-administering medication at home is growing. This is due to the increase of allergies and chronic diseases (Roy, 2021). Supporting this need are the benefits that the autoinjector has in eyes of the consumer. Benefits such as, easy self-administration, improved patient compliance, reduced anxiety and dosage accuracy (Roy, 2021).

However, the industry that this product belongs to, the pharmaceutical industry, has a downside. The pharma sector alone is responsible for 52 mega ton CO_2e (Belkhir, 2018).
Moreover, the autoinjector emits 813 gCO_2e (gram Carbon dioxide equivalent) per unit. And a little less than half of those emissions are due to the amount of raw materials that go into this product. A founding company who plays a big role in the part of the supply chain where raw materials are used is called Ypsomed. Ypsomed is a company known for its production of infusion systems for self-medication. This founding company is responsible for 314 gCO_2e of the autoinjector and therefore the most emitting stakeholder due to raw materials used in the production of the autoinjector.
Most autoinjectors today end up in landfill or are incinerated after a single use. The end-of-life of the autoinjector, including the complete incinerations of the autoinjector, the combination of recycling and incineration of the packaging and leaflet, represents 81,3 gCO_2e of the total equivalent of the autoinjector.
Both production and the end-of-life phase of the autoinjector could possibly profit from the use of recycled plastics, bringing down the footprint of the autoinjector and taking a first step towards a net zero emissions product.

Yet, there are a few subjects that might affect the potential of this product to become circular. For instance, which plastics is an autoinjector made from? The answer to that question will influence how we can recycle the plastic and what the material's properties shall be once recycled. And can we use these recycled plastics in the production of new autoinjectors? Furthermore, legislations, there are a lot of product specific rules the product has to follow. But the first bottleneck in this process is retrieving the autoinjectors from the user opposed to throwing them away after a single use.

space available for images / figures on next page

Initials & Name M M Schuringa Student number 4535138

Title of Project Increasing the circularity of the autoinjector introduction (continued): space for images

Material	Component	Weight (gr.)	%	g CO2 eq.	Mechanical / Chemical *solvent-based & depolymerisation	Sterilization
PC / ABS 10%		11.87	28.6	66	M	High Level Disinfection
POM		8.27	20	24	M	High Level Disinfection (purple piece) Decontaminated
Medical syringe		8	19.3	3.3		Sterilization
Stainless Steel		4.88	11.7	27	M	Decontaminated
PC		4.49	10.8	21	M / C	Decontaminated
PA 60% GF		1.3	3.1	6	M / C	Decontaminated
PBT 30% GF		1.26	3	6	M / C	Decontaminated
PP		0.876	2.1	3	M	Decontaminated
Rubber		0.6	1.4	7	M	Decontaminated
		41.55		163.3		

image / figure 1: the product with its materials and emissions

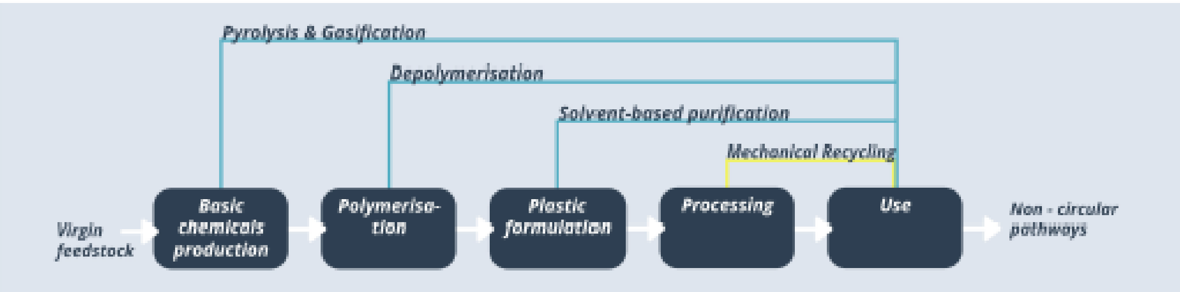


image / figure 2: mechanical and chemical recycling

PROBLEM DEFINITION **

Limit and define the scope and solution space of your project to one that is manageable within one Master Graduation Project of 30 EC (= 20 full time weeks or 100 working days) and clearly indicate what issue(s) should be addressed in this project.

The disposal of single use autoinjectors is not favorable because of two reasons:
1. The autoinjector is considered hazardous waste and should therefore be collected.
2. Valuable materials are disposed after only a single use. The raw materials that go into the autoinjector represent almost half of the CO2e of the product.

During my research I will be focusing on the second reason. Because what if we were to replace some of those raw materials with recycled plastics, and the footprint of the autoinjector can be decreased? To address this matter two sub-questions arise:
1. What are the technical and chemical developments in mechanical and chemical recycling (which one is more sustainable). And which is best applicable to the plastics of used in the autoinjector.
2. Open loop or closed loop? Which one is best applicable to the autoinjector considering the outcome of the first sub-question.

Research question: Can we reduce the environmental impact of the autoinjector through increasing the circularity of the raw materials used in the product?

ASSIGNMENT **

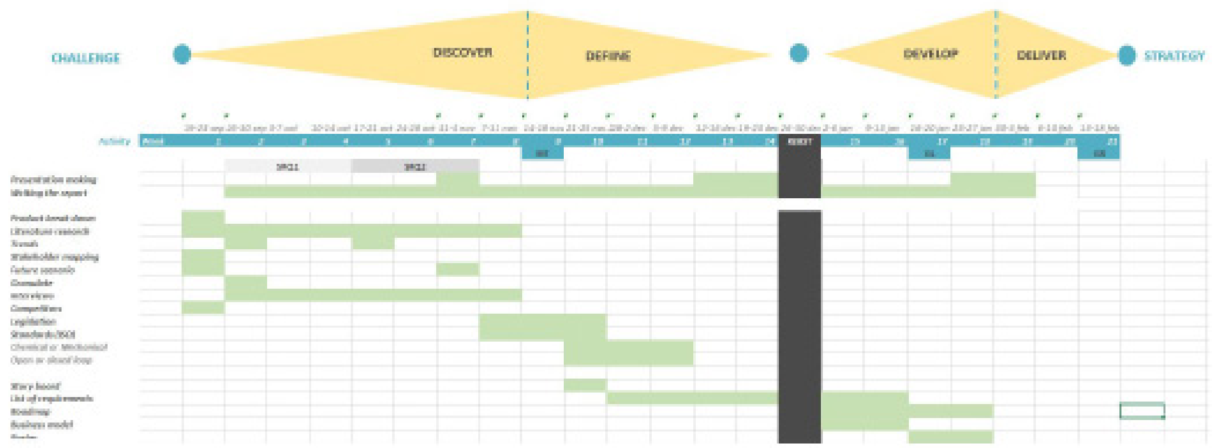
State in 2 or 3 sentences what you are going to research, design, create and / or generate, that will solve (part of) the issue(s) pointed out in "problem definition". Then illustrate this assignment by indicating what kind of solution you expect and / or aim to deliver, for instance: a product, a product-service combination, a strategy illustrated through product or product-service combination ideas, ... In case of a Specialisation and/or Annotation, make sure the assignment reflects this/these.

During my research I will look into the possibilities for the autoinjector to become more circular starting with primary research into how the product is composed and literature research to broaden my knowledge on the two sub questions. Whereafter I will talk to experts on the matter of recycling (chemical, mechanical, material properties), production, end-of-life and legislations to further assess whether it is possible to return the materials to the autoinjector and close the loop, or repurpose them into another product. After having made some well weighted considerations I will provide a strategic roadmap that will give insight into what technological, stakeholder or legislation related developments will do to the future of the autoinjector.

PLANNING AND APPROACH **

Include a Gantt Chart (replace the example below - more examples can be found in Manual 2) that shows the different phases of your project, deliverables you have in mind, meetings, and how you plan to spend your time. Please note that all activities should fit within the given net time of 30 EC = 20 full time weeks or 100 working days, and your planning should include a kick-off meeting, mid-term meeting, green light meeting and graduation ceremony. Illustrate your Gantt Chart by, for instance, explaining your approach, and please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any, for instance because of holidays or parallel activities.

start date 20 - 9 - 2022   13 - 2 - 2023 end date



Initials & Name M.M. Schuringa Student number 4535138

Title of Project Increasing the circularity of the autoinjector

MOTIVATION AND PERSONAL AMBITIONS

Explain why you set up this project, what competences you want to prove and learn. For example: acquired competences from your MSc programme, the elective semester, extra-curricular activities (etc.) and point out the competences you have yet developed. Optionally, describe which personal learning ambitions you explicitly want to address in this project, on top of the learning objectives of the Graduation Project, such as: in depth knowledge a on specific subject, broadening your competences or experimenting with a specific tool and/or methodology, ... Stick to no more than five ambitions.

I have always had a curiosity for the medical world. Therefore, I chose the medical technological entrepreneurship minor during my bachelors. However, I lost that side of design for a while and was motivated to pick it up again and do my thesis in that area. Combining my newly acquired strategic skills, heart for sustainability and curiosity for medical design and become and expert on in my field. When it comes to material research the subject is a little out of my scope but I am keen on acquiring knowlegde on it because it is applicable and helpful in multiple industries to become more sustainable and therefore very relevant.

FINAL COMMENTS

In case your project brief needs final comments, please add any information you think is relevant.

Initials & Name M.M. Schuringa Student number 4535138

Title of Project Increasing the circularity of the autoinjector

2023

Master thesis

MEIKE SCHURINGA