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The smart bin

WRITTEN FOR CYCLUS N.V. AS PART OF COMPANY PROJECT: SYSTEMS ENGINEERING DESIGN PROJECT AT THE TU DELFT

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Acknowledgements

First, we want to acknowledge the work of Lisanne Abutan, Birgit Cornelissen, Robin Liu, and Mark Vermeulen as parts of their work are included verbatim or paraphrased in the current report. As preparation for the project, we did a smaller, similar project. In this project, Dylan Aliberti, Brammert Habing, and Jonathan Pilgram worked with the people mentioned above. The goal of the project was to get accustomed to Systems Engineering principles by designing a system on paper. We worked together for one day a week for half a year. Due to the hard work of the whole group, the project ended up becoming a reality when Cyclus N.V. expressed interest in continuing the work.

Second, we want to express our sincere gratitude for the possibility Cyclus N.V. has given us. The company, responsible for collecting garbage in Gouda and twelve other municipalities, welcomed us with open arms. Everyone in the company was interested in our work, gave us support when needed and helped us by providing considerations which none of us had thought of. In space, materials, or other needs we never experienced any shortage. We enjoyed every day spent at the office, because of the open atmosphere and the fine colleagues. Two people should be highlighted. Emma Raijmakers (specialist product development) and Linda Boot (CEO). We met weekly to discuss the progression of the design. The feedback, directions, and genuine interest we received is invaluable. Besides discussing our design, they also provided us with unique opportunities, such as presenting our design to the alderman of the 9 municipalities participating in Cyclus N.V. They also made sure we had an enjoyable time during our project, by, for example, letting us get our hands dirty with garbage collection for a day.

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During the writing of the report ChatGPT 3.5 has been consulted several times for minor editorial help (OpenAI, n.d.).

List of abbreviations and definitions

- AI: Artificial Intelligence. A collection of computer algorithms, that can be trained to fulfil complex functions. Examples are object recognition, reading of written language and ChatGPT.
- CBS: Central Bureau of Statistics in the Netherlands
- Contamination: waste of a different waste stream than the bin is meant for. For example, an apple in the plastics (PMD) bin.
- DIFTAR: Differentiated Rates (Gedifferentiëerde Tarieven in Dutch). A system where people pay extra for processing of residual waste, while separated waste streams are included in the standard municipal tariffs. DIFTAR is meant to encourage people to separate waste.
- GFT: Organic waste (Groente, Fruit en Tuinafval in Dutch)
- LAP3: Third Landelijk AfvalPlan, Government plan to manage waste. Executive framework of Wm.
- MA: Morphological Analysis. A way of finding the best solution given the functional decomposition and requirements of a system.
- MC: Morphological Chart. A chart containing all possible solutions for the function of the system.
- OPK: Paper and cardboard waste (Oud Papier en Karton in Dutch)
- PMD: Plastics, metals, and drink cartons (Plastic, Metaal en drankenkartons in Dutch)
- System input: the waste the user provides to the system.
- System output: the processed waste that is taken from the system and is not put back.
- Wm: Wet milieubeheer, law environmental management
- WTE facility: Waste-to-energy facilities, otherwise known as incinerators. WTE facilities incinerate waste to generate energy from the incineration process.

Contents

Introduction

In November 2019, the European Parliament declared a climate emergency, and with good reason. Oberle et al. (2019) found natural resources usage has more than tripled from 1970 and continues to grow. The extraction of natural resources accounts for more than 90 percent of our biodiversity loss and water stress. If we continue our current course, we will need the resources of three Earths by 2050. The European Commission presented the EU Circular Economy Action Plan in March 2020, an action plan to move from a 'take-make-dispose' society to an environmentally sustainable circular economy by 2050, ensuring greenhouse gas emissions are significantly reduced (Green Deal: key to a climate-neutral and sustainable EU, 2023; How the EU wants to achieve a circular economy by 2050, 2023).

The authors of this report—Dylan Aliberti (specializing in machine learning methods), Brammert Habing (proficient in prototype engineering), Tim Mulder (expert in profound analysis), and Jonathan Pilgram (skilled in team organisation), students of the research Master Applied Physics at TU Delft—take the climate emergency very seriously. Averaging 23 years old, these authors understand the imperative for immediate, sustainable resource management to ensure a healthy earth to live on for the future. We design a system using system engineering. System engineering is a systematic way to find the best possible system design for a multi-faceted complex problem. The tools of system engineering are for example used by NASA for their space exploration systems (Hirshorn, 2016), moreover, the Dutch government infrastructure organisation Rijkswaterstaat uses system engineering to ensure the needs of their stakeholders are satisfied and the design choices can be justified for all parties involved (Rijkswaterstaat, 2013). Clearly systems engineering is a powerful tool to solve complex problems. The power of systems engineering lies in the fact that it uses scientific thoroughness and analytical skills usually associated with engineers to systematically go through the full design process step by step, resulting in a system design considering all aspects of the problem. To start the system engineering process the problem to be solved must be clearly defined. The goal of the further process is to find the best possible solution based upon the analysis done in the report.

Problem statement

The current way of acquiring more non-renewable resources to produce more products and afterwards disposing of said products can not last forever (Pachauri, Meyer, & The Core Writing Team, 2015). Non-renewable resources are running out, causing shortages all over the world, which in turn creates political tumult (Qasem, 2010). The high consumption of carbon non-renewables creates greenhouse gas emissions, which accelerate global warming, leading to more and fiercer droughts and disasters (UN Department of Economic and Social Affairs, n.d.). Disposing of products create carbon emissions (Eurostat, n.d.) and pollute the environment leading to health problems and loss of biodiversity (O. Ukaogo, Ewuzie, & V. Onwuka, 2020). The problem lies at the hearth of the way we see products. We use them as consumables, with a finite lifetime, disposing the products as garbage when they lose usefulness instead of recycling to win back the resources contained within. Winning back resources from waste-streams created by households all over the world could be the key to ensure a safe future.

In a landscape of ever-changing and more complex separation legislation, households lack the means, knowledge, and motivation to separate waste fully. Cyclus, a Dutch garbage collection company based in Gouda, finds that up to 87% of the waste received as residual waste could still be recycled when properly separated, collected, and processed (de Afval Spiegel, 2022). Currently, residual waste is either burned or landfilled. The mixing of waste streams, so-called contamination, with residual waste is costly to resolve post collection. Contamination of residual waste is mainly caused by organic waste (de Afval Spiegel, 2022). Helping households separate waste from residual waste is the main goal of our project because it is a necessary step towards a circular economy.

The smart bin

To solve the problem statement above we propose a system which acts as a smart bin in households. The smart bin accepts household waste, identifies the waste stream it belongs to, and finally stores the waste in the correct container. Hence, the system makes it much easier for people to sort their waste according to regulations implemented in the Netherlands. Currently the regulations describe six different household waste streams in the Netherlands:

- Organic waste (GFT)
- Paper and cardboard waste (OPK)
- Plastic, metal, and carton waste (PMD)
- Glass waste
- Textile waste
- Residual waste

In addition to separating and storing the waste, the system must handle waste streams, such as organic waste (GFT), with extra care to reduce smell and other unpleasantries. The system takes up a similar amount of space compared to current waste bins in use, made possible by a smart layout of the storage compartments according to the average need of the Dutch household and a possibility to personalise the layout of the storage compartment. Furthermore, the system collects data for waste management at home. The data can be used to notify the collection company. One of the use cases for this data is to notify collection companies when waste needs to be collected. Lastly, the system will even have a possibility to add new future waste streams. Our final design is shown in Figure I.1

Figure I.1: the render of our final design. The system has six bins to separate GFT, OPK, PMD, glass, textile and residual waste and place for the addition of an extra storage, which a household can use as they wish. The size of the bins is to accommodate to the average household needs. The lid on top can be opened and contains a sensor module using a capacitive sensor and spectroscopy sensors to measure the waste. A sub-system of conveyor belts and flippers moves the waste into the correct storage. The bin is shown next to a kitchen counter to show how easily implementable the system is. This render is made using Autodesk Fusion 360.

The system engineering tools and report structure

Designing the smart bin was done based on system engineering tools. The smart bin is a complex system consisting of multiple sub-systems working efficiently together, which calls for a thorough analysis provided by systems engineering. Starting with the problem statement, different tools of system engineering are used. The tools used in the report include a stakeholder analysis, system definition matrices, list of requirements, functional decomposition, morphological analysis, qualitative analysis, quantitative analysis, and a component analysis (Sage & Armstrong Jr., 2000). What each tool exactly entails is described in their respective sections. In addition to the six tools described above, two steps are added. Firstly, an extensive literature analysis of waste processing to help understand the challenges that are faced in the field of waste processing, which is the first chapter of the report. Secondly, the detection Means are tested in a prototype, which is described in the report.

An overview of the system engineering tools used in the current report is now presented. Each tool used in the report has a common goal and only works when used together. The goal of these tools is to guarantee that the problem is investigated fully, and that the solution found solves the problem defined. For example, the stakeholder analysis, located in the second chapter, is a tool to identify and understand the interests, expectations and influence of various stakeholders involved in the project. Also, the current solutions proposed by competitors are analysed. The result is used for defining the needs and bounds of the system in the system definition matrices, located together with the list of requirements in the third chapter. The list of requirements of the system is the result of previous steps and concludes the problem investigation. The next three steps focus on finding the solution for the problem and are all located in the fourth chapter. The functional decomposition gives the functions the system must be able to perform to achieve the requirements. A morphological analysis is to find Means to solve the specific functions. The fifth chapter combines the Means to create design solutions, consisting of a diverging and converging phase. The goal of the diverging phase is to list all viable solutions, followed by the converging phase in which the best solution is chosen through a qualitative and quantitative analysis of the fulfilment of the requirement of each solution. Furthermore, the component analysis lists all the components needed to implement the best solution, to give a handhold to start production of the system. The chapter concludes with discussing the final design.

The other added step, unique to our report, is the prototyping of the detection sub-system, which is as the sixth chapter. Without a working detection sub-system, it is impossible to make anything 'smart' about the smart bin. Besides, the four of us being physicists makes us experts in designing detectors and analysis of the data, so we chose to focus on where our talents lie. The choice to prototype the detection sub-system first is then only natural, and we are immensely happy to share the results of the prototype. Nevertheless, further steps will need to be taken to integrate our prototype in the full system (which needs to be built in the future), for which there is a recommendation in the conclusion located at the end of the report.

1 Literature analysis of waste processing

The problem at hand is not a simple one to tackle, so the first step is to gather information necessary for understanding the complexity of the problem. Scientific papers, regulations and reports from many sources provide the foundation for the background information provided in the chapter. The goal is to provide enough information to see the full scope of the problem, what is currently done and to provide ideas for viable solutions.

First, we delve further into the goals of the Green Deal as presented by the EU (and ratified by the Netherlands), to explain what is meant by a circular economy for municipal waste. Secondly, we examine the effects of linear economies, illustrating how waste is managed when a society does not transition to a circular economy. Thirdly, we look at how waste is currently handled in the Netherlands. Here we consider the size of different waste streams, current regulations, and a brief discussion on the techniques used in the Netherlands to separate waste.

1.1 The European Green Deal

In 2020, the European Union (EU) presented the European Green Deal, a roadmap for Europe becoming a climate-neutral continent by 2050. The green deal states that each participating government should reduce greenhouse gas emission of their respective country by 55% in 2030 compared to 1990 levels. In 2050 the green deal aims to reduce the emission levels even further to a net zero impact. The EU aims to keep the global warming below two degrees Celsius with the goals of the Green Deal (European Commission, Secretariat-General, 2021). As part of the EU, the Dutch government tries to reach the climate goals by using a multidimensional approach, including methods such as decarbonizing current processes, increasing energy efficiency, and securing new renewable energy sources.

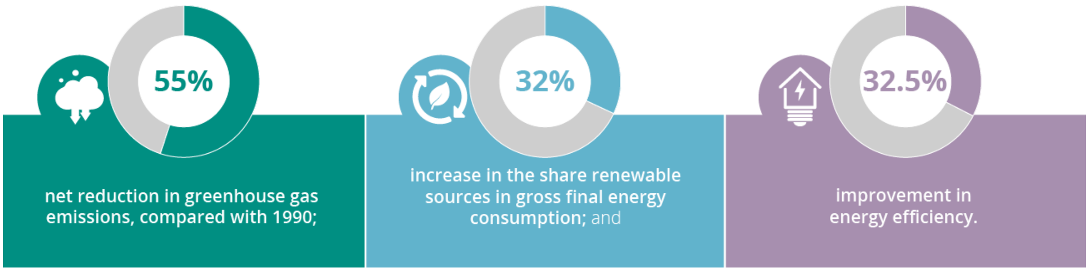


Figure 1.1: Climate goals for 2030 as stated in the Green Deal proposed by the European Union, which the Netherlands has adopted (European Union, 2022).

The Dutch government recognises moving towards a circular economy as crucial for reaching the climate goals. In 2030 the government wants to reduce raw resource use by 50% and in 2050 a fully circular economy without dependency on raw resources (Ministerie van Economische Zaken en Klimaat, November 2019, p. 33). As part of the EU Green Deal, the Dutch government also adopted the Circular Economy Action Plan. The plan outlines various aspects of a circular economy that need to be accomplished to be successful, such as designing products to be recyclable, using fewer toxic materials and harmonising separate waste collection systems. In 2030 the target is to recycle 50% of municipal waste, which only needs to increase further moving forward (Directorate-General for Communication (European Commission), 2020, p. 16).

Circular economy

Historically, resources are often reused to overcome scarcity. For instance, the practice of using organic waste as a fertilizer for new crops dates to the earliest days of agriculture. More recently, after the Second World War, recycling practices were set up in Central Europe to recover precious metals.

Today, the looming resource scarcity is different from the resource scarcities before in the sense that all previous crises could be resolved by acquiring resources that are lying elsewhere. However, since the 1970s it became clear that the Earth has a finite amount of resources. Humans use as much ecological resources as if we lived on 1.75 Earths (Ecological Footprint, 2023). We must move to a circular economy before natural resources are exhausted.

The experts do not agree on a single definition of circular economy, going as far as to debate the need for a unified definition of 'the circular economy'. Currently, the circular economy is merely a utopian concept, not yet proven to be successfully implementable. Our saving grace with the lack of definition is the fact that the need to be sustainable surpasses the need for a definition. Research striving for a circular economy is still considered useful and necessary, as the current 'linear economy' is not able to handle the coming resource scarcity.

The ideal circular economy

In an ideal circular economy, resources are reused as much as possible (Figure 1.2), as opposed to a linear economy, where products are disposed of after use (How is a circular economy different from a linear economy?, sd). The ideal circular economy would be necessary for a sustainable society, as all resources are then acquired from waste, minimizing environmental impact.

Figure 1.2: Schematic of a circular economy (left) and a linear economy (right) (How is a circular economy different from a linear economy?, sd); The schematic on the left shows how everything in a circular economy that is made, is also recycled and no waste is produced; The schematic on the right shows how in a linear economy everything is made from raw materials from nature. Then, after a product is used, it is disposed of creating waste.

In an ideal circular economy, properly recycling valuable materials and substances from a waste stream is necessary. From recycling, valuable resources can be recovered and they can be used for production again, removing the need to extract those materials and substances again. Secondly, disposing of waste in the environment causes pollution and environmental harm.

The Circular Economy is often referred to as the Zero Waste Economy. However, achieving a state of zero waste is not sufficient to address the problem of resource scarcity. If the European Union manages to bring 100% of all waste mass back into the economy, it could only substitute 37,8% of the total mass currently used. Recirculating waste back into the economy is not enough to keep up with current consumption methods (Sileryte, 2023). So even if a material loop is successfully closed by recycling, it eventually results in loss of quantity and quality, because of ever present inefficiencies. So, even getting the most out of our waste is not enough to move towards a fully sustainable system.

Current production chains need to be reinvented to prevent waste or use source parts differently. The Dutch government defines a ladder, ranking different waste handling strategies from circular to linear. This ladder is known as the R-ladder (Figure 1.3) (Potting, Hekkert, Worrel, & Hanemaaijer, 2016).

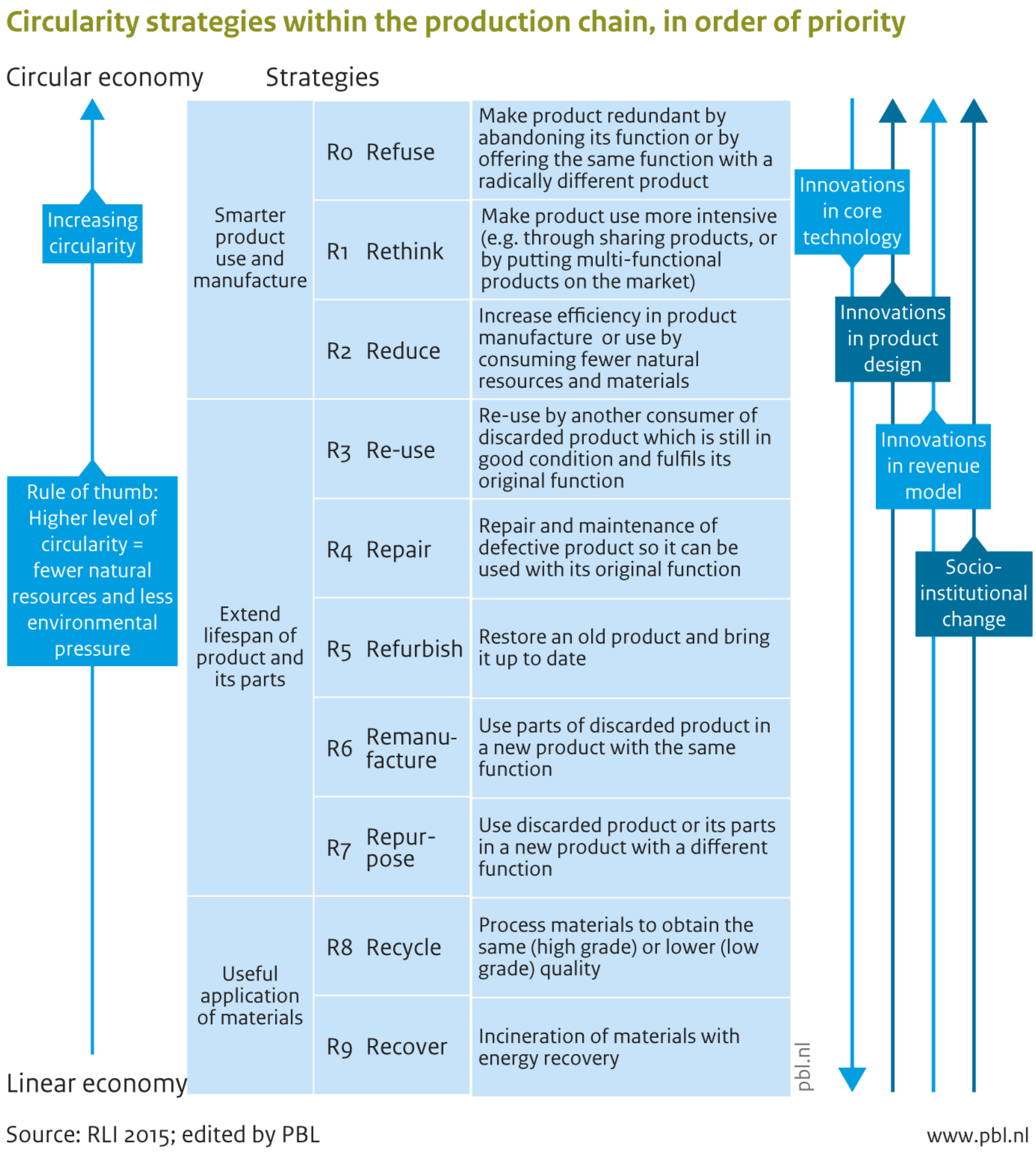


Figure 1.3: The R-ladder. The diagram depicts the hierarchy of circularity for nine strategies. Note that in practice all nine of them need to be used to a certain extent. Aiming for a circular economy, society needs to strive for arranging the economy as high as possible on the R-ladder (www.pbl.nl, 2015).

To reach the ideal circular economy, as outlined by the European Green Deal, the production of processes needs to be rethought from the ground up, using the strategies as outlined in the R-ladder. However, the production of waste is inevitable, as there are always losses. Recycling our waste is crucial now and will remain important in the future.

1.2 Linear economy

A linear economy is not sustainable. Eventually, natural resources will run out, leaving us with only waste. Examples of resources running out in the future are fresh water, fossil fuels, phosphorus, and rare earth metals (Ruz, 2011). Besides the resources depleting, the growing amount of waste poses problems with storage and environmental pollution. Part of Dutch household waste ends up in waste-to-energy (WTE) facilities, otherwise known as incinerators. The remaining ash is landfilled. This is not circular since resources leave the economy permanently. Although a perfect circular economy would be ideal, it is unachievable in practice, because processes always have some loss. Hence, WTE conversion and landfill are always needed. What humanity can do is minimize the amount of waste that is disposed of. Recycling, WTE conversion and landfilling are compatible with each other (Waste to Energy Conversion Technology, 2013). Good WTE facilities and landfills are desirable even with a near-circular resource economy. Let us look more closely at current WTE and landfill technology.

Waste-to-energy (WTE) facilities

WTE facilities, also known as incinerators, produce energy by incinerating waste and utilizing the heat. This method is used primarily in Europe, North America, and Asia. In the Netherlands, WTE conversion contributed to 10.8% of the renewably produced energy of 2018, which is 0.8 % of total energy used (Hernieuwbare energie in Nederland 2018, 2019). After incineration, 10% of the original volume and 25% of the original mass remains in the form of ash (Waste to Energy Conversion Technology, 2013). Sometimes, metals can be recovered from the ash, and the remaining part is landfilled. Processing waste in a WTE facility before landfilling has several advantages over dumping waste unprocessed into landfill (Waste to Energy Conversion Technology, 2013):

- Since only 10% of the volume remains, and metals are retrieved from the ash, the number of landfills needed is decreased by tenfold.
- The total greenhouse gas emissions are reduced compared to landfilling (considering released gases and preventing greenhouse gas emissions by generating energy).
- WTE conversion retrieves 600 kWh per ton waste, while landfill, if gases are captured, only retrieve 65 kWh per ton waste. Furthermore, WTE conversion gives the energy immediately, while landfill gives it slowly over long time periods.
- Metals can be recovered from the ash, which would otherwise end up in landfill. This is more efficient than processing raw metal ores.

During incineration of waste, a variety of gases are produced. Modern WTE facilities have methods to reduce and control the rate at which toxic gases get released into the atmosphere.

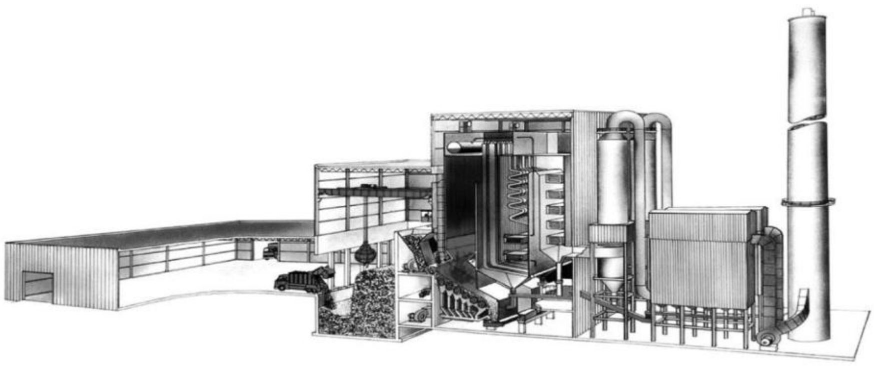


Figure 1.4: 'Typical arrangement of a WTE plant, with tipping floor on the left, bunker, hopper, furnace, boiler, and air pollution control system on the right.' (Waste to Energy Conversion Technology, 2013).

Landfill

Landfilling is the practice of dumping waste at a large central place. Historically, landfilling was done by allocating land and dumping waste on it, which is a cheap way to dispose of your waste. However, this has some environmental problems, which are mostly solved by the more modern sanitary landfills. The problems of classic landfilling are the following:

- Multiple greenhouse gases are released, most of which are methane and carbon dioxide, which contributes to accelerated global warming.
- Liquid can leak from the waste into the environment, which is then called leachate. This contaminates groundwater.
- Sometimes landfills catch fire. While a WTE facility can control and reduce toxic gases that are released when incinerating waste, a classic landfill cannot. Thus, toxic substances are released into the atmosphere.

The modern sanitary landfills reduce the risk of environmental pollution by building a large construction which can collect leachate, and extract gases so they do not end up in the atmosphere. Current landfills are built in a layered structure to reduce the risk of leachate encountering nearby groundwater. This groundwater is monitored to ensure the necessary action can be taken when contaminants leak through (Vaverková, 2019).

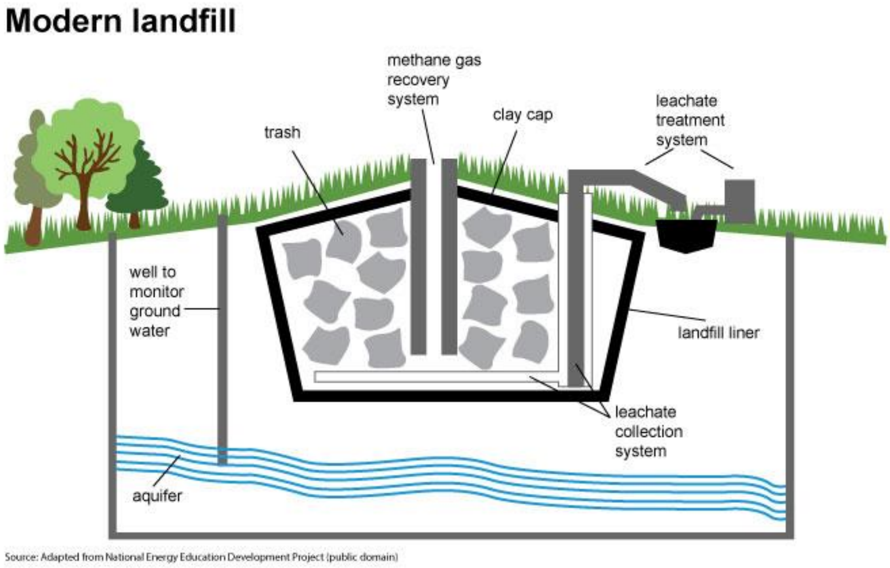


Figure 1.5: Sanitary landfill. Leachate is collected, gas is controlled, and groundwater is monitored to make sure it stays clean (U.S. Energy Information Administration, 2022).

1.3 Households Garbage Streams in the Netherlands

The Netherlands already has an extensive system to separate household waste, which we explore in the current section. First, we dive into the composition of household waste. After that, we investigate the implementation of current regulations. Finally, we conclude with a brief discussion about pre- vs post-separation.

Household waste composition

Improving household waste management requires knowledge about the composition of household waste. We can divide the overall waste stream into two distinct types of household waste, namely: small household waste and bulky household waste. The Netherlands collected 8.467.000 metric tons of household waste in 2018. The Central Bureau of Statistics in the Netherlands identifies different waste streams, which can be categorised as seen in Figure 1.6 (CBS, Centraal Bureau voor Statistieken, 2023).

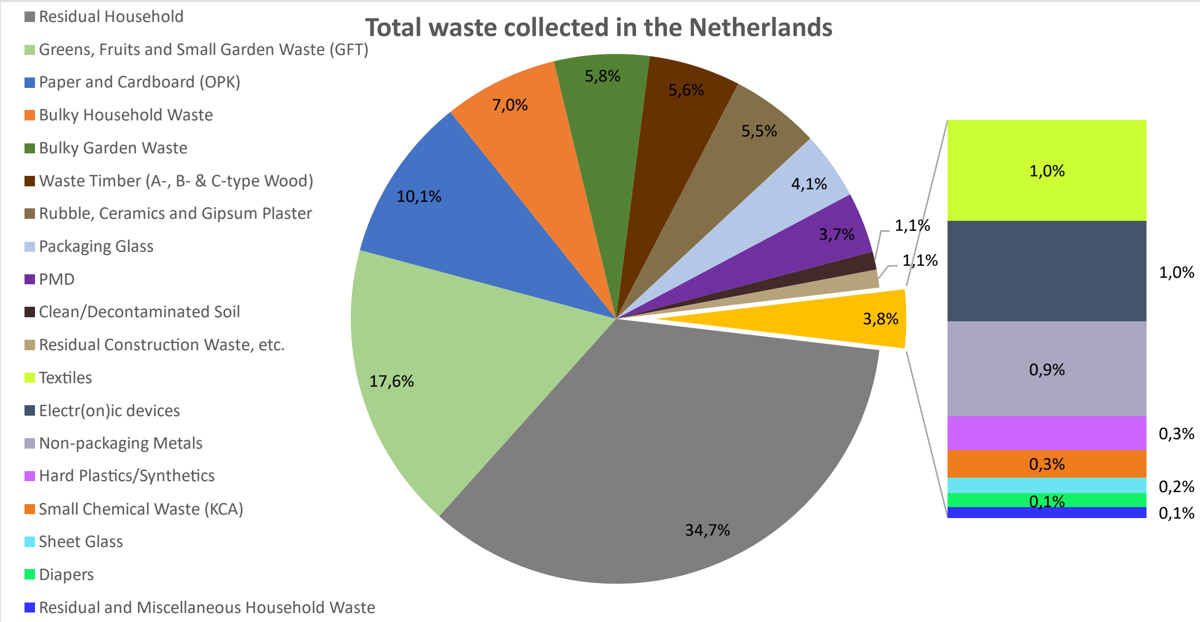


Figure 1.6: Household waste collected by municipalities in the Netherlands measured in mass percentage, as of 2018 (CBS, Centraal Bureau voor Statistieken, 2023). The largest share in the chart, residual household waste, contains all non-pre-separated waste, so the residuals still contain portions of other waste streams. A report finds that only 21% of the residual waste is correctly thrown away as residual waste (de Afval Spiegel, 2022). Therefore, the real composition of waste produced in the Netherlands differs from the chart. The legend shows the waste streams in order of biggest share. For exact descriptions of each stream, see Appendix A: Definitions of waste streams in the Netherlands.

Better defined streams are more easily recycled, whilst mixed streams often require further separation before finding a useful purpose. To ensure streams that are easily recycled, the Dutch government defines a waste management plan, which is described in Appendix A: LAP3 regulations on waste streams.

Residual household waste composition

The collected residual household waste in Gouda has been investigated to check the separation quality of the residual waste (de Afval Spiegel, 2022), summarised in Table 1.1. We can compare and link the statistics of the residuals bin to the 34.7% residual household waste collected in the whole of the Netherlands (CBS, Centraal Bureau voor Statistieken, 2023). The statistics clearly show a discrepancy in the amount of waste which can be separated. For instance, 23.4% of organic waste in the Netherlands reported by the CBS is not all the disposed organic waste in the Netherlands. Using the statistics of the contents of the residuals and the size of the total share (see Table 1.1 and Figure 1.6), we find that another 12.6% of Dutch organic waste is buried in the residual bin. Making the real share of Dutch household organic waste more in the range of 36%. A third of which cannot be correctly processed due to incorrect disposal. This means that a lot of headway can be gained if residual household waste is further separated, preferably at the source.

Table 1.1: The composition of residual waste household waste by category. Numbers mentioned are in percentage of total weight (de Afval Spiegel, 2022).

WASTE CATEGORY	LOW RISE	HIGH RISE	CITY CENTRE	AVERAGE
ORGANIC WASTE	33.7	44.0	26.9	**36.4**
PAPER AND CARTON	4.5	6.4	5.7	**5.3**
HYGIENE PRODUCTS	23.9	23.7	23.5	**23.8**

DRINK CARTONS	0.8	1.0	0.9	**0.9**
PLASTICS/SYNTHETICS	8.3	7.3	7.6	**7.9**
GLASS	2.4	2.4	2.3	**2.4**
METALS	2.5	2.2	2.1	**2.4**
TEXTILES	3.7	3.6	6.1	**4.0**
RUBBLE AND CERAMICS	2.8	0.8	0.2	**1.8**
TIMBER	2.3	0.4	0.7	**1.4**
SMALL CHEMICAL WASTE	0.1	0.1	0.3	**0.1**
ELECTRIC DEVICES	0.3	0.1	1.0	**0.3**
REMAINING WASTE	14.7	7.9	22.7	**13.4**
TOTAL	100.0	100.0	100.0	**100.0**

Pre- vs. post- separation

In the Netherlands there are two kinds of waste separation, namely pre- or post-separation. Pre-separation of waste is households separating their waste into different bins at home, which are then collected separately. Full post-separation, on the other hand, entails a general collection of all waste, which is later separated in a dedicated facility (Stap, 2020).

Currently, there is a debate between municipalities and the respective collection companies whether pre- or post-separation is more effective. For plastics in the Netherlands, post-separation outperforms separation at home in combination with curb side collection in terms of the amount of plastic waste that can be recycled. Post-separation can salvage about 8.4 kg of recycled plastics per inhabitant per year, in comparison to the 7.6 kg plastic recycled per inhabitant per year with pre-separation (Dijkgraaf & Gradus, 2020).

Post-separation does have some downsides. The first being that organic waste (GFT) that is post-separated cannot be used for composting because the contact with residual waste lowers the quality of the waste stream too much. As such, the most one can still get out of the post-separated organic waste is biogas, which is worth less than high quality compost (Vereniging Afvalbedrijven, 2017). The second downside is that the amount of high-quality post-separation installations in the Netherlands is not enough to accommodate all the waste being post-separated, so large investments from municipalities are required (Attero B.V., 2017). The third downside is that it makes residents less involved in the separation of their waste, whilst waste processing companies are putting in effort to involve residents more in the separation process (Rietbergen, van Zeeland, & Polinder, 2018).

Pre- and post-separation should not be viewed as competing, but as complementary. For different waste streams, other strategies are more effective. For example, the approach of Omrin, a post-separation facility, allows them to reuse 74.2% of the PMD waste (Omrin, n.d.). Omrin collects PMD waste with the residual waste and has a facility to separate the plastics. This facility encounters problems with paper waste in the pile of residual waste, so combining the power of pre- and post-separation would mean these facilities reach a higher yield. On the other hand, for kitchen scraps and other compostables (GFT), it is more worthwhile to separate beforehand. So, perfect separation will require a combination of pre- and post-separation, using specific techniques for every waste stream.

2 Stakeholders and competitors

Systems engineers always start by considering the question: 'To whom does the problem matter? And why?' Answering the question gives the stakeholders and competitors of the system. The stakeholders are then ordered according to a Mendelow's matrix, which gives an overview of the interest in and power over the system for each stakeholder. Interest is the amount the stakeholder is influenced by the system, whilst power is the amount a stakeholder can influence the system's success. Key players, both high in interest and power, were identified, from which the needs are investigated in the next step of the system's engineering process. We had the chance to interview some stakeholders involved. The key findings are presented afterwards. Finally, we discuss systems that are designed by competitors to solve similar problems.

2.1 Stakeholders

The stakeholders have various levels of interest and influence on the system. All stakeholders have unique needs, expectations and/or limitations. The relevant stakeholders are presented in Figure 2.1. The four 'key players' during our design are households, garbage collection companies, the municipality and Dutch society. The 'key players' are the stakeholders that are integral to the success of our project and thus extra consideration is taken to see the problem from their perspective.

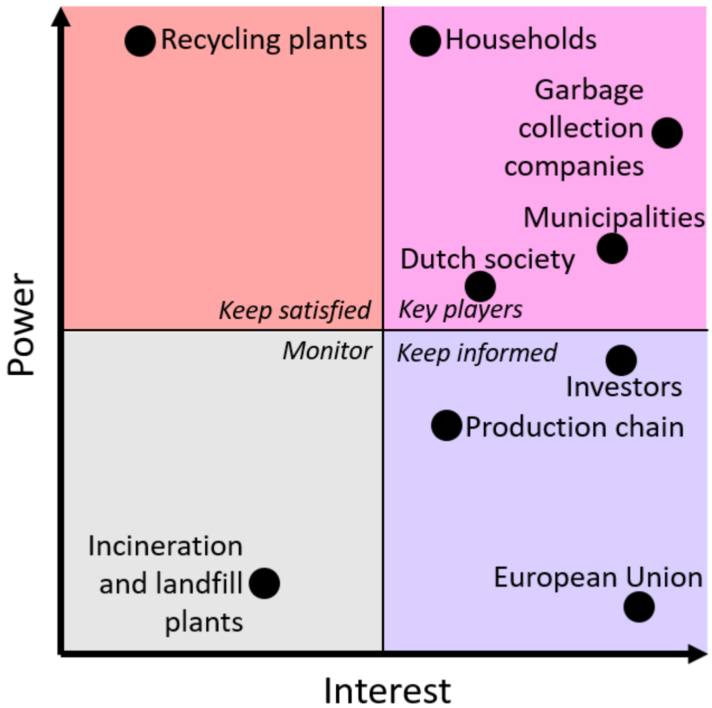


Figure 2.1: Mendelow's matrix. Different stakeholders are categorised according to the amount of interest they have in our system and the power they have over us.

Households

Households are the ones who use our system on a day-to-day basis, so we identify them as key players. During operation, the users have the highest interest in our system as they will use it daily. Households also have a high influence on the design. If the users are not happy with our system, they will choose an alternative. The system helps households in improving their waste separation, so naturally, it must operate within the constraints of their lives. For example, using the system should not take too much time.

Garbage collection companies

Our system plays part in the processing of waste, hence the needs in the waste processing industry should be considered in our project to make sure our system is useful and has a positive impact on the entire process of waste management. To get insight into how the waste processing industry operates, the project is done as an internship at Cyclus N.V., the garbage collection company in the Dutch municipalities Bodegraven-Reeuwijk, Gouda, Kaag en Braassem, Krimpen aan den IJssel, Krimpenerwaard, Nieuwkoop, Waddinxveen and Zuidplas.

Municipalities

We intend the system to become a part of waste management within the Netherlands, so the system must adhere to the Environmental Protection Act, which is enforced by the municipality. The Environmental Protection Act (*Wet milieubeheer* – Wm) prescribes which waste streams are collected. Properly separated waste streams also generate more profit for the municipality, so if our system helps with waste separation, the municipality might invest in the implementation of our system.

Dutch society

As a society, we strive for a circular economy, and a clean and healthy environment. The global environmental impact of Dutch waste contributes to modern problems such as climate crisis and the natural resources of Earth running out. Besides, the Netherlands is mandated by EU laws to reduce the impact of their waste. This makes waste collection a societal issue, therefore it is important to take the needs of society into account.

Non key players

Besides the four key players, there are other stakeholders. The first additional stakeholders are the Recycling plants. The recycling plants decide the contamination quality of waste streams they admit recycling and therefore dictate to which degree waste categories must be separated. The recycling plants are not interested in the methods behind the separation. Recycling plants in this way have power over our system, but no real interest. The second additional stakeholders are the investors, the production chains, and the European Union. These stakeholders are all interested because of economic and/or environmental reasons, although none of them hold much power over our system. The last relevant stakeholders are incineration and landfill plants. These stakeholders hold neither power nor interest but are big players in the current waste processing industry. By improving the recycling rate, less waste is incinerated and/or landfilled, but these facilities continue to exist since some residual waste always remains (14% of household waste according to (de Afval Spiegel, 2022)). So, they have neither great power nor interest in our system.

2.2 Interviews with Cyclus N.V. (garbage collection company)

Our team organised in-depth interviews with Cyclus workers to gain insight into their opinions, ideas and consult their expertise. In preparation of these interviews, we consider the two main topics. The first being a question for potential system users and the second for garbage collection companies. As people at Cyclus N.V. fall in both groups of stakeholders we could learn about two stakeholders at once.

- Why do people not separate waste?
- What do garbage collection companies need to improve recycling?

We brainstormed about these questions to formulate the questions for the interviews. The questions formulated include both broad questions and questions specific to certain functions. Recurring or interesting findings are listed below, ranging from human behaviour influencing quality of waste separation to the current state of waste management.

Human behaviour

The effectiveness of waste separation relies on residents' willingness to separate their waste properly. Drawing from Cyclus’ experience with residents, we can categorize them into three main groups:

1. Well-prepared: people who put in effort to consistently separate waste correctly. They have many bins at home to collect waste. Most of their waste ends up in the correct waste stream. The only things preventing them from perfect separation are changing separation rules and the smallest pieces of waste which are too much of a hassle to separate fully.
2. Willing: this group desires to separate waste correctly but lacks the knowledge or infrastructure to do so. They may not understand which waste belongs to which stream, and some may even question the point of separating waste. Lack of awareness about various systems in place at their respective municipality and insufficient space for multiple bins hinder their efforts. However, if properly informed and provided with convenient solutions for home infrastructure, they would be willing to separate waste. Interviewees estimate this group to be the biggest.
3. Unwilling: Some residents actively do not want to cooperate. The reasoning may vary, ranging from disbelief in usefulness of separation to a strong reluctance to put effort into the process.

DIFTAR, short for Differentiated Rates, is a waste management system adopted by some municipalities to motivate households to separate their waste. Under DIFTAR, residents pay extra for each time they dispose of residuals, while the costs for managing the other streams are included in the standard municipal fees. Proper separation of waste can potentially reduce residuals by up to six times, offering an average four-person household means to cut expenses on waste management by 150 euros per year. See Table 2.1 for a savings example. Data suggests DIFTAR works, as the amount of residual waste decreases after the introduction of DIFTAR. However, DIFTAR is not always successful. Around underground containers of big flats, residents tend to throw residuals in the wrong container to spare expenses, leading to increased contamination.

Table 2.1: Table with example of savings per separated waste stream of the residual waste in municipalities using DIFTAR. The assumption is that an average household empties a 140L Kliko container residual waste each week which costs 3,50 euros per emptying DIFTAR regulations in the municipality of Gouda (Belastingsamenwerking Gouwe-Rijnland, n.d.). The savings are found by the volume percentage of each waste stream in the residual waste (de Afval Spiegel, 2022).

Waste stream removed from residual waste	Savings per year
Organic (GFT, 14% of volume)	25 euros
Plastics, metals, and cartons (PMD, 34% of volume)	62 euros
Paper and cardboard (OPK, 7% of volume)	13 euros
Glass (1% of volume)	2 euros
Textile (2% of volume)	4 euros
Hygienic waste (16% of volume)	29 euros
Other recyclable waste (8% of volume)	15 euros
Total savings with perfect separation	**150 euros**

One of the most interesting findings during the interview was the impact of contamination of GFT on residual waste and vice versa. GFT waste, being one of the most profitable waste streams, is found a lot in residual waste. Besides, GFT is often contaminated with residuals. So, by separating GFT out from the residual waste stream, a lot of headway can be gained. We also found many more interesting facts which are not entirely related to the problem at hand. All the interesting findings are summarized in Appendix B: Interesting findings during interviews.

Design aspects

Multiple aspects need to be considered when designing a system. During the interviews, attention was given to safety and environmental aspects. Environmental impact always needs to be considered in a practical way. For this purpose, the garbage triangle has been defined: environment vs costs vs service. Ideally, organizations like Cyclus would offer the best service for no cost and fully environmentally friendly. In practice however, decisions need to be made weighing these three aspects against each other.

Going back to the safety aspect of system design, the following guidelines were mentioned to provide a quick overview of what to consider:

- Prevent crushing and pinching
- Cover all electrics
- Hygiene
- Ergonomics

Economics & Politics

The municipality does not take much initiative. The policymakers focus on the garbage collectors and limiting the cost of current operations, while investigation into alternatives to current operations is limited. According to employees, Manufacturers should have more responsibility for the sustainability of their products to reach a circular economy. Privatizing garbage collection is also mentioned, the Dutch city of Doorn being an example.

The municipal discussion aside, some other economic aspects were mentioned in the interviews. In the future, waste will be separated into more categories to approach a circular economy. A processor of a certain waste stream only emerges when there is enough waste to be processed in that stream. But when the processor is not yet a business, there is no incentive to separate that specific waste stream. To break this cycle, our system needs to be future-proof and make it easy to add new streams. That way, society can move swiftly to a circular economy. A circular economy also implies little to no residual waste. Residual waste is the most expensive waste stream to process, alongside mixed construction, and demolition waste. This supports the idea of DIFTAR (making people pay for dumping residual waste), see more about that in 'Human Behaviour' above.

Current garbage collection and processing

The current system of garbage collection and processing was also discussed in the interviews. The compatibility with the current infrastructure is relevant in the design of our system since good compatibility would imply a lower implementation cost of our system. Discussing the current operation is also relevant in finding gaps in the current garbage management system. The insight in any potential shortcomings allows for potential improvement and where in the waste process these improvements have the greatest impact.

One of the challenging areas in current waste processing indicated in our interviews is the contamination between different waste streams. Too much contamination makes it impossible to properly recycle. For each waste stream a different contamination percentage is allowed. If this contamination percentage is exceeded, the otherwise separated waste is rejected by the waste processors and is processed as residual waste. Residual waste, being the least profitable and the most polluting, is incinerated or landfilled. Incineration only recovers the energy in the product, but the materials are forever lost.

The net environmental impact of waste collection and processing is positive, according to Cyclus workers in the interviews. Good separation forms the basis for recycling and is a crucial step both for preventing environmental pollution and for using less resources.

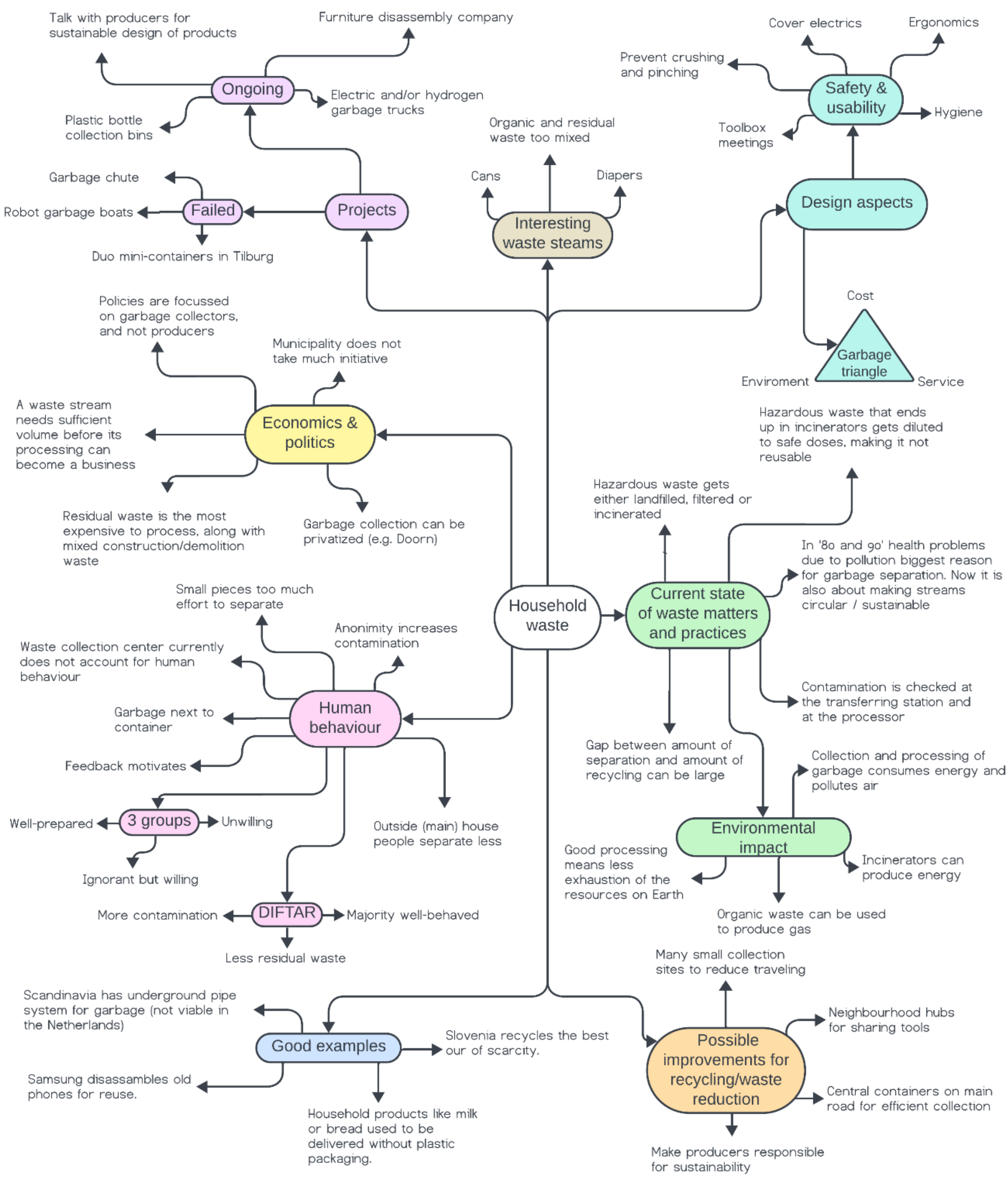


Figure 2.2 Overview of information, opinions and ideas that came up during the interviews with Cyclus workers. See Appendix B: Interesting findings during interviews for the details about each element in the figure.

2.3 Organic waste mystery

From the interviews, it becomes clear that organic and residual waste get mixed more than other waste streams. In fact, 36% of residual waste is organic (GFT), which is a larger portion than any other waste stream. Conversely, 4 % of GFT consists of waste that belongs in the residual bin (Kwaliteit ingezameld gft-afval in Nederland, 2021). This is curious since GFT is the easiest waste stream for a human to recognise. Purely based on GFT being recognisable, it should be one of the best-separated waste streams if we assume that humans are willing to separate. Furthermore, GFT waste is easily separable as it is never a composite of different materials. Something else must be going on, which we have dubbed the GFT mystery. We have compiled a list of reasons commonly mentioned by people when asked why GFT might not be separated well.

- GFT ferments in the bin and starts to stink. People want to get this mess out of their house quickly and do not want to wait until the GFT bin is full. Instead, they throw it in residual, which is taken out of the house more often.
- While cooking, people often get small pieces of GFT, for example while peeling potatoes. They want to get rid of it in the nearest bin and might not want to walk to their GFT bin if they do not have it right next to them. To overcome this, some people have small litre-sized bins on the countertop.
- GFT is often put in compostable garbage bags. Those bags cannot handle the moisture of GFT well, leading to lots of frustration from people whose bags rip while being taken away. Besides, the bags are hard to discern from traditional plastics, prompting some processing companies to post-separate the bags from the GFT (Vereniging Afvalbedrijven, 2015).

Proper household separation of GFT is a crucial step towards a circular economy since current post-separation methods are not able to efficiently separate GFT from residual waste. Hence, considering the problems of GFT is crucial when creating a successful design for our system.

2.4 Competing systems

Luckily, we are not the only one trying to solve the problem of waste separation at home. This section explores some of the alternatives and discuss their feasibility. We contacted a similar startup called WAST-e which produces a system that can recognise waste based upon their barcode. Another interesting party we contacted is Omrin, which does post-separation of waste. Finally, we consider a startup from Eindhoven called Plaex, which sells a fully automated garbage separation bin.

WAST-e (barcode-based scanner)

Jelle Vijhuize, the creator of WAST-e, was happy to discuss his ideas about waste separation with us. He also showed a working prototype of his product, which is currently used at two locations. The prototype was able to recognise most barcodes on products and would then give advice on which stream the waste belongs to. Technologically there were still some challenges, like the barcode database not being extensive enough. The result is that some barcodes are not recognised or correctly labelled. Besides, not all waste has a visible barcode (such as GFT or mashed up waste). Finally, the GFT mystery implies that advising people is not enough to have a significant impact on separation of waste.

Nevertheless, the technology of the barcode scanner is interesting and is interesting to use as a coaching device in public and semi-public environment. However, due to the coaching role WAST-e takes and the fact that—even with a perfect database—it can only handle products with a barcode; we do not think the system solves the problem of household waste separation. A picture of WAST-e is shown in Figure 2.3.

Figure 2.3: Photo of the WAST-e digital waste coach (Vijhuize, 2023). It shows the ready state on screen. Below is a small barcode scanner, which tries to identify presented products. Afterwards the screen shows the correct waste stream for each component of the product.

Omrin (post-separation company)

Omrin is the waste processing company for the surroundings of Friesland. We contacted the spokesperson of Omrin to ask them questions about their company. Omrin collects GFT-, OPK, glass, textile, and chemical waste separately. PMD waste is collected with the residual waste. To separate PMD waste from the residual waste, Omrin uses post-separation. Their approach allows them to reuse 74.2% of the waste (Omrin, n.d.).

Omrin employs a meticulous process to separate plastic from residual waste, focusing on five specific types: High Density Polyethylene (HDPE), Low Density Polyethylene (LDPE), Polyethylene Terephthalate (PET), Polypropylene (PP), and Polystyrene (PS), as well as Polyvinyl Chloride (PVC) (Vos, Plastic Identification Anywhere, 2021). Utilizing advanced technology, Omrin relies on near-infrared (NIR) cameras to distinguish these various plastic types, as all different types of plastic show a distinct reflective infrared spectrum. However, challenges arise with layered plastics, exemplified by shampoo bottles featuring labels made of different plastic materials than the bottles themselves. To address this issue, Omrin is actively exploring the use of image recognition technology, showing promising results, although it encounters complications when packaging designs change. Once the plastic type is identified, Omrin utilises air pressure to blow the plastic off the conveyor belt. However, complications arise when the plastic stream is contaminated with OPK waste, as paper is lightweight and easily carried by air pressure, and wet paper tends to adhere to plastic surfaces. Despite these challenges, Omrin continues to refine their methods to enhance plastic separation efficiency.

Plaex (automatic sorting bin)

The startup Plaex is the furthest in development of a similair product, called Garby. We had a video conference with two of the founders of the startup. Currently, they are running a pilot with several of their products at companies, depicted in Figure 2.4. Garby is a smart bin that is able to sort thrash in four categories: plastics (PMD), paper (OPK), organic (GFT) and residuals. All four storage compartments are 60L. The user can put in one item at a time, and then it gets automatically sorted to the correct storage compartement. They claim that the system is able to do this at a speed of 2.75 seconds per item with an 87.5% accuracy. The system identifies with a vision-based Artificial

Intelligence (AI) and sorts with proprietary mechanics. The vision-based AI makes the system very easily adaptable to new wastreams, as the intelligence can just be retrained with the new waste stream in mind.

There are, however, some downsides too. The processing time of 2.75 seconds could agrevate users and discourage users from using the system, which they plan to circumvent by allowing multiple inputs at the same time. Finally, 87.5% accuracy is not enough to prevent the OPK (3% allowed contamination) and GFT (5% allowed contamination) stream from becoming too contaminated. Possibly they can increase the accuracy in the future by expanding the dataset on which the AI is trained or add a different type of sensor. Finally, using a vision based AI has limitations. The AI will need to be trained (anew) to recognize every (new) product, otherwise it will not identify the product correctly. Let alone when packaging of products change. As an extreme example, when the Dutch football team participates in the world championship almost everything in the Netherlands will have orange packaging, confusing a vision based AI. Smaller changes in packaging are continuously happening.

Figure 2.4: The Garby bin, with the input on top. On front the four streams it can sort are depicted.

3 System Definition

This chapter presents the system definition matrix, a tool from the systems engineering approach which helps in obtaining a clear overview of why the system is necessary and what the system needs to do to be useful. After the system definition matrix, the bounding (limiting factors) of the system is considered.

Engineers and scientists are keen on immersing themselves in technical problems. Not only out of love for these kinds of problems, but they are also educated to solve technical problems. The problem-solving mindset is useful for approaching technical challenges but has one big issue. The engineer is not thinking about what problem he should be working on. Scoping is a tool to help figure out what the system should do to be useful. On the other hand, keeping check on the bounds makes sure the system is feasible.

3.1 Scope of the system

The first step of scoping is the formulation of the needs of the stakeholders. The needs give insight into why the system is necessary and what our system needs to do to be useful. We formulate the needs for the four most important stakeholders, Garbage Collection Companies like Cyclus, Dutch Society, households, and the municipality (Gouda).

Table 3.1: The needs of our four most important stakeholders: garbage collection companies, Dutch society, households, and the municipality. For every need we have formulated objectives, which state what our system must do to satisfy the need of the stakeholder.

Need of stakeholder	Objectives of the system
Garbage collection companies need to collect garbage according to LAP regulations	Output disposable in a mini container
	Output disposable in a (underground) container
Municipalities need to comply with the Environmental Protection Act (Wet milieubeheer – Wm)	Separate Dutch household waste
	Improve recycling of Dutch household waste
Households need to dispose their garbage	Store waste
	Fit in a household
Dutch society needs to reduce the global environmental impact of Dutch waste	Operate without harm to the outside world
	Encourage users to use the system
	Decrease the net environmental impact of waste

For each need a variety of objectives are defined as goals of our system. The objectives are formulated to answer: what must our system do to satisfy the need of the stakeholder? Our objectives are divided into lower- and higher-level objectives. The lower-level objectives specify what is necessary for the high-level objective to be met, whereas the high-level objective shows why the lower-level objective is important. The lower-level objectives, or sub-objectives are linked to criteria. Criteria define how to assess the performance of our system and thus are always defined with a measurable unit. For each need a table with the objectives, sub-objectives and criteria is made. The needs and the corresponding objectives are found in Table 3.1.

Garbage Collection Companies

For the Garbage collection companies, we formulated the need: 'Garbage collection companies need to collect garbage according to LAP regulations.' The LAP regulations are the Dutch policy framework for waste handling. The third plan (LAP3) has been in effect since 2017. The three objectives that follow from this need are:

1. Output disposable in a mini container
2. Output disposable in a (underground) container

The two objectives arise from the fact that some households present their waste via a mini container, and other households provide their waste in an underground container, depending on the size of the house. So, the system must be compatible with both types of containers to ensure compliance with current collection techniques used by garbage collection companies. The objectives are then split into sub objectives for each household waste stream that is collected, with corresponding criteria defined by the size of the respective container. Found in Table 3.2.

Table 3.2: Objectives, sub-objectives, and criteria for the need: garbage collection companies need to collect garbage according to the LAP regulations.

Objectives	Sub-objectives	Criteria
Output disposable in a mini container	Dispose GFT waste output in a mini container	The output of the system fits in a standard mini container from Kliko with a volume of at least 60 L
	As above, but for PMD	As above, but for PMD
	As above, but for OPK	As above, but for OPK
	As above, but for textiles	As above, but for textiles
	As above, but for residual	As above, but for residuals
Output disposable in a (underground) container	Dispose GFT waste output in a (underground) container	The output of the system fits in an (underground) GFT waste container
	As above, but for PMD	As above, but for PMD
	As above, but for OPK	As above, but for OPK
	As above, but for glass waste	As above, but for glass waste
	As above, but for textiles	As above, but for textiles
	As above, but for residuals	As above, but for residuals

Municipalities

Dutch municipalities must comply with the law made by the Dutch government, so the need is formulated as: ‘Municipalities need to comply with the Environmental Protection Act (Wm).’ The law dictates that municipalities need to separate waste and in which streams. Burning residual waste is costly, so municipalities prefer to recycle waste to keep costs low. The high-level objectives are

1. Separate Dutch household waste.
2. Improve recycling of Dutch household waste.

The first objective is achieved by separating out all the waste streams that can be collected at home (or at an underground container). The sub-objectives define the five streams that need to be separated from residual waste. The criteria of separation are defined by the average composition of residual household waste in Gouda (de Afval Spiegel, 2022), as getting a better than average separation of residual waste means improvement. For the second objective the same waste categories are chosen, and thus very similar sub-objectives emerge. The criteria are found by the percentage at which the waste stream is rejected by the recycling companies and thus becomes residual waste. Found in Table 3.3.

Table 3.3: Objectives, sub-objectives, and criteria for the need: Municipalities need a clean and healthy living environment.

Objective	Sub-objective	Criteria
Separate Dutch household waste	Separate GFT waste	The mass percentage of GFT waste in the residual waste stream is lower than 36%
	Separate PMD waste	The mass percentage of PMD waste in the residual waste stream is lower than 7%
	Separate OPK waste	The mass percentage of OPK waste in the residual waste stream is lower than 5%
	Separate glass waste	The mass percentage of glass waste in the residual waste stream is lower than 2%
	Separate textile waste	The mass percentage of textile waste in the residual waste stream is lower than 4%
	Allow addition of a new waste stream	The system can operate with any combination of the above-mentioned waste streams
Improve recycling of Dutch household waste	Minimize contamination of GFT waste	The contamination of GFT waste is less than 5% measured by mass
	Minimize contamination of PMD waste	The contamination of PMD waste is less than 15% measured by mass
	Minimize contamination of OPK waste	The contamination of OPK waste is less than 3% measured by mass
	Minimize contamination of glass waste	The contamination of glass waste is less than 5% measured by mass
	Minimize contamination of textile waste	The contamination of textile waste is less than 5% measured by mass

Households

The need formulated for households: households need to dispose their waste. Obvious, but a very important need for our system. The high-level bjectives are:

1. Store waste.
2. Fit in a household.

An average four-person Dutch household produces about 40 kg of waste in a week (Milieu Centraal, 2023). Now we can combine the statistics of the waste composition in the Netherlands (CBS, Centraal Bureau voor Statistieken, 2023) and the composition of residual waste found in Gouda (de Afval Spiegel, 2022) to convert the 40 kg a week to volume for each storage bin to store a week worth of waste. For the full calculation, see Appendix C: Volume calculation of waste division. The first objective ensures that the system has the capacity to store the waste. The sub-objectives are the storage of all the categories of waste collected in households. The criteria are based on the average composition of waste, with a possibility to add storage for a future introduced waste stream.

The second objective is to ensure the system fits in a Dutch household. The sub-objectives describe all kinds of goals that need to be met to get the system in households, such as maximum size and marketability. Marketability is interesting as good separation can cut expenses quite a bit for households living in a municipality using DIFTAR (Up to 150 euros a year according to Table 2.1). So, paying a higher price upfront for your garbage can very well be worth it in the long run. The criteria are based on respective standards, estimates or, for the more subjective goals, surveys among potential users. Found in Table 3.4.

Table 3.4: Objectives, sub-objectives, and criteria for the need: Households need to dispose of garbage.

Objectives	Sub-objectives	Criteria
Store waste	Store GFT waste	The system can store 10L of GFT waste
	Store PMD waste	The system can store 25L of PMD waste
	Store OPK waste	The system can store 10L of OPK waste
	Store glass waste	The system can store 5L of glass waste
	Store residual waste	The system can store 10L of residual waste
	Store textile waste	The system can store 5L of textile waste
	Allow additional storage for extra waste streams	The system can be fitted with another storage of 15L
Fit in a household	Design for marketability	The system costs less than €250, -
	Reduce smells	Less than 5% of the users experience the system as smelly
	Dispose input waste quickly	The system must allow deposition of waste within 2 seconds
	Operate easily	95% of the users can operate the system without further instruction
	Operate safely	Is certified according to directives and standards of CE certification for household electronics
	Fit in a household	The size has a maximum height of 2 m
		The size has a maximum width of 1 m
		The size has a maximum depth of 80 cm
	Weigh little	The system does not weigh more than 20 kg unloaded.
	Reduce nuisances	Less than 5% of the users experience nuisances caused by the system
	Operate silently	The system produces maximally 50 dB of noise during operation
	Please aesthetically	90% of the users find the system aesthetically acceptable
	Operate durable	The system must operate for over 10 years
	Operate hygienically	The system must be cleanable with common household cleaning utilities

Dutch society

The need of Dutch society is: 'Dutch society needs to reduce the global environmental impact of Dutch waste'. The global environmental impact of Dutch waste contributes to modern challenges such as the climate crisis and the natural resources of Earth running out. Besides, the Dutch society is mandated by EU laws and national regulations to reduce the impact of their waste. The three objectives for this need are:

1. Operate without harm to the outside world.
2. Encourage users to use the system.
3. Decrease the net environmental impact of waste

The first objective is split into harming the environment and harming the existing utilities infrastructure, which can be tested against existing regulations. Without users using the system there is no societal benefit. The objective is split into three sub-objectives. The user can be engaged with statistics about amount of CO2 reduction their use of system has caused. The system should be inviting to use i.e., people should instantly recognise that the system is a garbage bin. The user should also have monetary incentives to use the system, such as reducing the residual waste stream, which for example saves money if the municipality for uses DIFTAR.

The third objective is split in sub-objectives which all together ensure that the system does not in some way damage the environment when adding all effects together. The three parts covered are the production process, the durability of the system and the costs during operation. In an ideal world all of these would put minimal strain on the environment. The criteria are based upon circular design principles and comparisons with similar products. Found in Table 3.5.

Table 3.5: Objectives, sub-objectives, and criteria for the need: Dutch society needs to reduce the global environmental impact of Dutch waste.

Objectives	Sub-objectives	Criteria
Operate without harm to the outside world	Operate without harming the environment	The system does not leak harmful gases
		The system does not leak harmful fluids
		The system does not release harmful particles
	Operate without damaging the utilities infrastructure	The system adheres to the regulations of the Dutch utilities infrastructure
Encourage users to use the system	Provide users with statistics about the CO2 reduction of the system use	The kg CO2 equivalent impact of the system is measurable with 95% accuracy
	Make usage inviting	95% of potential users recognize the system as a waste bin directly
	Provide users with monetary incentives	The system reduces the residual household waste per year by 30 kg
Decrease the net environmental impact of waste	Make reparation easy	The technical manual is freely available on the internet
		Spare parts can be ordered
		The inner mechanics of the system are accessible with a screwdriver
	Recycled at end-of-life cycle	The system design uses no glue or other irreversible construction in between replaceable parts
	Produced with few non-renewable resources	The system is designed with 60% mass percentage recycled materials
		The system is designed with less than 5% mass percentage rare-earth materials
	Produced emitting little greenhouse gases	The production of the system emits no more than 300 kg CO2
	Minimize resource usage during operation	The system does not consume resources during operation
		The system uses less than 50 W average during operation

	Make a positive impact on waste recycling	The system reduces the negative impact of household waste by 200kg CO2 equivalent per year.

3.2 Operation bounds

Table 3.6 shows the operation bound in a system definition matrix. The bounding contains the constrains, parameters and variables associated with the system. The constraints are various limitations to the system imposed by the needs of the stakeholders. The parameters are external factors that need to be taken in account when deploying the system. Finally, the variables are measurable quantities that need to be taken in account during operation.

The most important bounds are created by the fact that households have limited amounts of resources. Users want the system to be as small as possible, as cheaply as possible and operating as quickly as possible. During interviews and other conversations about the system, time and time again these considerations were mentioned. Moving forward, extra weight should be given when considering requirements associated with space usage, operation speed and costs.

Table 3.6: Bounding part of the system definition matrix.

Constraint	Parameter	Variable
Waste is accumulated inside households	The average house size	Space of the house [m^2]
	The average amount of people in a house	Waste produced by a person [kg]
Recycling centres cannot process contaminated waste streams	Infrastructure to hand in waste streams	Distance from a home to an underground container [m]
	The knowledge of the populace about proper waste separation	Separation grade currently achieved [%]
	Local regulations for recycling	Amount of waste streams that must be separated at home [#]
	The efficiency of existing techniques to separate and recycle waste	Post-separation accuracy per waste stream [%]
Households have a limited budget	Willingness of the government to invest in improved waste management	Budget of household for a new garbage bin [€]
Households have limited space for separating waste	Amount and types of waste produced	Physical dimensions of the system [W*H*D]
Households have limited time for separating waste	Willingness to spend time to separate waste	Time spent throwing away waste, compared to before adoption of the system [s]
		Time spent getting waste from the system into the garbage disposal chain [s]

4 The functionality of our system

The groundwork is finished in the above section. Using the knowledge of the problem attained in the first chapter combined with the stakeholder's point of view of the second chapter and the system definition of the third chapter, finally the design of the system starts. The goal of the chapter is to present a concrete design option for a smart bin by using some of the most powerful tools of system engineering: listing requirements, a functional decomposition, and a morphological analysis. First the requirements of the system are defined, being 102 total. The biggest conflicts in the requirements are discussed. The requirements serve as the basis for the next few steps of the design process. The functional decomposition gives the functions the system must fulfil to adhere to the requirements. The morphological analysis finds suitable Means to fulfil each of the functions. Means for detection of waste are implemented in a prototype to test the feasibility. The result of the morphological analysis forms the basis for the fifth chapter of system design.

4.1 List of requirements

Table 4.1 to Table 4.6 list the requirements of the system. Requirements are measurable goals the system can or cannot reach. The requirements define what the system must do and can later be used to determine whether the system achieves the required purpose. The requirements are grouped under the following categories: general, user-friendliness, household suitability, sustainable and affordable design, and safety. Requirements of the same category are grouped in a single table.

Table 4.1: General requirements.

General (GEN)	
GEN-1	The system must store a minimum of 20 kg GFT waste.
GEN-2	The system must store a minimum of 5 kg PMD waste.
GEN-3	The system must store a minimum of 8 kg OPK waste.
GEN-4	The system must store a minimum of 4 kg glass waste.
GEN-5	The system must store a minimum of 2 kg textile waste
GEN-6	The system must store a minimum of 3 kg residual waste.
GEN-7	The system must decrease the mass percentage of GFT in the residual waste stream below 36%.
GEN-8	The system must decrease the mass percentage of PMD in the residual waste stream below 7%.
GEN-9	The system must decrease the mass percentage of OPK in the residual waste stream below 5%.
GEN-10	The system must decrease the mass percentage of glass in the residual waste stream below 2%.
GEN-11	The system must decrease the mass percentage of textile in the residual waste stream below 4%.
GEN-12	The system must be operable with any combination of the GFT, PMD, OPK glass, textile, and residual waste streams.
GEN-13	The system must finish processing waste in 3 hours.
GEN-14	The system must minimize the contamination of GFT waste to at most 5% measured in mass. [kg]
GEN-15	The system must minimize the contamination of PMD waste to at most 15% measured in mass. [kg]
GEN-16	The system must minimize the contamination of OPK waste to at most 3% measured in mass. [kg]

GEN-17	The system must minimize the contamination of glass waste to at most 5% measured in mass. [kg]
GEN-18	The system must minimize the contamination of textile waste to at most 5% measured in mass. [kg]
GEN-19	The system must motivate users to separate 10% more, measured in mass [kg].
GEN-20	The system must give the user feedback about where their waste ends up with 90% accuracy.
GEN-21	The system allows the user to fill the storage capacities up to 50% for the different types of waste.
GEN-22	The system must correctly classify waste at least 95% of the times.
GEN-23	The system can be fitted with another storage of 15L.
GEN-24	The system reduces the residual household waste by 30 kg per year.
GEN-25	The system does not consume resources during operation.
GEN-26	The system uses less than 50W average during operation.
GEN-27	The system must measure the kg CO2 equivalent impact of the system with 95% accuracy.
GEN-28	The system reduces the negative impact of household waste by 200 kg CO2 equivalent per year.

Table 4.2: Requirements relating to the compatibility with current waste processing infrastructure.

Compatibility with current waste processing infrastructure (CWP)	
CWP-1	The system must have an up-front adaptation cost for the current garbage processing services that is no more than 5% of their yearly budget.
CWP-2	The system must not increase the yearly expenses for the current recycling infrastructure.
CWP-3	The system must not damage the Dutch utilities infrastructure.
CWP-4	The system must decrease the number of rejected containers at the recycling centre by 10%.
CWP-5	The GFT output of the system fits in a standard mini container from Kliko with a volume of at least 60L.
CWP-6	The PMD output of the system fits in a standard mini container from Kliko with a volume of at least 60L.
CWP-7	The OPK output of the system fits in a standard mini container from Kliko with a volume of at least 60L.
CWP-8	The residual output of the system fits in a standard mini container from Kliko with a volume of at least 60L.
CWP-9	The GFT output of the system fits in an underground GFT waste container.
CWP-10	The PMD output of the system fits in an underground PMD waste container.
CWP-11	The OPK output of the system fits in an underground OPK waste container.
CWP-12	The glass output of the system fits in an underground glass waste container.
CWP-13	The textile output of the system fits in an underground textile waste container.
CWP-14	The residual output of the system fits in an underground residual waste container.

Table 4.3: Requirements relating to safety.

Safety (SAF)	
SAF-1	The system must conform to the General Product Safety Regulation (European Commission, 2022)
SAF-2	The system must conform to the safety standards and directives required to receive a CE certification (Rijksdienst voor Ondernemend Nederland, 2013)
SAF-3	The system must prevent the contamination of the user by at least 99% of pathogenic microorganisms residing in the garbage storage, during correct operation.
SAF-4	The system must resist at least 99% of intrusion attempts by pets and children under the age of six.
SAF-5	The system must withstand cleaning by water and soap.
SAF-6	The system must conform to IP44 water and dust intrusion standards.
SAF-7	The system must resist intrusion attempts by malicious actors.
SAF-8	The system does not leak harmful gases.
SAF-9	The system does not leak harmful fluids.
SAF-10	The system does not release harmful particles.

Table 4.4: Requirements relating to the user-friendliness of the system.

User-friendliness (USR)	
USR-1	The average users must be able to read the user manual within 15 minutes.
USR-2	The user can install the system within 30 minutes.
USR-3	The system must be accessible according to the European Accessibility Act.
USR-4	Children of six years and older must be able to use the system.
USR-5	The user should be able to perform basic maintenance.
USR-6	The system must have an uptime of 99%.
USR-7	The system must be operable whilst standing upright.
USR-8	In 99% of the first use interactions, users use the correct interfaces.
USR-9	The system must be acceptable by 80% of the 5 most common demographics in the Netherlands.
USR-10	The system must be directly recognisable by 95% of users.
USR-11	The system must have a technical manual freely available on the internet.
USR-12	The system must have spare parts that can be ordered.
USR-13	The system's inner mechanics must be accessible with a screwdriver.
USR-14	The system must accept 5 L of waste within 1 minute.
USR-15	The system must allow emptying of any waste stream within 1 minute.
USR-16	The system should allow the user to empty the waste storage without the system having access to power.
USR-17	The system should allow the user to deposit waste into the residual storage without the system having access to power.

Table 4.5: Requirements relating to the household suitability.

Household suitability (HHS)	
HHS-1	The system has a maximum height of 2m.
HHS-2	The system has a maximum width of 1m.

HHS-3	The system has a maximum depth of 80cm.
HHS-4	The system maximally extends 30 cm in any direction.
HHS-5	The system must pass an experimental test for odour with an equal score compared to normal garbage bins.
HHS-6	The system must be classified as aesthetically acceptable by 90% of the potential users.
HHS-7	The system maximally produces 50 dB of noise during operation.
HHS-8	The outputs of the system must be disposable in their respective underground container.
HHS-9	The system must be shippable from factories to retailers.
HHS-10	The system must adhere to all relevant postal service guidelines for shipping.
HHS-11	The system must work for ambient temperatures between 5 °C and 50 °C
HHS-12	The system must prevent exposure of toxic materials to the environment.
HHS-13	The system must allow deposition of waste within 2 seconds.
HHS-14	The system must not cause nuisances for 95% of potential users.
HHS-15	The system must maximally weigh 25 kg.
HHS-16	The system must fit in a package which is maximally 20% larger in volume than the system during transport.

Table 4.6: Requirements relating to a sustainable and affordable design.

Sustainable and affordable design (SAD)	
SAD-1	The system must have a production process with an emission of less than 300 kg CO_2 – equivalent of greenhouse gases.
SAD-2	The system must cost at most € 100 to produce in mass production.
SAD-3	The system must have a guarantee of 7 years before it must be replaced.
SAD-4	The system must have a repair price lower than € 20 per year, averaged throughout its lifespan.
SAD-5	The system must have a retail price of no more than € 250.
SAD-6	The system must compensate at least an equal amount of cash to users as they receive currently for recycling/incentive to recycle.
SAD-7	The system must have packaging that is sustainable.
SAD-8	The system must prevent extra expenses for users/be financially beneficial.
SAD-9	The system must be made using parts that are interchangeable by the end user (e.g., if they break or are used up).
SAD-10	The system must be repairable using off-the-shelf products.
SAD-11	The system must be produced in a way that is ethically correct as defined by third party ethical audits, e.g., without using slave labour or other exploitative means.
SAD-12	The benefits of the system on recycling must be quantifiable for policy makers with 95% accuracy.
SAD-13	The system must be recyclable at the end of its lifetime.
SAD-14	The system should be locally manufactured.
SAD-15	The system design uses no glue or other irreversible construction in between replaceable parts.
SAD-16	The system is designed with 60% mass percentage recycled materials.
SAD-17	The system is designed with less than 5% rare-earth materials.

Conflicting requirements

Not all requirements are independent of each other. Achieving some can impede the performance of the system for other requirements. Below is a list of requirements that are in conflict and a mitigation of the conflict.

GEN 1-6 with HHS 1-4

The general requirements 1 through 6 define the minimum amount of waste the system must be able to store. Household suitability requirements 1-4 define the maximum size the system can have to fit in a household. The conflict is that storage takes up space, but the system itself cannot take too much space. Solving this requires optimising the size of the storages during prototyping and the first phase of rollout.

GEN 7-12 with GEN 14-18

General requirements 7 through 12 are about decreasing the mass percentages of waste streams within residual waste. 14 through 18 set the limits on the contamination of the waste streams. The conflict is that an easy solution for the first set of requirements is to separate everything, even when the system has no accurate identification. The second set can be ensured by throwing everything in the residual bin when there is any doubt in the measurement of the system. The conflict can be solved by optimising the accuracy of the system through prototyping and going as near as possible to the bounds defined by the requirements.

SAD 2 with SAD 1,7,11,14,16,17

Sustainable and affordable design requirement 2 limits the production costs of the system to 100 euros, while 1,7,11,14,16,17 all require in some way sustainable and ethical production. In the current economy sustainable and ethical production is sometimes more costly than other methods, which means that they conflict with the maximum of the production costs. The mitigation is to limit production costs as much as possible to have wiggle room for eventual extra costs of using sustainable and ethical production.

4.2 Functional decomposition

The next step towards a concrete system design is a functional decomposition of the system. A system is designed to achieve a goal. Whatever the goal may be, the system must function such that the goal can be realized. The functional decomposition is a Systems Engineering tool that helps us find and define the functions.

High-level functions

We start the functional decomposition by looking at the goals of our system. We identify five main goals/functions:

1. The system allows for the addition of a new waste stream.
2. The system incentivizes the use of the system.
3. The system separates waste.
4. The system collects household waste.
5. The system switches on/off.

If our system mananges to succesfully perform the five fucntions, we consider our design a succes. The question remains how our system actually achieves the functions. To answer the question, we define sub-functions. Sub-functions state what is required for the success of the high-level functions. The sub-functions are more concrete, to the level of being solved directly. If we are still not clear on how to achieve the sub-fuction, we again divide the sub-function in lower level sub-functions. For example, it is clear how one can design something for our system to switch on/off, but how our system separates waste requires many sub-functions. The highest level functions can be found in Figure 4.1.

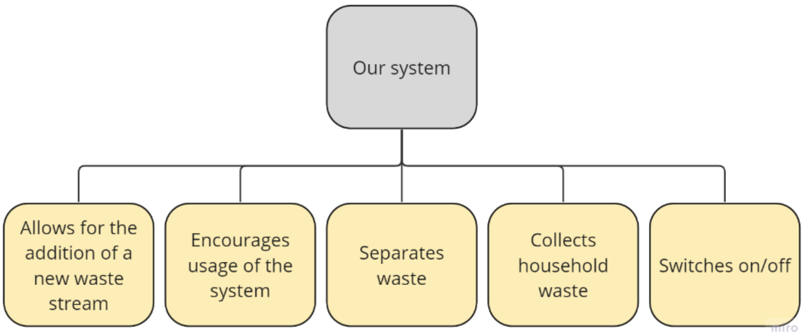


Figure 4.1. The highest-level functions in our functional decomposition.

For the second, third and fourth highest-level functions, sub-functions are needed to make the necessary design more concrete.

Our system encourages the use of the system

Figure 4.2 gives the sub-functions for the high-level function 'The system incentivizes the use of the system'. The function is important, because if our system does not incentivize its usage, households find a replacement. We identify two sub-functions to incentivize usage of the system.

- F1: The system is suitable for a household.
- F2: The system communicates data.

In our interviews with Cyclus, the team noticed two big problems preventing proper waste separation. Firstly, most households do not have the space for all bins of the different waste streams that can be separated at home. Secondly, residents do not separate waste because they do not realise the effect of waste separation. F1, and F2 are the two functions of our system to stimulate the usage of our system and to stimulate waste separation in general.

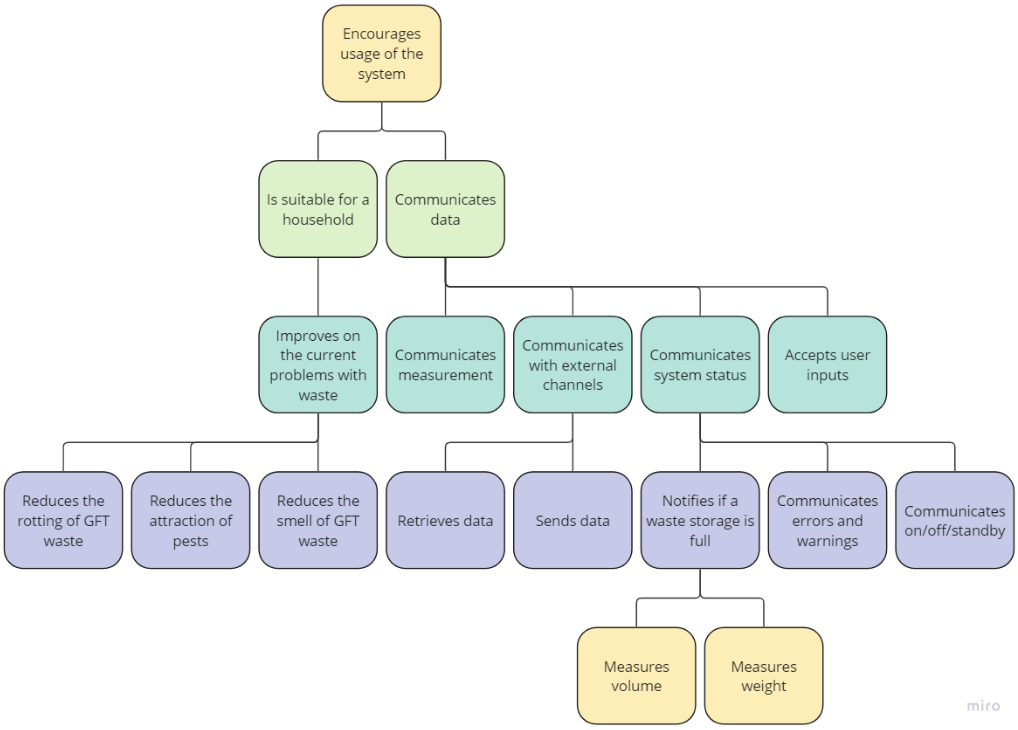


Figure 4.2. The functional decomposition for the high-level function 'The system encourages usage of the system'. This figure defines all the sub-functions of the system to satisfy the high-level function.

Our system separates waste

The most important goal of our system, and the motivation behind this project, is to separate waste. The functional decomposition of the function ‘our system separates waste’ can be found in Figure 4.3. The user of our system can present waste to the system, and our system should act on this and get the waste to the correct storage. We identify two sub-functions necessary to separate waste:

- F1: The system gets waste in the correct storage.
- F2: The system identifies different waste streams.

The first thing our system needs to do is identify in which waste stream the presented piece of waste belongs. As set by the Environmental Protection Act (Wm), we currently consider six waste streams, GFT (organic), PMD (plastics, metal, and drink cartons), OPK (old paper and cardboard), glass, textile, and residual waste. After the identification of the presented waste, the system should act and make sure the waste ends up in the correct storage. The presented waste does not necessarily belong to a single waste stream, in that case it would require our system to divide up the presented waste into parts that go into different bins.

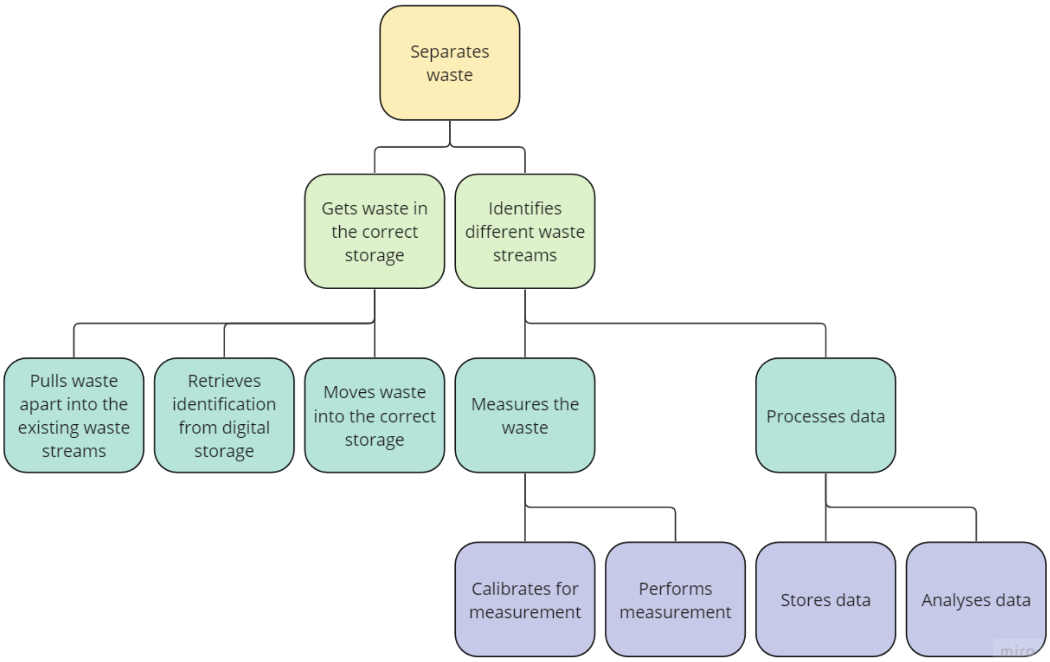


Figure 4.3. The functional decomposition for the high-level function 'The system separates waste'. This figure defines all the sub-functions of the system to satisfy the high-level function.

The system collects household waste

Our system replaces the standard bin in households, so part of its function should be that of a normal bin. The high-level function related to this is 'the system collects household waste'. This high-level function has three sub-functions:

- F1: Our system keeps its main functionality without power.
- F2: Our system allows for emptying of the storage.
- F3: Our system stores the different waste streams.

These sub-functions are divided further as shown in Figure 4.4.

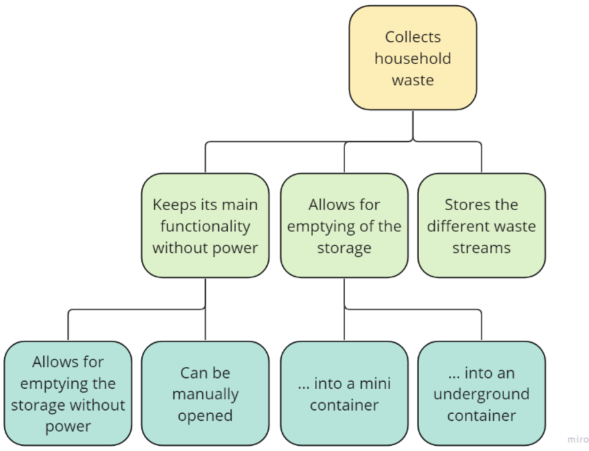


Figure 4.4. The functional decomposition for the high-level function 'The system collects household waste'. This figure defines all the sub-functions of the system to satisfy the high-level function.

4.3 Morphological analysis

This chapter contains the first step in designing our system. In the previous chapters we have defined the functional decomposition of our system. We use the subfunctions to perform the Morphological Analysis (MA), a systematic and creative process that gives us the tools to do a qualitative systematic exploration of potential design solutions.

The first step of the MA is to create the Morphological Chart (MC). For each function, the MC contains all Means to accomplish the function. A mean can be seen as some component that achieves something in the system. For example, if your system has as a function 'the system has an off/on switch.,' a mean for this could be an off/on switch or button.

Not all Means included in the MC are actually feasible, which is quite all right. When designing a system, you must think outside of the box. The only criterium is that the mean fulfils the specific function. Later in the MA, unfeasible solutions are eliminated.

The Morphological Chart

We created the MC in Miro, a visualisation program, the MC is represented as a matrix containing the functions on the rows and the Means on the columns. Considering all subfunctions from the Functional Decomposition, the MC got quite big. We believe presenting the chart in this report does not have much added value. If you are interested, the MC can be found in Appendix D: Full morphological Chart. The steps to get to solutions are be described, but not explicitly shown.

Many of the Means included can be combined. For example: to measure whether presented waste is organic waste, we could use a spectroscopy sensor, this can be combined with any other sensor. The usage of one sensor does not stand in the way of the usage of another sensor. We keep the chart (relatively) simple by excluding combinations.

Elimination of Means

The morphological chart includes any mean we could think of. Nothing was too absurd to be included. However, some of the included Means are not possible (yet) or are not realistic to work out. These Means are eliminated before generating solutions. For example: we eliminate using gravitational wave detection for measuring weight as a detector is currently 4 kilometres long, or the usage of worms to detect whether waste is organic, since 1,000 worms eat 125 grams of organic waste per day (Urban Worm Company, 2017).

Two of the most promising Means for detection of waste—a spectroscopy sensor, and a capacitive sensor—are tested for feasibility by prototyping a sensors sub-system. See chapter 6. The other means are rated for feasibility in the next chapter on system design by using a qualitative and quantitative analysis.

5 System design

The moment has arrived to design the system fully and perform the last step of systems engineering. We use the Means of the morphological analysis to generate possible solutions for the system. The solutions are tested against the most important requirements, first qualitatively, then quantitatively. Finally, a component analysis of the final design is given.

5.1 Solutions

The feasible Means can be grouped into several usable combinations. Two combinations—communication and detection—are described first. Systematically trying all possibilities using the usable combination of Means yields seven many solutions, of which most will not be feasible at all. Nevertheless, we found seven viable solutions, which are described after the combinations. A sketch of these solutions can be found in Figure 5.1.

Communication

Encouraging system use involves effectively communicating data with users. Residents neglect separation of waste because they perceive it as futile, remaining uninformed about the benefits of proper waste sorting. By showing users the environmental impact of their waste separation, we aim to emphasize responsible waste management. The system also sends timely reminders to empty their waste bins. Integrating gamification is another strategy to consider. An illustrative example of gamification of waste management is at the Dutch theme park 'De Efteling,' with 'Holle Bolle Gijs' where a paper waste bin triggers an captive audio response, motivating children to clean up.

The most promising combination of means for interacting with the users is a combination of a display, LEDs, and a speaker. This combination is implicitly integrated into all the proposed solutions.

Detector sub-system

In our solutions, we use different types of sensors to automatically recognise the waste, most of our solutions use the detector sub-module which we are prototyping. The prototype consists of a capacitive sensor and a spectroscopy sensor. The detector sub-system scans the material properties of a presented sample. More on the working of the detector sub-system are found in chapter 6. We use this type of detector sub-system in the solutions below unless specified otherwise.

Solution 1: Status quo

The status quo solution is the solution closest to the current generally accepted waste bins. The user will have to do the complicated tasks, like waste identification and moving the waste to the correct storage. The user opens bins by pressing on the top. The focal point of the solution is that the size of the bins for the six fine household waste streams are finetuned according to the need of the household: saving space, thus, making waste separation at home easier.

Solution 2: Assisting the user

This solution assists the user in separating their waste. The system has the detector sub-system mentioned above. After measuring, the system automatically opens the correct storage system, and the user can throw the waste in the correct bin. The bins are organised in the same way as the status quo solution. With the usage of minimal technology – only to measure the waste, no processing system – the space occupied by the system is minimised.

Solution 3: Analogue cyclone smart bin

The solution uses density to separate different waste streams using little electronics. The waste is first ground down to small pieces, which are then swept up into a cyclone using strong air currents. Different materials have different densities, and thus will be swept up to a different extend, which can be used to separate the materials into different bins.

Solution 4: Conveyor smart bin

Inspired by Dutch deposit return machines; the solution uses a conveyor belt to move the waste to the detector and correct bin. The user can only present one waste item at a time, as the system cannot pull apart waste. To prevent annoyance, the conveyor belt immediately moves the waste away, so the user can throw in the next waste item. The measurements are done using the standard detection sub-system, after which conveyor belts moves the waste to the correct bin.

Solution 5: Minecart smart bin

This solution uses (multiple) carts with the standard detection sub-system that move above the storages. When the cart is in place above the correct bin, the cart is emptied. To increase processing speed the system could employ multiple carts at the same time, so the user can throw away multiple items at the same time in the different carts.

Solution 6: Assisting the user with visual identification

As an alternative to solution 2: solution 6 differs primarily in the scanner sub-system. Visual identification with machine learning can be used as an alternative to the standard detection sub-system. There is, however one main drawback to visual identification. It requires a comprehensive database with material composition of all products, leading to constant updates due to (new) packaging changes.

Solution 7: Pressurised air smart bin

The solution uses precisely targeted jets of pressurised air to pull apart the waste and push it into the correct storage bin. All waste goes on to a plate, serving as the detector sub-system. The system determines the waste types and then used a complex system targeting system of air jets to push the waste to the correct bin(s).

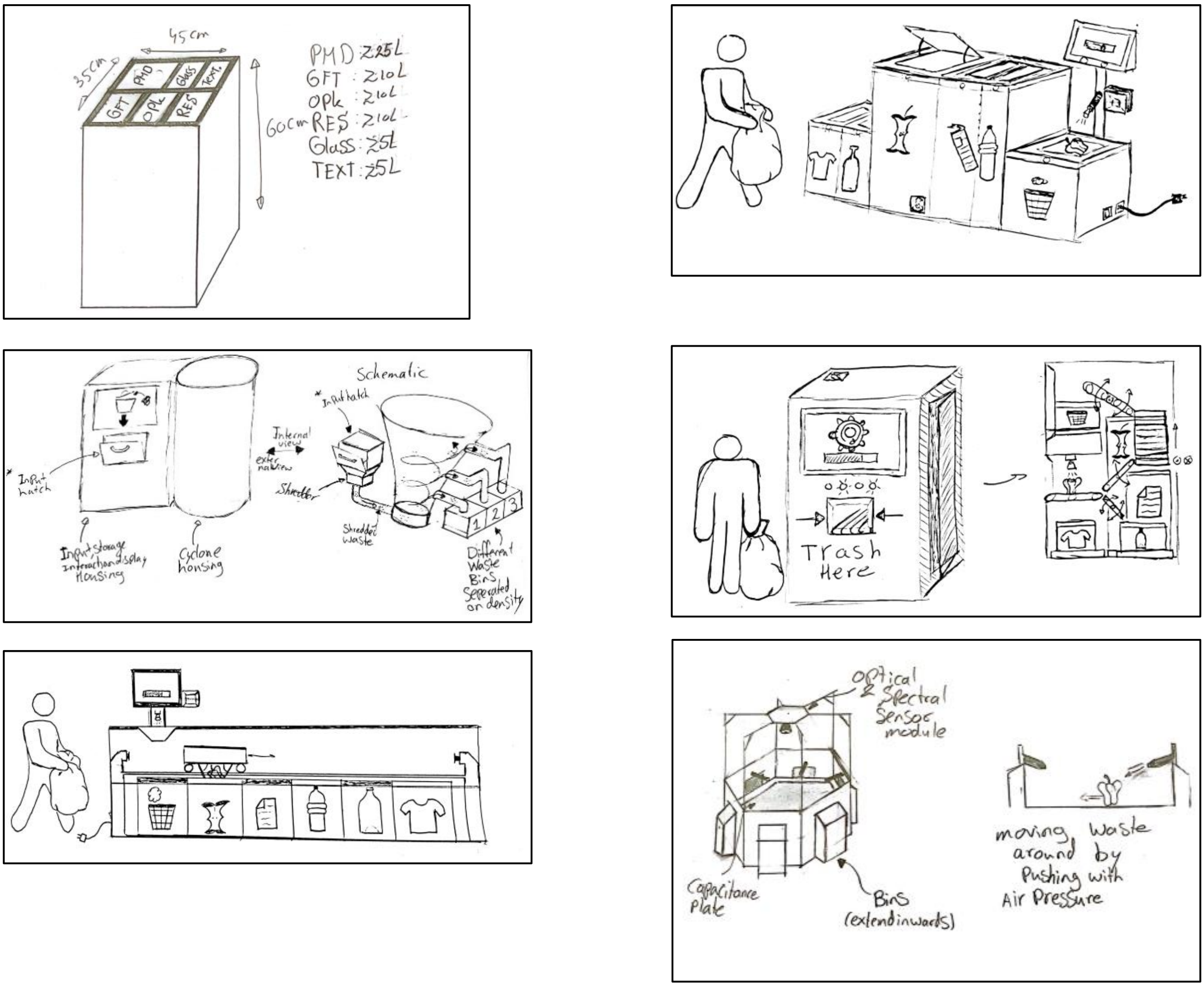


Figure 5.1: sketches for six of the solutions. Top left: Solution 1, Status quo. Top right: Solution 2, assisting the user. Middle left: Solution 3, analogue cyclone bin. Middle right: Solution 4, Conveyor smart bin. Bottom left: Solution 5, minecart smart bin. Bottom right: Solution 7: Pressurised air smart bin. Solution 6 is omitted from the sketch as the only difference with solution 2 is the type of sensor module used. These sketches are not to scale.

5.2 Evaluation criteria for solutions

From the list of requirements, we select the most important criteria to grade the solutions on.

1. Waste storage capacity: this criterion constitutes all the requirements regarding the storage capacity for the waste streams.
2. Separation quality: the amount of waste that is removed from the residual bin.
3. Contamination prevention: this criterion constitutes all the requirements regarding contamination between the different waste streams.
4. Processing capability: the requirements regarding processing speed and ease of input (one item at a time or a whole heap)
5. Encourages its use: tests how well a solution motivates the user to use it.
6. Environmentally friendly: multiple requirements are linked to achieving a system that positively contributes to the environment. This criterion constitutes all the requirements regarding the environment.
7. Cost: the system must be purchasable by households.

8. Compatibility: this criterion constitutes all the requirements regarding the current waste processing infrastructure.
9. Safety: this criterion constitutes all the requirements regarding safety.
10. User-friendliness: this criterion constitutes all the requirements regarding user-friendliness, like smell and sound produced during use of the system.
11. Household suitability: this criterion constitutes all the requirements regarding household suitability, like size and weight.
12. Cleanability: the ease cleaning the system after use.

Solving the GFT mystery

The Organic waste mystery (described on page 15) shows that automatization and smell reduction are very important improvements to be made in a smart bin. Whilst GFT is the most recognisable waste stream and easily separable, it is also the waste stream found the most in residual waste. Hence, the most important challenge in waste separation at home is not to help users identify waste correctly, but really to make it more appealing to separate. The best solution must be a solution that makes separation easier and provide other conveniences, such as smell reduction for GFT waste. For this, we tested an off-the-shelf product, the Joseph Joseph Intelligent Waste Stack 4 Liter. This product has an air opening on top, with an air filter against the smell. In our testing, the product worked well. The continuous inflow of fresh air reduced the overall smell and rotting, combined with the air filter, the GFT waste did not smell. We implement this air filtration compartment in our system to solve the GFT mystery.

5.3 Qualitative analysis

Each solution is graded per criterion. We create the 'trade-off table', which contain the criteria in the left-most column and the solutions in the rows. Using a colour code, we grade how well solutions satisfy each criterion. We grade this as (1) exceeding the criterion (blue), (2) meeting the requirement (green), (3) having correctable deficiency (orange), or (4) not fulfilling the requirement (red). From the 'trade-off table' (see Table 5.1), the three best performing solutions are selected.

Table 5.1: The 'trade-off table' for the eight solutions we found. S1: Status quo, S2: Assisting the user, S3: Analogue cyclone dustbin, S4: Conveyor dustbin, S5: Minecart dustbin, S6: Assisting the user, visual identification, and S7: Pressurized air dustbin. The colour represents how well the solution satisfies a specific criterion. Blue: the solution exceeds the requirements linked to the criterion, green: the solution meets the requirements, orange: the solution has correctable deficiencies with respect to the requirements and red: the solution does not meet the requirements.

	Solutions						
	S1	S2	S3	S4	S5	S6	S7
Waste storage capacity	green	green	orange	green	green	green	green
Separation quality	red	green	red	green	green	orange	green
Contamination prevention	red	green	red	green	green	orange	green
Processing capability	orange	orange	red	blue	blue	orange	blue
Encourages its use	green	green	green	green	green	green	green
Environmentally friendly	blue	blue	red	green	green	green	orange
Cost	blue	blue	orange	green	green	blue	red
Compatibility	blue	blue	blue	blue	blue	blue	blue
Safety	blue	blue	orange	green	orange	blue	orange
User-friendliness	green	green	orange	blue	green	green	red
Household suitability	blue	blue	red	green	green	green	red
Cleanability	green	green	blue	orange	blue	green	blue

5.4 Quantitative analysis

The quantitative analysis selects the best option from our final four solutions of the qualitative analysis. We use the same criteria as before, giving each criterion a weight to indicate how important the criterion is for the functionality of our system. The criteria and their respective weights can be found in Table 5.2. The next step is to grade each solution on a scale from one to ten for all criteria. Finally, multiply the grades with the weights for each criterion and then add them all together to determine a final score for each solution. The results are found in Table 5.2.

Table 5.2: The quantitative trade-off table. The established criteria and their weight factors together with the decided upon scores for each of the criteria for the four chosen solutions are shown in the table. The final scores are calculated by summing the weight multiplied with its respective score per solution, included in the bottom row (Sum).

		Solutions			
	Weight	S2	S4	S6	S7
Waste storage capacity	9	8	7	7	8
Separation quality	8	8	8	8	6
Prevents contamination	10	6	8	8	5
Processing quality	8	5	9	9	5
Encourages its use	7	7	8	8	7
Environmentally friendly	4	9	8	8	8
Cost	5	9	8	8	9
Compatibility	7	10	10	10	10
Safety	9	9	7	6	9
User-friendliness	7	7	9	8	7
Household suitability	9	9	8	8	9
Cleanability	6	7	6	8	7
Sum		689	711	707	659

Most criteria do not show much difference in the grading per solution. This is because the four systems are similar. All systems are compatible with currently used garbage bags, three of the solutions use the same sensors, and all the solutions have similar ways of communication with the user and allow the same usage of data to optimise the waste processing industry. An example for optimization, data on the weight and volume of waste produced by a household can give the waste processor information on when to collect waste and prevent the collection of almost empty bins.

After quantitative analysis, the four remaining solutions score very similar. Only for a few criteria, big differences between the solutions arise. Solution 2 and 5 score worse than solution 4 and 6 on 'prevents contamination' and 'processing quality'. Solution 2 and 5 scan the waste before opening the correct bin; the user throws the waste into the correct bin. Two drawbacks arise. First, the user can circumvent the usage of our scanning component and manually open the (wrong) storage. Secondly, the user must wait for the scan to complete before the correct bin opens, which takes time. On the other hand, solution 4 and 5 score worse than solution 2 and 5 on 'safety'. This is because solution 4 and 5 have much more moving components that can get something stuck, extra precautions should be taken to still achieve the wanted safety levels.

We recommend further development of solution 4: conveyor belt. Overall, the solution scores best considering the criteria. Although scoring worse than other solutions for two criteria, safety and cleanability, we believe work can be done to make sure alleviate these downsides; whilst we consider other solutions to have more fundamental problems that are harder to fix. For example, the worse scoring for processing quality of solution 2 and 6 is linked to the way the bin works, thus is much harder to solve. Another reason for the recommendation of the conveyor belt is that it is used in post-separation factories. Perhaps, the workings of the factory conveyor belt can be adapted to a home scale system.

5.5 Component Analysis

The system has five sub-systems and many modules. The current section makes clear how the different modules and subsystems interact with each other. The system broadly consists of five sub-systems. First the detection sub-system, which determines the type of waste put in the system. Second, the mechanical sub-system, which moves the waste to the correct storage compartment. Third, the storage sub system, which stores and measures the waste. Fourth, a communication sub-system to communicate with the user. Finally, a power sub-system to supply the power for the full system. All the sub-systems are connected to a central processing board that processes the signals, does the calculations, and communicates with all sub-systems. A diagram of the entire system is given in Figure 5.2.

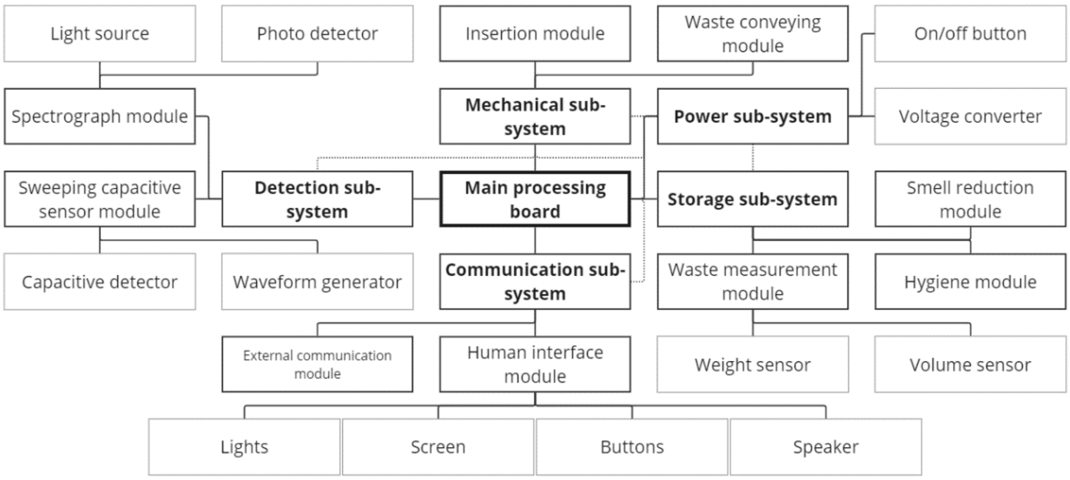


Figure 5.2: Diagram of the system. In the middle the main processing board with all the sub-systems connected to it. Each sub-system is divided into modules to perform certain tasks. Many modules are worked out into their respective components.

The sub-systems have been worked out as detailed as possible in the current phase of design. Some modules require additional prototyping before a making a final design choice and thus the exact parts are left open for further interpretation.

Detection Sub-Systems

The system preforms measurements to determine the type of inserted waste when triggered by the board computer. The results are sent back to the central board computer to interpret the measurements. The detection sub-system consists of two modules: capacitive sensing and a spectrograph. The sweeping capacitive sensing consists of a waveform generator to send different sinusoidal frequencies to the waste. A capacitive detector then detects the capacitive properties of the waste. The spectrograph module consists of a light source and a photo detector to detect the reflection of the waste for different wavelengths of light. Chapter 6: Prototype of detection sub-system goes more into depth on this sub-system.

Mechanical sub-system

After performing a measurement and determining the kind of waste, the system must move the waste to the correct storage compartment. The mechanical system is a conveyer belt on which the input waste can be placed. After detection, the conveyer belt moves the waste to the correct storage compartment using flippers to kick the waste off the belt in the respective bin.

Storage sub-system

Storing waste in the correct compartment is the goal of the system. The storage sub-system has four modules. A hygiene module, a smell reduction module, a waste measurement module, and an actual bin. The hygiene module must help keep the storage compartments clean but is currently not designed yet. The smell reduction module will be an air filter. The measurement module consists of a weight sensor at the bottom of each storage compartment and a volume sensor in each storage compartment. Finally, the bin stores the required volume of waste per stream and allows for the usage of store bought garbage bags. See Figure 5.3.

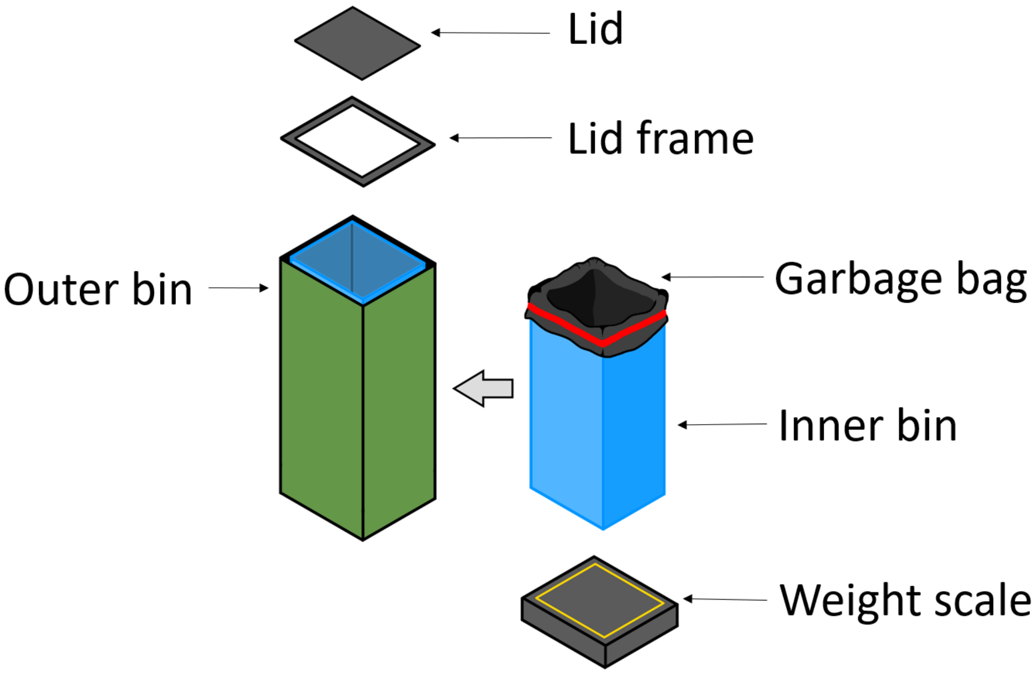


Figure 5.3: Schematic representation of a storage compartment. The volume sensor, which is not mentioned, is included in the bin.

Communication sub-system

The communication sub-system relays all the information to the user and central server. The external communication module, an off the shelf Wi-Fi module, communicates with the server via internet. The human interface module communicates locally with the user through lights, a screen, buttons, and a speaker.

Power sub-system

Connected to all sub-systems and the main processing unit is a power sub-system. The power sub-system has two parts. An on/off button for the user to shut down the system and a voltage converter to supply the correct voltage to each sub-system.

5.6 The final design

We present the final design in the current section. The 3D models are made in Fusion 360 (Autodesk, n.d.). The design incorporates all the features of solution 4: the smart conveyor bin. The user can put the waste in the top, where it falls on a conveyor that takes it quickly to the detection sub-system, so the user can put in the next waste almost directly. The detection sub-system will be the optimized version of the prototype presented in chapter 6. After determining the waste type, a complex sub-system consisting of conveyors, that has yet to be prototyped, will move the waste to the correct storage bin. The sizes of the storage bins are chosen in size according to the requirements in section 4.1. Each bin includes a weight scale to determine the waste statistics. On top, the system has a screen displaying the operation status to the user. See Figure 5.4 for renders of the system within the context of a household kitchen. Notice that it easily fits within a kitchen closet space.

Figure 5.4: the render of our final design. The system has six bins to separate GFT, OPK, PMD, glass, textile and residual waste and place for the addition of an extra storage, which a household can use as they wish. The size of the bins is to accommodate to the average household needs. The lid on top can be opened and contains a sensor module using a capacitive sensor and spectroscopy sensors to measure the waste. A sub-system of conveyor belts and flippers moves the waste into the correct storage. The bin is shown next to a kitchen counter to show how easily implementable the system is. This render is made using Autodesk Fusion 360.

The system does not only encompass all the waste storage and separation needs for the modern household, but also multiple other advantages. The statistics collected by the waste bin can inform collection companies on when to collect the waste and keep users engaged with reducing the amount of waste they produce. If the system works perfectly, then it can reduce the amount of residual waste up to six times. Meaning that with our system, when a residual waste container of a family used to be emptied biweekly, it will need to be emptied only four times a year. The amount of infrastructure costs that can be saved for collection companies is enormous, because bins need to be emptied less often. The household needs to pay less costs for their garbage collection, because the garbage collection needs to charge less for the collection of waste (let alone when a family lives in a municipality using DIFTAR regulations, hence charging extra for residual waste; see Table 2.1). Municipalities can be provided with statistics to help them better understand where to make policies to further improve waste management. Finally, due to the better separation of the waste the Dutch society will be a step closer towards the ever-important goal of a circular economy.

6 Prototype of detection sub-system

The first (and only) part we chose to prototype is the detection sub-component to prove the working principle. Designing a smart bin requires a well-designed detector, since there is no need for further development of an auto-sorting bin without a sub-system that can classify the waste type correctly. First the workings of the spectroscopy sensor and capacitive sensor implemented in the prototype are explained, then the setup of the prototype is shown, followed by the results, finally recommendations for further development are given.

6.1 Spectroscopy sensor

A spectroscopy sensor measures the reflection of electromagnetic radiation on a sample. Electromagnetic radiation is a form of energy that propagates as both electrical and magnetic waves traveling in packets of energy called photons. The wavelength of the photon determines the type of electromagnetic radiation. The most well-known type of electromagnetic radiation is visible light. The visible spectrum is between wavelengths of about 380 to about 750 nanometres. At lower and higher wavelengths of electromagnetic radiation we get ultraviolet (UV) and infrared radiation (IR) respectively. The UV region covers the wavelength range 100 – 400 nm and the IR region covers the wavelength range 780 nm – 1 mm.

Humans see using a spectroscopy sensor, the eye. Colour vision is the ability to differentiate between light composed of different frequencies. Colour perception begins with light stimulating three different types of photoreceptors in the eye. Each cone is sensitive to different wavelengths of light. The brain receives the information from these cones and creates our perception of colour. We, humans, use our sensors to sense the world around us. Simply looking at an object gives us enough information to decide in which waste stream an object belongs. A spectroscopy sensor might give the board computer the information necessary to imitate what humans can do with their eyes.

For our prototype we use eight different types of photoreceptors. One sensor measuring UV light, six sensors measure visible light, and one sensor measures infrared light. To prevent unwanted outside influences, we create the prototype such that no external light reaches the measurement. This means we need to provide our own light source. For this we use 8 LEDs with different peak intensities, see Table 6.1. Our system uses these eight sensors to gain information about the presented waste, and mimic human eyes in judging to which waste stream a presented object belongs.

For future designs, we recommend looking deeper into the infrared spectrum. Plastics have distinct reflective properties in the infrared spectrum which could be used to identify plastic from other waste streams. Currently, the highest wavelength our sensor measures is 950 nm, but it could be interesting to set up a spectroscopy sensor measuring the wavelengths of near-infrared LEDs in nanometres: 855, 940, 1050, 1200, 1300, 1450, 1550, 1650 (Vos, Plastic Scanner, 2023).

Table 6.1: Peak wavelengths of the LEDs used in the spectrograph. The second column gives the corresponding colours.

Wavelength	Colour
950 nm	Near infrared
650 nm	Red
600 nm	Orange
570 nm	Bright yellow
550 nm	Bright green
500 nm	Green
450 nm	Blue
365 nm	Ultraviolet (UV)

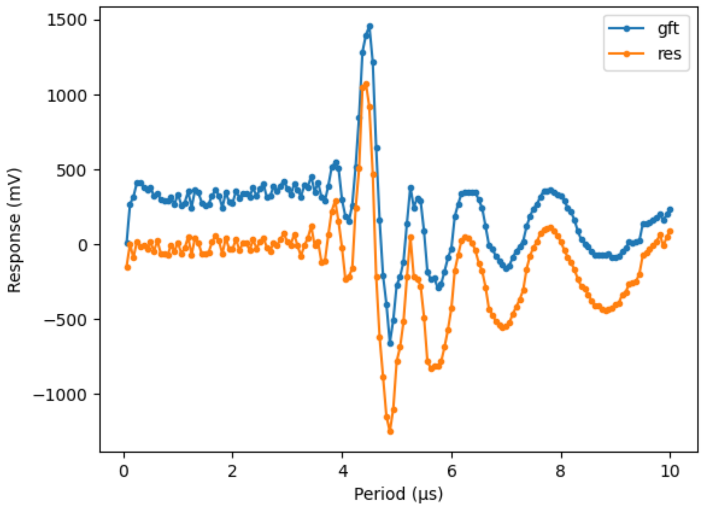


Figure 6.1: A measurement of two samples of the sweeping capacitive sensor. The blue line is a measurement of a GFT sample, the orange line is a measurement of a non GFT sample. The shape of these graphs is similar, but GFT is shifted upwards compared to the non GFT measurement, which is enough for the machine learning algorithm to distinguish between the two. The shape of the GFT sample is characteristic for GFT waste. The shape of the non GFT measurement differs a lot depending on the sample.

6.2 Capacitive sensor

In electrical engineering, capacitive sensing is a technology that can detect and measure anything that is conductive or has a dielectric constant different from air. Some phones use capacitive sensing touchscreens. The working principle is to make a charged layer underneath a resistive layer, such as glass. If you then touch the screen with an object (a finger) then the charged layer-glass-object forms a capacitor of which the strength is dependent on electrical properties of the object. The touchscreen detects the change in capacitance, of which the strength is dependent on the electrical properties of the object. A finger, containing a lot of water, creates a strong response, whilst a piece of paper/plastic does not. Hence, a phone with a capacitive touchscreen should react to organic materials (e.g., banana) but not to paper and plastics. So, the capacity gives information on the material type.

The capacitive sensor used in our system is a sweeping capacitive sensor. The difference with a touchscreen being that it measures the capacitive properties of the object along a frequency range of electricity. The electrical properties of most materials (an exception would be metals) strongly depend on the frequency applied, which means that the whole frequency range can be used to fingerprint materials. In a way it works like a spectrograph for the electric properties of the object. Especially GFT has a signature response caused by the moister content when put on a sweeping capacitive sensor.

Figure 6.1 shows two measurements by the sweeping capacitive sensor. The blue line displays a measurement of GFT waste, the orange line a measurement of non GFT-waste. At this point in time we are only interested in separating GFT from the other streams, but for future development, separating all six waste streams is necessary. The shape of this blue graph is characteristic of GFT samples, whereas the orange line differs a lot depending on the sample. Some samples barely produce any response, while others are so much like the GFT shape that our current machine learning algorithm cannot distinguish them.

6.3 Prototype setup

The most important goal of the protype is to show that waste can be identified using relatively simple components. Due to the simple components the total price of the components of the prototype is 120 euros. We chose to prototype using a spectrograph, connected to a Raspberry Pi and a sweeping capacitive sensor build using an Arduino board. Choosing a combination of these two sensors is sensible, because a spectrograph is currently the de-facto standard in waste separation techniques for PMD & OPK and a capacitive sensor excels in detecting moisture content, i.e., GFT. The two sensors can thus rely upon each other's strengths to classify waste. After validating the working of both sensors individually, the system was integrated in a wooden shell. Traditional machine learning techniques provide the classification of the waste types based upon measurements of the sensors. First a lot of waste is measured using the prototype, which the machine learning algorithm uses to learn the distinction between the waste types. The algorithm can then be used to determine the waste type using a measurement of new waste put into the prototype.[1] The detector sub-system we prototyped is shown in Figure 6.2.

Figure 6.2. The detector sub-system we prototyped. On the top we have a black spectroscopy module, containing different spectroscopy sensors and LEDs. On the bottom we have brass plate which is connected to a circuit to create a capacitive sensor. Measurements are performed with the lid close to prevent outside interference.

All the components are represented in Figure 6.3, which is now described in detail. The Raspberry Pi acts as the central processing unit from which the system operates. Also, it provides power to most of the components. The spectrograph is directly connected. The infrared detector (slightly modified to do an analogue reading) and optical light spectrograph are off the shelf components. The UV light detector, however, does not include a light source by default, so an external Hi-power UV LED with a power supply is connected through a MOSFET to regulate the power. The Raspberry Pi uses serial communication to use the Arduino Uno for capacitive detection. The design and code are adopted from (Illutron, 2012). After a read command the Arduino board provides a reading of the full capacitive spectrum of the object. To do the reading correctly, the board passes a driving signal through a smoothing circuit of passive electrical components to the conducting detection surface. Another passive circuit is used to provide correct measurements of the object. Refer to Appendix E: List of prototype components for an extended list of components used for the prototype and Appendix F: Sweeping capacitive sensor circuit for the design of the capacitive sensor circuit.

[1] The code can be provided by the authors upon request

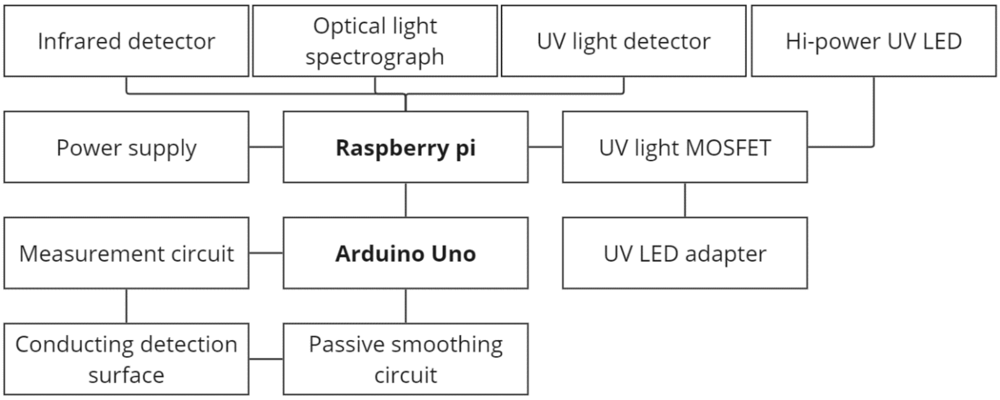


Figure 6.3: Diagram of the electronic components of the detection sub-system prototype. The central processing hub is the Raspberry Pi, which is connected to the spectrograph on top and to the capacitive detector at the bottom of the diagram. The capacitive detector is handled by the Arduino Uno.

6.4 Results of the prototype

The best results are obtained using the support vector machine learning with a linear kernel. We used a dataset containing 174 different waste samples scanned using the prototype. The samples were provided by the public city bin collection service of Cyclus. For full composition see Table 6.2.

Table 6.2: The composition of the test data set. Total size is 174. There are 103 non-GFT items in total.

Category	**GFT**	**OPK**	**PMD**	**Glass**	**Metal**	**Residual**
Scanned samples (N)	71	24	25	11	11	32

The data set is used to cross validate the machine learning and find the average number of correct predictions. We first present the results for separating GFT from non-GFT as this was the goal defined for the prototype. The confusion matrix is found in Table 6.3. We can see that in 83% of the cases GFT is correctly detected and in 86% of the cases non-GFT is detected correctly. The results are within 10% accuracy of the current competing systems described in chapter 2.4. The imperfect detection can be explained by small GFT samples, because the response of the capacitive sensor scales with the size of the sample; so, small GFT samples do not exhibit the signature response. 2.4

Table 6.3: Confusion matrix of the machine learning. The diagonals elements are correctly detected samples. The off-diagonals elements are incorrect detections.

	GFT detection	Non-GFT detection
GFT sample	59	12
Non-GFT sample	14	89

However, we took the prototype one step further and tested separating the samples into the full six categories. The resulting confusion matrix is found in Table 6.4. The prototype is not designed to fully separate, hence we expect the prototype to perform worse. This is confirmed by further inspection, because after full separation the correctly detected GFT samples lowers to 75%, which is still comparable to competing systems. Table 6.5 shows the correct detection rate for all the categories. The results indicate that there still work to be done to take the prototype from a sub-system that can discern GFT waste from non-GFT to a full-fledged detection sub-system.

Table 6.4: Confusion matrix of the machine learning for full separation of the waste samples. The diagonals elements are correctly detected samples. The off-diagonals elements are incorrect detections stating the categories confused with each other.

	GFT detection	Glass detection	Metal detection	OPK detection	PMD detection	Residual detection
GFT sample	53	1	6	3	2	6
Glass sample	0	3	3	0	1	4
Metal sample	5	1	2	2	0	1
OPK sample	3	0	2	15	0	4
PMD sample	4	1	3	3	7	7
Residual sample	9	3	4	4	3	9

Table 6.5: Correct detection rate when all waste categories are detected by the prototype.

Category	**GFT**	**OPK**	**PMD**	**Glass**	**Metal**	**Residual**
Correct detection (%)	75	62	28	27	18	28

Interesting to note is that prototype makes the most detection GFT when it is residual waste or vice-versa as indicated by Table 6.4. Most probably the confusion arises from moist residual waste samples (wet newspapers) or samples containing multiple types of waste (an apple sticking to plastic bags). Both samples should be put in residual waste, because they cannot be processed properly in another waste stream. However, they are very similar to GFT samples, so the machine learning cannot discern the samples well. We expect less of these types of samples originating within households. Waste tends to get wet more often when exposed to the outside environment, due to rainfall. Mixed samples can pose a problem for the finalized version of the detector, which will need to be monitored closely.

6.5 Recommendations to improve the detector sub-system

The first prototype of the detector sub-system achieves detection rates for GFT comparable to competing systems. For other waste streams, however, it does not achieve good enough detection rates yet to adhere to the requirements about contamination. Here we present recommendations to improve the detector sub-system.

We have five recommendations for improvements. The first improvement is: add a weight sensor to the detector. A weight sensor will make it easier to detect small GFT waste, as the machine learning can correlate the weight with the response of the capacitive detector. Besides, a weight sensor is easy to implement and very cheap. The second improvement is: increase the infrared band of the spectrograph to 1650 nm. Plastics have signature responses further in the infrared band, which can be used to detect plastics better (Vos, Plastic Scanner, 2023). The third improvement is: increase the sensitivity of the capacitive detector by optimizing the circuit, increasing power of the waveform generator, and removing the plastic layer around the metal detection plate. Higher sensitivity means faster and better visibility of signature responses for material types. The fourth improvement is: increase the dataset of the waste samples used to train the machine learning algorithm. A larger dataset will allow machine learning algorithms to recognize patters more accurate, hence increasing the number of correct detections. The fifth and final improvement is: try a neural network recognition algorithm. A neural network will need a lot more data to train on, however, it is able to recognize even more nuances than the support vector machine learning currently employed. Thus, we expect a neural network to increase the number of correct detections even further. We believe that using these five improvements the correct detection rate for every waste stream can be optimized to the levels stated in the requirements.

Figure 6.4. We have prototyped a detector sub-system, seen on the left, using a spectroscopy module on the top of the wooden lid, and a brass plate to measure the capacitance on the bottom of the wooden box. The wooden box is placed inside an actual bin to give a more accurate representation of how the sub-system would be used. On the right there is a zoom-out of the prototype, showing the power cord.

Conclusion and recommendation

The current report has investigated the problem of household waste separation in the Netherlands using a system engineering approach. The first chapter gave a literature analysis of the problem from which we found that another 87% of residual waste can be recycled when separated properly. The second chapter gave an overview of stakeholders and competitors, which made clear that there currently are no good solutions yet and provided us with the GFT (organic waste) mystery. The GFT mystery is the fact that we find 36% GFT in the residual waste stream, whilst one would expect that GFT is easily recognisable and thus separated correctly. The third chapter presented the system definition, which gives an overview of all the needs the system must fulfil within certain constraints imposed by the deployment of the system. The fourth chapter took the information gathered in the first three chapters to list all the requirements the system must adhere to, decomposed the system in solvable function and gave all the Means to solve the functions. Also, the fourth chapter presented the prototype we developed for testing the spectrograph and capitative sensing as Means for detection. The fifth chapter expanded upon the fourth chapter by combining the Means to concrete solutions, from which the best one is chosen through qualitative and quantitative analysis.

The resulting solution is the conveyor smart bin (see section 5.6). The system is inspired by a Dutch deposit-return machine. On top, there is a hole in which waste can be inserted. Underneath the hole there is a conveyor belt, which takes the waste to the detection sub-system. After identification, the waste is taken to the correct internal storage compartment. The storage system measures the weight and provides certain benefits for waste streams. It will, for example, reduce the smell of GFT waste, thus solving the organic waste mystery (see section 2.3). The resulting waste separation is communicated to the user through a combination of a display, LEDs, and speakers. The goal of the communication is to incentivize the user to keep on using the system to improve waste recycling. The system can lower the amount of residual waste by up to six times, which improves the efficiency of the waste collection industry. Besides, the improved separation brings us one step closer towards a much-needed circular economy.

Even though we used the many powerful tools of systems engineering and even managed to prototype two Means for detection of waste, there are bound to be unforeseen flaws in the above solution. Especially as we are lacking expertise to implement the Means of all the sub-systems. For example, a mechanical engineer would be much more suited to design, implement and test the mechanical sub-system. Nevertheless, we are very happy with the research we did because we do think we have investigated the problem very thoroughly and have lain a strong basis to eventually create a useful product. The prototype also shows the power of very cheap detectors (the full prototype costed 120 euros, which can be lowered when taken into mass production) as it already recognizes 83% of the GFT waste correctly. We presented improvements to further increase this percentage in section 6.5. Our sincere recommendation would be to go further with development of a smart bin, but with an inter-disciplinary team of engineers. We would recommend a team consisting of at least a physicist, industrial designer, and a mechanical engineer.

As far as we found, none of the competitors use the combination of sensors we use or have as much in-depth knowledge of the problems within household waste separation in the Netherlands. So, if the means to fund additional development is lacking, then selling the knowledge of the problem and the detector sub-system to one of our competitors could be interesting.

Our team

Left to right: Tim Mulder, Dylan Aliberti, Brammert Habing, Jonathan Pilgram. In front of the Cyclus building.

Ten weeks of working together has taught us a lot. Some of us have never worked together so intensely in a team and none of us have done such an extensive engineering project before. We learned a lot in a short time. Not only new skills to apply to the project, but also a lot of soft skills that are useful in a professional environment. Aspects of the teamwork are highlighted.

At the start we defined a 'team contract' which states how we wanted to work together and gave guidelines in case there would be some problems within the team. Soon it became apparent that for all of us the people would always go before the project, meaning that we gave each other space to be themselves and work independently. We also planned four team events where we would do an activity together, to get to know each other better. The result being that at the end the team is very fond of each other. Another big advantage is that everyone ended up working hard on the project, not by some external motivation, by the intrinsic respect for the team.

Working together so intensely always bring challenges. In the beginning we found it hard to work together effectively, as we did not know the strong suits of each other yet. However, after a few weeks' things took a turn for the better as we started to know the capabilities of each other better. The last half of the project the team functioned very professionally and effectively.

Finally, a team of four physicists is very flexible and easily goes in-depth into a complex problem. Everyone understands what the others are doing and can take over if needed. However, designing a smart bin requires a lot of skills which are taught more in other fields. A recommendation would be to add engineers from other fields of studies, such as industrial design and mechanical engineering.

We learned a lot about being an engineering team and we are all very happy with the result.

"Engineering is the art of directing the great source of power in nature for the use and convenience of humans" -Thomas Thredgold

Bibliography

(2013). In T. Michael, *Waste to Energy Conversion Technology.* 80 High Street, Sawston, Cambridge CB22 3HJ, UK: Woodhead Publishing Limited.

Aan de slag met afval. (n.d.). *Beeldbank*. Retrieved February 25, 2023, from https://www.aandeslagmetafval.nl/beeldbank

Association of Plastic Recyclers. (2018, July 20). *Near Infrared (NIR) Sorting in the Plastics Recycling Process.* Retrieved from https://plasticsrecycling.org/images/Design-Guidance-Tests/APR-RES-SORT-2-NIR-sorting-resource.pdf

Attero B.V. (2017). *Openbaar eindrapport project Nascheiden ONF.* Attero B.V. Retrieved November 7, 2023, from https://projecten.topsectorenergie.nl/storage/app/uploads/public/5c4/f11/4a4/5c4f114a4c44a417761887.pdf

Autodesk. (n.d.). *Autodesk.eu*. Retrieved November 10, 2023, from Fusion 360: https://www.autodesk.eu/products/fusion-360

Avalex. (n.d.). *Wat mag er in?* Retrieved February 25, 2023, from https://www.avalex.nl/wp-content/uploads/2021/12/poster-Glas-1.pdf

Belastingsamenwerking Gouwe-Rijnland. (n.d.). *Tarieven gemeente Gouda 2022*. Retrieved November 7, 2023, from BSGR: https://www.bsgr.nl/belastingen/tarieven/gouda/

Bijleveld, M. M., Bergsma, G. C., & Nusselder, S. (2016). *Circulaire economie: een belangrijk instrument voor CO2-reductie.* CE Delft.

CBS. (2022, December 6). *Afvalbalans, afvalsoort naar sector*. Retrieved from nationale rekeningen: https://opendata.cbs.nl/statline/#/CBS/nl/dataset/83554NED/table?dl=51317

CBS. (2022, December 6). *Afvalbalans, afvalsoort naar sector; nationale rekeningen*. Retrieved from CBS Statline: https://opendata.cbs.nl/statline/#/CBS/nl/dataset/83554NED/table?dl=51317

CBS, Centraal Bureau voor Statistieken. (2023, July 6). *CBS StatLine Gemeentelijke afvalstoffen; hoeveelheden*. Retrieved 9 21, 2023, from Gemeentelijke afvalstoffen; hoeveelheden: https://www.cbs.nl/nl-nl/cijfers/detail/83558NED?q=totaal%20huishoudelijk%20afval

Cyclus N.V. (n.d.). *GFT+E*. Retrieved September 18, 2023, from Cyclus N.V.: https://cyclusnv.nl/gfte

Dakskobler, L. (2019, May 23). From no recycling to zero waste: how Ljubljana rethought its rubbish. The Guardian. Retrieved September 13, 2023, from https://www.theguardian.com/cities/2019/may/23/zero-recycling-to-zero-waste-how-ljubljana-rethought-its-rubbish

de Afval Spiegel. (2022). *Sorteeranalyses 2022 gemeente Gouda.* Tilburg.

Dijkgraaf, E., & Gradus, R. (2020, July 16). Separation of Plastic Waste: Better for the Environment and Lower Collection Costs? *Environmental and Resource Economics*, pp. 127-142. doi:10.1007/s10640-020-00457-6

Directorate-General for Communication (European Commission). (2020). *Circular economy action plan.* EU Publications. Retrieved September 11, 2023, from https://op.europa.eu/en/publication-detail/-/publication/45cc30f6-cd57-11ea-adf7-01aa75ed71a1/language-en/format-PDF/source-170854112

Ecological Footprint. (2023). *Global Footprint Network: Advancing the Science of Sustainability*. Retrieved from footprintnetwork.org: https://www.footprintnetwork.org/

European Commission. (2022, June 30). *General Product Safety Regulation*. Retrieved from commission.europa.eu: https://commission.europa.eu/business-economy-euro/product-safety-and-requirements/product-safety/general-product-safety-regulation_en

European Commission, Secretariat-General. (2021). *COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS 'Fit for 55': delivering the EU's 2030 Climate Target on the way to climate neutrality.* Brussels. Retrieved September 11, 2023, from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021DC0550

European Union. (2022). *What are the EU's targets for 2030?* Retrieved November 2, 2023, from https://www.eea.europa.eu/signals-archived/signals-2022/infographics/what-are-the-eu2019s-climate/image/image_view_fullscreen

Eurostat. (n.d.). *Green house gas emissions from waste*. Retrieved September 8, 2023, from Eurostat: https://ec.europa.eu/eurostat/web/products-eurostat-news/-/ddn-20200123-1

Glenammer Lab Test Sieves. (2021). *What is a sieve shaker?* Retrieved February 25, 2023, from https://www.glenammer.com/what-is-a-sieve-shaker/

Green Deal: key to a climate-neutral and sustainable EU. (2023, May 3). Retrieved from europarl.europa.eu: https://www.europarl.europa.eu/news/en/headlines/society/20200618STO81513/green-deal-key-to-a-climate-neutral-and-sustainable-eu?&at_campaign=20234-Green&at_medium=Google_Ads&at_platform=Search&at_creation=RSA&at_goal=TR_G&at_audience=the%20green%20deal&a

(2019). *Hernieuwbare energie in Nederland 2018.* Centraal Bureau voor de Statistiek. Retrieved from https://www.cbs.nl/nl-nl/publicatie/2019/40/hernieuwbare-energie-in-nederland-2018

Het Klokhuis. (2015, April 23). *Hoe worden glazen frisdrankflesjes gerecycled? | Doen Ze Dat Zo?* Retrieved February 25, 2023, from YouTube: https://youtu.be/-85G_pwXOQM

Hirshorn, S. R. (2016). Fundamentals of Systems Engineering. In S. R. Hirshorn, *NASA Systems Engineering Handbook* (pp. 3-16). Washington: National Aeronautics and Space Administration.

How is a circular economy different from a linear economy? (n.d.). Retrieved 9 27, 2023, from A&A Packaging: https://www.aandapackaging.co.uk/how-is-a-circular-economy-different-from-a-linear-economy/

How the EU wants to achieve a circular economy by 2050. (2023, January 18). Retrieved from europarl.europa.eu: https://www.europarl.europa.eu/news/en/headlines/priorities/circular-economy/20210128STO96607/how-the-eu-wants-to-achieve-a-circular-economy-by-2050

Igini, M. (2022, April 18). How Waste Management in Germany is Changing the Game. earth.org. Retrieved September 13, 2023, from https://earth.org/waste-management-germany/

Illutron. (2012, June 4). Advanced Touch Sensing. Retrieved October 10, 2023, from https://github.com/Illutron/AdvancedTouchSensing

Kenniscentrum InfoMil. (n.d.). *Archief Nederdlandse Emissierichtlijn Lucht (NER).* Retrieved March 2, 2023, from InfoMIl: https://www.infomil.nl/onderwerpen/lucht-water/lucht/ner-archief/

Kliko Groep. (n.d.). *Vierwielcontainers.* Retrieved March 2, 2023, from https://www.kliko.nl/vierwielcontainers/

(2021). *Kwaliteit ingezameld gft-afval in Nederland.* Royal HaskoningDHV.

Machinex Recycling. (n.d.). *Full line of MACH series screening separators*. Retrieved February 25, 2023, from https://www.machinexrecycling.com/products/mach-ballistic-separators/

Maltha. (n.d.). *Over Maltha*. Retrieved February 25, 2023, from https://www.maltha-glassrecycling.com/nl-nl/

Milieu Centraal. (2023, September 29). *Afval scheiden: cijfers en kilo's*. Retrieved from Milieu Centraal: https://www.milieucentraal.nl/minder-afval/afval-scheiden/afval-scheiden-cijfers-en-kilo-s/

Ministerie van Economische Zaken en Klimaat. (November 2019). *Integraal Nationaal Energie- en Klimaatplan 2021-2030.* Nederland. Retrieved September 11, 2023, from https://open.overheid.nl/documenten/ronl-d5298e21-e4c7-476d-822c-d713cb38a71e/pdf

Ministerie van Infrastructuur en Waterstaat. (2023). *Producentenverantwoordelijkheid*. Retrieved from afvalcirculair: https://www.afvalcirculair.nl/onderwerpen/afvalregelgeving/producentenverantwoordelijkheid/

Ministry of Environment. (2017, December 28). 새해에 달라지는 제도 - 자원순환법 시행 (System that changes in the New Year - Enforcement of the resource circulation law). Ministry of Environment.

Nederlandse Brouwers. (n.d.). *Bruine Nederlandse Retourfles (BNR)*. Retrieved February 25, 2023, from https://www.nederlandsebrouwers.nl/biersector/duurzaamheid-en-ketenbeheer/verpakkingen/statiegeld-retourflessen/

NTR. (2021, October 11). *Hoe worden batterijen gerecycled?* Retrieved from schooltv: https://schooltv.nl/video/hoe-worden-batterijen-gerecycled-inleveren-sorteren-en-hergebruiken/

O. Ukaogo, P., Ewuzie, U., & V. Onwuka, C. (2020). Environmental pollution: causes, effects, and the remedies. In P. Chowdhary, A. Ray, D. Verma, & Y. Akhter (Eds.), *Microorganisms for Sustainable Environment and Health* (pp. 419-429). Elsevier. doi:https://doi.org/10.1016/C2018-0-05025-2

Oberle, B. e. (2019). *Global Resources Outlook 2019.* International Resource Panel.

OECD Publishing. (2021). *Environment at a Glance 2020: OECD Indicators - Circular economy - waste and materials.* Retrieved June 2, 2022, from https://www.oecd-ilibrary.org/sites/f5670a8d-en/index.html?itemId=/content/component/f5670a8d-en

Omrin. (n.d.). *Koploper in nascheiding - Jouw afval nogmaals onder de loep*. Retrieved November 3, 2023, from Omrin: https://www.omrin.nl/ons-verhaal/ontdek-omrin/duurzaam/de-reis-die-jouw-afval-maakt/2-koploper-in-nascheiding

Omroep West. (2017, April 14). *Johan gaat Scheiden: Aflevering 4 - Glas.* Retrieved from https://omroepwest.bbvms.com/view/regiogrid/2787411.html

Oorcheck. (n.d.). *Wat is te hard?* Retrieved March 2, 2023, from https://www.oorcheck.nl/gehoorschade/hoe-ontstaat-schade/wat-te-hard/

OpenAI. (n.d.). *ChatGPT*. Retrieved from OpenAI: https://chat.openai.com/

OVAM. (2021, August 9). *Huishoudelijk afval en gelijkaardig bedrijfsafval 2017.* Retrieved from ovam.vlaanderen.be: https://ovam.vlaanderen.be/c/document_library/get_file?uuid=bfe5c909-f142-2513-e03d-1b7f4e2ee03e&groupId=177281

Pachauri, R. K., Meyer, L. A., & The Core Writing Team. (2015). *Climate Change 2014 Synthesis Report.* Geneva, Switserland: Intergovernmental Panel on Climate Change. Retrieved from https://archive.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_FINAL_full_wcover.pdf

Paganellis, A. (2012, June 1). *Touché with Arduino*. Retrieved November 3, 2023, from Arduino Blog: https://blog.arduino.cc/2012/06/01/touche-with-arduino/

Potting, J., Hekkert, M., Worrel, E., & Hanemaaijer, A. (2016). *Circular Economy: Measuring innovation in the product chain.* Den Haag: PBL.

Qasem, I. (2010). *Resource scarcity in the 21st century: conflict or cooperation?* The Hague Centre for Strategic Studies (HCSS) and TNO. The Hague: Koninklijke De Swart. Retrieved September 13, 2023, from https://hcss.nl/wp-content/uploads/2010/09/qasem-2010-resource.pdf

Recycling Network Benelux. (n.d.). *Hoe werkt statiegeld?* Retrieved February 25, 2023, from https://recyclingnetwerk.org/themas/statiegeld/hoe-werkt-statiegeld/

Reloop. (2017, June 19). *Deposit Return: How it Works (SHORT VERSION).* Retrieved from YouTube: https://www.youtube.com/watch?v=YgReEalhkjw

Rietbergen, M., van Zeeland, R., & Polinder, L. (2018). *Reframing: Groente- en Fruitafval.* Utrecht: Design Innovation Group.

Rijksdienst voor Ondernemend Nederland. (2013, October 4). *CE-markering: stappenplan*. Retrieved from rvo.nl: https://www.rvo.nl/onderwerpen/eu-wetgeving/ce-markering/stappenplan

Rijksoverheid. (2021). *Landelijk afvalbeheerplan 2017-2029.* DGMI, Directie Duurzaamheid. Den Haag: Rijkswaterstaat. Retrieved from https://lap3.nl/beleidskader/: https://lap3.nl/beleidskader/

Rijksoverheid. (2023, 09 26). *wetten.nl - Regeling - Wet milieubeheer - BWBR0003245*. Retrieved from overheid.nl Wettenbank: https://wetten.overheid.nl/BWBR0003245/2023-07-01#Hoofdstuk10

Rijkswaterstaat. (2013). *Systems engineering*. Retrieved November 2, 2023, from Rijkswaterstaat: https://www.rijkswaterstaat.nl/zakelijk/zakendoen-met-rijkswaterstaat/werkwijzen/werkwijze-in-gww/systems-engineering

Rijkswaterstaat. (2023, 06 19). *Wet milieubeheer*. (Ministerie van Infrastructuur en Waterstaat) Retrieved from Rijkswaterstaat.nl: https://www.rijkswaterstaat.nl/water/wetten-regels-en-vergunningen/natuur-en-milieuwetten/wet-milieubeheer

RIVM. (n.d.). *Geur: samen meten aan luchtkwaliteit.* Retrieved March 2, 2023, from https://samenmeten.nl/stoffen/geur

Ruz, C. (2011). The six natural resources most drained by our 7 billion people. *The Guardian*. Retrieved 9 18, 2023, from https://www.theguardian.com/environment/blog/2011/oct/31/six-natural-resources-population

Sage, A., & Armstrong Jr., J. (2000). *Introduction to systems engineering.* Wiley-Interscience.

Sileryte, R. (2023). *Geographies of Waste: Significance, Semantics and Statistics in pursuit of a Circular Economy.* TU Delft Open. doi:10.4233/uuid:745aee5b-75a3-42e7-a044-01aa1f9cdcf5

Sillanpää. (2019). The Circular Economy: Case Studies about the Transition from the Linear Economy. Elsevier Science. doi:https://doi.org/10.1016/C2017-0-02916-6

Smith, Y. R., Nagel, J. R., & Rajamani, R. K. (2019, March 15). Eddy current separation for recovery of non-ferrous metallic particles: A comprehensive review. *Minerals Engineering*, pp. 149-159. doi:10.1016/j.mineng.2018.12.025

Sres, K. (2020, June 11). Chasing zero waste: How Slovenia has become a European frontrunner of the zero waste cities movement. (R. Recupero, Interviewer) Retrieved September 13, 2023, from https://zerowastecities.eu/chasing-zero-waste-how-slovenia-has-become-a-european-frontrunner-of-the-zero-waste-cities-movement/

Stap, J. (2020, January 21). *Leids Plastic*. Retrieved from YouTube: https://www.youtube.com/watch?v=9R7i2V7h9Go

STIBAT. (n.d.). *Inleveren, ophalen, sorteren en recyclen*. Retrieved February 25, 2023, from legebatterijen.nl: https://www.legebatterijen.nl/alles-over-batterijen/inzamelen-sorteren-en-recyclen/

StudioNAND. (2014, Oktober 24). *StudioNAND/tact-hardware: Tact Sensor Circuits*. Retrieved November 3, 2023, from Github: https://github.com/StudioNAND/tact-hardware

U.S. Energy Information Administration. (2022, October 18). *Biomass explained*. Retrieved from eia.gov: https://www.eia.gov/energyexplained/biomass/landfill-gas-and-biogas.php

UN Department of Economic and Social Affairs. (n.d.). *The 17 Goals*. doi:https://sdgs.un.org/goals

Urban Worm Company. (2017, May 21). *How much should I feed my worms?* Retrieved November 3, 2023, from https://urbanwormcompany.com/how-much-to-feed-worms/

Vaverková, M. D. (2019). Landfill Impacts on the Environment—Review. *Geosciences*. doi:10.3390/geosciences9100431

Vereniging Afvalbedrijven. (2015). *Factsheet: Dragers gft.* Vereniging Afvalbedrijven. Retrieved November 7, 2023, from https://www.verenigingafvalbedrijven.nl/public/Factsheets/6/bestand/VA-Factsheet-Dragers%20gft.pdf

Vereniging Afvalbedrijven. (2017). *Factsheet: Kwaliteitscompost maak je samen.* Vereniging Afvalbedrijven. Retrieved from https://www.verenigingafvalbedrijven.nl/public/Factsheets/2/bestand/VA-Factsheet-Kwaliteitscompost%20maak%20je%20samen.pdf

Vijhuize, J. (2023). *smart waste management*. Retrieved November 3, 2023, from WAST-e: WAST-e

Vloedgraven, V. (n.d.). *Afvalbeheer duurzaam beheren: Discoursanalyse van het afvalbeheer en -beleid van Nederlandse gemeenten.* Retrieved from https://theses.ubn.ru.nl/server/api/core/bitstreams/7370fe01-4a38-46cf-957b-86bf87326db1/content

Vos, J. d. (2021). *Plastic Identification Anywhere.* Delft: TU Delft.

Vos, J. d. (2023, June 2). *Plastic Scanner*. Retrieved from docs.plasticscanner.com: https://docs.plasticscanner.com/how_it_works

Waste Management Review. (2018, September 13). *Product Spotlight: STADLER ballistic separator.* Retrieved from https://wastemanagementreview.com.au/stadler-ballistic-separator/

www.pbl.nl. (2015). Retrieved November 2, 2023, from https://data.pbl.nl/api/embed/infographic/data/en/cem16/001s/01/001s_cem16_01_en.pdf

Zink, T., & Geyer, R. (2017). Circular Economy Rebound. *Journal of Industrial Ecology*, 593-602.

Appendix A: Definitions of waste streams in the Netherlands

Multiple definitions can be used for the different household waste streams. In the columns the different definitions of waste streams are mentioned as defined by ‘De Afval Spiegel’ and the Central Bureau of Statistics (CBS) (de Afval Spiegel, 2022) (CBS, Centraal Bureau voor Statistieken, 2023).

Table A.1: The definition of different household waste streams as defined by ‘De Afval Spiegel’ and the Central Bureau of Statistics (CBS)

DISTINCT HOUSEHOLD WASTE STREAMS	DEFINITION BY ‘DE AFVAL SPIEGEL’	DEFINITION OF CBS (FIGURE 1.6)
ORGANIC WASTE (GFT)	Organic waste such as: compostable garden waste and kitchen scraps. Compostable garden waste such as: greenery, pruning debris, leaves, and foliage, but no animal cadavers. Kitchen scraps, such as: peelings and shells, bread and (cooked) food ware.	Greens, Fruits, and Small Garden Waste (GFT) + Bulky Garden Waste
PAPER AND CARDBOARD (OPK)	Reusable paper and carton, such as: carton boxes stripped of any (plastic) stickers, paper only packaging and printed paper. Other types of paper are seen as non-reusables, such as: wallpaper materials, pizza boxes (because of oil contamination and the like) or paper packaging containing glued-on plastics linings. These non-reusable paper materials are disposed of in the residual bin.	Idem
HYGIENE PRODUCTS	Diapers, incontinence products and female hygiene products. Other hygienic paper materials, such as paper kitchen towels and tissues.	Diapers
DRINK CARTONS	(Empty) Drinking cartons and packaging, containing an inner lining of plastic.	Part of PMD
PLASTICS/SYNTHETICS	Plastic packaging and other non-packaging plastics and hard plastics. Plastic packaging is separated into P(M)D collection. While plastic non-packaging material and hard plastics are disposed of in the residual bin or must be brought to collection centres.	Part of PMD
GLASS	Packaging glass, glass panes and glassware e.g., all glass types. Packaging glass is collected in the public glass bins. The other glass types belong in the residual bin or need to be disposed of at the recycling centres.	Packaging Glass + Sheet Glass
METALS	All types of metals. Metals used in packaging such as canned products, tin cans etc., make up the M in PMD and so belong in the PMD waste stream. All other non-packaging metals, such as: pans, grates, racks, cables etc., can be brought to an ironmonger or the recycling centres.	Part of PMD + Non-packaging Metals
TEXTILES	Textiles, such as: clothing, bedlinen, blankets, shoes; regardless of reusability. But no duvets or comforters and pillows, these belong in the residuals.	Idem
RUBBLE AND CERAMICS	All stonelike materials, such as: brick, cement, debris, tiles and slabs, ceramics, or porcelain etc.	idem
TIMBER	All types of wood.	Waste Timber
SMALL CHEMICAL WASTE	Paints (the liquids or powders itself, but not the empty cannisters), batteries, accus, ink cartridges, certain energy saving lightbulbs, etc.	idem
ELECTR(ON)IC DEVICES	All types of electric devices with power cords, regardless of working order.	Idem
REMAINING WASTE	Everything not mentioned in the above categories, such as: cat litter, cleaning cloths or wipes, candles, vacuum cleaner dustbags, cosmetics, garden hoses, etc.	-

LAP3 regulations on waste streams

The Dutch government made a national plan to manage waste, which is called LAP3 (third Landelijk AfvalPlan). The LAP is a framework for all institutions either producing or processing garbage within the Netherlands prescribing details of permits, licenses, and general rules, issued by the Dutch government. LAP3 is an important tool used by the government to move from a linear to a circular economy, because it upholds the acquired knowledge and practices of a circular economy. The LAP3 functions as a roadmap for the Dutch society to transition from a linear to a circular economy. For example, Chapter B.1 of the LAP3 is dedicated to transitioning towards a circular economy (Rijksoverheid, 2021).

The legislative power behind LAP3 originates in law environmental management (in Dutch 'Wet milieubeheer Wm'). This legislation provides the legal tools to protect the environment. The Wm describes the environmental plans and programmes, environmental quality requirements and standards. Also, the Wm provides the rules for permits and licenses regarding waste management. Furthermore, inspection and enforcement of the law are described. The enforcement tools included are mostly financial instruments, such as: levies, dues, and compensation for damages and other types of fines. Finally, the Wm requires public access and appeal to environmental data and statistics. In Wm, the LAP3 is the executive protocol concerning resource management and waste disposal (Rijkswaterstaat, 2023).

The law environmental management (Wm) mandates municipalities to separately collect specific waste streams, dividing household waste into small and bulky categories. Small household waste, generated within private households, is collected locally. Bulky household waste, differing significantly in nature or size, must be presented separately and can be picked up by collection companies or brought to designated centres. Despite being called recycling centres (in Dutch: 'Milieustraten' or 'afvalbrengstations'), these facilities primarily function as collection points, emphasizing the importance of separate collection as the initial step in the recycling process according to government regulations.

Figure A.1: Grondstoffencentrum Krimpen a/d IJssel: an example of a (bulky) waste collection centre operated by Cyclus NV. Photograph received from Cyclus NV.

Small household waste obligations

Both Wm and LAP3 obligate municipalities to separately collect the following small household waste streams, namely: compostable waste, metals, plastics/synthetics (PMD), glass(ware), paper (OPK), textiles, dangerous waste streams (small chemical waste for example) and used electr(on)ic devices. Municipalities are, by law, not required to separately collect any other streams. The streams mentioned here are usually collected at home. The obligations set by law are summarised in the Table A.3.

Table A.2: Obligation to separately collect small household waste (Rijksoverheid, 2021).

SMALL HOUSEHOLD WASTE STREAM	OBLIGATION TO SEPARATELY COLLECT BY/ON BEHALF OF MUNICIPALITIES
COMPOSTABLE WASTE	Obligated, but exemption is possible when separate collection is not technically feasible or excessively expensive
METALS	Obligated, but exemption is possible when no negative consequences arise on the size and quality of potential recycling and/or reuse.
PLASTICS/SYNTHETICS	Obligated, but exemption is possible when no negative consequences arise on the size and quality of potential recycling and/or reuse.
GLASS(WARE)	Obligated, but exemption is possible when no negative consequences arise on the size and quality of potential recycling and/or reuse.
PAPER	Obligated, no exemptions possible.
TEXTILES	Obligated, no exemptions possible.
DANGEROUS WASTE STREAMS (SMALL CHEMICAL WASTE)	Obligated, no exemptions possible.
USED ELECTR(ON)IC DEVICES	Obligated, no exemptions possible.
OTHER WASTE STREAMS	No obligations

Bulky household waste obligations

Municipalities are also obliged to provide a place to deposit other waste, such as the bulky household waste at collection centres. According to LAP3, municipalities are required to offer collection at municipal collection centres for at least eighteen different waste streams. Some streams must be collected entirely separate, whilst others are allowed to be collected as a mix to be separated later (Rijksoverheid, 2021). See Table A.3 for the details.

Some of the waste categories are both mentioned as small and bulky household waste, because the obligations leave some room for interpretation. For recycling, however, the indecisiveness and disagreement about waste management leave much to be desired.

Table A.3: Obligations on waste separation of bulky household waste at collection centres (Rijksoverheid, 2021).

OBLIGATED TO ALWAYS COLLECT SEPARATELY	MIXED COLLECTION POSSIBLE
Electr(on)ic equipment	Roofing material
Asbestos	Gypsum/plaster material
Impregnated timber (type-c)	A and B-type timber
Gas cylinders/fire extinguishers/other pressure holding containers	Mixed stonelike material (not being asphalt or gypsum) / rubble
Soil (depending on quality)	Matrasses
	Paper/cardboard
	Sheet glass or glass panes
	Vehicle tires
	Expanded polystyrene foam
	Bulky garden waste
	(Hard) plastics and synthetics
	Metals
	Textiles

Appendix B: Interesting findings during interviews

Possible improvements for recycling/waste reduction

The employees of Cyclus had many interesting ideas to improve waste separation and even reduce the amount of waste reduced in households. Some ideas are applicable to our project, but some are beyond our scope. Here we list some of the most interesting ideas beyond our scope:

- Set up many small collection sites: To recycle bulky household waste, people must travel to a waste collection site. A long travel time can be discouraging. Because of the travel time, residents may throw their bulky household waste in the residual waste. Hence, setting up many small collection sites throughout neighbourhoods would decrease travel time and improve the amount of bulky waste submitted correctly.
- Neighbourhood hubs: Certain kinds of tools, e.g., drills, are only needed on rare occasions. By sharing one drill with the whole neighbourhood, instead of each person buying their own, the number of drills that are bought and disposed of is reduced. A system like this uses one of the highest principles on the R-ladder from Figure 1.3, 'rethink'.
- Central mini containers on main roads: Currently garbage collectors ride through every street to collect waste. This collection could be more efficient if everyone brought their waste to the main roads instead of beside the house. This would require the cooperation of people to walk to the end of their street with their waste. The efficiency improvement is estimated to be 10 – 20 %.
- Make manufacturers responsible for sustainability: By making manufacturers responsible for recycling their own products at the end of the product's life cycles a more circular economy can be achieved[2]. The producer of a product has the best means to disassemble and reuse parts and/or recycle materials. For example, Samsung has a factory for disassembling phones.

Interesting waste streams

During the interviews, a couple of waste streams came up that are particularly interesting to consider.

- Diapers: Diapers is being considered as a possible separate waste stream in the future.
- Cans: Cans currently belong either in PMD or should be handed in for deposit return. Cans could be efficiently recycled if they were collected as a separate waste stream.
- Organic waste vs residual waste: Organic waste and residual waste are more contaminated with each other than other waste streams. By specifically improving separation between organic waste and residual waste, much can be achieved.

Projects

Multiple projects have been mentioned during the interviews, some of which have been piloted in the past and failed, and some still ongoing.

- Failed projects

[2] In the Netherlands, this is known as extended manufacturer responsibility (EPR) (in Dutch: Uitgebreide ProducentenVerantwoordelijkheid - UPV). EPR states producers are financially and often organisationally responsible for the waste management of the products they place on the market.
Currently, the following products are involved: Car tyres and end-of-life vehicles, batteries and accumulators, electrical and electronic equipment, textiles, packaging, and disposable plastic (Ministerie van Infrastructuur en Waterstaat, 2023).

- Garbage chutes in flats: A system where inhabitants of flats can put separated waste in chutes which collects everything in a central container in the basement. The system worked, but apparently it was not interesting enough to keep building this in flats.
  - Robot garbage boats: Robot boats that autonomously move through the canals in Amsterdam to transport waste. This project failed due to collisions with other boat traffic.
  - Compartmentalized mini containers: In Tilburg (Netherlands) people have mini containers with 2 separate compartments, which should be convenient for separation and collection of waste. However, the project was shut down because it proved inconvenient with collection.
- Ongoing projects
  - Electric and/or hydrogen-powered garbage trucks: The aim is to make all garbage trucks zero-emission vehicles. Electric and/or hydrogen powered technology is interesting for this purpose. A few models have been built for testing, but currently there are problems with weight, range and charging time, preventing organisations like Cyclus to go fully zero-emission.
  - Talk with producers for sustainable design: Making common household-objects better suited for reuse (albeit with modular parts) lies higher on the R-ladder than recycling. Ways to accomplish this are being investigated.
  - Plastic bottle collection bins: A pilot in Gouda is going on where bins are placed for collecting plastic bottles. When checked, the bins were practically empty, which could mean either good or bad things (good because they might not be needed due to already good bottle collection at home, or bad because people ignore it and/or are not informed).
  - Furniture disassembly company: furniture contains many reusable materials, like timber and cushioning. Currently, there is no infrastructure to reuse these materials. Cyclus is trying to start a business to disassemble and reuse these materials.

Good examples

During the interviews, some examples came up of good systems and/or places that handle recycling well, of which we might learn.

- Slovenia is one of the poorest countries in Europe, and yet it recycles the best. This indicates that scarcity of resources motivates a country to recycle better. They have no choice but to have as much of a circular economy as possible.
- Scandinavia has underground pipelines to transport separated waste. This idea has also been pitched in the Netherlands, but the ground here is not suitable, as the ground slowly sinks down.
- Samsung has a factory to disassemble old phones.
- Common household products like milk used to be delivered at home in glass bottles, which you could hand in the next time the milk man came by. Such a system could curb the use of plastic packaging.

Appendix C: Volume calculation of waste division

The current appendix will explain step by step how to get from the average weight of waste produced each week by an average household to the amount of volume for each waste stream the system needs to be able to store. As a starting point we take the average weight a four-person household produces, which is 40 kg a week (Milieu Centraal, 2023). We know the average composition of Dutch household waste (CBS, Centraal Bureau voor Statistieken, 2023) and the composition of residual waste found in Gouda (de Afval Spiegel, 2022). Now we use the following formula:

$$M_{waste\ stream} = M_{weekly}(P_{CBS} + 0.347 \times P_{Afval\ Spiegel})$$

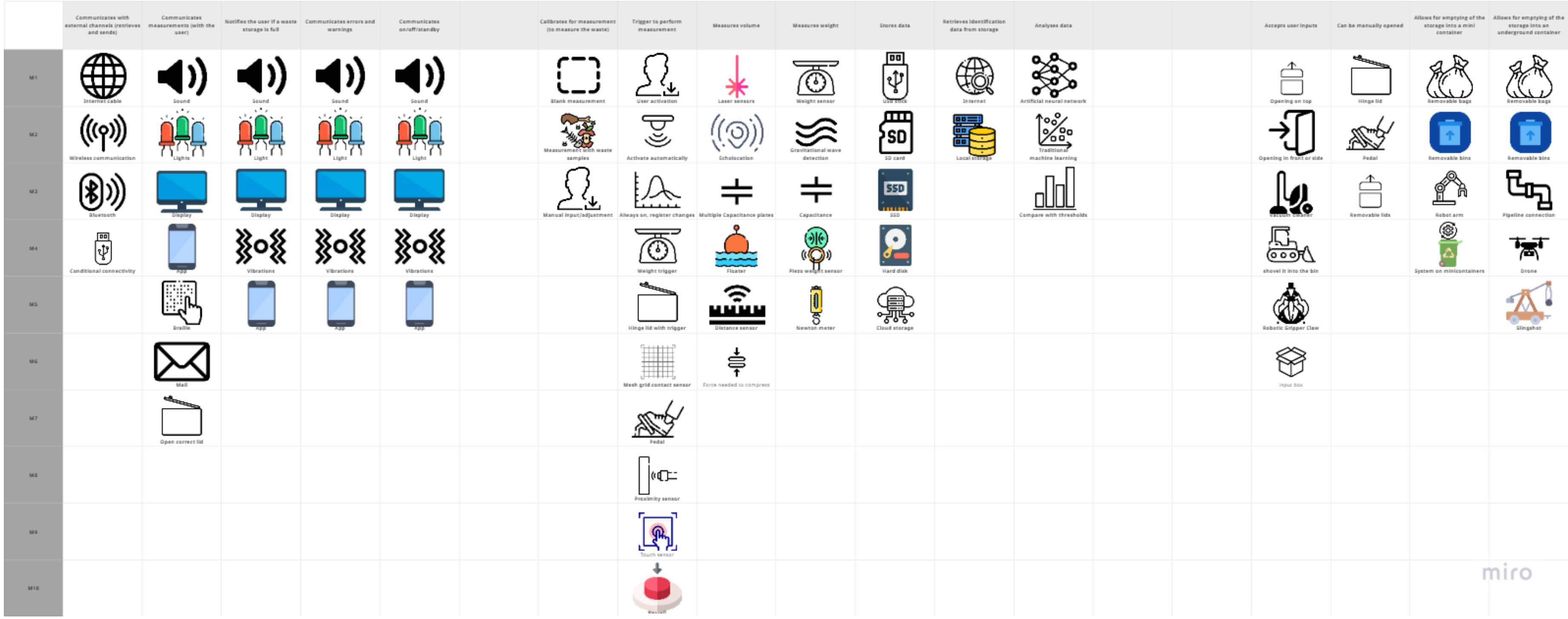
Where $M_{waste\ stream}$ is the weight of individual waste stream (GFT, OPK, PMD, glass, textile, or residual), M_{weekly} is the waste weight an average four-person Dutch household produces weekly, P_{CBS} is the mass percentage of the waste stream according to the CBS and $P_{Afval\ Spiegel}$ is the mass percentage of residual waste according to the Afval Spiegel. The CBS only measures the waste that is collected (of which 34.7% is residual) and thus misses the extra waste of each category found in the residual waste according to the Afval Spiegel. The Afval Spiegel measured the waste in both weight and volume so a conversion factor for weight to volume can be determined. The weights, conversion factors and final volume have been summarised in the table.

Waste stream	Weekly weight	Conversion factor	Weekly volume
GFT	20 kg	0.4 L/kg	7.8 L
OPK	8 kg	1.4 L/kg	11.2 L
PMD	5 kg	4.9 L/kg	24.3 L
Glass	4 kg	0.5 L/kg	2 L
Textile	2 kg	0.5 L/kg	1 L
Residual	3 kg	1.0 L/ kg	3 L

For the requirements in the report, we rounded the weekly volume to the most sensible multiple of 5L. This means that GFT becomes 10L, OPK 10L, PMD 25L, glass 5L, textile 5L and residual 10L. The residual bin is taken a bit more spacious to accommodate for waste that is hard to identify and thus will be shunted to residuals to prevent contamination.

Appendix D: Full morphological Chart

	F1 identifiction of GFT	F2 identification of OPK	F3 identification of Glass	F4 identification of Metal	F5 identification of Textiles	F6 identification of PMD		Allows for the addition of a new waste stream	Moves waste into the correct storage	Pulls waste apart
M1	Ask user	Ask user	Ask user	Ask user	Ask user	Ask user		Clip-on system	Flippers	Blender
M2	Visual identification	Visual identification	Visual identification	Visual identification	Visual identification	Visual identification		Glue	Robot arm	Shaking plate
M3	Blower	QR/Barcode scanner	QR/Barcode scanner	Blower	Blower	QR/Barcode scanner		Magnets	Air pressure	Chemicals
M4	Centrifuge	Blower	Blower	Centrifuge	Centrifuge	Blower		Adjustable dividers	Tilting plate	Controlled explosions
M5	Opacity	Centrifuge	Centrifuge	Opacity	Opacity	Centrifuge		Welding	User	Trained animals
M6	Spectroscopy	Opacity	Opacity	Spectroscopy	Spectroscopy	Opacity		Rope	Vacuum cleaner	Robot arms
M7	Capacitance	Spectroscopy	Spectroscopy	Capacitance	Capacitance	Spectroscopy		Screws	Shaking plate	(Electro)Magnetism
M8	Resistance	Capacitance	Capacitance	Resistance	Fire	Capacitance		Hooks	Conveyor belt	Pressurised water
M9	Waste Sluice	Fire	Waste Sluice	(Electro)Magnetism	Moth	(Electro)Magnetism			Move the storage system to input	Pressurised air
M10	Fire	Worm	Melting	Waste Sluice	Fungus	Waste Sluice			Open correct lid	Fire
M11	Worm	Fungus	Solubility & Buoyancy	Melting	Solubility & Buoyancy	Fire			Funnel	Flippers
M12	Fungus	Solubility & Buoyancy	Identification by animals	Solubility & Buoyancy	Identification by animals	Solubility & Buoyancy			Pressurised water	Ask user
M13	Solubility & Buoyancy	Identification by animals	Röntgen imaging	Identification by animals	Röntgen imaging	Identification by animals			Input box	Shredder
M14	Identification by animals	Röntgen imaging	Geiger counter	Röntgen imaging	Geiger counter	Röntgen imaging				Funnel
M15	Röntgen imaging	Geiger counter	Weight/density	Geiger counter	Weight/density	Geiger counter				
M16	Geiger counter	Weight/density	Radar reflectivity	Weight/density	Radar reflectivity	Weight/density				
M17	Weight/density	Radar reflectivity		Radar reflectivity		Radar reflectivity				
M18	Radar reflectivity									
M19	Sieve									
M20	Smell									
M21	temperature and moisture release									


Communicates with external channels (retrieves and sends)
Communicates measurements (with the user)
Notifies the user if a waste storage is full
Communicates errors and warnings
Communicates on/off/standby
Calibrates for measurement (to measure the waste)
Trigger to perform measurement
Measures volume
Measures weight
Stores data
Retrieves identification data from storage
Analyses data
Accepts user inputs
Can be manually opened
Allows for emptying of the storage into a mini container
Allows for emptying of the storage into an underground container
M1
Internet cable
Sound
Sound
Sound
Sound
Blank measurement
User activation
Laser sensors
Weight sensor
USB stick
Internet
Artificial neural network
Opening on top
Hinge lid
Removable bags
Removable bags
M2
Wireless communication
Lights
Light
Light
Light
Measurement with waste samples
Activate automatically
Echolocation
Gravitational wave detection
SD card
Local storage
Traditional machine learning
Opening in front or side
Pedal
Removable bins
Removable bins
M3
Bluetooth
Display
Display
Display
Display
Manual input/adjustment
Always on, register changes
Multiple Capacitance plates
Capacitance
SSD
Compare with thresholds
Vacuum cleaner
Removable lids
Robot arm
Pipeline connection
M4
Conditional connectivity
App
Vibrations
Vibrations
Vibrations
Weight trigger
Floater
Piezo weight sensor
Hard disk
shovel it into the bin
System on minicontainers
Drone
M5
Braille
App
App
App
Hinge lid with trigger
Distance sensor
Newton meter
Cloud storage
Robotic Gripper Claw
Slingshot
M6
Mail
Mesh grid contact sensor
Force needed to compress
Input box
M7
Open correct lid
Pedal
M8
Proximity sensor
M9
Touch sensor
M10
miro

	Reduces the rotting of GFT waste	Reduces the smell of GFT waste	Reduces the attraction of pests	Keeps itself clean		Stores GFT waste	Stores PMD waste	Stores OPK waste	Stores glass waste	Stores textile waste	Stores residual waste		Switches on/off
M1	Cooling	Vacuum sealing	Vacuum sealing	Pressurised water		Bag	Compressor	Compressor	Bag	Bag	Compressor		Button
M2	Toxins	Cooling	Cooling	Manual		Bin	Bag	Bag	Bin	Bin	Bag		Lever
M3	Sterilizing radiation	Perfume dispenser	Perfume dispenser	Brusher		Blender	Bin	Bin	Shredder	Store waste in a general bin with coordinates	Bin		Pedal
M4	Drying	Toxins	Toxins	Auto Clean			Shredder	Shredder	Smelter		Shredder		Pressure plate
M5	Vacuum	Sterilizing radiation	Deadly ionising radiation	Dry-cleaning (like steam)			Store waste in a general bin with coordinates	Store waste in a general bin with coordinates	Store waste in a general bin with coordinates				Plug/unplug the power cord
M6	Pasturisation	Drying	Drying	Integrated bin pressure washer									Laser sensor
M7	Black soldier fly	Vacuum	Heating	Internal desinfection dispenser									Proximity sensor (infrared reflection)
M8		Pasturisation	Taser	Pasturisation									Touch activation (capacitive sensor)
M9		Control oxygen flow	Trained Guard dog	Internal bin scraper									Mesh grid contact sensor
M10		Composting	Ivy	Storage in bag									
M11		Microorganisms	Lavender	Sand/Microparticle blast									
M12		Burner	Traps										
M13		Air filtration system	Lasers										
M14		Black soldier fly	Mosquito sound										
M15			Scarecrow										
M16			Smoke deterrent										
M17			Strong hull										

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Appendix E: List of prototype components

- Raspberry Pi 5 8 Gb
- Grove hat for Raspberry Pi
- Arduino Uno R4
- Grove cables
- Grove – UV Sensor
- Grove - Infrared Reflective Sensor v1.2
- AS7262 6-channel Spectral Sensor (Spectrometer) Breakout
- Mini High Power Led 3 Watt UV 360-365NM.
- Grove – MOSFET
- AMS1117 3.3V Power Supply Module
- Terminal block to 2.1mm DC (Direct Current) barrel jack – Female
- 12V power adapter

Appendix F: Sweeping capacitive sensor circuit

Below is a diagram of the sweeping capacitive sensor circuit used. The diagram is from (Paganellis, 2012).