Aalborg University

Manufacturing Technology

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Data Collection Strategy for Post-Consumer Plastic Recycling Line

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Data Collection Strategy for Post-Consumer Plastic Plastic Recycling Line

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Abstract:

The project motivation is to investigate how plastics recycling company AVL can improve their post-consumer process line through data collection. Throughout the problem analysis, three cases are established, while inputs from other companies provide focus points for the case work. Case A presents a strategy for collecting data on the resource usage of the line. This has two goals; *documenting* the emissions and *reducing* the emissions. A three step strategy is derived, which will allow AVL to maintain a strong market position while continuously improving the line resource efficiency. Case B revolves around time management. A three step strategy is provided, in which the theory of constraints is introduced to discuss how the line efficiency can be improved, exemplified through discrete event simulations. Also, continuous data collection and predictive maintenance techniques are discussed. Case C investigates how material data can be sampled throughout the line both manually and automatically. A two step strategy is presented, allowing AVL to firstly try many different sample points, by implementing manual data collection. Then, ideas are presented for automatizing data collection to lower the OPEX of collecting data, based on the results from step 1. Finally, the three data collection strategies are combined in a complete five step strategy, and the potential gains from each step are discussed.

Preface

This project is written in LaTeX. For references, the Harvard method is used, indicated by "(name,year)". The sources are listed in order of appearance at the end of the report. All illustrations, graphs, figures and tables are made by the group unless stated otherwise in captions. The majority of figures are vector graphics, and references in the report will work as hyperlinks. It is therefore recommended that this project is read digitally, as it is possible to zoom without decreasing the quality.

The Appendices can be found at the back of the report. These contain relevant information for the reader, which has not been included in the main document. They are divided after the chapters, in which they are introduced.

Four companies have provided insights in relation to this project. Therefore, the group would like to thank AVL, RollTech A/S, Expo-net A/S and Fibertex A/S for collaborating and welcoming us.

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Nomenclature

Abbreviations

AAU Aalborg University

AVL Aage Vestergaard Larsen

CAPEX Capital Expenditures

EPR Extended Producer Responsibility

EU European Union

FEF Freight Emissions Factor

HDPE High-density polyethylene

IR Infrared Light

LDPE Low-density polyethylene

MUDP Miljøteknologisk Udviklings- og Demonstrationsprogram

NIR Near-Infrared Radiation

OECD Organisation for Economic Co-operation and Development

OEE Overall Equipment Effectiveness

OMNIR On-Line Near Infrared Sensor

OPEX Operating Expenses

PE Polyethylene

PET Polyethylene terephthalate

PP Polypropylene

QC Quality Control

REACH Registration, Evaluation, Authorization and Restriction of Chemicals

TOC Theory of Constraints

UN United Nation

Symbols

A Area - varying index

CO_2 Equivalent Carbon Dioxide emissions [t_{CO2}] - varying index

$CO_{2,eq}$ Carbon intensity [$\frac{t}{t}$] - varying index

D Distance [km] - varying index

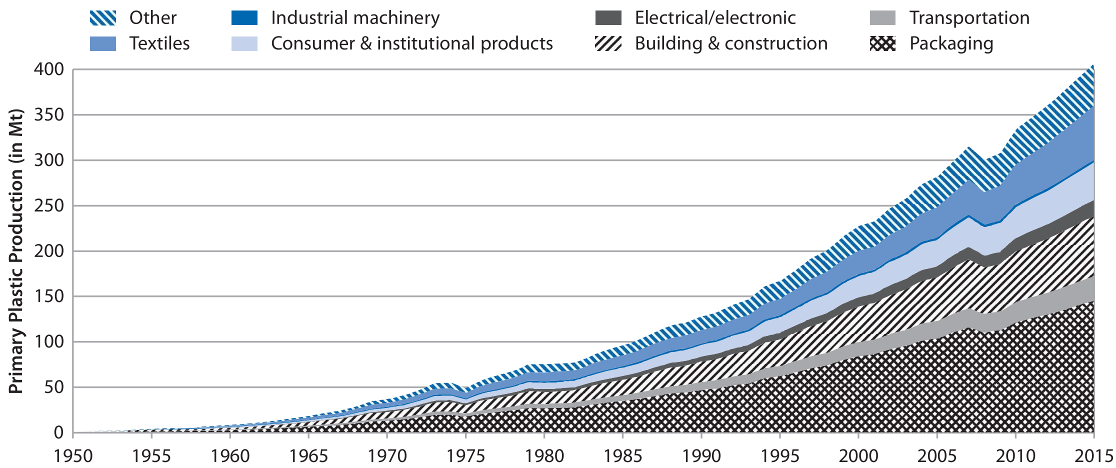
E Electricity [kWh] - varying index

m Mass [kg] - varying index

Contents

Introduction 1

Plastic continues to be an important material in the production of both consumer and industrial products. Since the 1960's the world production of plastic products has increased twentyfold. With plastic production comes plastic waste. According to UN (2021), the annual amount of plastic waste in 2021 is 300 million tons, and it is expected to double within the next 20 years, according to EU (2021). Recycling of the plastic waste is difficult due to the many different types of plastics and additives. Thus only 9 % of the plastic waste ever produced has been recycled, 12 % has been incinerated, while the last 79 % is still placed in land fills or in the nature. A part of the plastics that are disposed in the nature ends in the oceans, resulting in 8 million tonnes of plastic waste being released into the oceans every year. Of the 400 million tonnes of plastic waste produced worldwide in 2015, over a third been used for packaging, making it the biggest source of plastic waste, as seen in Figure 1.1. Due to the fact that this waste type mainly ends up in the municipal waste bins, efficient plastics recycling of municipal waste is crucial.



Source: Geyer, Jambeck and Law (2017[1]), *Production, use, and fate of all plastics ever made,* http://bit.ly/2uBs8AT.

Figure 1.1: Global primary plastics production by sector, 1950 to 2015 (million tonnes). (OECD, 2018)

In recent years, a significant part of the plastic waste in developed countries has been exported to China. However in 2020 China decided to ban imports of plastic waste, with the exception of high quality sorted plastics. This has forced developed countries to consider recycling more of their own plastic waste, thus adapting to a more circular economy according to Geographic, 2021. An example of this is the EU's goal of increasing the recycling rate of plastic packaging waste to 50% by 2025 and to 55% by 2030, as mentioned in Lopez, 2021.

1.1 Plastic Waste Treatment in Denmark

Even though the EU average rate of packaging plastics recycling was around 40% in 2020 (European Court of Auditors, 2020), the Danish recycling rate for plastic packaging was estimated to be only 14% in 2019, according to the Danish Ministry of Environment, Nygaard Madsen et al., 2020 page 65. In Figure 1.2, an overview of the overall Danish plastic waste handling is seen, based on data from 2016. While only 2% of the plastic waste was put into landfills, 57% is incinerated. According to the Danish Ministry of Environment and Food, This is a reflection of the Danish economic regulation of the waste sector in Denmark, which creates an incentive to burn plastics in CHP plants for energy recovery, Danish Ministry of Environment and Food, 2018 page 32. Even though Figure 1.2 shows that 28% of the Danish plastics waste is exported, expert interviews by McKinsey indicate, that only 50% of the exported plastics waste is actually recycled, Høngaard Andersen et al., 2019.

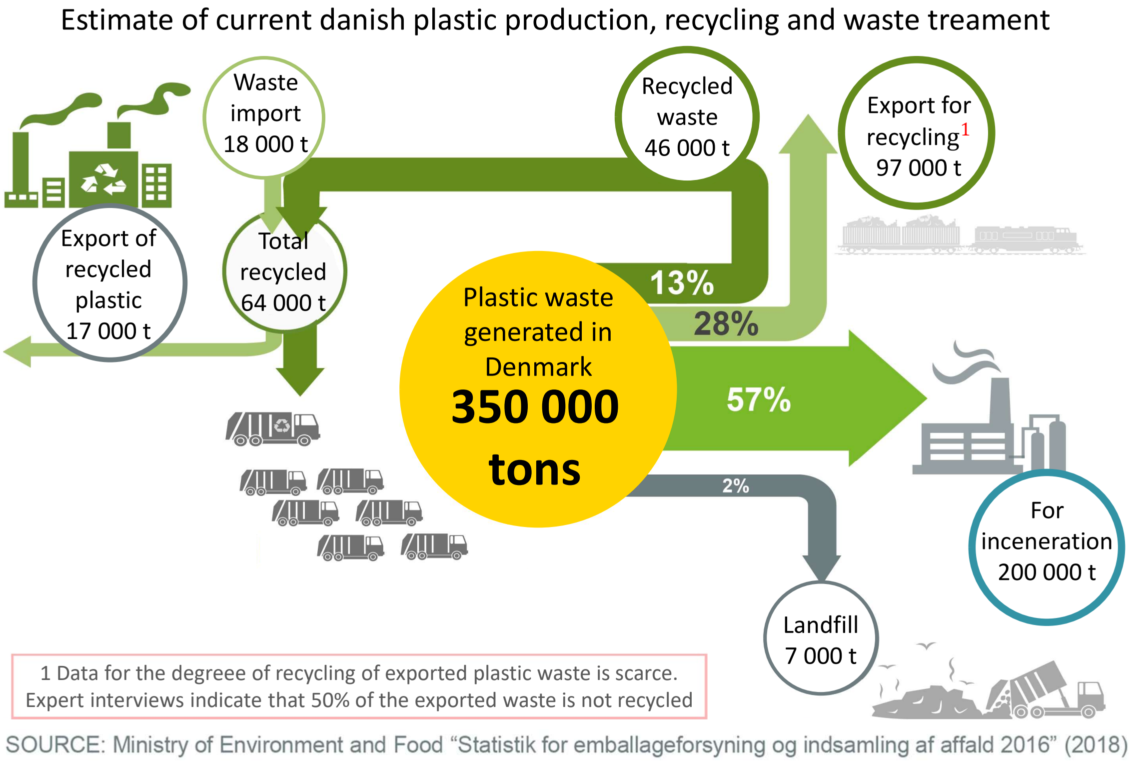


Figure 1.2: Danish plastic waste generation, plastic waste treatment and plastic recycling. (AVL, 2020)

In conclusion, the plastic recycling capacity in Denmark is small, compared to the produced amount of plastic waste. Furthermore, when looking at plastic packaging in municipal waste, the recycling rate is far from complying with the 2025 and 2030 EU goals. To increase the recycling capacity of plastics waste in Denmark, the Danish Ministry of Environment is mainly betting on growth in the private sector driven by better market conditions: "A waste treatment sector exposed to competition with more standardized collection of plastics waste will secure a more cost-efficient and environmentally better waste handling through a bigger and better functioning market", translated from Danish Ministry of Environment and Food, 2018, page 32.

1.2 AVL

The biggest recycler of high quality plastics in Scandinavia is AVL (Aage Vestergaard Larsen A/S), located in Northern Jutland in Denmark. The company employs around 60 people and is responsible for around a third of all plastics recycling, done in Denmark. Since the company was founded in 1972, it has mainly been dealing with industrial plastic waste of various types. However, the company is moving into recycling of household plastic waste, also known as post-consumer waste, and has been developing a production line for this purpose since 2013 (AVL, 2021c). So far, the production line has been tested and it is ready to be assembled in a single production hall in the autumn of 2021. (AVL, 2021b)

Most industrial plastic waste is handled in batches, each containing large quantities of similar objects. An example of this is old trash bins from various Danish municipalities, of which AVL have recycled over 2.000 tonnes, according to AVL, 2021a. As seen in Figure 1.3, the trash bins consist of a limited number of plastic types which are easily separated. Other types of industrial waste handled at AVL include: HDPE boxes used in food industry, plastic piping and discarded packaging. Common properties for most of the industrial plastic waste types handled at AVL include the limited amount of plastic types used in each waste type. Secondly, the different plastic types in the industrial waste are easily separated from each other. And lastly, large quantities are available of each waste type, allowing for the recycling process to be specifically adjusted to handle each type of waste.

Figure 1.3: Municipal trash bins, recycled at AVL. (AVL, 2021a)

Figure 1.4: Bales of post-consumer plastic waste. Picture from: Dansk Industri, 2020

Post-consumer waste is on the other hand more challenging to recycle. This waste type is not homogeneous, as batches will contain many different plastic types, as seen in Figure 1.4, of which only PP and HDPE is actually recycled at the new AVL line. Furthermore, post-consumer waste contains impurities such as paper from labels, sand and dirt, while larger contaminants such as metal and glass are removed in a presorting process before the waste arrives at AVL. To deal with the impurities, the post consumer plastic must go through various washing, grinding and density sorting processes. These processes will also sort out most of the unwanted plastic types, before an optical sorting process is able to remove final impurities in order to achieve PP with 95% purity and HDPE with a purity of 98%, according to AVL (Appendix B.1 on page 95). A more detailed description of the production line and the various process steps is needed and will be provided in Section 2.3.

1.3 Project Motivation

A collaboration has been initiated between AVL and the project group, resulting in two company visits, during which the project group was able to ask questions and see the post-consumer process line. The information gathered during these visits can be seen in Appendix B.1 on page 95. As a part of the process of implementing the new post-consumer process line, AVL would like to gain more knowledge about the resource use throughout the line. This can potentially help AVL establish a stronger market position, through better documentation of environmental impact of their plastics, compared to virgin plastic suppliers. Furthermore, they would like a framework for testing the process setup and parameter changes with the aim of localizing bottlenecks and improving the efficiency of the line, also known as a digital twin. A discrete event simulation, describing the process line, material flow and the resource use might help achieve this insight.

However, through the collaboration with AVL, it became evident, that little data is available on the process line. Furthermore, few specific considerations have been made on a systematic data collection plan. It makes little sense to build a complicated simulation model, when no data is available and especially when no plan for data collection has been made. For this reason, the project group chooses to focus the project on data collection cases, in agreement with AVL. Based on this product description, a mission statement for the collaboration between AVL and the project group has been formulated, see Appendix A.1 on page 93. The presented cases must help AVL secure a favourable market position in the future, help them document resource usage and aid them in the operation and improvement of the process line in the future.

The processing of post-consumer waste at AVL must be analyzed, including their stakeholders, business case, market conditions, value chain, technologies in the processing line and their resource consumption. Based on these analysis, specific data collection cases must be established, to later be evaluated and prioritized to lastly establish the problem statements for the project. Based on the above, the project motivation can be established:

Project motivation: *"Which data collection cases can help AVL improve their production line and market position, and how?"*

Problem Analysis 2

In this Chapter, the problem analysis will be conducted based on the project motivation. The goal is to collect a number of data collection cases that can be evaluated in the end of the chapter. The problem analysis will be conducted by investigating four major themes, surrounding AVL:

- Firstly, AVL and their business will be described. This will include a stakeholder analysis and an outline of AVL's economy.
- Secondly, the post-consumer process line will be described. This includes the material flow, the resource usage and the technologies that are used in the line.
- Thirdly, a description of the plastic types, commonly found in the post-consumer waste, will be made. This description will include their usage, prices and demands. Furthermore, additives will be covered as well.
- Lastly, a market analysis will be conducted to look at global, European and local tendencies and conditions. This analysis will also investigate the plastics recycling industry and conclude on inhibitors within the industry.

At the end of the problem analysis, the cases will be summed up and they will be prioritized. The output of the problem analysis will be a limited number of relevant data collection cases, on which the problem statements and further work will be based.

2.1 Stakeholders

Before diving deeper into problem analysis it is important to understand who are the stakeholders that influence AVL as a company and how do they shape AVL's decisions and goals. A stakeholder influence map, which can be seen in Figure 2.1, will be used to define the stakeholders, as well as the relations between them. After analysing the map, bilateral influence between stakeholders and AVL can be spotted, and different levels of importance can be connected with both AVL and the household plastic process line. Because of that, the map is shaped depending on the prioritisation of each stakeholder and its influence, regarding the cases this project puts under observation. This is why some clouds in the map are colored blue, as they represent bigger importance for the project. Things stated above will cause some of the stakeholders to emerge again and again throughout the report, but some of them will not gain that much attention. Furthermore, some will stay ignored, even though they can be considered as overall important. For example, when recycling plastic, everyone can agree that the environment should be one of the most important stakeholders, but it is not included in the map, as it affects every stakeholder equally.

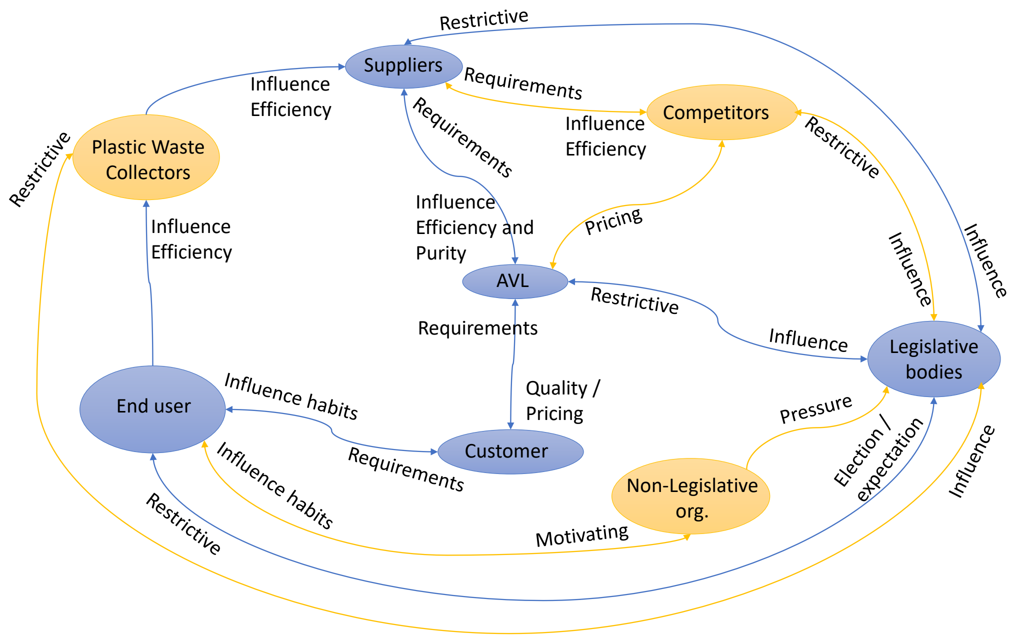


Figure 2.1: Stakeholder influence map.

Map observation should start with "End user" as collecting household plastic waste starts with them, but they are also the final point of plastic circulation, as they hold the requirements for new products made out of recycled plastic. AVL's customers have predefined requirements for plastic properties, that enable them to meet these "end user's" requirements for good quality and low price of the product. After the end user sorts the waste, private sorting companies picked by the municipality are able to prepare the waste for AVL by picking it, sorting it furthermore and finally delivering it to AVL. These connections create a circular economy pattern on the left side of the map, as the influences are moving in a circle. Other circularities inside of the map can also be spotted and analysed in a similar way, while focusing on legislative bodies and competitors.

Legislative bodies hold the biggest overall stake in the map, that is interpreted by regulations and restrictions they provide. This way they could be driving this industry into further success while reducing pollution at the same time. AVL's goals can also be achieved while being driven by the same factors. Furthermore, developing end user's awareness and knowledge about sorting post-consumer plastic, in parallel with development of the process line and supply chain, could actually hold a key role in this circle by improving it's overall efficiency. This is because the better the consumers sort, AVL's input gets better quality, less impurities occur and then it becomes faster and easier to process it.

With legislative bodies driving the industry and influencing end users to improve the process line input, while at the same time staying ahead of their competitors, AVL will be able to move closer to its goals that will be described in next section.

2.2 AVL's Business Plan

The purpose of this Section is to describe AVL's business plan to gain an understanding of potential growths and dangers to their production line. A visual representation of AVL's business plan is shown in Figure 2.2, A larger version of the Figure can be found in Appendix B.8 on page 107. After having established the business plan, an overview of AVL's economy will be provided. The different boxes are described in the following list:

<table>
<tr><th>KEY PARTNERS</th><th>KEY ACTIVITIES</th><th>VALUE PROPOSITIONS</th><th>CUSTOMER RELATIONSHIP</th><th>CUSTOMER SEGMENTS</th></tr>
<tr><td rowspan="3">- Pre-sorting facilitys
- Municipality
- Government
- Consumers
- Customers
- Waste disposal companies
- Water treatment facilty
- REACH</td><td>- Ordering pre-sorted post-consumer waste
- Recycling
- Selling recycled granulate</td><td rowspan="3">- Recycling post-consumer waste
- Center-part of the Danish circular-economy process
- Supplying the need for recycled plastics</td><td>- Achieving high quality, low price recycled material, with a documentation for a low carbon footprint</td><td rowspan="3">- Surge in the need for high-grade recycled plastics by companies willing to pay the green premium</td></tr>
<tr><th>KEY RESOURCES</th><th>CHANNELS</th></tr>
<tr><td>- Municipal post-consumer pre-sorted waste
- Water for the wash
- Electricity
- Additives
- Recycled granulate</td><td>- Municipalities
- Advertisments
- Ecological projects
- Educational projects
- Danish circular-economy project
- Previously known costumers/suppliers</td></tr>
<tr><th colspan="3">COST STRUCTURE</th><th colspan="2">REVENUE STREAMS</th></tr>
<tr><td colspan="3">- Costs of water and electricity
- Costs of pre-sorted post-consumer plastics and additives
- Costs of development of the process line
- Employee saleries</td><td colspan="2">- Sale of recycled post-consumer plastics ganulate
- Technology (future)</td></tr>
</table>

Figure 2.2: Current business plan of AVL

- **Value Proposition** is a description of what value AVL brings to the market. They can become an essential part of the danish circular economy by providing an alternative to incineration of plastic and they can feed a growing demand for recycled plastics. This will be further elaborated on in Section 2.6.
- **Customer Relationship** is how AVL can maintain their customers. AVL can keep their customers by providing high quality recycled plastics with documented low carbon emissions. Furthermore competitive prices are necessary.
- **Customer Segments** include manufacturers of plastic products made from recycled material where the plastic is not downgraded during the recycling processes. Furthermore, the manufacturers seek to sell their products with a green premium.
- **Channels** covers the different methods for AVL to reach potential customers. AVL have many different channels they can use for advertisements and for work on municipality and/or government founded circular economy projects. AVL have also started an educational project called Cirkla Academy that educates the plastics industry in the uses of recycled plastics, which is also a way of finding customers and establishing connections (Cirkla, 2021). AVL have a previously established network in the recycled industrial plastics industry and this network can also be used to find customers for the post-consumer process line.
- **Key Activities** include buying presorted plastic waste from presorting facilities. Afterwards the bales of presorted post-consumer plastic is handled by the recycling line, where electricity and water are used to grind and clean the product, before it is finely sorted. Afterwards electricity is used to extrude the flakes into granulate which can be sold to the customers.

- **Key Partners** include the suppliers of AVL and the presorting facilities. Sharing and getting information from the suppliers can help AVL in creating an efficient line. Furthermore, the requirements from customers can also help AVL optimize their line to meet the needed plastic quality and quantity. Municipalities and the government can be partners both through funding and projects. Process waste is generated during the recycling and the water is contaminated, Therefore both waste disposal companies and water treatment facilities are potential partners.
- **Key Resources** includes electricity and water for the fine sorting and recycling processes. Additives are also needed during the recycling process in case there are specific requirements from the customer. The presorted post-consumer plastic input to the line and the recycled granulate that is sold to the customer are both resources as well.
- **Cost Structure** consist of the OPEX: cost of electricity, water, additives, salaries and presorted post-consumer plastics. Meanwhile, the CAPEX includes investments and developments for the post-consumer process line.
- **Revenue Stream** is divided between the sale of recycled plastic to the customers and the potential of selling their technologies and knowledge in recycling to other post-consumer plastic companies.

The business plan implies that there is a multitude of key partners and there is many channels for AVL to find both new suppliers and new customers. The customer requirements are, as shown in the stakeholder influence map, dependent on the demands of the end user. Assuming that the end-users are becoming increasingly aware of the CO2 emissions in what they buy, it is expected that the customers of AVL will have an increasing wish of being able to document the low carbon emissions in their recycled products. Furthermore, increasing the recycled plastic purity and the documentation of its quality, might allow AVL to move into new higher quality customer segments such as: food, cosmetics and medical products. AVL can thus increase their revenue stream by providing documentation for the resource use. Meanwhile, decreasing the cost can be achieved by decreasing resource usage and salary expenses.

The involvement of the resource usage in both the Cost Structure and Revenue Streams leads to the case of measuring and documenting resource usage.

Case 1 *How can the resource usage be measured, and how can the information be used to cut down resource usage?*

2.2.1 AVL Economics

It is in Denmark mandatory for joint-stock companies, like AVL, to publish their annual accounts. This annual accounts gives an inside in to the financial status of a company.

In 2020 the profit for AVL was 4 693 269 DKK, which resulted in an increase in their equity. The equity was Therefore as of 2020: 28 117 419 DKK, which includes both the post-consumer and industrial waste processing lines. This was an improvement from 2019 of over 1 million Dkk. This can also be seen in a increase of employees at AVL, which has been increasing from 2016 towards 2020, as seen in Table 2.1. (Beierholm Statsautoriseret Revisionspartnerselskab, 2020)

Year	2016	2017	2018	2019	2020
Avg employees	51	49	53	55	56

Table 2.1: Average amount of employees at AVL in the years 2016-2020

This increase in employee number is seen as a sign of prosperity. The post-consumer process line is also mentioned in the annual accounts. Here, AVL state that investments have been made in the new line. AVL's goal is to have the post-consumer process line up and running, turning a profit within 2021. However, the project has been delayed, and profit will likely appear in 2022 instead. A growth can be seen in the value of production lines and machines, as there is an increase in the production line and machines assets of AVL from 2019 to 2020 of 982 370 DKK, see Table 2.2. (Beierholm Statsautoriseret Revisionspartnerselskab, 2020)

	2020	2019	Difference
Production lines and machines	9 620 726 DKK	8 638 356 DKK	982 370 DKK

Table 2.2: Production line and machines assets at AVL in 2020 and 2019. (Beierholm Statsautoriseret Revisionspartnerselskab, 2020)

From the annual accounts it can be seen that AVL are increasing the overall investment in production equipment. A part of this new investment is invested into the post-consumer plastics recycling line. Furthermore it can be seen that the company has a growing number of employees, and a growing equity. The company is therefore considered to be in a good position to increase their production capacity and/or costumer segment. In the following Section the post-consumer process line will be presented in details. Furthermore, relevant cases for data collection will be established.

2.3 Process Line

The post-consumer process line at AVL is a result of a cooperation between multiple companies. This includes Reno Nord I/S, which is a household waste collecting and presorting company, and AL2-Teknik A/S, a company that produces water treatment equipment. AVL, along with a few cooperating companies, have been handed a MUDP (Miljøteknologisk udviklings- og demonstrationsprogram) donation of 2.35 mil DKK to develop the post-consumer plastic process line. MUDP is a danish fund sponsoring the development of environmentally friendly technologies. (Miljøministeriet, Ecoinnovation - MUDP, 2020)

This funding has been used to develop a prototype of the post-consumer process line. The prototype line has been tested and is now moved to a new location, to create a permanent production facility. AVL hope that the chosen design will prove to be a step towards a dominant design. Achieving this will allow AVL to turn their focus from development of new processes, into optimizing their existing process architecture and making variants. An example of this, is their goal to develop a variant of the post-consumer process line which can be used to make food packaging and medical grade plastics. In order to improve the production line and make variants, further knowledge about the processes is however needed. This includes currently missing knowledge about: capacities, the amount of waste being removed at each process step, efficiencies of processes, influence of impurities in the presorted plastic and more.

In the following sections, the post-consumer process line will be described as it will be set up in the new production hall. This is done by firstly looking at the input to the process line, i.e. the presorted waste. Then, the process steps and resource flow will be explained. Lastly, a brief discussion will be made on the degree of automation.

2.3.1 Description of the Presorted Plastics

The input of the post-consumer process line at AVL are bales of presorted plastics, sorted as either PP or HDPE. AVL have currently collected data from 4 batches of PP and 3 batches of HDPE as a part of the testing process of the equipment, prior to the final assembly of the line. The data is seen in Appendix B.3 on page 101, where the purity of the presorted plastics varies between 56-82 %, measured by the amount of target material, which is extracted from the presorted plastic batches. Thus, further sorting is needed to reach sufficient purities. AVL are only paying for the percentage of waste, that they are able to turn into recycled plastics. This is a trust-based agreement as the supplier's income is then partly dependent on AVL's ability to recycle plastics.

The impurities, present in the presorted PP or HDPE bales includes: other plastic types, sand, glass, dirt and paper. The sand causes the blades used for grinding to become dull, which increases the amount of maintenance required to keep the recycling process running. Generally, a more efficient post-consumer process line can be obtained if the presorting is improved to deliver the presorted material with a higher purity. This leads to a case regarding how AVL can improve the quality of the presorted plastic, by gathering data and supplying high quality feedback to their suppliers:

Case 2 *Could the presorting be improved by increasing the data collection on AVL's post-consumer process line?*

2.3.2 Layout of the post-consumer process line

The objective of this Subsection is to describe the different steps in the post-consumer process line. Figure 2.3 visualises the flow of the plastics, contaminants and resources in the AVL process line. A larger version can be seen en Appendix B.2 on page 100. Each process step is outlined in the list below:

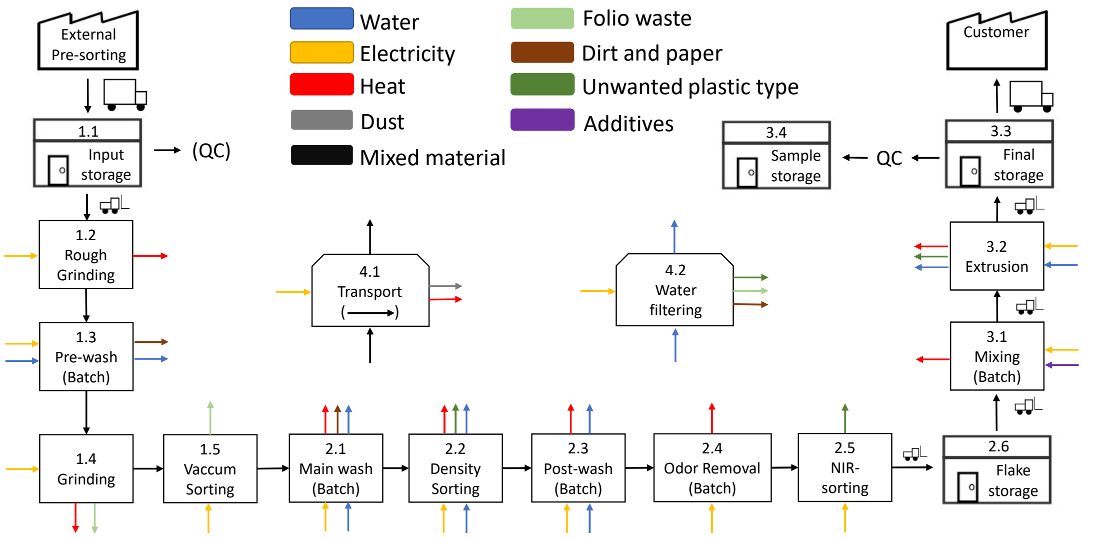


Figure 2.3: Flowchart over the process at AVL, based on information provided by AVL. The color of the arrows represent flow of different resources and materials. (Appendix B.1 on page 95)

- **1.1 Storage** is the area where the presorted plastic is stored after being delivered by suppliers. The plastic is moved from the storage to the process line with a forklift.
- **1.2 Rough Grind** is a process where the bales of presorted plastics are grinded to smaller pieces with a size of approximately 50 mm × 50 mm.
- **1.3 Pre-Washing** is the first wash of the input material. The pre-wash is done to remove sand and other unwanted heavy materials in the waste. By doing so, excessive wear from sand, rocks and glass is prevented in the following grinding and vacuum sorting processes.
- **1.4 Grinding** is the second grinding of the materials to reduce the size of the flakes to a size of approximately 10 mm × 10 mm, so they can be sorted by the vacuum sorter. The grinding process also partially dries the flakes, making them ready for the density sorting.
- **1.5 Vacuum Sorting** is a process where the lighter materials, such as films, are removed by an air stream. The removal of lighter pieces is important since they can introduce errors in the density sorting.
- **2.1 Washing** is the second wash, where leftover paper and other impurities are removed. The wash is necessary for the density sorting to perform sufficiently.
- **2.2 Density Sorting** is a process where the plastics with a density less than 1 g/cm^3 are separated from the plastics with a higher density. The higher density plastics are discarded as waste.
- **2.3 Post-Washing** is the last wash, which removes the last contaminants. The wash is run at a temperature of 68 °C, to better remove glued on labels and residual dirt. Furthermore, the process has showed promise in aiding in the removal of odor, it the process temperature is increased further.
- **2.4 Odor Removal** is a process where the plastics are heated to a temperature of 110 °C, to remove unwanted odor by blowing air through the flakes. Due to the requirements from the current customers, the odor removal is not currently active in the post-consumer process line.

- **2.5 NIR Sorting** is a machine that can identify different plastic types and colors by using a near-infrared sensor. The unwanted plastic flakes are then shot by an air nozzle to a container.
- **2.6 Storage** is the area where the sorted flakes are stored before mixing.
- **3.1 Mixing** is the last process before the extrusion. The flakes are mixed with colorants and other additives. Depending on customer needs, different batches of plastic can be mixed here to achieve the wanted properties.
- **3.2 Extrusion** produces the finished granulate. During the extrusion process, waste is generated because of the filter used in the machine.
- **3.3 Storage** is the area where the finished granulates are stored before shipping.
- **4.1 Transport** is the system that transports the flakes between processes in pipes using an airflow. Dust and small plastic particles are filtered from the airflow, before the NIR sorting. This prevents the sensors from being covered.
- **4.2 Water Filtering** is a process where the water is cleaned before being recirculated in the production line. The water filter consist of a rotating belt filtration system, where the rotating belt transports the waste particles to a container.
- **QC** is performed at the input and output of the post-consumer process line. While the input QC is only a visual inspection to check for large metal pieces, the final QC includes an analysis of the chemical composition and mechanical properties of the material.

During the research of the layout of the process line, a number of data collection cases have been established regarding the process capacities and material flow:

Case 3 *How can material sample testing be implemented at specific points in the line, and what can be gained from it?*

Case 4 *How can the capacity of each machine be measured, and how can this knowledge help in the optimization of the production line?*

Case 5 *How can a time logging system, logging downtime, lead-time, storage time, etc., be beneficial for AVL?*

As resource usage is a significant part of AVL's expenses, several cases regarding the resource usage have been established. Apart from looking at the electricity and water usage, as proposed in Case 1, the heat flow, discarded waste and water quality can also help document the process line resource flow:

Case 6 *How can the temperature of the material flow be measured, and what could be gained by collecting this data?*

Case 7 *Can it be profitable to measure the flow of heat in the used water?*

Case 8 *Can the water quality be measured, and can this information be used to better understand the washing processes?*

Case 9 *How could the amount of waste discarded in each process step be measured, and what would be gained by doing this?*

2.3.3 Degree of Automation

The degree of automation is high in the post-consumer process line. Only 1 to 2 workers will be present when the production line is operating. The tasks of the workers will mainly be to fill in the bales of input plastics, and change the containers that contain either the finished flakes or waste from the various process steps. Furthermore, they will have to overview the production line, as there is not many sensors installed.

One of the few sensors, that can help the workers to survey the production line, is the NIR sensor. The NIR sensor can detect many different material types. As previously mentioned, the NIR is currently used for the last sorting of the flakes, but the generated data can also be used for quality control and surveillance of the production line. This leads to the following case:

Case 10 *How could the data from the existing NIR sensor be used for quality control and surveillance of the production line?*

Adding more NIR sensors to the production line could also improve the surveillance and quality control of the production line, this is the subject of case 11.

Case 11 *What can be gained from adding more NIR sensors to the production line?*

Another possibility of optimization would be to add sensors on the different machines, that could help to predict when maintenance is needed. This could for instance be sensors capturing vibration, noise or temperature from the machines. This leads to the following case:

Case 12 *What could be gained from installing sensors on the machinery in the production line, to predict maintenance?*

As mentioned previously, the plastic flakes can be subjected to an odour removal process. Currently, there is no quality control performed on the plastic flakes after odour removal, except from the employees checking the smell using their nose. If the odor removal process is to be used as an integrated part of the process line, a case for using sensors in odour quality control is suggested:

Case 13 *How could a sensor be used for quality control after the odour removal and what could be gained from it?*

2.4 Plastic Types in Post-consumer Waste

The different plastic types found in post-consumer waste will be described in this section. Figure 2.4 gives an overview of the different plastics types in post-consumer waste. The Figure shows the amount of plastic that has been sold or used after their manufacturing, thus not including industrial plastic waste. What can also be recognized in the Figure is that most of the post-consumer plastics consist of packaging products.

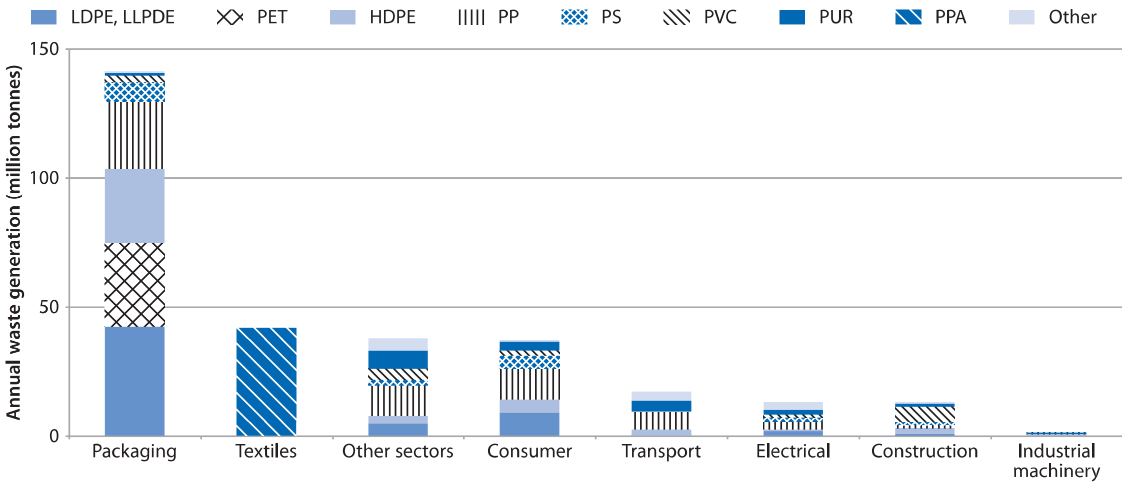


Figure 2.4: Plastic types found in different types of post-consumer plastics. (OECD, 2018)

In Figure 2.4 it can be seen that most packaging is made of four plastic types: HDPE, LDPE, PET and PP. Of these four very common plastic types the post-consumer process line at AVL recycles HDPE and PP.

LDPE is known for being difficult to recycle, because the most common LDPE products are wrappings, bags and flexible containers. The thin products can tangle up in machinery and they are often more contaminated than hard plastic types according to Plastic experts, 2021. For this reason, the post-consumer process line has been designed to sort out the LDPE, mainly using the vacuum sorter.

Originally the post-consumer process line at AVL was intended to handle PET, PP and HDPE. But tests performed during the development showed that the input PET had to much variety in the chain lengths. Thus, leading to a poor output quality of the PET. Because of the poor test results of the PET, AVL have decided to only process PP and HDPE in the post-consumer process line, as mentioned in Plastics Recycling World, 2020.

2.4.1 Prices of Plastics

AVL make a profit by refining sorted discarded plastics into a granulate, which is then sold to be used in the production of new plastic products. The output granulate from AVL has a pureness of at least 95% for PP and at least 98% for HDPE (Appendix B.1 on page 95). The impurities in the plastics along with the extrusion, means that the recycled plastics are of a lower quality than virgin plastics. This can also be seen in the prices for different grades and types of plastics, which can be seen in Figure 2.5. According to AVL this price difference, between virgin and recycled plastics, have been reduced in previous years, due to high customer demand for recycled plastics (Appendix B.1 on page 95).

In Figure 2.5, it is also worth noting the difference between the price of the recycled plastics and sorted waste plastics. This can be interpreted as the value added by AVL to the material. For AVL to have a profitable process line, the value adding has to be capable of covering the operating costs, such as wages, electricity, water, rent, depreciation of equipment, etc.

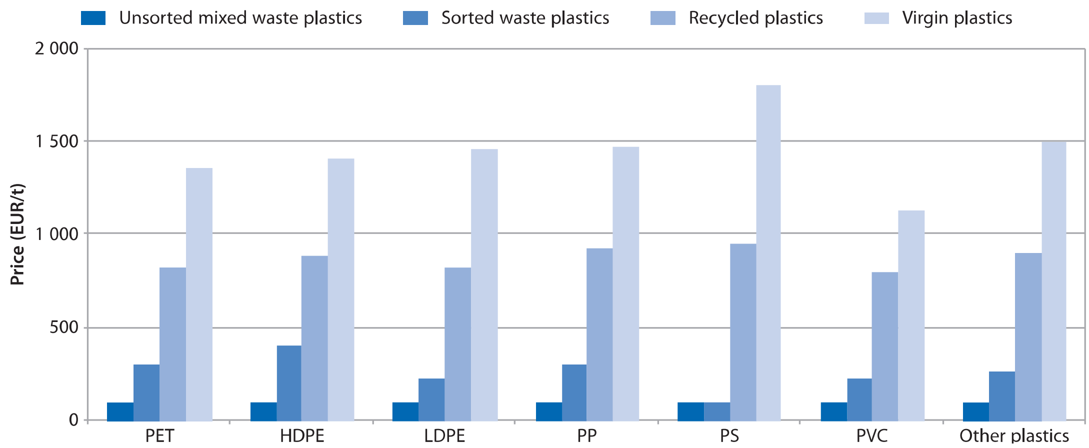


Figure 2.5: Value of different plastics types (2013-2015). (OECD, 2018)

The prices of both the presorted plastics and the output of recycled plastics are affected by many external factors. These factors ranges from input and output quality, where AVL have some control, to purely external factors such as oil and shipping prices (OECD, 2018).

2.5 Uses of Plastics

As seen in Figure 2.4, almost 150 million tons of plastic is used for packaging each year, but what types of product are being produced? In the following sections, the properties of virgin and recycled PP and HDPE will be shortly described. Then, the plastic production demands now and in the future will be investigated. Lastly, the use and effects of additives in plastics recycling will be covered.

2.5.1 PP

PP, or Polypropylene, was discovered in 1951 by scientists named Paul Hogan and Robert Banks who worked for Philips. Today it is one of the most commonly used plastic types in the world. Virgin PP is made by distillation of hydrocarbon fuels. After distillation, fractions of the fuel is mixed with other catalysts to make plastic. PP is not only used in the packaging industry. It is widely used because of its high flexible strength due to the semi-crystalline nature of the material. The crystal melting point of PP is 176 °C and it has a tensile strength of 32 MPa. PP is also very resistant to absorbing moisture and has a good impact strength. The PP can be used in an injection molding process, here the typical products being produced are plastic containers, tableware, plates, cups or trays. (Creative Mechanisms, 2016)

2.5.2 HDPE

HDPE or High-density polyethylene was discovered in the 1930, but was firstly used commercially after Word War II. HDPE differs from LDPE (low-density PE) by being a stiffer material. Other advantages with HDPE is UV-resistancy and resistancy to most chemicals. HDPE is used in the food industry because a bottle made of HDPE will be dishwasher safe. The melting point of HDPE is 136 °C, and it has a tensile strength of 29.6 MPa. HDPE is often blow-molded into bottles that are used as chemicals containers. Other than bottles, HDPE is also be used to make pipes, flowerpots, toys, grocery bags and many other products. (A&C Plastics, 2021)

2.5.3 Recycled PP and HDPE

All of the products, mentioned in the previous sections, can also be made with recycled plastics. However, when using recycled plastics, obtaining the same properties can become a problem, as PP and HDPE is sensitive to an array of different factors. The most important one being the purity of the PP or HDPE. Due to the different melting points and their chemical composition, the two materials cannot be completely combined. This means that if a bottle made of HDPE is blow-molded and the granulate contains too much PP, holes would develop because of the different melding points and general difference in properties. Furthermore, this explains the higher purity requirements for HDPE compared to PP, as mentioned in Section 2.4.1. The recycled HDPE will also contain a percentage of LDPE, but as these two plastic types are more compatible, its usually not an issue, according to AVL (Appendix B.1 on page 95). Another effect of insufficient purity in the recycled plastics is discoloring and changes in mechanical properties. Presorting is therefore an important step to limit the cross-contamination in the finished product.

According to Plastics Europe, 2020, closed loop recycling is difficult, especially when the product have high requirements. This is mainly due to chemical degradation from the extrusion and the general use of the plastic products in which the products can be subject to UV light, chemicals and general wear and tear, as investigated in Garcia, Scuracchio, and Cruz, 2013. Furthermore, additional impurities will be added to the recycled plastics every time its passed through the life cycle, also referred to as cross-contamination. Some of the effects from this are changes in mechanical properties, melting points and the rheology, which affects the behavior of the plastic during extrusion.

2.5.4 Plastic Production Demands

There is generally an increasing interest from consumers that more and more products are made of recycled plastic. Not only in the packing industry, but also other industries has show a greater interest in recycled plastics, in recent years. Figure 2.6 shows which sectors used the recycled plastic granulates produced in the year of 2020 in Europe.

If a high quality plastic bottle is recycled, the recycled plastic might not be of a sufficient quality to be made into a new bottle. Instead, the plastics will be used for medium quality products such as containers for soap or detergents or low quality products used in construction or agricultural equipment such as plastic matts or plant trays. In Figure 2.6, it is seen how the largest part of recycled plastics are used in construction, which is mostly low quality recycled plastics. This indirectly indicates the challenge of maintaining the quality of plastics when they are recycled.

During this project, several companies have been visited. Two companies had plastic manufacturing as a part of their production: Expo-net A/S, a manufacturer of extruded plastic nets, and RollTech A/S, a manufacturer of edge spacers for insulating windows.

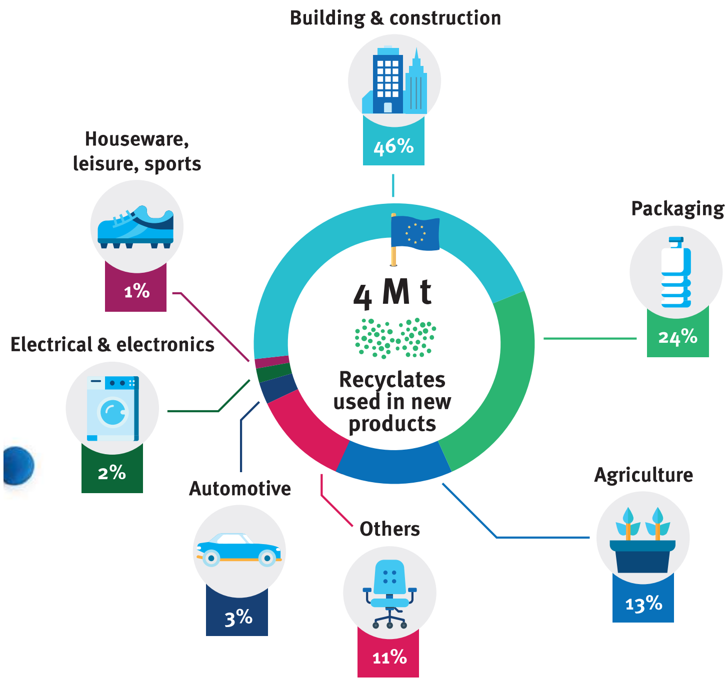


Figure 2.6: The use of recycled plastics in Europe (2020). (Plastics Europe, 2020)

Both companies responded that they had tested if they could use recycled plastics in their products. RollTech A/S was not able to meet the right tolerances on the plastic parts of their edge spacers. Expo-net A/S was able to use recycled products in one of their products but was only able to use 10-30 % of recycled plastics in the product, as the net extrusion process is quite sensitive to the material properties. Both companies responded that they to some extent were interested in using recycled plastics, but that the present-day properties are too poor. The quality can be improved by adding additives, this is described in Appendix B.5.

2.6 The Global and European Plastics Recycling Market

In the last few decades plastic production has outpaced every other material production in the world, from 2 million metric tonnes of plastic produced in 1950 to 322 million metric tonnes produced in 2015, as shown in the Amy L. Brooks, 2018. Plastics, mostly used for packaging, quickly became an important part of everyday life. While the world need for plastics was growing, not a lot of thought was put into the impact of production on such a large scale. That problem was "solved" in 1980s and 1990s. China and other Asian countries started importing large quantities of waste material, to reuse it. It was a mutual benefit process, because the world needed a solution for the waste and Asia had a surplus of cheap labour to reuse the waste material, that was better quality then the domestic one. (Aaron Mak, 2018)

In 2017 China launched a new policy called "The Operation National Sword", in which a new waste management strategy is implemented towards rejecting import of Western plastics waste, as shown in Amy L. Brooks, 2018. This has become a trend for the rest of the Asian countries, while for Europe it was the turning point and a incentive to start thinking about a more sustainable waste management future. Exports were reduced and

Europe had a newfound need for independence, so the circular economy idea rose in the need of handling own waste material and resource management. Visual representation on the impact of the import ban on European waste export can be seen in Figure 2.7. After 2015, a sharp drop can be seen in exporting waste, especially to China.

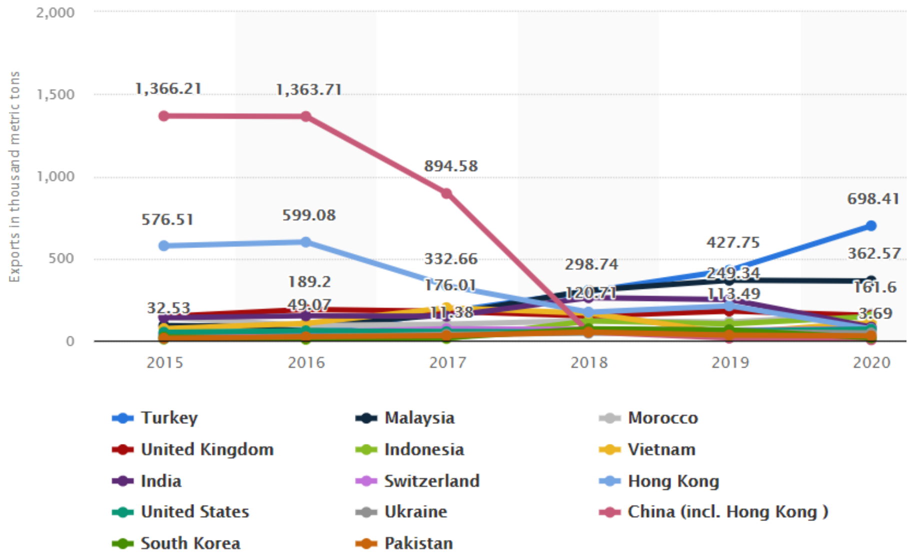


Figure 2.7: Annual volumes of plastic waste exported by the European Union from 2015 to 2020, by select destination* (in 1,000 metric tons). (Statista, 2021b)

2.6.1 Circular Economy in the EU

Circular economy is a model of consumption and production oriented on reusing, sharing, refurbishing, recycling, repairing existing materials as long as possible in the hope of responding to global challenges, like global warming and resource consumption. The use of raw plastic materials is increasing and only 9% of all produced plastic have been recycled by 2019. By 2018, this percentage grew higher to 9.1% according to Circle Economy, 2021. Benefits of circular economy model are related to economical growth, growth of employment, innovation stimulus and the environment. In regards to economical benefits, especially for the European Union, it is important to decouple the economical growth from the use and production of new raw materials. This will make labour valued higher than raw materials, which will increase the employment. (Nederland circulair, 2021)

In 2015, the European Commission decided to implement a new action plan for circular economy as seen in the brochure EU, 2021. Recycling plastics was defined as a priority and EU started preparing a new strategy focused on it. This is creating a foundation for a new ecological and economical plastics economy.

EU influences the plastics recycling market and promotes circular economy with regulations and legislation focused on plastic use and disposal. Because of the waste export market shrinking, EU countries are implementing new EPR (Extended Producer Responsibility) legislation and deposit return schemes as explained in Gemma James, 2019. EPR legislation is made to hold producers of plastic responsible for any negative environmental impacts that their product produces. It is an initiative for manufacturers to care about their product design and end-of-life cycle. Deposit return schemes are getting more and more popular, and are used by applying a surcharge while buying products, which is returned when the packaging is returned. An example of this is the Danish "pant" system. In Figure 2.8, it is seen that since 2015 there was a big rise in regulations, in regards to plastic bag usage. It is expected that more legislation will come in the future, which will favor the Circular Economy Strategy and the plastics recycling industry.

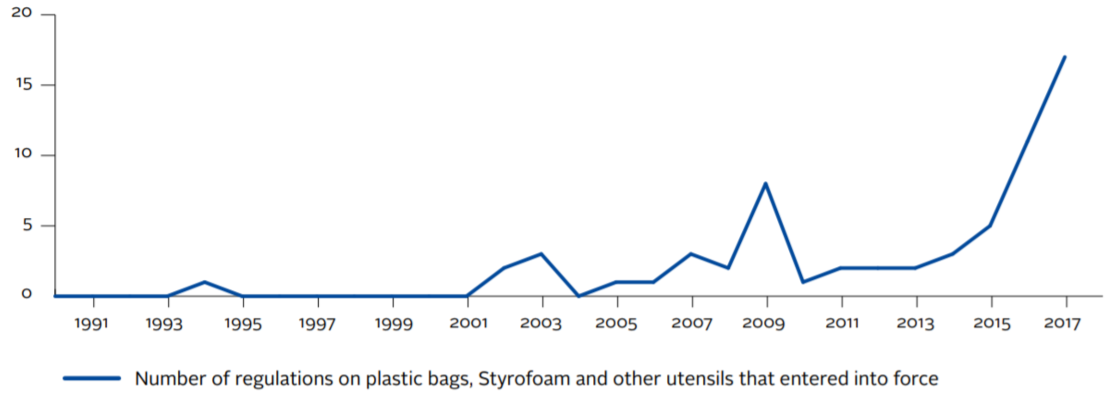


Figure 2.8: Estimated number of new regulations on single-use plastic coming into force at a national level (globally). (Gemma James, 2019)

There is a number of focus points for the European Union regarding the realisation of their goals. One of the key tasks will be to improve the quality of plastics recycling and this will require cooperation from both the public and private sector. Most of the recycling is happening in small and regional facilities, which brings the need for more scaled and standardised recycling operations for the market to function smoother. Also, since the quality of recycled plastics can vary depending on the supplier and it has to satisfy high safety standards, the suitability of the plastic can be a problem because of its chemical composition. This brings us to the point of improving separate collection and sorting of waste. National, regional and local authorities with recycling and sorting companies will play the main role in solving this problem. (EU, 2021)

2.6.2 Plastics Recycling Market in the EU

The estimated total plastics recycling capacity in the EU is 8.5 million tonnes, which manifests in a 3 billion dollar industry, according to Waste Management World, 2021. Meanwhile, the yearly European generation of plastic waste was 29.1 million tonnes, of which 60% is plastic packaging waste (Ravignan, 2020). Furthermore, a McKinsey report on the plastic recycling industry in Europe (Kirilyuk et al., 2020) showed that only 23 out of 57 surveyed plastic recycling companies would be handling municipal waste. Meanwhile, 43 of them were handling industrial plastic waste. The same trend is seen in a study by Antonopoulos, Faraca, and Tonini, 2021, which concluded an overall plastic packaging recycling rate within the EU of only 14%. In conclusion, the European plastic recycling industry is not fit to handle the huge amount of yearly generated post-consumer waste. Consequently, the European plastics recycling industry must grow substantially in the coming years, if the European Union is to meet its recycling goals while cutting down on exports, to become less reliant on other countries for waste handling.

European countries with a history of high focus on recycling and waste management also seem to have the biggest plastic waste recycling capacities, as concluded through an investigation, seen in Appendix B.6 on page 104. But a big part of this capacity currently focuses mostly on recycling of industrial plastic waste. Germany is concluded to have the largest and mostly developed plastics recycling industry, and can thus present a significant competition to Danish recycling companies, such as AVL. However, the coming capacity demand in the EU is expected to reduce the competitiveness in the industry. Generally, the coming growth in demand and the political willingness in the European Union establishes a favourable market situation for the European post-consumer plastic recyclers. This would allow for potential import opportunities to arise for AVL, if they can expand process capacity sufficiently.

2.7 Trends and Challenges in the Industry

When investigating the European plastic recycling industry, it is relevant to look into the common trends of other companies; What types of technology is used? What conditions do they operate under? What challenges are they facing? And what can be done to improve the market conditions of the industry? The following discussion will be based on a study of the European post-consumer plastic packaging recycling industry, conducted by researchers at the European Commission Joint Research Centre (Antonopoulos, Faraca, and Tonini, 2021). The study investigated five different post-consumer presorting facilities and eight different post-consumer plastic recycling plants from different European countries. Furthermore, a report by Organisation for Economic Co-operation and Development (OECD) on improving the plastics recycling markets globally (OECD, 2018) will be included in the discussion.

2.7.1 Analysis of European Plastic Recyclers

In Antonopoulos, Faraca, and Tonini, 2021, the presorting facilities are referred to as material recovery facilities (MRF's). Out of five of the investigated MRF's, two of them have provided numbers on the purity of their output of sorted HDPE, even though all five MRF's are sorting this plastic type. Both of the two MRF's who provided numbers report an output purity of 98%. The two PP-sorting MRF's report output purities of 98% and 92%, respectively. These numbers are generally high, when comparing to the reported PP and HDPE contents of the presorted waste received by AVL, as mentioned in Section 2.3.1. For more data, see Appendices B.4 and B.3. Even though the limited data is at risk of being anecdotal, it can indicate the following things regarding the presorted plastic:

- The presorted input, received at AVL has a lower purity compared to what is achievable at in other European countries. This can be supported by the experience at AVL that the output from Swedish presorting facilities is of higher quality than the output coming from Danish presorting facilities (Appendix B.3 on page 101).
- As AVL measures the input purity indirectly by looking at the amount of sorted PP and HDPE at the end of the post-consumer process line (Appendix B.1 on page 95). They might be sorting out large amounts of target material in their line, which supports investigating case 9.
- The purity of presorted HDPE is higher compared to the presorted PP. This cannot be concluded directly on the report, but a pattern seems to be present in the data from AVL (Appendix B.3), with an average yield of 60,5% for PP while being 79% for HDPE.

- The fact that only a few MRF's supply data on their output quality of HDPE suggests that data availability is very limited in this field. This is further supported by a COWI study (Ingenieurgemeinschaft Innovative Umwelttechnik GmbH, 2019), in which only 12 out of 240 companies had replied to their inquiries.

Antonopoulos, Faraca, and Tonini, 2021 also supplies information about the utilized process technologies used at the different investigated facilities. They do however not supply more detailed information on how the process lines are generally organized, as the investigated plants were not interested in supplying this information. When looking at the listed technologies, seen in Appendix B.4 on page 103, some general patterns can be derived for the recycling plants (denoted as REC's):

- Five out of eight investigated recycling plants utilize magnets and Eddy current separators. This might imply, that metals are present in the input to these process lines. According to AVL, this has not been a problem with the limited number of suppliers, that they have engaged with so far (Appendix B.1 on page 95).
- Sink/float separation and density sorting is a commonly used method, utilized by five of the recycling plants.
- NIR is the most commonly used sorting method, utilized by six of the plants. Moreover, all of these plants either utilize several NIR separators, or they route the material through the same NIR machine several times.

Due to the limited data on the output quality of the investigated recycling plants, the utilized technologies cannot be directly compared to these. However, it can be concluded that NIR sensors and density sorting mechanisms are widely used by the investigated European recycling plants. Furthermore, several NIR sorters are often combined with density sorting, which would support the argument for investigating cases 10 and 11. The common utilization of magnets and Eddy currents at recycling plants indicate that the presorted plastic supplies in some markets will contain significant amounts of metal.

2.7.2 Market Inhibitors in the Industry

Based on the above discussion and conclusions from OECD, 2018, the following general challenges can be concluded as being present in the plastics recycling industry:

- Data sharing in the industry is limited. This is both in terms of technological knowledge, but also in terms of market survey data. As suggested in OECD, 2018, this inhibits the ability of actors to make evidence-based decisions and interventions. In this case, the actors include both the recycling plants themselves, their suppliers, customers and legislative bodies.
- The presorted waste quality is varying dependent on the plastic type and supplier. Furthermore, the types of contaminants (such as metals) present in the waste can vary across different markets, as different methods and standards for collection and presorting of post-consumer waste varies between countries and even between municipalities.
- The above issue of industry secrecy makes it hard for new players to enter the market. This might inhibit the growth of AVL as well, as other recycling businesses in Denmark might help AVL develop the market and their technologies through collaborations. Furthermore, collaborations could increase the ability of AVL to push for greater standardization in terms of waste collection and presorting.

- According to OECD, 2018, primary and recycled plastics are globally treated as substitutes. And while virgin plastics has a higher market value, c.f. Figure 2.5, this puts the recycled plastics in an unfavourable market position of having to compete under the same market conditions while having a lower value. In Europe it seems that the demand for recycled plastics is currently quite high, but this might change as the recycling capacity increases within the European Union.

2.7.3 Initiatives to Overcome Inhibitors

The market inhibitors, presented above, must be overcome through greater collaboration in the industry, a higher degree of standardization and better legislation. Specifically, OECD, 2018 suggests five main categories of intervention:

- Regulatory: Putting a ban on landfilling and setting requirements for recycling rates. This approach has, to some degree, been practiced in the EU for some time. More intrusive legislation is expected to arrive, which will favour AVL in the long term.
- Economic tax: Virgin resource taxes or other tax incentives which financially encourages the use of recycled plastics in plastic products.
- Technology: Support technology innovation in plastic sorting and recycling. This is already practiced in Denmark and at EU level, and as mentioned in Section 2.3, AVL has received development fund investments for the development of technologies. It is expected that such investments will be available in the future as well, as Denmark and the EU is still far away from reaching their goals.
- Data and information: Better data and knowledge sharing within the industry. This includes the sharing of market data, technological data and best practices with competitors, suppliers and customers. Furthermore, raising public awareness can increase consumer sorting quality and drive a demand for products based on recycled plastics. AVL is already doing some of these things, for example through their Cirkla Academy, as mentioned in Section 2.2.
- Voluntary measures: Industry lead measures for greater standardization and commitments from plastic product companies to using more recycled plastics. An example of the latter, is Nestlé's commitment to reducing their use of virgin plastics by on third while ensuring recyclability of all their products (Nestlé, 2021). As public awareness increases, especially in the EU, more initiatives like these are expected to come.

In conclusion, AVL finds itself in a market which is expected to grow substantially in the coming years. And as they currently are the only significant player on the Danish market, they have a favourable market position. AVL can accelerate the change towards greater standardization by continuing their engagement with: the plastics industry, the legislative bodies and surrounding the industries, such as the presorting facilities. Furthermore, a larger customer segment, higher quality supply of presorted waste and better general market conditions for recycled plastics can be achieved. This increased engagement also requires efficient knowledge sharing between the marketing/sourcing department and the post-consumer process line operations at AVL. Based on the above, a data sharing case can be established:

Case 14 *How can data and knowledge sharing be increased in collaborations with competitors, customers/suppliers and legislative bodies?*

2.8 Case Delimitation

Through the problem analysis, cases have been established. Each case represents an area of interest, but not all of them will be a part of this report. A selection process is therefore needed to select the right cases for consideration. The cases will now be listed together with short descriptions.

- **Case 1 - Resource Usage:** Monitoring of the resource usage of each machine, such as water usage, electricity consumption, etc. This monitoring can be used for: surveillance of the production line, for optimization of resource usage and to provide emissions documentation for the recycled granulate.
- **Case 2 - Presorting:** Collection of the data from the production line, to be handed over to the suppliers. The objective is to help the suppliers improve their presorting, so less of the input to AVL is discarded.
- **Case 3 - Material Sample Testing:** The introduction of sample testing at different parts of the line. The samples will then be analysed and the results can be used for improving the line. Furthermore, it can used to determine where continuous data collection is needed. Lastly, it can be used to gain knowledge about quality properties of the presorted plastics.
- **Case 4 - Machine Capacities:** Testing the capacity of each machine. This knowledge will make it possible to improve the efficiency of the line, for example by making discrete event simulations.
- **Case 5 - Process time management:** Making a system that can log: run time, downtime, breakdown reasons and the maintenance of each machine. In the future it can be used for planning maintenance, lowering the downtime, calculating the OEE and identifying bottlenecks in the process line.
- **Case 6 - Temperature of Flow:** Measuring the temperature of the material flow. The hope is to find places where the heat of the material flow can be captured or insulated.
- **Case 7 - Heat in Water:** Measuring the heat in the water, to determine if heat can be captured for use in other processes. The data can also be correlated with quality data to uncover temperature dependencies of washing processes.
- **Case 8 - Water Quality:** The monitoring of water quality, to ensure that the water quality is sufficient for the given process. This knowledge might also help obtaining better knowledge of the efficiencies of the washing processes and the composition of the material, that is moved through them.
- **Case 9 - Measuring Waste:** The measuring of the amount of waste coming out of each process. This knowledge can help optimization of the process, and can also offer some data on what the presorting facilities should improve.
- **Case 10 - NIR Data Collection:** Collecting data from the existing NIR sorter. This is data such as plastic types and additives. This can be used for surveillance, quality control and optimization of the production line.
- **Case 11 - Additional NIR Sensors:** The implementation of additional NIR sensors on the production line. The possible benefits are: improved surveillance, continuous quality control and the ability to adjust process parameters from the data. This data can also be used for improvement or prioritization of the presorting facilities.

- **Case 12 - Maintenance Prediction:** The implementation of sensors that track data such as vibration, noise or heat from each machine, to predict when maintenance is needed. Furthermore, pressure and temperature sensor can be used to predict maintenance needs.
- **Case 13 - Odour Quality Control:** Performing quality control on the odour removal with a sensor. The gain of this is to get a more standardized quality control of the process, which will be useful if AVL are to start making food packaging and medical grade recycled plastics.
- **Case 14 - Knowledge Sharing:** Better information and knowledge sharing with other competitors, customers, suppliers and legislative bodies would benefit the overall development of the plastics recycling industry and its market conditions. It can also allow AVL to further develop their technologies by obtaining technical insight from other plastics recyclers.

As every case has its own potential benefit for AVL, the selection method will be based on a priority selection. Each case will be discussed to define their priority. By doing this the prioritisation then becomes a tool to delimit which cases will be solved in the following chapters.

2.8.1 Matrix Description

In order to select the cases that will be most relevant to look into, a matrix has been made. The function of the matrix is to categorize the cases according to two main criteria. One being the timeframe of implementation; when should AVL begin to implement each data collection system? The other criteria is the potential gain for AVL; how beneficial is each data collection case expected to be? Since it is really hard to give the cases any specific values in terms of time and potential gain at this stage of the project, multiple cases have the same placement in the matrix. In other words, the matrix should be considered as a methods for roughly sorting the many cases. The matrix has been established based on a common group discussion and can be seen in Table 2.3.

Table 2.3: Case matrix

GAIN/ TIME	**SMALL**	**MEDIUM**	**LARGE**
NOW	Knowledge Sharing	Material Sample Testing Process Time Management	Machine Capacity Resource Usage
SOON	Temperature of Flow Heat in Water	NIR Data Collection Additional NIR-Sensors Measuring Waste Water Quality	Presorting
LATER	Odour Quality Control	Maintenance Prediction	

As it can be seen, some of the cases are marked with red. Through discussion, these cases have been found non-relevant to investigate further. The argumentation for not continuing work on each of these cases will now be presented shortly.

In the first round of elimination, the following cases were eliminated:

- Temperature of Flow
- Heat in Water
- Odour Quality
- Maintenance Prediction

Most of the above cases have been eliminated based on the argument that the potential gain is too small. However, in the case of maintenance prediction, the timeframe is considered too long in relation to the only medium gain. The reason for the long timeframe of maintenance prediction is, that a lot of data and insight into the processes is necessary before the correct sensors can be set up.

In the second elimination round, only two cases are removed. The cases in question are the knowledge sharing case and the presorting case. Both cases are dependent on acting upon data that has already been found, rather than being actual data collection cases. Since no such data is available at the time of writing, the two cases are eliminated. However, both knowledge sharing and improved presorting can be seen as logical steps, when the sufficient base data has been made available.

In the final elimination, two additional cases are removed; "Measuring Waste" and "Water "Quality". The water quality case was created under the assumption that the water system could be improved by filtering and recirculating water locally. However, according to AVL, they have already implemented such a system (Appendix B.1 on page 95). Therefore, it is assumed that bigger gains can be achieved by looking into the other cases. The "Measuring Waste" case is eliminated as well, as it is considered a rather simple case. Implementation of the waste data collection would include manual logging of how often the waste containers are filled. At later stages, automatic waste measuring systems can be implemented.

The six remaining cases can be grouped together to create the following three cases. These cases will be the basis for the problem formulation in the following chapter:

A **Resource usage:** A system must derived, which can help collect, analyze and document the electricity and water usage throughout the process line.

B **Process time management:** A framework and plan must be made for collection of run time, downtime, breakdown reasons and the maintenance of each machine. This must be coupled with a way to determine machine capacities and the OEE of the line.

C **Material data sampling:** Specific points and methods for material data collection must be found. This will include a manual material sample testing plan, how to utilize the data from the existing NIR-sorter and how additional NIR-sensors can be implemented.

Problem Statement 3

In this chapter, the knowledge gained from group inspiration visits to three companies will be presented. Based on the experiences from the three visits, focus points for the case work will be established. Then, a problem statement is established on the basis of the problem analysis and the data collection experiences obtained from the company visits. The last Section in this chapter will contain the delimitations for this project.

3.1 Company Experiences

As briefly mentioned in Section 2.5.4 on page 16, other companies have been contacted in relation to this project. The goal was to look at similar industries and understand how they do data collection and what challenges there might be in implementing it. In total, three companies have given input to their experience with the subject of data collection. Each of these companies will briefly be outlined below, including the overall experiences, that where passed on to the project group during the visits. The various experiences will be summed up in the end and used as focus points for the case work in the following chapters.

3.1.1 Rolltech A/S

Rolltech A/S is located in Hjørring and is the world leading producer of spacers for double- and triple-layered windows (Rolltech, 2021). The spacers are produced from thin strips of sheet steel, which are rolled to the needed profile. Their higher value products combine a plastic extrusion process with the steel rolling to create a patented plastic-steel profile, called Chromatech, as seen in Figure 3.1. The profiles are produced in several parallelly running continuous processes at tolerances at the level of 10^{-2} mm, and they run the production 24/7. They produce over 110×10^{6} m/year, and to keep the tolerances, finely adjusted equipment is needed. Rolltech A/S sell their products to subcontractors of window manufacturers, so the product is located at a very low position in the value chain. Thus, the innovation at Rolltech A/S is mainly in terms of processes rather than products. They develop their production equipment in-house and with the help of consultancy firms.

Figure 3.1: The Chromatech profile, produced by Rolltech A/S. (Rolltech, 2021)

Eight years ago, Rolltech A/S started looking into a data collection plan to improve their process efficiency and maintain their market-leading position. Their data collection system was based upon Microsoft 365 and was developed by a consultancy firm at the price of 200 000 DKK. They have been gradually increasing their data collection effort ever since, but most of the data is however still typed in manually by production line workers. Recently, Rolltech A/S has expanded their data collection approach by starting to automatically collect data, some of which they do not yet know how to use specifically. This allows them to collect large amounts of data, which can be used for future implementation of machine learning systems.

A big part of the collected data are tolerance measurements. The automated rolling/extrusion line uses laser triangulation and image recognition technology to continuously measure the profile dimensions and steel strip surface quality, respectively. If insufficient tolerances or surface properties are detected, the machine will stop the extrusion process. A worker then has to take a sample, measure it, plot in the measured dimensions and adjust the equipment if necessary. The worker can determine whether the system must be adjusted by looking at the previously logged data. If there is a tendency, that the measurements are moving towards a certain tolerance limit, the equipment must be adjusted in the other direction. In this way, the automatic data collection system currently functions as an aid to the manual quality control. In the future, Rolltech A/S aims to make the most significant parameters self-adjusting, by automatizing the above described correction process.

The data collection strategy at Rolltech A/S is based on a gradual implementation, as outlined in Figure 3.2. It can be summed up in three overall steps:

1. Initially, they started small by collecting specific data which can be directly acted upon. The workers on the production line were responsible for typing in the data, so it was important for Rolltech A/S that the registration is simple and that it provides usable feedback to the line worker. In this way, the line workers are motivated to actually type in the data. During the initial implementation of the data collection, discussions were held with the line workers to ensure that the implemented system made sense for the workers. Rolltech A/S succeeded in doing so, and the workers are generally happy with the system.

2. Currently, Rolltech A/S is in the process of increasing both the amount and types of data points in their process line. They do this by setting up sensors and specific points, which can measure specific parameters, such as the outer profile dimensions or surface properties of the strips. This both serves as quality control, as described previously, but also allows Rolltech A/S to gather data for further analysis.
3. In the future, Rolltech A/S hopes to be implementing systems, that can automatically collect, analyse and act upon data. This will reduce the need for manual labor, potentially allowing their operation to be run "lights out" some of the time. Doing this requires a mathematical model of the system, which can be obtained in several different ways. It can be derived through experiments, through simulations or by training machine learning algorithms. Machine learning systems require large amounts of quality data to feed the algorithms. The definition of quality data will depend on the process, that is investigated, but feeding the machine learning algorithms with the wrong data will end up in a useless model. Furthermore, simulations can be implemented on different steps, starting with simple single-process simulations and ending in a full-scale digital twin of the process line. Automatic data analysis and process adjustment is specifically interesting for Rolltech A/S as they only have a few white collar workers employed to oversee the production line, resulting in limited resources for data analysis.

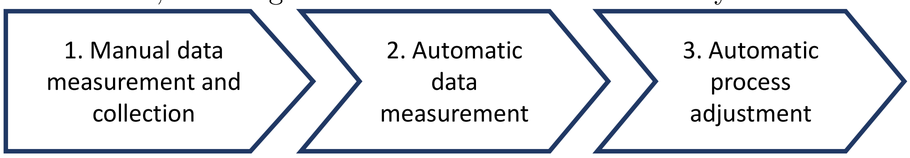
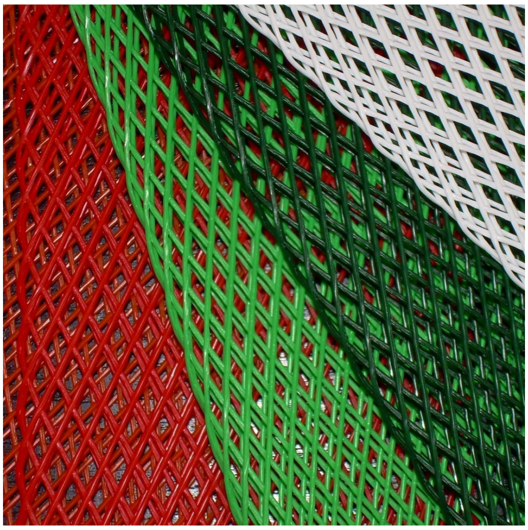


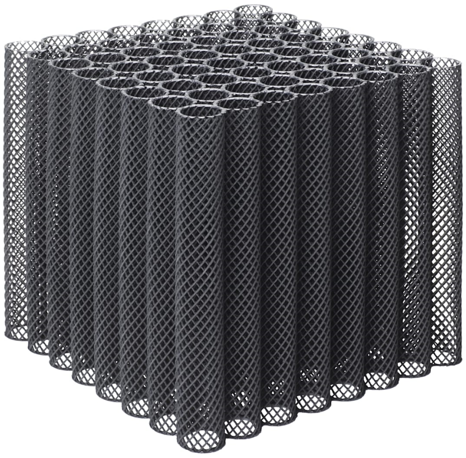
Figure 3.2: Outline of Rolltech A/S' gradual data collection implementation.

3.1.2 Expo-net

Expo-net is another high-volume production company located in Hjørring. They make all sorts of plastic nets using different variants of a proprietary extrusion process. The innovation at Expo-net is mainly in their products, as all their new products are derived from variants of the same fundamental net extrusion process. Examples of their products are seen in Figure 3.3. (a) shows filtration nets and (b) shows the Bio-blok which is a trademark product, allowing for biological rainwater filtration. The data collection at Expo-net is mainly focused towards maintenance. They have various systems that monitor their water and air circulation, as these systems are crucial for the production line efficiency and productivity. By monitoring pressure differences in the air and water systems, they have saved 65% of the maintenance costs of these systems, according to Expo-net. So even though data collection is not widespread at Expo-net, they still have achieved significant cost reductions in their maintenance budget. They did this by implementing a data monitoring system and rethinking their maintenance strategy based on the knowledge they achieved. Their current data monitoring system could be the first steps towards a greater data collection implementation.



(a) Techtextil, 2021



(b) AO, 2021

Figure 3.3: Examples of products made by Expo-net.

3.1.3 Fibertex Nonwovens A/S

The last company, which has given insights into their experiences with data collection, is Fibertex Nonwovens A/S. They make nonwoven textiles for, among others, the construction-, building interior-, car- and medical-industries (Fibertex Nonwovens, 2021). Figure 3.4 shows one of their textiles processes. Fibertex Nonwovens A/S has recently ended a data collection program where they had attempted to gain deeper insight into one of their processes. The continuous process creates a felt textile which is then rolled and cut. The mechanical properties of the felt material is important to some customers, and can vary from roll to roll. Fibertex attempted to use data from the textile-creating process machine and correlate that with the properties of each roll. This would allow them to supply their customers with more detailed information about the properties of each roll, going out of the Fibertex Nonwovens A/S factory. They did however not succeed in establishing this relationship, and ended up killing the project. Among the reasons behind the failure, Fibertex Nonwovens A/S mentioned the huge amount of data and the general approach to doing the data collection. Even though they could get a lot of data points, the data they had, was simply not the needed data type. In other words, they would have needed to set up external sensors to get the right data. Furthermore, they discovered that the mechanical properties would vary more over the width of the textile than along the length of it, meaning that the entire premise of the project was wrong. Apart from this project, Fibertex Nonwovens A/S have had no experience with doing systematic data collection. By comparing the Fibertex Nonwovens A/S case to what was done at Rolltech A/S, one could argue that Fibertex Nonwovens A/S skipped some important steps in their data collection implementation, resulting in them pursuing a non-feasible project.

Figure 3.4: A machine producing nonwoven felt at Fibertex Nonwovens A/S. (Fibertex Nonwovens, 2021)

3.2 Focus Points for Case Work

Based on the discussion above, some general focus points for implementation of data collection systems in continuous high volume process lines can be summed up:

- **Gradual implementation:** Rolltech A/S had spent eight years implementing their data collection system, and they are still in the process of improving and expanding it. It is concluded that proper data collection systems must be implemented gradually, as one cannot foresee exactly what data is needed. The gradual approach allows for an iterative process, where the initially collected data will indicate interesting points for further data collection. The iterative approach lowers the risk of failure, as had happened at Fibertex Nonwovens A/S. Lastly, the investments in the data collection systems becomes lower, as the implementation is broken up into smaller pieces and is spread over a longer period. Time frames can be over 10 years until a completely autonomous system is up and running. The initial cost of implementing a step 1 data collection system can be more than 200 000 kr.
- **Simplicity and usable feedback:** It is important that the data collection systems are easy to use. The line workers, who will often be the ones logging the data, must not feel that they are wasting their time with the systems. This supports the point of designing the system in such a way, that the line worker will get usable feedback from the system. Furthermore, the data must be easy to analyze and must be presented in a way, such that it is easy to understand the data and make decisions based upon it. White collar workers are often in short supply, so the systems must not require a lot of effort to actually get useful knowledge out of the data.

3.3 Problem Statement

The problem statement has been formulated based on the work, which has been presented throughout the problem analysis. The above focus points will serve as the general foundation when answering the problem statement and sub-statements.

"How can a gradually implemented data collection strategy be derived, to obtain knowledge about the processes and value chain at AVL's post-consumer process line while giving usable feedback?"

Because the problem statement is very wide, three sub-statements has been created to guide the work of the project. The three sub statements are inspired by the three cases found in the problem analysis case delimitation, Section 2.8.1. Each of the three sub-statements will be investigated and answered in their own chapter. After having answered each sub-statement, a final implementation strategy will be presented in Chapter 7 to give an overview of the timeframe and price of the implementation for the 3 cases. The three sub-statements are listed below:

Case A: *"How can information about the resource usage be obtained to sufficiently document the* CO_2 *emissions of AVL's post-consumer process line, and how can the information be used to decrease the resource usage of the line?"*

Case B: *"How can information about process time be obtained? How can this information be used to quantify the line efficiency and maintenance needs, and what can AVL gain from this knowledge?"*

Case C: *"How can a gradual implementation of material sampling, NIR data collection and additional continuous sensors be used to quantify the material composition throughout the line? And what can AVL gain from this knowledge?"*

3.4 Delimitations

A number of delimitations are done throughout this report. The following provides an overview of the delimitations:

- **Simulation of AVL's process line:** The simulations done in this project are not accurate representations of AVL's process line, due to the lack of information. Instead, proof of concept models will be used to investigate concepts by through a simplified model.
- **Discarding ideas with a presumed low viability:** Because of the time frame of the project, only the prospects that the group deems most viable will be described. This means, that many ideas for data collection and usage of data will not be discussed and presented, in order to bring more focus on specific cases and ideas.

Case A: Resource Usage 4

This chapter will seek to answer the first sub-statement:

> **Case A:** *"How can information about the resource usage be obtained to sufficiently document the CO_2 emissions of AVL's post-consumer process line, and how can the information be used to decrease the resource usage of the line?"*

Water, electricity and additives are the resources used at the post-consumer process line, as seen in the flowchart, Appendix B.2 on page 100. A brainstorm has been made to list the different parameters, which might influence the resource usage of the post-consumer plastic granulate. The influencing parameters have then been divided into three categories depending on the size of their expected influence, as seen in Appendix C.1 on page 109. These resource usage influences will be the foundation for the data collection strategies, which are presented in this chapter. However, the very small influences are not included in the further work.

A resource usage data collection strategy can be derived with two different purposes: to document the resource usage, and to reduce the resource usage, as indicated in the sub-statement. Depending on what the focus of the data collection is, the strategy will be different. For this reason, two different data collection strategies are derived separately; one for *documenting* the equivalent CO_2 emissions of the recycled plastic granulate, and one for *reducing* the resource usage at the AVL. A strategy for data collection with the aim of *documenting* the equivalent CO_2 emissions will be derived in the following Section. Then, potential ways to measure resource usage with the aim of *reducing* the resource usage will be discussed in Section 4.2. After having introduced each of these two strategies, they will be combined in a final resource data collection strategy for AVL in Section 4.3.

4.1 Data Collection Strategy for Emissions Documentation

As mentioned in Section 2.2 on page 7, AVL can reach new customer segments by documenting their resource usage and labelling the CO_2 equivalent emissions from the production of their granulate product. This can help AVL overcome the market inhibitor of being a substitute to virgin plastics, as mentioned in Section 2.7.2 on page 21. With better emissions documentation, AVL will be able to deliver a standardised product, which is expected to have an increasingly higher market value, as the plastics industry moves further towards a circular economy.

While no generally adapted industry standard for documenting the carbon footprint of recycled plastic granulates seem to be available, self-declared claims are a possibility. This should be done according to ISO 14021: "Environmental labels and declarations"(ISO, 2016). It states that self-declared environmental claims should be "clear, transparent, scientifically sound and documented". Furthermore, "all relevant aspects of the life cycle of the product" should be considered. When calculating the actual carbon footprint, ISO/TS 14067 (ISO, 2013) should be followed.

4.1.1 Plastic Recycling Supply Chain

An example of the circular supply chain of recycled plastic is seen in Figure 4.1. The CO_2 emissions, related to recycling the plastics, would ideally cover every step in the supply chain from step 2 and including step 7, while step 8 depends on the plastic product manufacturer. Furthermore, transportation emissions must be considered, especially if the presorted input is sourced from foreign countries or if the recycled granulate is exported.

As mentioned in Section 2.7.1, the quality of presorted plastics can vary quite a bit. Especially, if presorted waste is to be imported from other countries with different sorting standards and regulations. In the supply chain schematic, step 5 can be regarded as being done both at the presorting facility and at AVL. However, presorted waste with low purity will require more resources at AVL, while less resources are expected to have been spent at the presorting facility. In this way, the distribution of the various steps in the supply chain depends on the presorting facility.

Figure 4.1: A schematic of the circular supply chain for recycled plastics. (Miljøministeriet, 2021)

As a result of the above, documentation of resource usage will require AVL to overcome some of the market inhibitors relating to industry secrecy, mentioned in Section 2.7.2. Knowledge sharing between supply chain members is important in achieving a detailed emissions documentation, which includes all steps in the supply chain, and which accurately represents the differences in presorted waste quality. In other words, the CO_2 tracking-ability will increase as the conversation between supply chain members develops. Meanwhile, the conversation between competing plastic recyclers is crucial in establishing market standards, which will allow the market to further develop. In conclusion, knowledge sharing is a crucial part of CO_2 documentation, and the entire supply chain must be regarded in the CO_2 estimations.

Even though CO_2 documentation is expected to be attractive to most of AVL's costumers, not all customers will pay a premium for the documentation, and the requirements for the levels of detail of the documentation will also vary between customers. Therefore, the approach of this Section will be to present different steps of emissions documentation, in a fashion which is similar to what was done at Rolltech A/S, described in Section 3.1.1. Each proposed step of emissions documentation requires a way of collecting resource usage data and translating it into CO_2-equivalent emissions. This equivalent emmisions information can then be used to label the product. In the following subsections, three different steps of data collection for documenting resource usage will be presented.

4.1.2 Emissions Documentation Step 1: Rough Estimation

The first step of emissions documentation should be a rough estimate of the average resource usage at the AVL post-consumer process line. Thus, emissions documentation step 1 focuses on steps 6 and 7 in the supply chain, while including some of step 5. The estimate can be achieved by measuring the water and electricity coming into production hall. Referring to the resource flow in Appendix, B.2 on page 100, the estimate would then include the energy usage of all processes from 1.2 till 2.5 as well as the air transport system 4.1 and water filtering/circulation 4.2. The resource usage of the 3.1 mixing and 3.2 extrusion processes, which are placed at separate locations, should also be measured and included. Measuring could be done over a month to account for variations in the presorted input quality. Also, the amount of produced granulate must be measured during the same period, such that the CO_2 emissions can be estimated for 1 kg of granulate.

According to HOFOR, 2021, one cubic meter of danish tap water is in average responsible for 0.2 kg of CO_2-equivalent emissions. Furthermore, the CO_2 intensity of the Danish electricity grid was in average of 0.117 kg/kWh in 2020, according to Birr-Pedersen and Ejnar Helstrup Jensen, 2021. Using these factors, the CO_2 intensity of the finished granulate, $CO_{2,eq1}$, can be roughly estimated at step 1 detail by using Equation 4.1:

$$CO_{2,eq1} = \frac{m_{water,total} \cdot 0.2\,\text{kg/ton} + E_{total} \cdot 0.117\,\text{kg/kWh}}{m_{output}} \tag{4.1}$$

Where $m_{water,total}$ is the sum of the water consumption of the main hall and extrusion process during the measured period. E_{total} is the summed electricity use of: main hall, mixing process and extrusion process, during the measured period. And m_{output} is the mass of the recycled granulate, during the measured period. This estimate would mainly account for the influences 1, 5 and 8 in Appendix C.1 on page 109. While influences 3, 9 and 10 are indirectly included in the estimations, depending on how much these three influences vary over the measured period.

4.1.3 Emissions Documentation Step 2: Supply Chain

The second step of the equivalent CO_2 emissions documentation will include steps 4, 5, 6 and 7 in the supply chain. Thus, the step 2 documentation includes the emissions at the presorting facilities. Furthermore, it also includes the transportation between AVL and suppliers/customers and the forklift transport within AVL. The step 2 equivalent CO_2 emissions estimation can then be expressed in Equation 4.2:

$$CO_{2,eq2} = CO_{2,eq1} + CO_{2,presorter} + CO_{2,freight} + CO_{2,forklift} \tag{4.2}$$

The equivalent CO_2 emissions of the forklifts, $CO_{2,forklift}$, can be estimated by monitoring the chargers for the specific forklifts, used in relation to the post-consumer process line, and converting that power usage into CO_2 equivalent emissions. An average could be approximated based on a month of normal operation.

The equivalent CO_2 emissions related to the presorting facilities, $CO_{2,presorter}$, must be achieved through a collaboration between AVL and the presorting facilities. It should be done at a detail level corresponding to documentation step 1, as expressed in Equation 4.1. The process types and production layout is expected to be similar between AVL and the presorting facilities. Therefore, AVL should be able to help the presorting facilities document their resource use, after having done the step 1 implementation at their own facility. Due to the large differences between presorting facilities, it will be necessary to get CO_2 documentation every time a collaboration is engaged with a new supplier. In the future, greater national and European standardization could mean that AVL would not need to help each supplier document their CO_2 emissions.

The freight emissions, $CO_{2,freight}$, can be estimated through knowledge about the length of the trips, the load size and a freight emissions factor (FEF). As both upstream and downstream shipping emissions are influential, both of these must be considered. It is expected that the truck freight and shipping companies can deliver accurate FEF's, corresponding to their current emission levels. However, exemplary numbers from 2013 are seen in Appendix C.2 on page 112. Based on Mathers et al., 2014, the CO_2 equivalent emissions from transport can be expressed through Equation 4.3:

$$\begin{aligned} CO_{2,freight} &= CO_{2,truck} + CO_{2,ship} \\ CO_{2,truck} &= \left(D_{truck,input} \cdot \frac{m_{input}}{m_{output}} + D_{truck,output} \right) \cdot FEF_{truck} \\ CO_{2,ship} &= \left(D_{ship,input} \cdot \frac{m_{input}}{m_{output}} + D_{ship,output} \right) \cdot FEF_{ship} \end{aligned} \tag{4.3}$$

In the above equations, m_{input} and m_{output} are the masses of the presorted plastics and recycled granulate, respectively. $D_{truck,input}$, $D_{ship,input}$, $D_{truck,output}$ and $D_{ship,output}$ are the travel distances for the trucks/ships when supplying the presorted plastics and delivering the recycled granulate, respectively. It is seen how the purity of the presorted waste influences the CO_2 emissions related to shipping, through the relationship m_{input}/m_{output}.

The data needed for the above calculation would be collected from freight partners. The size of the shipping emissions are concluded to be highly dependent on the distance to suppliers/customers. Therefore, a more detailed CO_2 labeling will be delivery-specific. Apart from the resource influences, covered by emissions documentation step 1, an emissions documentation at step 2 will also allow AVL to directly account for influences: 2, 3, 4 and 7, in Appendix C.1 on page 109.

4.1.4 Emissions Documentation Step 3: More Data

A step 3 emissions documentation requires a more detailed data-foundation. When emissions documentation is the goal, it does not make sense to measure the resource usage of the individual machines. However, a number of other data types and collection schemes could be relevant:

- **Longer sampling periods:** Larger quantities of data can help give more precise evaluations of the equivalent CO_2 emissions. Fluctuations in the presorted plastic waste quality could arise from seasonal changes in consumer patterns. For example, increases in post-consumer plastic waste during Christmas might influence the quality of the presorted plastics and the amount of resources spent at the presorting facilities. By capturing data over a year, taking the average could give a more representative estimate. Furthermore, the most common plastic types found in post-consumer plastic waste can easily change during the coming years, as new regulation and financial incentives related to plastic packaging are implemented in the European Union.
- **Distinguishing plastic types:** Collecting more data could also allow AVL to look for differences in the resource usage when recycling PP compared to HDPE. This would require AVL to log which type of plastic they are recycling every day and correlating that data with measured resource usage.
- **Automatic resource monitoring:** By automatically monitoring the resources used at the process line and converting that into CO_2 equivalent emissions, AVL can easily update their documentation when changes and improvements are made to the process line. Furthermore, the system could be set up to automatically estimate and include the CO_2 emissions from freight by pulling data from their order system. Such a comprehensive system would allow AVL to supply batch-based emissions documentation, but would also be expensive to implement. It should only be pursued if a market demand for such documentation appears.

Having discussed different steps in *documenting* the equivalent CO_2 emissions related to the recycled plastic granulate, a strategy for data collection with the aim of *reducing* the resource usage will be derived in the following Section.

4.2 Data Collection Strategy for Lowering the Resource Usage

For AVL, two overall things can be gained by lowering the resource usage of the post-consumer process line: lower production costs and a reduction of equivalent CO_2 emissions. In other words, reducing the resource usage can both make the product "greener" and provide a financial gain for AVL, while maintaining the product quality. The reductions in production costs from decreasing the resource usage could be quite significant, as the power and water usage are among the main expenses related to the post-consumer process line.

Furthermore, cutting the carbon intensity of the production will build a good foundation for a leading position in the expanding market of household plastics recycling. AVL would currently gain a market advantage just by having a CO_2 certificate. However, in the future, the competitors will shift from being mainly virgin plastics producers to being other plastics recyclers. So as the circular economy develops and the recycled plastics market matures, as was discussed in Section 2.7.1, the need for limiting the resource usage at AVL will increase.

Lowering the resource usage can be achieved through refining and improving different processes of the production line. Based on the resource influences in Appendix C.1 on page 109, a discussion has been made on potential ways of achieving resource reductions. The discussion can be found in Appendix C.3 on page 114, and has resulted in a strategy for collection of the resource consumption data, with the aim of reducing the consumption. The strategy includes ideas on creating and implementing data collection systems, how the collected data should be analyzed and how improvements can be made to reduce the resource usage. The strategy deals with the parts of the supply chain that are within AVL and focuses on measuring the parts of the process line that affect the consumption the most.

The data collection strategy for reduction of resource usage is also divided into 3 steps, to represent a gradual implementation. By implementing well positioned data collection gadgets, the first steps towards lowering the resource usage are made. Later, more continuous data collection will be needed, to allow for continuous improvement. Some parameters, like maintenance, have a larger influence on production time and efficiency than water and electricity usage. And even though time can be regarded as a resource, this Section will focus only on reducing water and electricity usage. Time related savings opportunities will instead be analysed and discussed in Chapter 5.

4.2.1 Resource Reduction Step 1: Electricity Usage of Each Process

Assuming that step 1 of the emissions documentation has been conducted, overall knowledge of the water and electricity usage for the entire post-consumer process line has been obtained. Furthermore, the influence on equivalent CO_2 emissions will be known for the water and electricity usages, respectively. By multiplying the water and electricity usage with their respective prices, two questions can now be answered:

- What is the respective influence of the water and electricity usage on the total CO_2 emissions of the line?
- What is the respective influence of the water and electricity usage on the total resource expenses of the line?

It is assumed, that the electricity usage will make up the biggest part of both the CO_2 emissions and the resource expenses. The emissions documentation steps only provide information on the entire line. Therefore, the first step of data collection for reducing resource usage will be to gain deeper insight into the electricity usage of each process in the line. This can quite easily be done by installing watt meters on the processes and measuring over a one month period. The processes, that should be measured, are listed in Appendix C.4 on page 116, where it is also discussed how improvements can be made. Referring to the process line in Appendix B.2 on page 100, the processes includes all the washing, grinding and sorting processes.

The odour removal can be included, if it is used, and the mixing and extrusion processes should also be measured. Furthermore, the water and air transport systems in the line should be included, together with the forklift transport within AVL.

To sum up, the power usage should be measured at all process steps within the post-consumer process line. The measuring should be done over a relatively short period, as the goal is to only get approximate values. From this information, a process of improvement can be initiated by focusing on the most consuming process machines, which are also expected to have the biggest savings potential.

4.2.2 Resource Reduction Step 2: Water Consumption of Each Process Step

Step two of the data collection for resource reduction will include the water usage. Assuming that the biggest electricity users have been addressed in step one, water could now be the resource with the biggest potential for savings. Reductions in water usage can be achieved in two overall ways:

- **The layout of the water circulation and filtration system** can be rearranged to change the water consumption in the line. If the water is re-circulated more times or if the water is routed through several processes before entering the filtration system, savings in water and electricity usage might be achievable. However, as outlined in Figure 4.2 in the grey box, the layout of the water system is already quite complex, and according to AVL it is quite efficient (Appendix B.1 on page 95). Thus, the savings in water usage should be found in the various water-consuming processes, rather than the circulation and filtration system itself. The water usage of the extrusion process is an exception, as this process is not a part of the re-usage system. For this reason, re-using the extrusion water and its heat could be a potential savings opportunity. The water usage of the extrusion process would however firstly need to be approximated, to investigate if the savings potential is sufficient to invest time in doing this.
- **The process water usage** of the washing and density sorting processes is hard to determine, as the water is cleaned and re-circulated. If a washing process removes a lot of dirt, the water will become very polluted, and might not be fit for re-circulation. On the other hand, other washes might send the water back for re-circulation several times before letting it out in the sewage system. For this reason, determining the water usage of the processes would require measurements of both the water flow through the process, but also the general quality of the water as it leaves the process. Achieving only rough estimations on the water usage can therefore be a quite demanding task, and the results will be depending on the quality of the presorted plastics. Also, after having determined the water usage of each machine, the consumption still has not been reduced. That entire process would come afterwards. For the case of the extruder, the water consumption can quite easily be approximated.

AVL's water circulation system

AVL has established a water circulation system (Appendix B.1 on page 95), an simplified flowchart can be seen in Figure 4.2. The system is designed to ensure that all the machines and filters can drew on the water inlet if there is not enough reusable water for the process. The water trickles down from the third filter to the first. The fourth filter is used to mechanically and chemically clean the water from the wastewater tank before letting it in to the sewage.

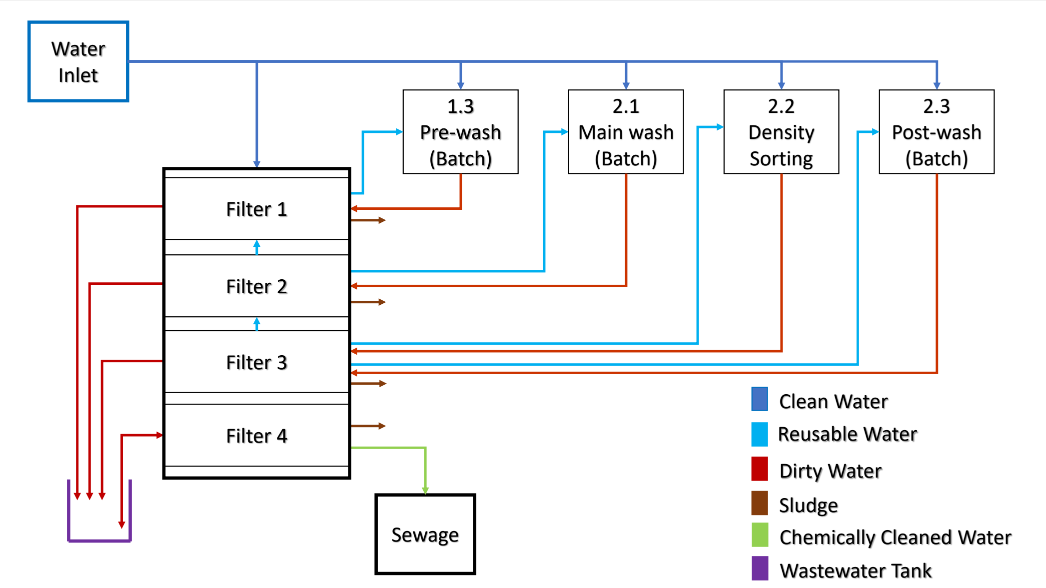


Figure 4.2: Schematic of AVL's Water circulation system.

To sum up, reducing the water consumption of the post-consumer process line can be a quite comprehensive task. Thus, it should only be done, if the financial and emissions savings potentials are big. One way to determine these savings potentials is by comparing the CO_2 emissions and financial costs of the water usage to the electricity usage, as described in emissions documentation step 1.

4.2.3 Resource Reduction Step 3: Correlating with Quality Data

Step 3 of data collection for resource reduction should provide a foundation for continuous improvement of the resource usage at the post-consumer process line. This would require an automatic data collection system, such that power and water usage data can be automatically sampled over longer periods, as presented in emissions documentation step 3. However, the data should now be measured at each process step, and not only for the entire line. Furthermore, at this step, AVL should start correlating the resource usage data with quality data of the processed material. Apart from the opportunities presented at emissions documentation step 3, differentiating between the processes and correlating with quality data will furthermore allow AVL to investigate and reduce the resource usage influences of:

- **Presorted plastics quality:** It is expected, that the changes in presorted plastics quality between suppliers and batches will have a significant influence on resource usage of the processes in the line. The parameters settings which fit a specific type of presorted waste composition might not be as good for other material compositions. Having knowledge about the effects of the presorted plastics quality can help AVL prioritize their suppliers. Furthermore, it might allow AVL to adjust their process parameters based on specific inputs. To obtain this knowledge, the resource usage data must be correlated with quality data on the presorted input.

- **Process parameter cross-interactions:** The above described process of relating the resource usage to the quality of the input of the post-consumer process line can be extended to look at the input of specific process steps throughout the line. This will allow AVL to uncover some of the cross-interaction between the process parameters of the different machines. For example, changing the parameters of the pre-wash 1.3 such that it cleans the flakes better will most likely result in a higher resource usage at this process step. However, the cleaner flakes now entering 1.4 grinding might allow this process to use less energy due to less resistance from contaminants. Many cross-interactions are expected to be present in the line, and uncovering some of them can allow AVL to improve their line efficiency without buying new equipment. Doing this, will require AVL to correlate the resource usage data with quality data on the flakes between certain process steps. Which specific process steps to look for interactions will depend on the results of resource reduction steps 1 and 2.

4.3 Combined Strategy of Resource Data Collection

Two potential strategies for data collection at AVL's post-consumer process line have now been presented, with the goals of either documenting or reducing the resource usage. A final strategy will now be presented, which seeks to combine the two. This strategy will also be divided into three steps, to represent a gradual implementation:

1. **Resource Data Collection Step 1:** Step one of the resource data collection strategy will include emissions documentation step 1. The knowledge from this step will allow AVL to provide a sufficient documentation of resource usage for the current recycled plastics market. When labeling their products with this estimate, AVL must clearly state how the emissions were calculated. Furthermore, it will allow AVL to get an idea of the emissions influence of their water usage compared to their electricity usage. Lastly, AVL can determine the financial costs of their water consumption compared to the cost of their electricity usage. Having this knowledge will lay the foundation for a targeted effort of resource usage reduction in the next step.
2. **Resource data collection step 2:** Knowing respectively the financial and emissions costs of the water and electricity usage at the process line, step 2 of the combined resource data collection strategy can be initiated. The goal of this step is to identify specific points of improvement in the line, relating to resource usage. This step will include doing either step 1 or step 2 of the resource reduction strategy, or both. If the electricity usage turns out to be the biggest expense in terms of finance and emissions, resource reduction step 1 should be prioritized. On the other hand, if the water usage turns out to be the most significant expense, resource reduction step 2 should be prioritized. If they turn out to have similar expenses, both steps should be conducted at this stage.

3. **Resource data collection step 3:** Having identified relevant points of improvements regarding the resource usage of the line, AVL should incorporate the continuous data collection, as described in resource reduction step 3. The processes which are concluded to be relevant points of improvement should be prioritized and the data should be correlated with material quality data. The continuous data collection will allow AVL to test and improve their line efficiency and adapt to changes in the presorted plastics. At this step, a more thorough emissions documentation should also be pursued. This means, that emissions documentation step 2 should be conducted. AVL can then provide a very detailed emissions description of their product, while also opening for the opportunity of gaining advantages from reducing emissions related to the presorting and transport. It is expected, that doing these things will allow AVL to maintain a favourable market position by having a product which is not only greener compared to virgin plastics, but is also greener than many other recycled plastic granulates, that will emerge as the industry grows.

Apart from being able to document and reduce the resource usage at different levels, the above strategy also opens up for the following three opportunities for AVL:

- **Consultancy:** When AVL has completed step 2 of the final resource usage data collection strategy, presented above, they are expected to have built up expertise in measuring, documenting and reducing resource usage. This expertise can be shared with other companies in the industry, to help push for greater standardization and the general development of the plastics recycling market. By doing so, AVL can help remove some of the market inhibitors, discussed in Section 2.7.2 on page 21. The other companies could be presorting facilities, current and potential customers of AVL and even foreign plastic recycling companies, that are not in direct competition to AVL. The data sharing can be done as a paid consultancy, to also create a new stream of revenue for AVL. Doing so would require AVL to expand their business plan.
- **Maintenance:** Continuously measuring the resource usage of the machines can allow AVL to identify maintenance related issues. If some process starts increasing its power usage even though the input material quality is unchanged, it might be due to maintenance needs such as dull blades or lack of lubrication. A more thorough discussion on data collection in relation to maintenance will be covered in Chapter 5.
- **Selling certificates:** Implementing the combined strategy, described above, could be the first step towards an emissions certification for AVL. Obtaining such a certification will allow them to sell carbon credits. In April 2021, Green Tech became the first plastics recycling company in Europe to get certified by Gold Standard (Tech, 2021). Gold Standard's certification of Green Tech is expected to allow Green Tech to sell 453 000 carbon credits. Each carbon credit, which corresponds to one tonne of CO_2, is sold for 47 \$ at the Gold Standard website (The Gold Standard Foundation, 2021). By getting certified and selling carbon credits, AVL can fund further expansion and improvement of their post-consumer process line. Furthermore, the certification would provide an incentive for reducing the emissions of their line even further by reducing resource usage.

4.4 Conclusion of Case A: Resource Usage

In conclusion, this chapter has investigated how information about the resource usage of the post-consumer process line can be obtained to document the equivalent CO_2 emissions and different levels of detail. Furthermore, it has been discusses how AVL can obtain and use resource consumption data to decrease the resource usage of the post-consumer process line. With the aim of simplicity and usable feedback, two gradual implementation strategies for resource usage data collection were derived: One with the goal of *documenting* the equivalent CO_2 emissions and one with the aim of *reducing* the resource usage of the line. These two strategies were combined in a final data collection strategy for the resource usage related to the plastic granulate recycled by AVL. The final strategy is outlined in the in Figure 4.3 and list below :

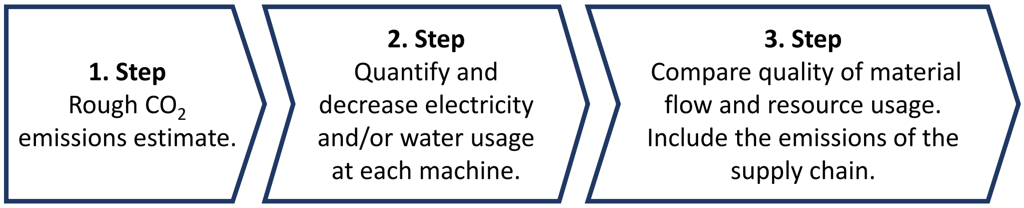


Figure 4.3: Visual representation of the resource usage strategy.

- Step 1 in the combined strategy will allow AVL to calculate the resources spent at their own factory. Furthermore, this knowledge will lay the foundation for step 2 by answering whether the water or electricity usage has the largest influence on emissions and costs, respectively.
- In step 2, either the water usage, electricity usage or both will be measured at each process step. This knowledge will allow AVL to initiate their improvement process at the most relevant points in the process line.
- At step 3, continuous data collection and correlation with quality data will allow AVL to begin an effort of continuous improvement and batch-based parameter settings. Furthermore, AVL should expand their emissions documentation by including their presorters and the emissions from transport between AVL and their suppliers/customers. This will ensure, that AVL can stay competitive in the emerging plastics recycling market, while also making them able to comply with future changes in the composition and quality of the presorted plastics.

Lastly, it is concluded that AVL could benefit from offering consultancy services to their suppliers, customers and even competitors. Furthermore, achieving a comprehensive documentation and low resource usage could lead to a certification, allowing AVL to sell carbon credits.

Case B: Process Time and Machine Efficiency 5

This chapter will seek to answer the second sub-statement:

> **Case B:** *"How can information about process time be obtained? How can this information be used to quantify the line efficiency and maintenance needs, and what can AVL gain from this knowledge?"*

The sub-statement above covers two of the cases introduced in the problem analysis: Case 4 Machine Capacity and Case 5 Process Time Management. The two cases are linked because different process times are needed to obtain data regarding the capacity and efficiency of each machine in the line. In the following sections, the need for data relating to process time management will be established. Furthermore, various techniques and technologies that can enable AVL to start monitoring the process time related parameters will be discussed. This will be presented through a three step data collection strategy, which aims to represent a gradual implementation.

5.1 Step 1: Process times

The objective of step 1 is to describe which fundamental process time parameters AVL should investigate. The first proposed parameter is to measure the availability of the production line by mapping the amount of the working hours, that the production line is running. Afterwards, a Subsection of downtime explores data from breakdowns that can be collected. Maintenance and planning of maintenance will be covered. Lastly, it is discussed how AVL can measure the capacities of their machines, as well as the benefits of doing so.

5.1.1 Availability

A crucial part of process time management is to find the availability of the line. The availability is to be seen as the ratio between The actual operation time, which can be seen as the effective running time of the line, and the planned operation time of the line. For the planning office it is important to know how much time, during a shift, the line is running and how much time is allocated for planned downtime or maintenance. However, at the production line, unplanned downtime can occur at all times. For this reason, the planned operation time can easily be affected, if unplanned downtime frequently shutdowns the line. In Figure 5.1, a planned shift, as well as the sub deviations of a days work, can be seen. (S. K. Subramaniam et al., 2008)

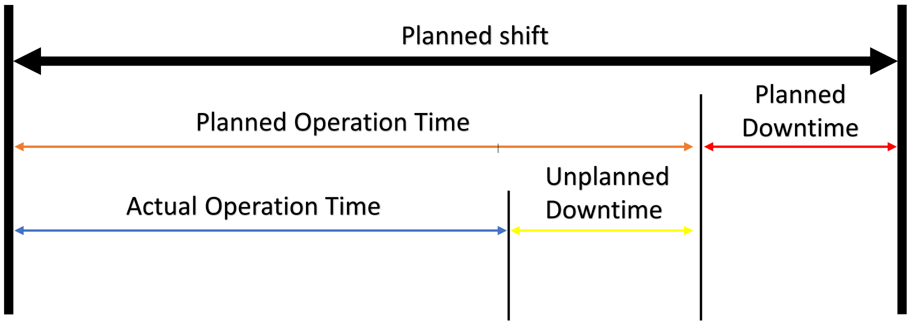


Figure 5.1: General breakdown of a production shift.

The availability can be used to improve planning and buying of input material for the production. Furthermore it can be used to predict lead times for the sales department. This means that all the supporting departments can benefit from getting a more accurate estimation of the actual operation time of the line. The problem with finding the actual operation time is that unplanned downtime is difficult to predict. However, by registering when a machine or the line is down, the downtime can be estimated using the historically collected data. In the following section, a system for collection of a downtime will be researched.

5.1.2 Downtime

Downtime can be measured in many different ways, and the degree of automation can vary both from line to line and from machine to machine. In compliance with what was learned at RollTech A/S, which can be seen in Figure 3.2 on page 29, it is important to start simple. For the downtime this can be accomplished by simply creating a spreadsheet with all of the machines in the line. Whenever the line is down, a production worker will note the following data in the spreadsheet:

- **1. The length of the down time:** The first data-point is needed in order to find the actual operation time. The actual operation time can be calculated after the sufficient data has been acquired over a period of time. Further benefits of finding the availability will be looked at in Step 2.
- **2. The reason for the down time:** Knowledge can be gained by not only noting the length of the stop, but also the reason. By encouraging the workers to state the reasons why the line is down, potential flaws in the design can be spotted and corrected. Furthermore, regular breakdown patterns can be spotted, leading to better maintenance intervals. And lastly, if a new production line is commissioned, these flaws can be avoided.
- **3. Error codes from the machine:** The last data-point is error codes from the machines. The error codes, along with the information gained from the worker, can be used to gain knowledge about how unplanned maintenance of the machines can be prevented. Error codes in a modern process line can be collected and analysed using a supervisory control and data acquisition (SCADA) system. This is the same type of system used for data collection at RollTech A/S. SCADA systems can be setup to continuously collect the data, and directly calculate the actual operation time of the of the line. This is a higher level system and the implementation can therefore be costly.

In the focus points for the case work, which can be seen in Section 3.2 on page 31, it is decided that the data collection should be implemented gradually. For downtime noting, this means that data will be written on paper in the beginning. Later, after the workers have gotten used to this system, the complexity is increased by digitizing the data, for instance by using computers or tablets. Another aspect is the usability of the data. Before spending costly resources on more complex systems, AVL should look at the feedback to see if the investment can be justified. If AVL decide to implement permanent process time data collection, AVL must ensure to keep the workers motivated to perform the tasks.

5.1.3 Maintenance

Fixing maintenance related issues can be approached from two points of view. One focus is on reducing the frequency of regular maintenance, while the other is on avoiding the unplanned maintenance. When analysing savings related to maintenance, it is important to Figure out what causes the maintenance costs to increase and how to avoid it.

Having a good data collection system would help with recognizing the need for the maintenance. This system will also provide an opportunity for lowering the maintenance frequency, as well as more precise planning of it.

When talking about different types of maintenance planning, it is important to note the difference between corrective maintenance, preventive maintenance and predictive maintenance. Their relation to the investment can be seen in Figure 5.2. (Selcuk, 2016)

Corrective maintenance
This is a failure driven maintenance policy that lets the items run until failure, after which they are restored. This policy is only affordable in systems which are not so sensitive to breakdowns, and where the maintenance is not too big.

Doing corrective maintenance for a process line like the one in AVL is not a good idea, because the machines are connected in series. This leads to full stop of the production if one machine brakes down. Also, there is a need for having reserve parts for the whole production line, because waiting for replacement parts would take too long. Unplanned downtime with this maintenance method is unknown, thus it would create big risks for the line, when the processing will be run in a 3 shift production.

Preventive maintenance
This is a planned maintenance, which is scheduled in advance to help prevention of the failure. It is based on the operation time and manufacturer recommendations. In some literature, this is called time-based maintenance.

The next logical step for AVL is scheduling the maintenance in advance, if that practice is not done already. Usually this maintenance is performed with manufacturers instructions or by making a manual schedule. (Selcuk, 2016)

The Data-points, seen in the data-points list in Subsection 5.1.2, can give AVL the information about downtime, reasons for the downtime and error codes can be used to do planned maintenance. As mentioned in Section 5.1.2, a maintenance schedule could be made. Since some of the machines in the AVL post-consumer process line are built in-house, a custom maintenance schedule is needed. For the commercial available machines, the advised maintenance guideline from the manufactures should be followed. A big influence on the success of this method could be the input quality of the plastics. Maintenance that would occur due to dulling of the grinder blades, material getting stuck somewhere on the way to the output, or by water and air filters getting clogged up would become more predictable if the input quality became more consistent.

Predictive maintenance is a data driven maintenance policy aiming at failure prevention and improving maintenance efficiency, while achieving better safety, product quality, reliability and reduction in operation costs.

Predicting the maintenance is a complex task and it requires new data and sensors that are not available during the preliminary steps. This is the most precise method of removing unplanned downtime, but it requires additional investments. Section 5.3 on page 55 will dive into predictive maintenance.

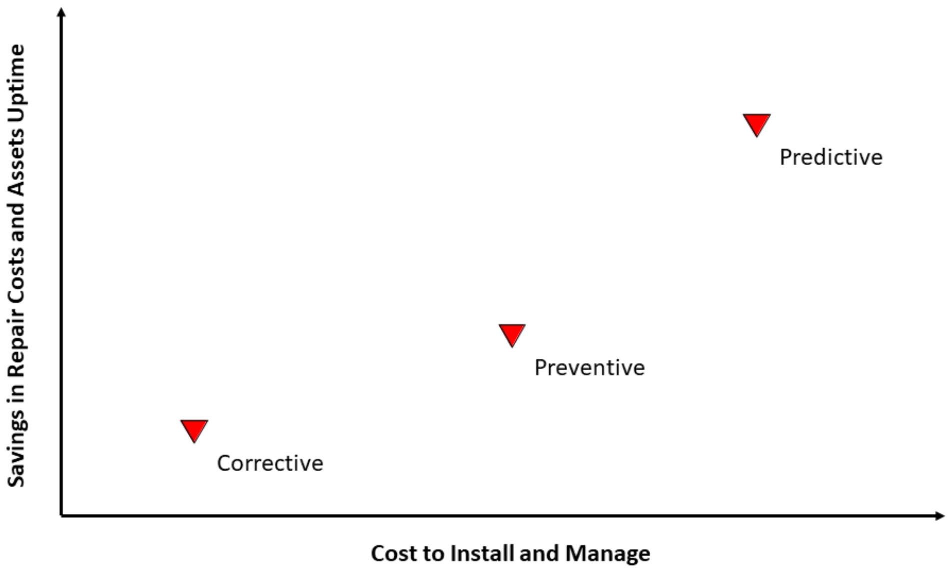


Figure 5.2: Maintenance strategies in relation to return of investment.

5.1.4 Process Capacity

The capacity of each machine is important to know, especially when having a production line where all machines are connected in series. The line is only as fast as its lowest capacity, so knowing what machine is the limiting factor is necessary if the performance of the line needs improvement.

Since some machines are batch-based and some are running continuously, capacity definitions will differ slightly. For the batch-based machines, the capacity can be defined as the batch size divided by the cycle time. Here, the cycle time must include the time used for filling/emptying the machine. For the continuous machines, the capacity is measured in material output of the machine per minute or hour.

AVL are currently not aware of the capacities of any of their machines on the post-consumer process line, besides the NIR sorter. Therefore, it is suggested that AVL spend time testing each machine individually. Finding the capacity could be done by feeding material manually to each machine and slowly increasing the material input, until the machine cannot keep up or the quality is lowered. Similarly, the cycle time of the batch-based machines could be found by experimenting with how short a cycle time, that can be used for getting a sufficient quality of the process.

In contrast to the continuous measuring of downtime, it is not necessary to keep measuring the capacities. If it is seen that there is too big of a difference between the machines, bottlenecks can be uncovered directly. The bottlenecks can then be moved and the overall production can be improved.

5.1.5 Recommended Implementation Strategy of Step 1

The aim of the first step is to gain a basic knowledge, about where to get started with collecting process time data. Since the gradual implementation is important, the first process time metric to be recorded should be the downtime. It is an easy way of getting started, while getting the workers at AVL involved. As soon as a spreadsheet has been made, the data collection can begin. The collected data will make it possible to determine the lead times, as well as a improve the planning of purchasing the post-consumer plastics. The capacities are the next parameters to collect. Some methods may cause the line to be down during the measuring thereby bringing a small cost in lost production. However, it is an important parameter that is crucial to know in the following steps.

5.2 Step 2: Theory of Constraints and OEE

After measuring the preliminary process time data in step 1, step 2 will describe how to make improvements to the line based on the collected data. In step 1, data was provided to help locating bottlenecks within the production line. However, locating bottlenecks is not beneficial if no action or improvement is done.

Making improvements to the line is a complex and continuous process. Implementing measurement and monitoring methods can provide knowledge about the workflow. Using the available data, and knowing when to collect new data, is also important. Theory of Constraints (TOC) is a method to process the data and achieve improvements upon the knowledge gained (Vorne, 2021). This theory makes use of an iterative mindset to improve complex systems by solving the bottlenecks, or constrains. TOC and how it can be applied will be discussed in the following Section.

5.2.1 Theory of Constraints

The Theory of Constraints provides a scientific approach to finding bottlenecks and then improving the system. The core of this methodology is that every complex system has a bottleneck/constraint which limits the throughput of the whole process. When that constraint is improved, the whole system is improved. After finding out the constraint and improving it, another constraint shows up. By iteratively improving constraints like this, the whole system is improved step by step. A list of the benefits of using TOC can be seen below. (Vorne, 2021)

- Growth in Profit
- Fast Improvement
- Improved Capacity
- Reduced Lead Times
- Reduced Inventory

Finding and eliminating the constraints comes in five steps shown in the Figure 5.3. In Appendix D.2 on page 120 is a description of each of the steps along with a order of implementation and improvement techniques.

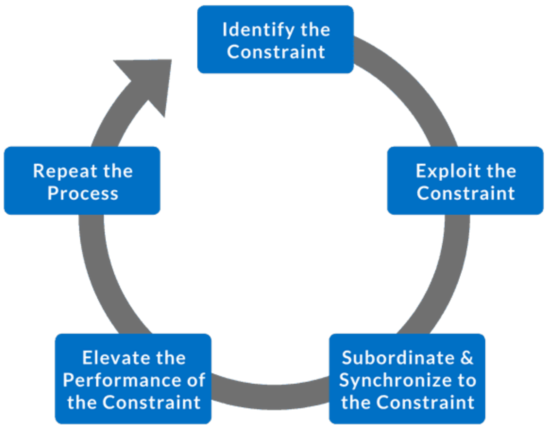


Figure 5.3: Five Focusing Steps. (Vorne, 2021)

All of the steps are to be seen as iterative. This means that the consequences of the each step should be studied after it is completed. If a preliminary implementation is not sufficient, then exploiting a constraint with one of the other techniques seen in Appendix D.2 on page 120 must be considered. When improvements have been found between the steps, the final step is to repeat all steps thereby creating an iterative process.

Due to the time limitations it has not been possible collect data and apply the theory of constrains on the post-consumer line. However, to show what can be gained from collecting the data from step 1 and then using the theory of constrains, a simulation has been set up. It will be explored in the following Section.

5.2.2 Simulation of Simplified Production Line

A simplified production line will be made in this Section in Enterprise Dynamic. The line will not be the same as the line at AVL. It will only contain three machines, two will be running continuously (machine 1 and 3) and one machine between the two will be batch-based (machine 2). In the simulation the continuous machines have the same capacity and the batch-based cycle time is set to match them. It would have been preferable to measure the capacity of all three of the machines at AVL, but this was not possible. Therefor, the simulation has been made to investigate the behavior of a production line with both batch-based and continuous machines, as this occurs at AVL's post-consumer processing line. The process line modeled in Enterprise Dynamic can be seen in Figure 5.4

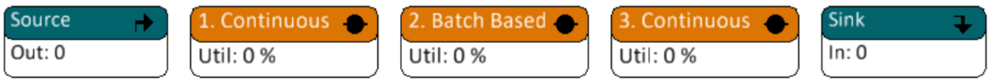


Figure 5.4: Enterprise Dynamics simulation layout.

By simulating the line in Enterprise Dynamic, improvements to the line can be made according to the five steps in the Theory of Constraints seen in Section 5.2.1.

The first simulation is set to run for 10 shifts of 8 hours. The effect of the improvements will be monitored by using Enterprise Dynamic's status monitor. The status monitor show utilization of each machine. This simulation is not set up to take any kind of downtime into consideration. Throughout the simulation, the status of each machine has been monitored. The results of this can be seen in Figure 5.5.

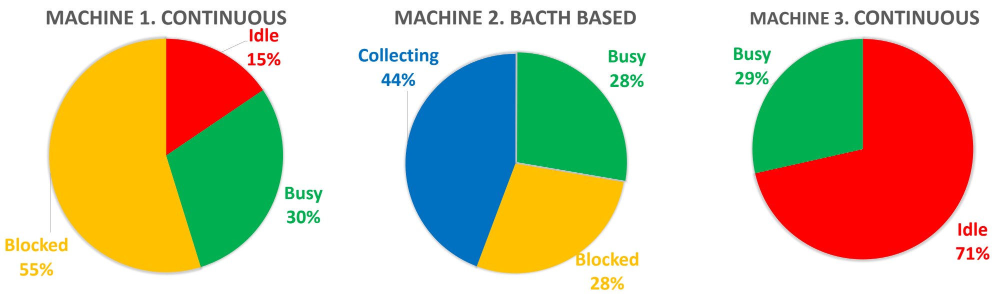


Figure 5.5: Simulation 1 with no buffers.

The constraint in this first iteration has been identified at machine 2. At AVL this could have been noticed by an operator, or a visual inspection could reveal a breach in the material flow. The utilization of the first continuous running machine is only around 30 % according to the simulation. The machine is either blocked or idle for the remaining 70 % of the time. The theory of constrains exploit step is used, to solve the constrain. For the following iteration a buffer will be placed in front of machine 2. This means that machine 1 can operate, even though machine 2 is collecting or busy. The second simulation iteration is then run and the new information regarding the utilization can be seen in Figure 5.6.

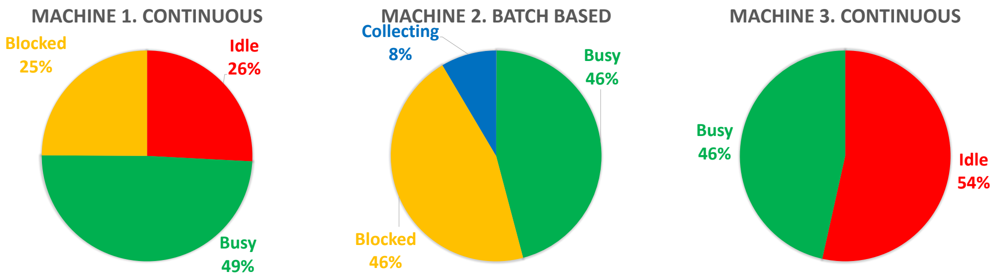


Figure 5.6: Simulation 2, buffer in front of machine 2.

By introducing the buffer it can be seen that machine 1 is now busy 49% of the time. In the AVL case, a buffer could be a silo big enough to contain material equal to the cycle capacity of the batch-based machine.

However, there is still some room for improvement. The new buffer in front of machine 2 has resulted in increased percentage where machine 2 is blocked. In the first iteration, machine 2 was not able to get rid material 28% of the time and this has increased to 46% of the time. The constraint has simply moved one machine so machine 3 is now the bottleneck. This was expected, as this is seen from the theory of constrains in the subordinate step in Appendix D.2 on page 120. The upstream process is running more efficiently and machine 3 is the one constraining the flow of material. A buffer is placed in front of the new constraint and the simulation is carried out as seen in Figure 5.7.

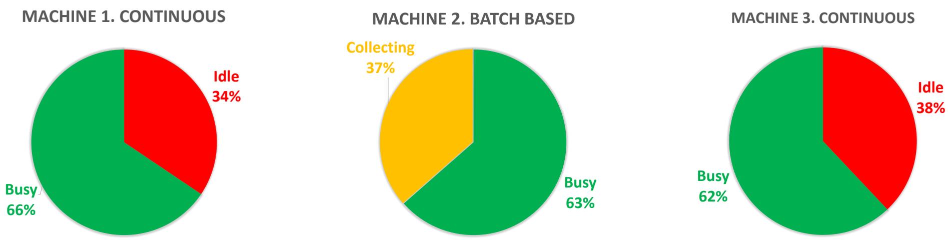


Figure 5.7: Simulation 3, buffer in front of and after batch based machine.

From the three pie charts, it can be seen that the machines are not blocked and the only time they are not running was when the material is too low. If this happens, the machines will be idle.

As a part of the simulation setup, the amount of material that is allowed through the line has been set to a constant amount. To prove that this is the reason for the machines being idle, the allowed flow of material has been increased in the last simulation. This can be seen in Figure 5.8.

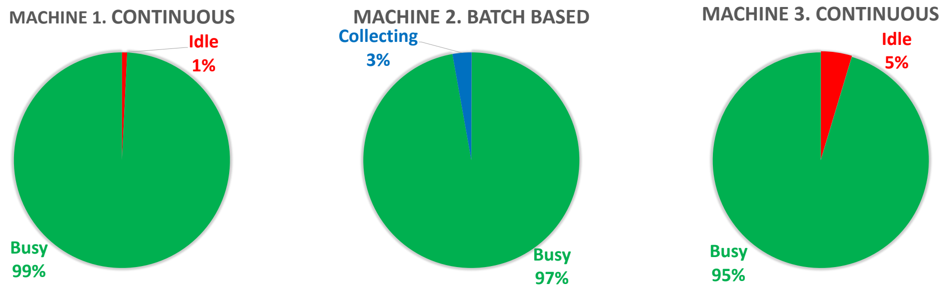


Figure 5.8: Simulation 4, buffer in front of and after batch-based and increased input rate.

The amount of idle time in this simulation has been reduced significantly. However, increasing the material flow is not always possible. In a production line, like the one at AVL, increasing the amount a material is not possible since not all the machines have the same performance. Therefore, a measuring tool is needed that includes not only the availability, but also the capacity, so the performance of the machines can be found. Such a tool is in the theory of constrains the Overall Equipment Efficiency (OEE). In the following Section, it will be explained how the OEE of a machine is calculated and how this can help gain the knowledge needed to improve a production line.

5.2.3 OEE

Overall Equipment Efficiency is as mentioned an integrated part of the Theory of Constraints used to measure the equipment efficiency of the machines and the entire process line. In other words, OEE is used to monitor and analyse the manufacturing process.(S. K. Subramaniam et al., 2008)

The method is simple and considered as a production equipment efficiency index. This index is calculated in order to compare the effectiveness of machines in the line. The main focus of OEE is calculating the losses in production. Those can be separated into three parts: Availability, Performance and Quality. The relationship between them can be seen in the Equation 5.1:

$$OEE(\%) = Availability \cdot Performance \cdot Quality \tag{5.1}$$

Availability

The availability of the line has already been described as a part of step 1. For the OEE calculation, however, the availability is defined as the ratio between the planned operating time and actual operating time, as seen in Equation 5.2:

$$Availability = \frac{Actual\,Operating\,Time}{Planned\,Operating\,Time} \tag{5.2}$$

Performance

The performance of a machine or a production line is a measure of how well the capacity is utilized. There is a lot of factors that can influence the performance of the machines. Some of them are machine wear, type of input, misfeeds, operator's inefficiency etc. The performance is considered as the ratio between the net run time to the planned run time. The performance for a batch-based machine can be seen in Equation 5.3. (S. K. Subramaniam et al., 2008)

$$Performance_{Batch} = \frac{(Machine\,Ideal\,Cycle\,Time \cdot Total\,Batches\,Produced)}{Planned\,operating\,time} \tag{5.3}$$

Many of the machines on the AVL post-consumer process line run continuously, so another calculation method is used in these cases. The calculation of performance for the continuous machines is the ratio between output and the capacity of the machine times. Here, the output and capacity are expressed as mass per time. This can be seen in Equation 5.4.

$$Performance_{Continuous} = \frac{Output}{Machine\,Capacity} \tag{5.4}$$

Quality

When considering quality, the actual productive time is the time used to produce good pieces. If AVL's post-consumer process line is looked at with the quality formula, the quality from a machine equals the fraction of the output material that has the wanted properties.

$$Quality = \frac{Good\,Pieces\,Produced}{Total\,Pieces\,Produced} \tag{5.5}$$

As the post-consumer process line is continuous, it is not necessarily obvious how "good pieces" and "bad pieces" are defined. In reality, it will depend on the type of machine, that is investigated. If the OEE is to be calculated for a grinder, good/bad pieces can be define through a size requirement of the flakes. Samples are then made to investigate how many of the flakes, that are within the tolerance. For a washing process, good/bad pieces can be defined according to how much residual dirt, that is present in the material after the wash. In other words, to measure the quality of the machines in the AVL post-consumer process line, it is necessary to perform material quality data collection. This could be done by taking out samples for analysis or by utilizing NIR sensors, this will be elaborated in Chapter 6.

It can be seen in the grey box below that the OEE of the NIR is low. This suggest that somewhere in the line there is a bottleneck preventing more material passing through. For AVL to improve the line, the OEE of the machines where constraints are located will be important. In the case of the NIR sorter, which is an expensive machine, the low OEE shows that the NIR sorter as a resource is poorly utilized.

OEE Example

As AVL do not know the exact capacity for most of their machines, it has not been possible to do an OEE of the line as a whole (Appendix B.1 on page 95). Instead, an OEE calculation has been performed for the only machine, that it has been possible to find specific capacity on. I.e. the NIR sorter, which is the TOMRA INNOSORT FLAKE model. The calculations can be seen in Appendix D.1 on page 119.

Figure 5.9: The NIR INNOSORT FLAKE. (TOMRA, 2019)

The OEE have been calculated both for when the NIR sorter is processing HDPE and PP. The reason for this is that the average throughput, as well as quality is different for the two output types. The calculated OEE for the NIR sorter is 10.7 % for HDPE and 9.4 % for PP. These low OEEs are mostly due to the NIR sorter having a very high capacity compared to its output. At AVL the output of the NIR sorter is ranging from 405 kg/h to 543 kg/h, (Appendix B.3 on page 101), which is low compared to the NIR sorting capacity of 4500 kg/h (TOMRA, 2019).

5.2.4 Recommended Implementation Strategy of Step 2

The first implementation step for AVL should be to go through the line while it is running, to see if a visual inspection can reveal any constrains. When a constrain has been found the four remaining steps in TOC should be conducted. This should hopefully give AVL a better understanding of where upgrades to the line may be beneficial. The last step of the TOC will require AVL to calculate the OEE of the machines that are seen as constrains for the line. By finding the OEE of the machines AVL will be able to take relative simple data and turning it in to a measurement tool providing them with a estimate of the efficiency of a given machine. However, in order to find the OEE, data on material quality is needed. How this data can be obtained will be described in Chapter 6.

5.3 Step 3: Predictive Maintenance

This step is focusing on usage and future usage of collected data to help with failure prevention and maintenance of the different processes in the post-consumer process line. Predictive maintenance uses indicators of deterioration to prevent unnecessary energy consumption, or in worse case failure. Important information to note is that 99% of machine failures are preceded by some indicators, according to Chang-Ching Lin, 2004. This means, that all of the failures can be predicted in real time, which is a big advantage compared to preventive maintenance from Section 5.1.3. If the failure comes before the scheduled maintenance it can give catastrophic results, because if the maintenance is not prepared with spare parts and tools in advance, it will result in a very long downtime. Since predictive maintenance is monitoring and probing the system for information in real time, it is able to predict the maintenance at the right time.

There are three steps of Predictive Maintenance (Selcuk, 2016):

- Data Acquisition
- Data Processing
- Maintenance Decision-Making

In terms of process time, if predictive maintenance is used correctly, the unplanned downtime seen in Figure 5.1 on page 46 can be drastically improved. Unplanned downtime can occur due to a multitude of reasons, for example at the AVL production line it could be the dulling of the grinder blades, material getting stuck somewhere on the way to output or by water and air filters getting clogged up over time. Malfunctions mentioned above can cause a "domino-effect" on processes after that, creating new problems for the process line. For example dull blades can cause badly ground material, that becomes harder to wash. In that case the grinder is not only spending more energy, but the whole process line is having traces of energy loss and damage. When trying to solve this issue, it is important to be notified when the time is right to perform reparations, so no further damage is done to the line.

5.3.1 Predictive Maintenance Techniques

After some research, possible techniques of doing the predictive maintenance can be listed, based on Chang-Ching Lin, 2004. This segment will go trough these techniques and elaborate options that would benefit AVL:

- **Measuring process parameters:** Some of the process parameters that can be measured are efficiency, heat loss, temperature, fluid pressure, humidity and flow rate. Abnormal changes of process parameters often indicate that something is wrong with the system, but it is important to note that some of the changes are caused by operational changes.
  Process parameters give a lot of information about the state of the machines. If machines like the grinder or the wash start consuming more power then normally, it could indicate something is wrong with them, or their specific parts. In AVL's case it should be noted that the information about the power consumption has to be carefully used in predicting the maintenance, because the difference in the input of plastics for recycling can influence power consumption. Fluid pressure drop and flow changes could indicate clogging of the water system.
- **Vibration analysis:** Analysing vibrations is a way to detect malfunctions in early stages of the problem. This analysis is used mostly on rotating equipment for continuous production or scheduled production. Some of the problems that vibration analysis can detect are: resonance problem, imbalance, eccentricity, misalignment of bearings and couplings, mechanical weaknesses, rubbing, bent shafts, cracks,

turbulence, turbine/fan blade defects, etc. This is the most common predictive maintenance technique used in the industry.
For the post-consumer process line, grinders are the first machines that come to mind when considering rotating equipment. If a connection would be made between the blade wear and vibrations on the machine, predictions for the blade replacements could be made. Another piece of equipment sensitive for vibration are the washes. Measuring vibration during the washing process could indicate problems with the machines, if the vibrations get to big.

- **Thermal imaging:** Every object with a temperature higher then the absolute zero emits infrared light (IR). An increase in the temperature of the object is followed by an increase in light wavelength, as mentioned in Chang-Ching Lin, 2004. This effect can be monitored by thermal imaging to create a visual representation of the object's temperature. Difference in temperature is shown in different colours or different shades of grey. It is important to note, that imaging is not only affected by temperature, but also by the shape of the object, view angle and surface conditions. Thermography has been used for a long time when detecting the problems in electrical and mechanical systems and some of its applications are: loose or corroded electrical connection, mechanical looseness, load problems, component failure and leaks in heating, ventilating and air conditioning (HVAC) systems.
Thermal imaging could be implemented to a lot of segments in AVL's production line. The temperature of the plastic flakes could show the state of the grinder. Also, if the air flowing trought the transportation system is hot, thermal imaging could detect air leakages.
- **Acoustic analysis:** Machines, when working, create sound and sound patterns under normal operating conditions. Sound patterns that change can be an indicator of malfunctions and process deterioration. There is also possibility to measure high-frequency sounds with ultrasonic measurement instruments. These devices could capture steam leaks, air systems leaks and find irregularities with the materials, especially metals. Some of the acoustic analysis possibilities are: leak detection in pressure and vacuum systems, pump capitation, bearing inspection, compressor valve analysis, steam trap inspection, etc.
The process of recycling plastics involves a lot of noise, which if measured correctly would give good indications on the state of the equipment. Washes and grinders would create more noise because of loose and deteriorated machine parts. With ultrasonic measurement instruments, leaks in the air systems connected to the vacuum sorter, or in the sorter itself, could be found.

In summery, it would be a good idea for AVL to first look at some of the available process parameters before implementing new sensors. This step is planned for the future, together with the Internet of Things, that will be explained in Chapter 7. All of the predictive maintenance techniques explained would be useful for the AVL's post-consumer plastics recycling line, but an emphasis has to be made on checking the source of vibration and sound patterns in regards to the quality of the input. If the machines act differently with different kinds of input, it could lead to wrong predictions by the sensors. If that is taken into consideration, thermal imaging would be a way to go forward.

5.4 Conclusion of Case B: Process Time and Machine Efficiency

Trough discussion, 3 steps of implementation have been made. The steps were planned from the perspective of AVL as a company and the state of their post-consumer plastics production line. To further develop this line it was important, as information from RollTech A/S indicates, to start simple and then expand in the future. The implementation is schematized in Figure 5.10.

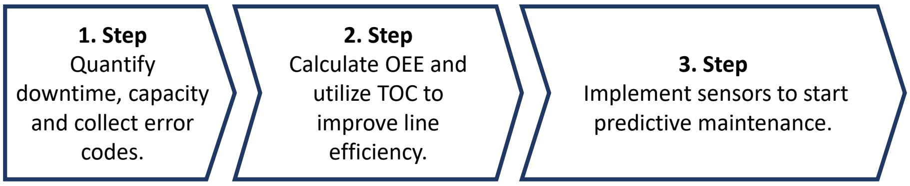


Figure 5.10: Visual representation of process time and machine efficiency.

- Step 1 covered rudimentary tasks related to data collection, that can be immediately implemented and improve the process line. If this step is done properly, with care, it will set up a good foundation for the next steps..
- Step 2 uses the data collected from step 1, with additional data gathering, to improve the process line by using the Theory of Constraints. The theory divides the strategy of implementation to the Five Focusing Steps, seen in the Figure 5.3. Because the data of the process line was limited, step 2 is more of a improvement guideline that focuses on creating a new strategic mindset on problem finding and solving. The simulation showed that having continuous and batch-based processes in succession can create constraints for the system, and using how the TOC can help resolve the constraints. A part of the method is calculating the Overall Equipment Efficiency. As an important measurement tool, it can be calculated and give the company better insight into their in-house built process line. For a line with a lot of unknown data, this is crucial step for further improvement.
- Step 3 looks into the topic of predicting the maintenance of the machines. Step 1 would give enough information for scheduling the maintenance (preventive maintenance), but exploring new real time data collection techniques creates an option of predicting the maintenance. Conclusion about the AVL process line is that analysing the process parameters, vibration, heat and sound patterns are some of the ways to predict deterioration of the machine parts, and lower the unplanned downtime shown in Figure 5.1, with predictive maintenance.

In conclusion, it has been shown how information about process time can be obtained to quantify the line efficiency and maintenance needs. Furthermore, it has been discussed what AVL can gain from doing so. It is necessary starting narrow with data collection and expanding in the future. Because of the immediate benefits and benefits further in the future, starting to think about data collection is important to consistently improve the production line.

Case C: Material Data Sampling 6

This chapter will seek to answer the third sub-statement:

> **Case C:** *"How can a gradual implementation of material sampling, NIR data collection and additional continuous sensors be used to quantify the material composition throughout the line? And what can AVL gain from this knowledge?"*

The objective of this chapter is to describe how material quality data collection could be implemented in the post-consumer process line. The chosen strategy is to divide the implementation into two steps to ensure gradual implementation. Step 1 consists of simple manual samples that are done to gain general knowledge about the line, but also to determine where it would be appropriate to implement automated data collection solutions. Step 2 consists of suggestions about how to make a more automated data collection system. This can be used to create mathematical model of the line, which is a prerequisite for obtaining a process line with automatic process parameter adjustments.

Decisions made in this chapter will be based on experiences from the group's visits to AVL and the interview in Appendix B.1 on page 95, due to the lack of data existing at AVL right now. Company visits to Expo-net A/S, RollTech A/S and Fibertex Nonwovens A/S will also be used to provide knowledge about data collection solutions, as described in 3.1.

6.1 Material Data Sampling Step 1

The purpose of step 1 is to test how much variation there is in key material parameters for the flow, this could be material types, humidity, size of plastic flakes etc. Step 1 should be implemented as an initial low CAPEX method to uncover if there are places in the line where a more continuous data collection is needed. Step 1 is therefore planned to be implemented for a limited time span, with the purpose of gathering knowledge about the process line, and also as a prerequisite towards an automated data collection.

There are many ways material sampling could be implemented in the process line, and it would yield different information about different parts of the process. A brainstorm was done to explore different ideas for material sampling on the line. Afterwards the different methods were described and it was visualized in a Figure how they covered different areas of the flowchart. This process can be found in Appendix E.1 on page 123. Afterwards four areas of sampling was found, by looking at what areas they covered. The 4 sampling points were chosen to give a large amount of information while using a small amount of sampling points. The four ideas and their placement can be seen in Figure 6.1.

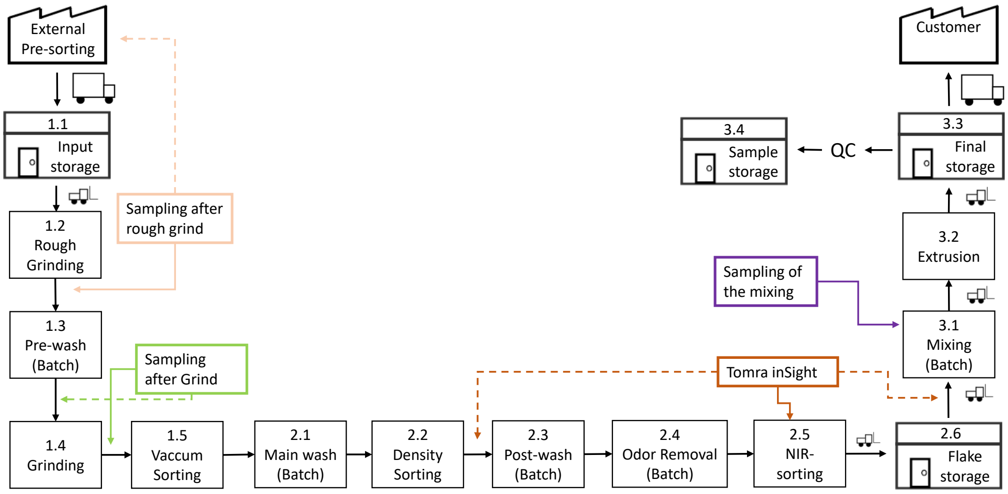


Figure 6.1: Flowchart, with the four sampling areas shown. Full arrows show the placement of the sampling, while dotted arrows present the place where sampling could potentially provide useful information.

6.1.1 Potential Gains from Step 1

The objective of this Subsection is to describe each of the proposed sampling points. Furthermore the potential gains for each of the sampling points will be presented. Note that the potential gains are based on assumptions, as the group has had limited access to the production line.

Sampling After Rough Grind

It is assumed that by sampling after the rough grind it is possible to gain usable knowledge about the presorted post-consumer plastic delivered from the supplier. Only metal has been removed before the grinding process. Furthermore, assuming that the blend is to some degree homogeneous, a sample can be presentable for a specific batch. If it is found that the batches are not homogeneous, it could be a good idea to increase the amount of samples taken per batch. The samples can be investigated to determine the material composition; how much plastic is present and which types? Furthermore, the flake sizes can be measured.

There are multiple gains that can be uncovered based on these assumptions. Some of them are shown in the following list, with information about how they could be handled.

- **Monitoring supplier quality** can make it possible for AVL to adapt their production line, if it is noticed that a specific supplier has a consistently low quality. This could be done by changing some of the process parameters to account for the low quality or to inform the supplier about what they should specifically focus on to improve their sorting. Furthermore, sudden changes in the quality of the presorted waste can be discovered. Depending on the agreement with the supplier it could be possible to create a fining system for batches with poor quality.

- **Supplier quality improvement** can be evaluated through continuous sampling of the input from the supplier, as it would be possible to see changes in the quality. If the quality is not improved after informing the supplier, AVL could choose to find another supplier or pay less for shipments.
- **An increase in average quality of presorted plastics over time** is expected to happen, as Denmark's presorting will tend to meet other European countries presorted material quality, which is currently higher than in Denmark. If this is the case, it would be ideal to adjust the process line to fit the higher quality of presorting.
- **A change in flake size** can be an indicator that grinder blades are in need of maintenance.

To sum up, sampling after the rough grind can mostly be used to survey the quality of presorted waste. This data can be used to help the suppliers, as they could then improve the quality of their sorted plastics. If the input plastic has less impurities it can improve the output quality and quantity. Furthermore, it could result in fewer breakdowns if there is less dirt, sand, rocks and metal present in the input material.

Sampling After Grind

For this sampling it is assumed that after two grinds and the first wash, a homogeneous blend has been obtained. The only previous process where contaminants are removed is the Pre-wash. Thus, if these samples are compared with the samples from the rough grind, the efficiency of the Pre-wash can be determined.

- **Measuring amounts of Sand, dirt, rocks and glass** can hold two potential gains. If the amounts of impurities are high, it can mean that presorting is insufficient or the pre-wash is too short. If the amounts of impurities are small the pre-wash can speeded up or less water can be used.
- **Size of the flakes** can be used to determine if the grinder needs maintenance. If changes in the size of the flakes appear it could be an indication of needed maintenance.
- **Amount of folio and thin flakes of PP and HDPE** in the mixture is interesting as it gives an estimate about how much material that the vacuum sorter needs to remove. Furthermore, if the sample can be compared with the information gathered after the rough grind, it could be possible to see if the grinder creates folio or thin pieces of the PP and HDPE. These thin pieces are then lost in the vacuum sorting. If the grinder creates this loss of product, it could be an indication that it should be adjusted.
- **Humidity of plastic** is important, because if the humidity of the plastic is too high, the vacuum sorter will not be efficient at removing the folio. Therefore, if the plastics are too humid, the friction generated in the grinder has not dried the plastic sufficiently. If this is the case, the grinder parameters can be changes or some sort of drying process can be implemented.
- **Temperature of the plastic** can be measured to obtain two potential gains. Firstly, it could help predict needed maintenance of the grinder. Secondly, if there is a high temperature in the plastic, AVL could consider improving the isolation in the tubes. Before moving in this direction it should be evaluated if there is any process that cools the plastic before the post wash or odor removal process.

As described above, the sampling after the second grinding process can be used to evaluate if the material is ready to be processed in the vacuum sorter. Furthermore this sample point can be used to asses how well the pre-wash has performed.

TOMRA Insight

The last sorting process in the production line is the NIR sorter, which is capable of detecting different types and colors of plastics. The NIR sorter at AVL's post-consumer process line is from the brand TOMRA, which is a Norwegian recycling equipment manufacturer. TOMRA also provides a data monitoring platform called Tomra Insight. This software provides near real-time data from the processing line (TOMRA, 2021). The data from the sensor is expected to provide valuable information regarding the following processes:

- **Output quality and composition** of the plastics can be determined with the NIR sensor. Furthermore it can be used to evaluate the performance of the density sorting, as this is the last sorting process before the NIR sensor.
- **Predicting mixing quality** with data collected from the NIR sensor can also deliver valuable data for the next process, which is the mixing. With detailed information regarding the output material composition, the mixing process can be improved. For instance, the amount of additives or higher quality plastics needed in the mix, could be calculated with the information from the NIR sensor.
- **Real time surveillance** from the TOMRA Insight applications can be a valuable tool, as it provides the possibility of monitoring the process from anywhere. This gives the production manager an opportunity to survey the line from his office. It also enables the manager to get an overview of how the production systems have performed, during the evening or night shifts, when he is not at work. Another advantage of this system is that no manual labor is needed in order to gather the data.
- **General processing efficiency** can be evaluated through the continuous data logging from the NIR sensor. The NIR will be able to show how well the process line has performed as a whole. If the quality or quantity of the output suddenly drops, it will suggest that there is a problem in one of the previous processes on the line. Thus, collecting the data from the NIR sensor can be used to make a warning system, that would detect when the line is not performing adequately. For instance, when a machine urgently needs maintenance or has other problems. Although, it will not be possible to determine the specific machine that is not performing satisfactorily, only by analysing the NIR data. Furthermore, the NIR data can be compared with samples after the rough grind, which have been analyzed in a lab, to investigate the loss of target material throughout the line.

To sum up, implementing data logging on the TOMRA NIR sorter is a way to get continuous data from the line, without installing more hardware. The data can be used for quality control of the process line output, as well as general monitoring of output quality and quantity.

Sampling in the mixing process
After the plastic have been sorted in the post-consumer process line, it is stored in small containers at a storage facility. When a customer orders a granulate, the plastic flakes are mixed in big batches before they are extruded. During this process additives or higher quality plastics can be added to improve the material properties. The potential benefits of sampling at this process step can be seen in the following.

- **Quality Control** of the mixing can be performed by collecting samples from the mix. These samples can then be tested in the existing lab at AVL through mechanical or chemical tests, with a goal to determine whether the mix has the desired properties. A big advantage of doing the quality control already in the mixing process, is that it is still possible to improve the material properties by adding additives or higher quality recycled plastics in the mixing process.
- **General processing efficiency** can be seen by analysing samples from the mixing process. The disadvantage of using the samples to evaluate the efficiency of the process line, is that the data is delayed. This is because the plastics are stored in a storage area for some time before reaching the mixing process. Thus the data cannot be used for adjusting the line to individual batches, but only as historic output quality data.
- **Extrusion efficiency** can be determined if samples from the mixing process are analysed. This is because AVL already performs quality control analysis on the granulate after the extrusion process (Appendix B.1 on page 95). By analysing plastics on both before and after the extrusion process, it can be determined how much the material properties deteriorate because of the extrusion. As described in Garcia, Scuracchio, and Cruz, 2013, extrusion will always negatively impact the material properties, but it might be possible to improve the process with more data available from the mixing process.
- **Humidity** can be detected by measuring the humidity in the samples from the mixing process. If the humidity is high, it suggests that plastics were not dried sufficiently after the post-wash or that the humidity is too high in the storage facility.

As described above, doing data sampling at the mixing process can be a way to determine the quality of the end product, at a point where it is still possible to improve it. It is furthermore a way to evaluate the extrusion process, as the test performed on the extruded granulate can be compared to the samples from the mixing process.

6.1.2 Sample Methods

In this Subsection a plan for the implementation of the 4 sample points mentioned above will be derived. Firstly, the sampling method is decided, then the sampling rate is examined and chosen. Afterwards the workload for taking the samples will be examined and considerations regarding the workers motivation to take the samples will be made.

Defining the sample type
The size of samples and the way of collecting them can be defined in two ways, as a random sample and as a standardized sample. The random sample types will not be the focus of this project, because the value of standardization outweighs the fact that the random sample is easier to perform for the line workers.

After doing a brainstorming, three ways of defining the samples were found, as it can be seen in Table 6.1. In the table, the needed work from a line worker and the risk of getting a bad sample that is not representative for the entire batch, are evaluated. The methods that should be implemented are related to the information that is sought and to the degree of homogeneity.

Method	Work	Risk of Bad Sample
Single Sample from Line	Small	High
Combine Several Samples	Medium	Medium
Sample From Large Homogeneous Bucket	High	Low

Table 6.1: Sample types.

Sample Rate

Similarly to the sampling method, the rate of samples can be standardized or random. There are some benefits to doing random samples, as it is a way to avoid aliasing. For this project it is assumed that the mixture is random and not time dependent, therefore aliasing is unlikely. Furthermore, it is easy to insure that a line worker takes a sufficient number of samples if there is a standard interval.

Six different sampling rates have been found through discussion. Each sampling rate will be evaluated according to; the amount of data it will generate, the time the worker will have to handle the sample, the convenience of gathering the sample for the worker and the quality of the data, see Table 6.2. The explanation for the ratings can be seen in Appendix E.2 on page 124.

Rate	Amount of Data	Available time for analysis	Convenience	Quality of Data
Time interval	Low-High	Low-High	Low	Low-High
Change of Batch	Low	Very High	High	Low
Input of Bale	Medium	Medium	High	Medium
Specific Amount Per Day	Low-High	Low-High	High	Low-Medium
During Break-down	Low	High	Medium	Low
According to previous sample results	Medium-High	Low-Medium	Low	High

Table 6.2: Sample Rate methods and their qualities.

Sample Analysis Techniques
The work load of handling the data is dependent on what information is sought. The information that is sought will be based on the potential gains described previously. This Section will seek to define what information is needed to achieve these gains.

- **Supplier quality** and changes in input quality can be monitored with information regarding the sample composition. An advanced method would be needed in order to gain detailed knowledge regarding the material composition in the mixture. If the desired information is the amount of rocks, glass, dirt and sand, it would be possible to gain this information using simple tools.
- **Amount of sand, dirt, rocks and glass** can be found by analysing the sample with a granulation sieve and a weight measurement. When pouring the sample in the granulation sieve, the sand and dirt will be separated from the sample, and this fraction can then be weighed. The rest of the sample can then be poured onto a tray, where the line worker removes rocks and glass into two separate containers. Afterwards the glass and rock containers can be weighed and compared to the total weight of the sample, giving an indication about the amount of the contaminants.
- **Flake sizes** can be measured by having a line worker performing flake size control, by using a granulation sieve, which would then divide the sample into smaller portions of equally sized flakes.
- **Degree of homogeneity** can be determined with a mixture of a granulation sieve, and the infrared spectrometer in their laboratory to define the amount and types of different contaminates in the sample.
- **Amount of folio and thin flakes of PP and HDPE** can be measured using one of two methods, depending on the depth of the needed information. If the amount of folio is the sought information, a line worker could separate the sample and weigh the fractions. If the loss of PP and HDPE is the sought information, a material analysis can be done either in their lab using the infrared spectrometer or by using NIR-sensor in their line.
- **Humidity of the plastic** can be checked to see if the plastic is dry enough for the vacuum sorting process or extrusion process. This can be done by using the moisture analyzer in their laboratory.
- **General processing efficiency** can also be described through a sample of the mixture. The sample can be analysed in the lab, with advanced sensors, to determine its material composition.

6.1.3 Recommended Implementation Strategy

As many different sampling methods, rates and analysis techniques have been presented previously in this section, a more specific implementation plan will be defined. The implementation plan can be seen in Table 6.3.

This report recommends the following three sample analysis techniques; granulate sieve, folio with humidity and TOMRA inSight. These three are recommended because the granulate sieve and assessment of folio in a sample can be done simultaneously. Afterwards, the humidity of the plastics can be tested. It is expected that these tests, including the task of weighing the material after the humidity test, can be done within a time frame of 10 min.

Sample methods	Recommendation
Analysis methods	1. Granulate sieve 2. Folio with humidity 3. TOMRA inSight
Sample Rate	1. Input of Bale 2. Time interval
Sample Method	1. Combine Several Samples

Table 6.3: Recommended sample handling.

These two sample analyses could provide information about the suppliers and the efficiency of the Pre-washers capability to remove; dirt, sand, rocks and glass. Furthermore it will help to evaluate if the friction in the grinder is sufficient to remove water from the plastic, in order for the vacuum sort to work properly. Finally, by comparing the amount of folio that is present at the NIR-sorter, with the amount of folio present before vacuum sorter, efficiency of the vacuum sorter can be evaluated. This is one of the reasons why the Tomra inSight is recommended.

The TOMRA inSight can also offer data regarding the output quality of the process line. This can be used as a general measure of how is the process line performing. The knowledge of the output quality can additionally be used in the mixing process. Furthermore, the implementation of the TOMRA inSight is, regarding the ideas presented in this section, the least labour-intensive way to collect data. The only resource that is needed is the time, that the production management would use while analysing the numbers from TOMRA insight. The only downside of this solution is investment requirement for the software. The price is unknown, as it has not been possible to get the price from TOMRA.

Two sample rates are recommended, because they have different strengths and weaknesses. Sampling at each input of bale has a medium amount of data, available time for analysis and quality of data. It has a high convenience which makes it easy to implement for the line worker, and is the sample rate method that should be utilized for the majority of the step 1 data collection. To ensure that the amount of data is sufficient to gain general knowledge about the mixture, it is recommended that for 1-2 months the mixture is sampled with a higher sample rate. During this period, it might be necessary to insert an extra line-worker to handle the sampling and analysis.

The recommended sample method is to combine several samples, this requires a medium amount of work, and a medium risk of bad samples. An issue with choosing this method is that it decreases the convenience of the sample for the line worker. With this recommendation it is important to keep the motivation of the line worker in mind. This will be discussed in the next part.

Line Worker Motivation:
As mentioned in Section 3.1 RollTech A/S had a number of interesting experiences with data collection. One of these experiences was that the implementation went smoother, when the workers felt that the data collection helped them in performing their job. Different ways to motivate the workers have been brainstormed and these will be described in the following. The found ways of motivation can be divided into positive and negative motivations. Positive motivation means motivating the worker by rewards. Negative

motivation means to motivate the worker by some kind of penalty if goals are not met. (Hanan Parvez, 2021)

Among the positive motivations is the fact that the samples should lead to fewer unexpected breakdowns, thus making the workday easier. Another positive motivation idea could be to offer the workers some kind of bonus or benefit, if they achieve the goals regarding data collection. This would of course cost some money for AVL, but it would also provide a strong incentive for the worker to perform the samples as specified.

Ways of using negative motivations to get the worker to take the wanted samples have also been found. One solution could to implement a system where the workers needs to sign in information about who has taken each sample, so the management can monitor the sample collection. Another method could be to implement some system to notify the worker when it is time to collect another sample. This could be by sounding an alarm or by having some colored light turn on. Both of these methods could help the worker to take the samples at the needed times.

It is difficult to determine which of these methods that are the best solution. This decision is up to the management at AVL, as they know what would be the best solution for their workers. It is emphasized that the workers are an important part of implementing data collection and that they should be motivated to perform this extra task.

6.2 Material Data Sampling Step 2:

As mentioned, the first step of the material flow data collection is implemented to get an overview of how the process line behaves in different conditions. If the sample data collection shows a big variation in the collected data, it would suggest that it can be feasible to implement a more continuous data logging.

This continuous or near continuous data could then be used to adjust process parameters, to optimize process output. Furthermore, resource usage can be reduced and the OEE of the entire line can be improved. In this section, different possible solutions to implement a more permanent and automatic material data collection are presented.

The process of choosing where more automated data collection systems could be implemented, should be based on the experiences from step 1. But as it has not been possible to perform any data samplings at AVL's process line, the decision has mainly been based on choosing equipment that is easy to implement and is able to collect relevant data.

Figure 6.2 offers an overview of the ideas found for step 2. The ideas can, as shown in the Figure, be divided into two categories: continuous data collection and automatic sample collection. The continuous data collection is performed with sensors, that can collect data without the need for stopping the line or taking out samples. The automated sample collection is similar to the sample method proposed in Section 6.1, but an automatic system for collection of samples will be proposed in this section.

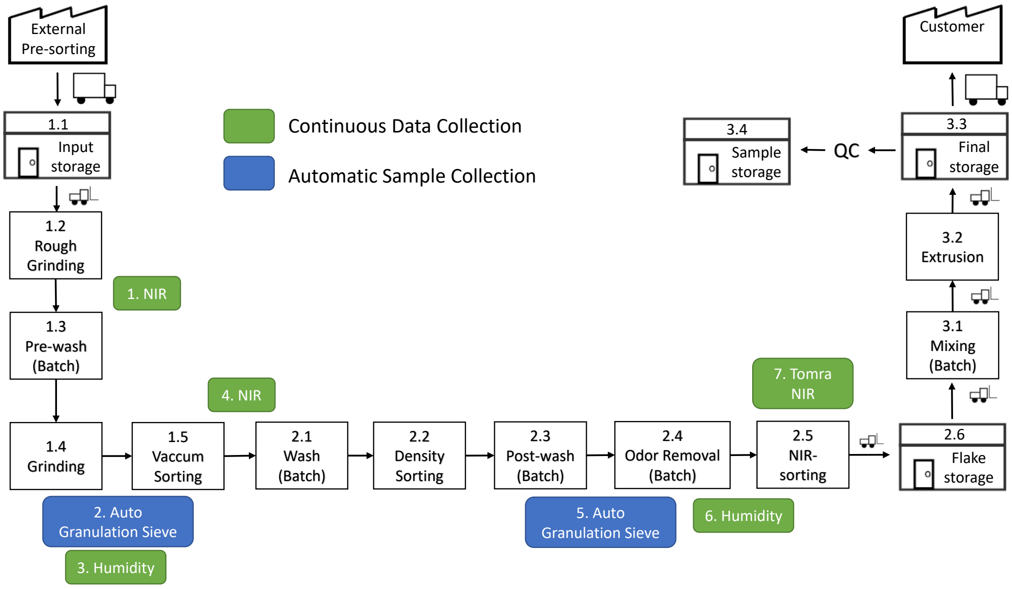


Figure 6.2: Proposed sample points for a more autonomous data collection.

6.2.1 Continuous Data Collection

Two types of continuous data collection are proposed: humidity and NIR sensors. An advantage for these methods compared to the automatic sample collection is that they are non-destructive and they are not disturbing the flow of the line.

NIR

The implementation of an extra NIR sensor is suggested for two positions in the line, right after the rough grind and after the vacuum sorting. The purpose of this NIR sensor is to collect data about the composition of the mixture, especially the amount of PP or HDPE in the material flow. Furthermore, the data can also be used to identify which other plastic types, that are present. This information might be relevant for the presorters.

If the fraction of PP and HDPE is known after the first grind, feedback can be given to the suppliers. Furthermore, if the input weight and composition of a bale is known, as well as the output weight and composition, the wasted PP and HDPE in the line can be calculated.

The NIR after the vacuum sorting can be used to evaluate the efficiency of the sorting, and if it is used in combination with a NIR at the rough grind, the loss can be calculated as well. This information can be used to change the parameters of the pre-wash, grinding and vacuum sorting.

Humidity

As seen in Figure 6.2, there are two proposed places for continuous humidity data collection: before the vacuum sorter and on the NIR sorting. The reason for this is that both processes are affected by water. If the plastic is moist it will become heavier, thus making the vacuum sorter less efficient. Furthermore, humid plastic can become a problem for the NIR sensor because water's absorption spectrum in the infrared region, is similar to the plastic spectrum, according to D. M. Scott, 1994. By continuously collecting data at these points it would be possible to adjust the drying process to increase the efficiency of the two sorting processes. In this report two methods for collecting information about the humidity are proposed; A moisture meter or a NIR Sensor.

For the moisture meter it is assumed that the air-moisture in between the plastic flakes correlates with the moisture on the flakes. This thesis should be analyzed, through experiments. The advantage of the moisture meter is that it is a fairly cheap sensor compared to the NIR sensor and it is often accompanied with a temperature sensor which could potentially be used for maintenance prediction.

NIR Sensor

NIR is an abbreviation for near infrared, which are the wavelengths ranging from 800 nm to 2500 nm on the electromagnetic spectrum. This spectrum is useful for measuring the composition of solid materials. The NIR sensor works by admitting light of the wavelengths within the near infrared range. The sensor detects how much of the light and which wavelengths that are reflected back. This reflection can be used to detect a number materials and a curve of this can be seen in Figure 6.3. (KPM Analytics, 2021)

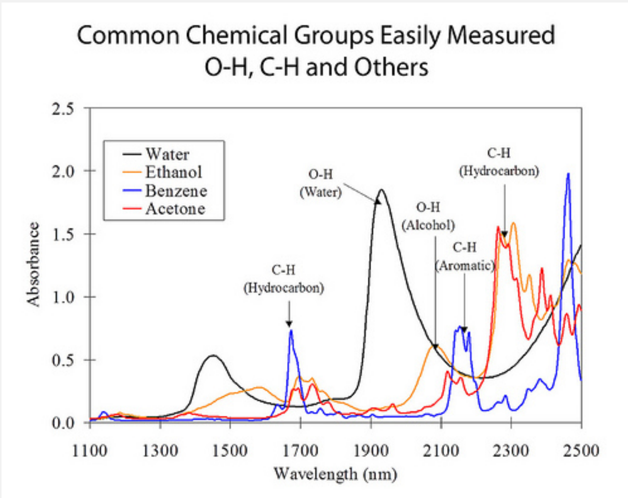


Figure 6.3: Examples of measurements from a NIR sensor. (KPM Analytics, 2021)

The other method is a NIR sensor. As previously mentioned, water can affect the information gathered in the infrared spectrum. If there is a peak found in the absorption spectrum of water, extra drying could be applied as a precaution. A producer of a NIR sensor that can detect the moisture range is Finna Sensors which has the OMNIR capable of predicting moisture in the range of 0.1 % to 95 % ±0.1%. (Finna, 2021)

6.2.2 Automatic Sample Collection

For some of the points in step 1 it is not possible to make a continuous data collection. Therefore it is proposed to implement an automatic sample collection, so workers will not have to manually collect material samples in the long term.

Purpose

The proposed solution is to implement a system that is capable of collecting samples and placing these in a granulate sieve. The granulate sieve can be used to determine the amount of dirt and sand after the different washes. Furthermore it can be used to see what shape and sizes the flakes have, which could be used to check whether one of the grinders needs maintenance.

Concept for Automatic Sample Collection System

A simple way of constructing an automatic sample collection system, would be to introduce a plate that can be rotated, so a portion of the flake mixture is redirected into the granulation sieve. This rotation could be on a timer, or related to information about when a new bale is inserted in to the line, see Figure 6.4. The size of the sample will be evaluated after the material has been sorted in the granulation sieve. A small loss can occur in the sieve, but this is neglected, since it is assumed that the loss is very small, compared to the effort it would take to input a weighing process before the sieve.

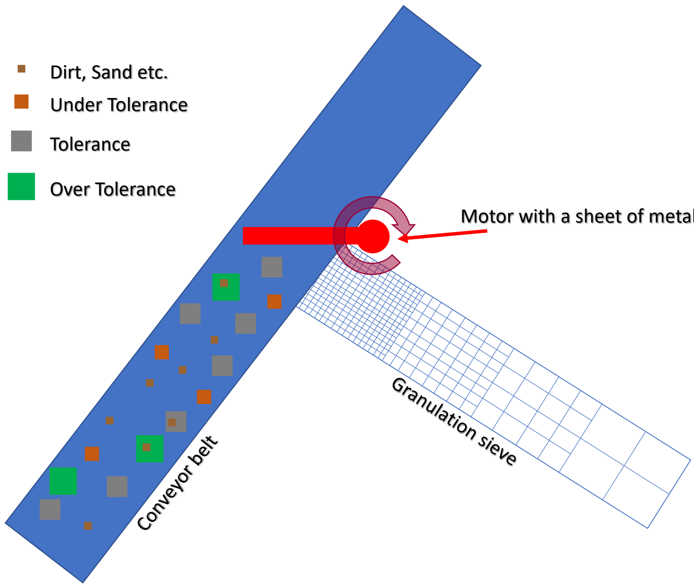


Figure 6.4: Concept of automatic sampling combine with automatic granulation sieve.

Granulation sieve

It is expected that the vacuum sorter and density sorter are operating most effectively, if the sizes of the plastic flakes are within a certain size tolerance. For the automatic granulation sieve it is proposed to use four mesh sizes in order to gain information about how much of the material is in each size group. The size groups are: over tolerance, on tolerance, under tolerance and small particles, such as dirt and sand. The potential information in the different mesh sizes is described in the following list.

- **Over tolerance:** If the flakes are to large it could become a problem at the vacuum sorting, furthermore there are a higher risk of air bubbles forming on a larger surface, which could compromise the density sorter. There could be a connection between needed maintenance of the blades and the presence of large flakes.
- **On Tolerance:** Here it is important to remember that the mesh size is not the median of the tolerance but the lowest size that is tolerated.

- **Under Tolerance:** If the flakes are too small, it can become hard for the density and NIR sorting to work efficiently.
- **Dirt and Sand:** The final fraction of the sample will then contain small particles of sand, dust and dirt etc.. This fraction has a high impact on the maintenance on the following washing process and the density sorter. Furthermore, microplastics will be present in this fraction. They can pose problems by clogging up systems such as filters and by covering the NIR sensors.

The automatic granulation sieve could be designed by having a surface with changing mesh size, at a small angle. By vibrating the surface, the sample should slowly move down the surface. Therefore the mesh size should start small and increase while moving down. At the first Section of the mesh, sand and dirt should be removed and gathered in a hopper, which would lead it into a weight scale. This design should be repeated down the mesh till all four fractions have been collected.

After the automatic sorting into these four fractions, they should be weighed, so a weight concentration of them can be found. If the concentration of dirt and sand is too high, the pre-wash process should be adjusted, or another process should be implemented into the line. If the flakes size does not fit within the tolerance, the grinding process parameters should be adjusted.

6.2.3 Recommended Implementation Strategy

In this section, it will be presented in which order the continuous data and automatic sample collection should be implemented, as it can be seen in Table 6.4. This Section is based on the assumption that the highest variance in data collected from step 1 would be at the beginning of the line.

Priority	Placement	Method	Potential Gain
1	Rough Grinding	NIR	1. Continuous description of supplier quality. 2. Makes an evaluation of the loss in the line possible.
2	Grinding	Granulation Sieve	1. Describe the quality of the pre-wash and grinding process. 2. Predict maintenance. 3. Process adjustment of later washes.
3	Vacuum Sorting	NIR	1. Evaluate loss from the grinding and vacuum sorting. 2. Evaluate efficiency of vacuum sorter.
4	Grinding	Humidity	1. Evaluate if the mixture is dry enough for the vacuum sorter.
5	Post-Wash	Granulation Sieve	1. Evaluate the efficiency of the post-wash.
6	Odor Removal	Humidity	1. Ensure that the flakes are dry.

Table 6.4: Proposed priority of automatic data collection.

As it can be seen from Table 6.4 the priority is defined from the amount of potential gain. The highest priority is the description of the input from the suppliers, as previously mentioned in Section 2.6. It is expected that the presorting will improve, therefore it is relevant for AVL to adjust the process line accordingly. For this reason, the automatic data collection close to the input is the highest priority. Furthermore, most of the other implementations are dependent on the input information.

6.3 Conclusion of Material Flow Data Collection

This chapter has investigated how data collection of the material flow can be implemented and what can be gained from it. Many different data sampling points have been found and their respective benefits have been described. The implementation have been divided into two steps, to ensure a gradual implementation, as schematized in Figure 6.5.

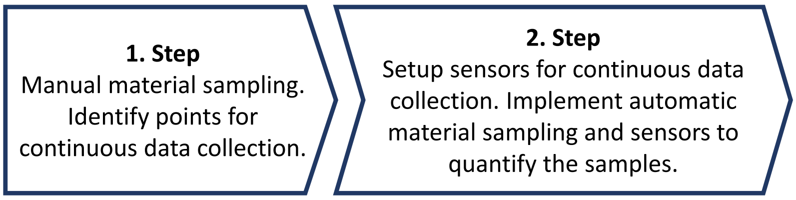


Figure 6.5: Visual representation of the material data collection strategy.

- Step 1 is supposed to be a data sampling strategy with a limited life span, as the sampling methods are labor intensive. The basic idea is to gather general knowledge about the process line and to determine if there are places on the line where more continuous data collection is needed. The recommended implementation plan can be seen in Table 6.3.
- Step 2 is a more autonomous data collection, where the suggestions from this report are to implement more NIR sensors and an automatic sample collection system. The automatic sample system can be used for checking the amount of dirt in the material and flake size. Meanwhile, the NIR sensor can describe the material composition of the flakes in the material.

These two implementation steps are based on the limited data AVL have provided about their process line, as well as the group's assumptions about process problems on the line. Following steps 1 and 2, recommendations should ensure a gradual implementation which was one of the focus points from the company visit described in Section 2.3. Furthermore, the simplicity of the sample analysis should allow for the line workers to understand and agree with the reasons for the data collection. These steps are not enough to get automatic process adjustment, but would pave the way for a mathematical model, which is a prerequisite for an eventual automatic process adjustment system.

Final Implementation Strategy 7

This chapter will present the final roll-out plan for the implementation of data collection at AVL, based on the steps from all three cases. It will also be discussed how an IoT solution can help bring all the data types together. Then, the finances of implementing the various roll-outs will be evaluated. Lastly, the business plan, seen in Section 2.2 on page 7, will be updated, based on the knowledge gained from the three cases.

7.1 Roll-out Strategy

The final data collection implementation will be explained through different roll-outs. Within each roll-out, one or more of the steps in the different data collection strategies will be implemented. During each roll-out, there should not be too many case steps at once, to ensure that the line workers can still receive simple and useable feed back. Implementing too many steps at once can lead to a similar failure as what happened at Fibertex Nonwovens A/S. Therefore, it is in this project suggested that each roll-out is limited to two implementation steps at a time. The roll-out plan is summed up in Table 7.1 and Figure 7.1. An explanation of the different roll-outs is provided in the list below:

Roll-out	1	2	3	4	5
Case A Step no.	1	2		3	
Case B Step no.	1			2	3
Case C Step no.		1	2		

Table 7.1: Suggested roll-out of the final data collection plan.

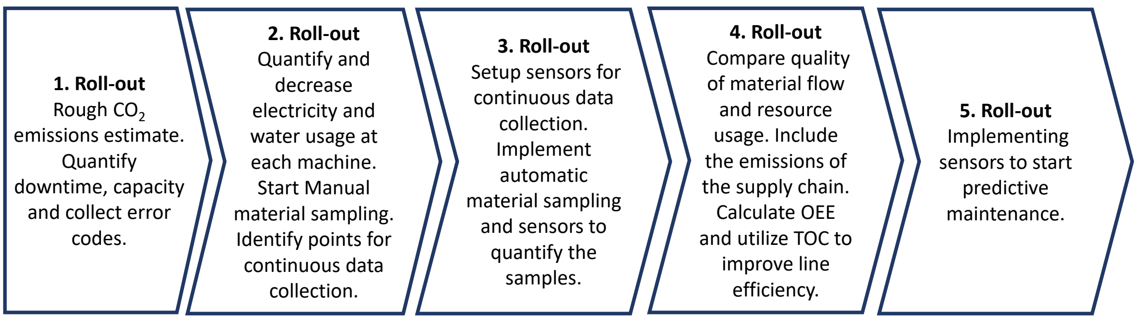


Figure 7.1: Outline of the final data collection implementation strategy.

1. Because AVL's potential costumers are interested in the CO_2 emissions, this should be a part of the first roll-out. Furthermore, as established in case B, it is important for some internal departments to know the capacity of the process line. The time

frame for this roll-out is quite short because a rough estimate of CO_2 emissions is obtained easily, and the creation of a data sheet for the gathering of downtime, can also be done easily. The tests to calculate the capacity of the line will lower the efficiency of the line while it is conducted. Therefore, it should be possible to do the first roll-out within 0.25. This gives 2 weeks to document the CO_2 emissions and create the data sheet. Furthermore, it is assumed that the capacity of a machine can be tested in a week, this should be done for each of the ten machines in the line.

2. In the second roll-out, the resource step 2 should be implemented, because it uses the information from the first roll-out to decide whether to focus the improvement effort on electricity or water usage. This will give a potential economical feedback in terms of a decreased resource usage. At the same time, the first step of the material sampling should be started, because the remaining steps of the resource and process time data collection strategies are related to the material data sampling case. The time frame for this roll-out should be long enough to ensure that several places in the material flow can be sampled to find the most relevant areas to implement continuous data sampling. At the same time, the energy usage can be linked to the material quality samples. It is suspected that 1.75 Year should be sufficient to ensure that sufficient data and knowledge is obtained for the next roll-out.
3. For the third roll-out the automatic sampling and continuous data collection should be implemented, as described in step 2 of the material data collection strategy. This roll-out has a higher CAPEX than the rest, because of the purchase of sensors. This would be a process, where the line should be stopped to setup and calibrate sensors. This roll-out will ensure that it is possible to quantify the material flow of the process line. The time frame of the third roll-out is hard to estimate, as it can be very time consuming. This is due to the complicated implementation and because of the large amount of data, that needs processing. It is assumed that sufficient data to make adjustments could be collected in 6 months. But to observe the seasonal changes, it would be necessary to collect data for at least a year.
4. The fourth roll-out should be using the information gathered from the material flow, to decrease the resource usage and increase line efficiency. The line efficiency can be increased by calculating the OEE to find and relieve the bottlenecks. Since TOC is an iterative method, the time frame before this roll-out is concluded would be several years. However, significant efficiency improvements from removing the worst bottlenecks can be expected within a year. After a year, it is also assumed that TOC is an integrated thought process, so the next roll-out can start after 1 Years to 2.5 Years has passed.
5. Finally, predictive maintenance can be established in the fifth roll-out. The roll-out should decrease the unplanned and planned downtime, making the line more efficient. The time frame for this roll-out is hard to predict, but data has been gathered since the first roll-outs. Some of this data might be useful in the implementation of the more complex maintenance prediction systems. This roll-out is many years into the future. Furthermore, it is highly dependent on the results of the previous roll-outs. Therefore, it is quite uncertain exactly how and when the roll-out will be implemented.

7.2 Internet of Things

Internet of Things or IoT refers to a trend of implementing devices with computing, sensing and communication capabilities. They are connected to form a network. (Bin Guo, 2016) This technology has a multitude of applications, with some being remote monitoring and maintenance. In the AVL post-consumer process line, it could be important to start implementing devices that are connected in a network during the second roll-out, as shown in the Table 7.1. Since new sensors tend to be expensive, thinking into the future and investing at the start cuts the costs in the long run. Replacing them later in order to implement IoT would be expensive. Also, the OEE calculations shown in Section 5.2.3 can be calculated automatically with IoT and monitored in real time. If the line will be monitored by predictive maintenance, after the second roll-out there will already be existing sensors. Furthermore, using IoT for maintenance gives AVL opportunities to monitor the line remotely. Combining all the IoT sensor data from the line in a automated data analysis system will greatly reduce the amount of time, that white collar workers need to spend monitoring and improving the line. An example of such a software platform could be the cloud-based Microsoft Azure.

7.3 Final Implementation Finances

This Section offers an overview of the financial costs of each roll-out in the final data collection implementation. The calculated prices are divided into CAPEX and OPEX. Investments in equipment are calculated as CAPEX and wages are calculated as OPEX. The OPEX prices are based on assumptions about how many working hours that are needed for each step. Three different wages have been used in the calculation, depending on who is expected to solve the task, these can be seen in the following:

- Blue collar worker: 300 DKK/h
- White collar worker: 500 DKK/h
- External consultant: 800 DKK/h

As the calculated prices are based on rough estimations, the exact numbers will not be presented in this section. The prices have instead been divided into four categories, to give an overview of the costs of the implementation roll-out:

- Low = Cost $<$ 50 000 DKK
- Medium = 50 000 DKK $<$ Cost $<$ 100 000 DKK
- High = 100 000 DKK $<$ Cost $<$ 750 000 DKK
- Very High = 400 000 DKK $<$ Cost

Table 7.2 offers an overview over the calculated prices, the calculations can be seen in Appendix F.1 on page 127. The OPEX levels, shown in the Table, are based purely on the costs during the implementation phases. During this phase, many working hours are needed, sometimes in combination with expensive consultants. As a result of this, the automatic data collection systems have very high OPEX compared to the manually collected data methods. However over time, the OPEX of the automated solutions will become lower than the manual collection methods. Furthermore, the quality and quantity of data will be significantly larger when using the automated systems, which justifies the higher initial costs.

Roll-out		1	2	3	4	5
Case A step no.	CAPEX		Low			
	OPEX	Low	Medium		Medium	
Case B step no.	CAPEX					High
	OPEX	Medium			High	High
Case C step no.	CAPEX		Low	Very High		
	OPEX		Low	High		

Table 7.2: The expenses needed to implement the roll-outs, divided in to the steps from the 3 cases and further divided in CAPEX and OPEX.

It can be seen in Table 7.2, that the roll-outs 1 and 2, can be completed a low cost. According to the estimations in Appendix F.1 on page 127, the first two roll-outs can be completed for less than 200 000 DKK. These roll-outs are important, as they can give a lot of knowledge about how to best implement roll-outs 3, 4 and 5. As the last 3 roll-outs are expected to be considerably more expensive, these should be reconsidered and planned in details, using the results from the two first roll-outs. According to the estimations in Appendix F.1 on page 127, roll-outs 3 and 4 can be completed for less than 800 000 DKK. It is emphasized, that especially the price estimations for roll-outs 3 and 4 are connected to a great amount of uncertainty. However, it is concluded that the price of the first four roll-outs is low compared to the price of the NIR sorter in the process line, which costs 1.7 million DKK. The price of roll-out 5 has not been evaluated due to the large amount of uncertainty connected to this roll-out.

Taking into account all of the potential gains, that have been suggested throughout this report, the price of implementing the first four roll-outs seems reasonable. However, a more precise cost evaluation will be possible after completing roll-outs 1 and 2. It will then be possible to better quantify the costs from implementing further steps, because a more specific implementation plan can be derived after having collected data manually for two years. Furthermore, it will be possible more precisely evaluate the potential financial gain from doing further data collection at this point.

7.4 Business Plan

Throughout this report, several ideas have been proposed which can be summed up in a new business plan for AVL's post-consumer process line, as seen in Figure 7.2. A larger version can be seen in appendix F.1 on page 131. In the business plan, the changes are outlined in red, and they are described in the following list:

- **Value Proposition:** Through the data collection and knowledge exchange with suppliers, AVL will be able to influence legislation and standardization of the presorting in Denmark and potentially in the EU. Furthermore, data collection and data handling know-how will also become a value for AVL. Finally, carbon credits will become a value for AVL, if they achieve a CO_2 certification.
- **Customer Relationship:** As AVL gain more knowledge about their process line, the post-consumer plastics market and data collection, it will become possible to maintain and obtain new costumer relationships through knowledge-exchange.

- **Customer Segments** Through knowledge-exchange of plastics recycling data and data-collection know-how, all companies related to the plastics recycling value chain can become customers of AVL. Furthermore, new customers can be found at companies in other industries, that are looking into reducing their CO_2 emissions. AVL can help them achieve this by sharing their knowledge through consultancies or by selling them carbon credits.
- **Channels** Through consultant work, AVL can expand their costumer portfolio.
- **Key Activities** AVL will have two new key activities. Firstly, collaborations with key partners in the value chain will allow AVL to increase their knowledge, improve presorted plastic quality, drive standardization in the industry and reduce emissions in other steps of the value chain. The second new activity is data collection and handling, for the improvement of the line efficiency and reducing financial costs and emissions.
- **Key Partners** Through knowledge sharing and collaboration with foreign plastic recyclers, AVL can sell their know-how, obtain technical and market knowledge, and push for greater industry standardization at EU level.
- **Key Resources** Data and knowledge will become a key resources that AVL can use to create revenue and maintain supplier and customer relationships. Furthermore, the data will allow AVL to keep the line efficient and competitive, and it allows them to document their emissions.
- **Cost Structure** The CAPEX and OPEX of the line will increase, because sensors are needed to obtain information and salaries need to be paid for the employees who will analyse the data.
- **Revenue Stream** With the new business plan AVL can obtain three new revenue streams: Selling data, selling carbon credits and through consulting work with presorters, customers and foreign plastic recyclers.

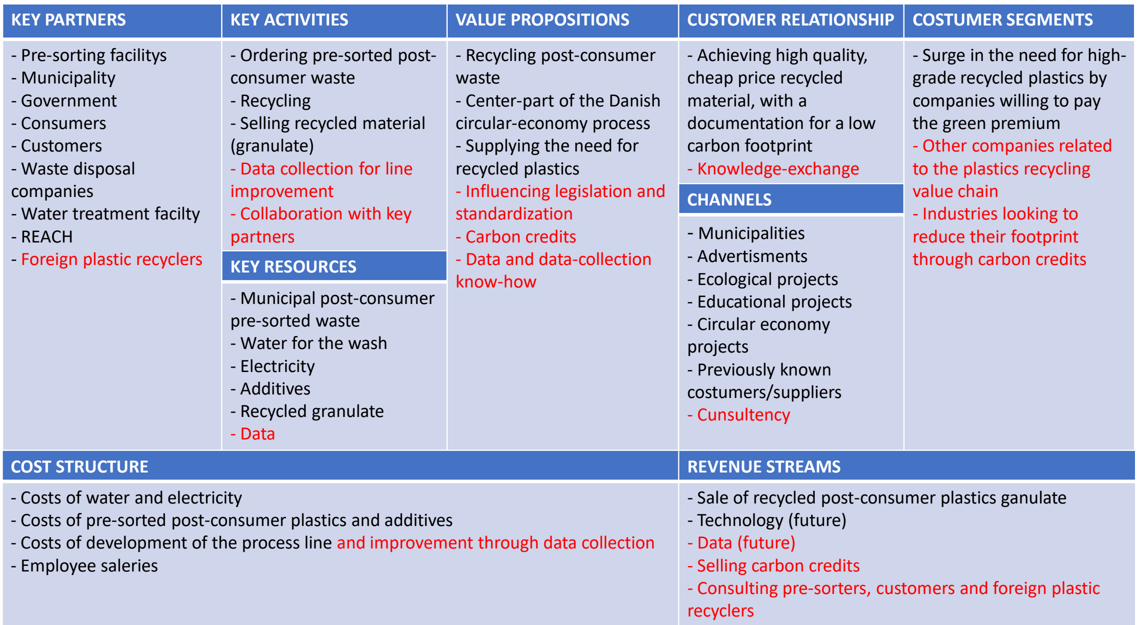


Figure 7.2: Proposed updates of the AVL business plan (marked in red).

Conclusion 8

This project took starting point in Danish plastics recycling company Aage Vestergaard Larsen A/S, who are about to establish a new continuously running post-consumer process line. For AVL to get a stronger market position, more knowledge about the resource use throughout the line was needed. Furthermore, it quickly became evident to the project group, that AVL need more knowledge about their line, to be running it continuously in three shifts. In order to gain this knowledge, data is needed and the following project motivation was formulated **in Chapter 1**:

> **Project motivation:** *"Which data collection cases can help AVL improve their production line and market position, and how?"*

In Chapter 2, the problem analysis was carried out with the goal of establishing data collection cases. The analysis focused on investigating and discussing: stakeholders, AVL as a company, their post-consumer process line and the plastics recycling market, which included the status of legislation, standardization and trends within the sector. The established cases were then listed in Table 2.3 and six cases were chosen as the best to pursue. The six cases were then reduced to three cases through a discussion.

In Chapter 3, visits to three different companies: RollTech A/S, Expo-net A/S and Fibertex Nonwovens A/S were presented to evaluate data collection experiences from similar industries. Two points of focus for the further project work were derived; gradual implementation and simple useable feedback. Based on the problem analysis and company visits, a problem statement and three sub-statements were formulated:

> *"How can a gradually implemented data collection strategy be derived, to obtain knowledge about the processes and value chain at AVL's post-consumer process line, while giving usable feedback?"*

In Chapter 4, the sub-statement for case A was investigated and answered:

> **Case A:** *"How can information about the resource usage be obtained to sufficiently document the CO_2 emissions of AVL's post-consumer process line, and how can the information be used to decrease the resource usage of the line?"*

A three step *resource* data collection strategy was derived, focusing on emissions documentation and reduction of resource usage at AVL, as well as at other points of the supply chain. The full conclusion of the findings and implementation strategy can be seen in Section 4.4 on page 43.

In Chapter 5, sub-statement for case B was investigated and answered:

> **Case B:** *"How can information about process time management be obtained? How can this information be used to quantify the line efficiency and maintenance needs, and what can AVL gain from this knowledge?"*

A three step *process time and maintenance* data collection strategy was derived. The strategy included how to quantify process time and maintenance needs by using TOC and OEE in combination with different strategies for maintenance planning. The full conclusion of the findings and implementation strategy can be seen in Section 5.4 on page 58.

In Chapter 6, the sub-statement for case C was investigated and answered:

> **Case C:** *"How can a gradual implementation of material sampling, NIR data collection and additional continuous sensors be used to quantify the material composition throughout the line? And what can AVL gain from this knowledge?"*

A two step *material* data collection strategy was derived. The first step focuses on investigating strategic point at the line through manual sampling, in order to find points of interest for continuous data collection. Step two investigated techniques and technologies that will allow for continuous material data collection. The full conclusion of the findings and implementation strategy can be seen in Section 6.3 on page 72.

In Chapter 7, after answering each sub-statement, a final implementation strategy was presented and discussed. A roll-out plan for how and when the steps from each case can be implemented was firstly derived and summed up in Figure 7.1. Based on this, the problem statement has been answered by providing a final data collection strategy for AVL. The strategy covers AVL and relevant supply chain links, while ensuring a gradual implementation and usable feedback. Implementing the strategy will allow AVL to obtain a market leading position, while ensuring the foundation for continuous improvement of the line efficiency.

Then, the financial cost of the final implementation were estimated and discussed. The financial estimations were divided into OPEX and CAPEX and summed up in Figure 7.2. It was concluded, that the first two roll-outs are reasonably priced, compared to the cost of some of the machines in the process line, while the costs of roll-outs 3 and 4 are uncertain. It is suggested that roll-outs 1 and 2 are initiated now, while the plans for further data collection must be re-evaluated after two years time, on the basis of the knowledge obtained from the initial data collection.

Lastly, an updated business plan was introduced, to include the opportunities and changes, which have been introduced throughout this report. This includes getting an emissions certification and selling carbon credits together with the possibility of selling knowledge and doing consultancies based on the data collection at AVL.

Future Work 9

After having implemented data collection at large scale, the next step for AVL would be to establish a digital twin of their process line. What this requires, and what can be gained from it will be discussed in this Chapter. Furthermore, a number of questions for further work are presented.

9.1 Digital Twin

In the future, when AVL have improved their data collection and thereby obtained more knowledge about the line, it could be possible to develop a digital twin of the line. A digital twin consists of mathematical models, that can be used to simulate different parameters on the production line. This digital twin can then be used for experimenting with reconfiguration of the process line. At present time it is necessary for AVL to implement new solutions in their production line to test them. The current procedure of testing and evaluating three possible solutions can be seen in Figure 9.1, where many expensive and slow implementation and testing steps are necessary.

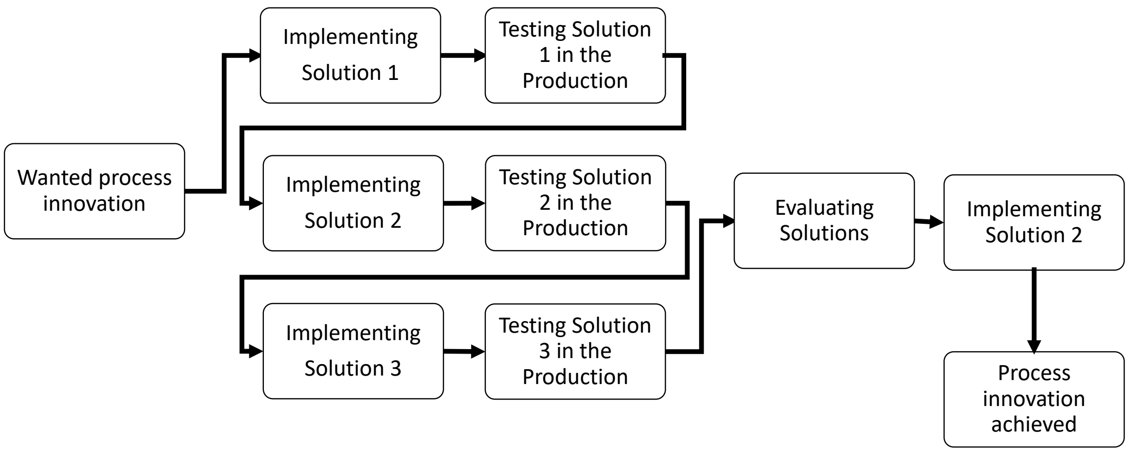


Figure 9.1: The choosing of solutions for the production line, without a digital twin.

The using of a digital twin can be very valuable, as results of experiments can be approximated, by only doing calculations. This procedure of testing possible solutions, is exemplified in Figure 9.2. Here it can be seen how the decision process is simplified by using a digital twin, as it is only necessary to implement one solution, i.e. the solution evaluated as the most suitable.

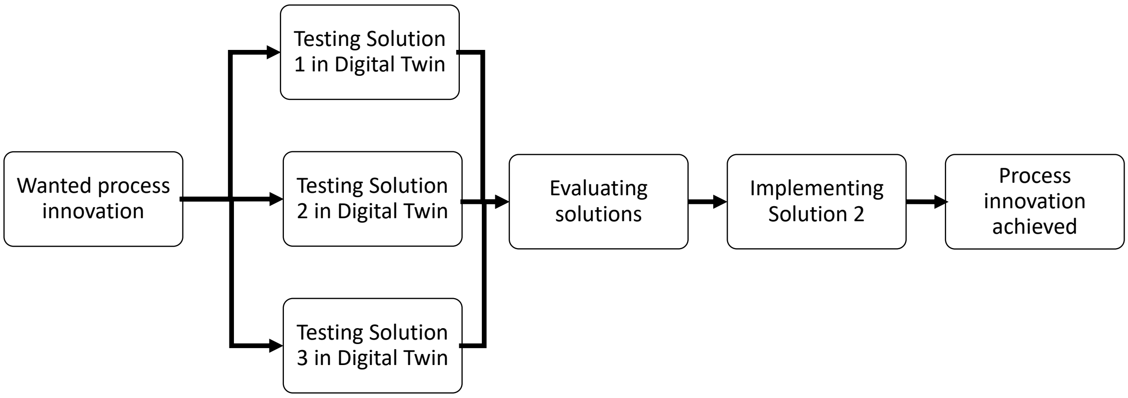


Figure 9.2: The choosing of solutions for the production line, by utilizing a digital twin.

Another application of the digital twin could be to use it for capacity and inventory planing. By having a mathematical model that can precisely predict the quantity and quality of the output of the line, it would be possible to plan inventory and sales. It will not be necessary to have as big an inventory buffer, which would release cash that can be used for other things. The capacity planning can also be used by the sales division, because they will able to calculate when they are able to deliver to the customers.

A digital twin can also be used in the input buying department of AVL. With time an AI could be trained to determine the input quality by analysing photos of the plastic bales. If photos of input bales are compared with the measured output quality, it would probably be possible to train an AI to approximate input composition just from photos. A system like this could be used by AVL to calculate prices on the input from suppliers. Furthermore, it could be used on the production line to adjust process parameters according to the input composition. This could potentially cut down resource costs and increase the OEE while also increasing the output quality.

But for AVL, achieving such a complex system is still far out in the future. Reorganising the production line to be data driven is a long process, which should be done gradually over time, as mentioned throughout the chapters of this report. Developing and using a digital twin is therefore considered to be a step that could be implemented far out in the future.

9.2 Questions for Further Work

Throughout this report, a number of questions have been defined, investigated and answered, including the problem statement and the three sub-statements. However, while working on answering these questions, a number of new questions have arised. These new questions can be the foundation for the further work on AVL's data collection implementation. The questions are listed on the next page, ordered by which Chapter they are related to:

Problem analysis

1. What specific steps should AVL go through, in order to push for greater standardization in the Danish plastic waste systems? Through which channels would they have the largest influence?
2. How can AVL most efficiently influence legislation and drive standardization in the plastics recycling industry?
3. Which of the other cases, established in the problem analysis, could be interesting to investigate?

Case A

4. What would it require from AVL in terms of documentation, fulfilling standards and collaboration with certifiers to get a certification, allowing them to sell verified carbon credits?
5. Based on freight emissions and financial costs, from which countries should AVL consider importing presorted plastics? And what benefits could there be in terms of the quality of the presorted plastics?
6. Based on freight emissions and financial costs, to which countries should AVL consider exporting the presorted granulate? And what benefits could be gained in terms of selling price, demand and product requirements?
7. After having collected resource usage data, how should AVL go about the specific optimization work for each of the relevant processes?

Case B

8. Is it possible to adjust the actual operation time to match the demand for granulate or is a scaling of the line needed?
9. How can a SCADA system be implemented to the production line?
10. What is the current maintenance system at AVL and how can it be changed toward preventive or predictive maintenance?
11. If a constraints are found at the line, are AVL capable of getting the needed investment for a solutions?
12. If Step 3 is to be implemented, do AVL have employees with the right qualification for doing so or is external help needed?

Case C

13. Could other sampling points be utilized to collect valuable data?
14. Could the line be capable of recycling PET, if automatic sampling and continuous data control are implemented?
15. Can the process parameters be adjusted automatically by implementing automatic and continuous data control?

Etc.

16. When AVL are to establish their next post-consumer process line, how can data collection be thought into the architecture of the process line most efficiently? What specific knowledge and data would be relevant to have, before the next line is designed and built?
17. Could a mechanical dirt removal system, utilising a vibrating sieve, be implemented to save water in the washes and decrease maintenance?

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Appendices: Introduction A

A.1 Mission Statement

Product Description:	• A plan of implementing relevant data collection on the post-consumer process line.
Benefit Proposition:	• The ability to simulate changes of the process, to increase the overall equipment efficiency and decrease the resource usage. • Improved quality control, which will lead to benefits such as knowing quality of different suppliers and improving the output quality of the line. • The ability to predict material flow, throughput time and size of inventory. • Document the resources used in the process and the environmental impact, increasing the value of the products through certifications.
Key Business Goals:	• A finished plan by December 2021. • An analysis of the current post-consumer plastics recycling process line. • Proposition of relevant points of data collection, how to analyze it and how the data can be used to improve the process line. • Implementation of the proposed data collection systems will be evaluated through economic considerations and technical reviews of the proposed solutions.
Primary Market:	• AVL - Post-consumer plastics processing line.
Assumed points of interest:	• Method for data collection of: - Energy and water usage. - Process line efficiency - Material and waste flow - Quality control • The proposed solutions will be based on the connected post-consumer plastic recycling process line. • Scenarios will be built on assumptions due to lack of real-life data.
Stakeholders:	• AVL • Production management. • Production staff. • Suppliers. • Government. • Customers of recycled plastics.
Cooperation:	• The group expects to visit AVL 1-3 times between October and December. • Primary contact is Lars Nyborg. • The group expects to receive relevant data from AVL regarding the post-consumer plastics processing line. Such as resource usage, process flow, operations costs and prices and expenses of the machines.

Appendices: Problem Analysis B

B.1 Interview with AVL (15-09-2021)

B.1.1 Questions Regarding Input to the Process:

1.1 What plastic types are recycled?
PP and HDPE is profitable to recycle. At the moment, HDPE is sold to be used for plastic bags and PP is sold to be used for brushes.

1.2 What is the purity of the input plastics?
Contains a lot of cardboard and paper, dirt and other plastic types. Can also contain metal parts, but not too much. They have been able to reuse 50%-70% of the household plastic waste. Purity of input is only known after the process.

1.3 Is the household plastic processed prior to arrival at AVL?
The waste is presorted prior to delivery. It is pre-processed, but still dirty.

1.4 How much household plastic waste is processed daily?
The new process line could produce 1000 kg / hr. Current capacity is 700 kilos of plastic per production line, and output is 400 kilos per production line. The last 7 years, they have at least produced 1.000 tons extruded material each month - by far mostly based on industrial plastic. It's getting harder for them to get the household plastic waste, as it needs to be presorted. However, there is a huge amount of not-recycled household plastic waste and most of it gets burned.

1.5 How efficient is usage of water? How much electricity,chemicals, etc. ?
They are efficient in the use of water and power. No chemicals is used while washing the plastic.

1.6 What are the prices of household Waste?
The price is variable depending on purity. Between 2 dkk/kg to 4 dkk/kg.

1.7 Where does the plastic come from?
They get the plastic mostly from danish collectors – sorted in HDPE and PP, but sometimes also from Swedish collectors which have better quality. Plastic comes from the sorting facility, but they are considering new sources.

1.8 Is there a big difference in quality between municipalities or shipments?
Every shipment they get is different quality.

B.1.2 Output:

1.9 Quality of the produced plastic
They are able to achieve 98% concentration of HDPE and 95% of PP -> they sell it for high quality products (or at least they want to do that). HDPE has traces of LDPE, but due to compatibilness between these two, it does not represent a problem for quality. The finished products is ready-to-use to produce new products. In the extruding process they use a mesh 40 filter to ensure the finished product is as clean as possible. They save finished products for quality testing. They test their products in-house and keep sample of each batch for 3 years for warranty reasons.

1.10 Plastic types on output?
The recycled plastic is not mixed with virgin plastic or industrial plastic. They consider the quality sufficient to not mix in virgin plastic. They do not mix with industrial waste, as the household waste is worth more - "end consumer" plastic waste is considered "greener" and is in high demand among costumers. *However, they mix the household plastic with various plastics to create the right plastic mixtures for the customer.*

1.11 Is there quality control on output?
They make quality control after extrusion process.

1.12 Mixing with virgin plastics or industrial plastic? Ready to use or ready to mix?
They do not mix it with industrial plastic because it loses value that way.

1.13 How much household plastic has been recycled so far?
Not much, they have been doing batch-by-batch and researching. The production will increase when the equipment is relocated.

1.14 How much is recycled daily
About 700 kilos per production line per hour.

1.15 How is the water handled?)
The water is reused through the various processes, after being processed through the new added machines for water filtering which is quite efficient. When water gets too dirty it is processed at AVL and sent to the public waste facility. They spend a large amount of money on water.

1.16 What are the prices of end product?
Price for granulate is approximately 10 dkk/kg to 13 dkk/kg.

1.17 Are there any bi-products?
Bi products include: metals, paper and PET.

1.18 Is unusable plastic land-filled or incinerated?)
The waste products from the process are incinerated.

1.19 Who are your customers?
A wide range of different customers. But customers that mainly produce for the retail industry.

1.20 What is the storage/inventory capacity? How does it function?
The time, which the plastic spends in storage, can vary a lot. For the moment, it is easy for them to sell their products. They pack the cleaned plastic in 500-1000kg packaging. In total, they have approx. 35.000 sqm of production and storage halls. 80% of AVL's total area is used for dirty plastic and finished products, the last 20 % is used for production facilities. The post consumer plastic material must be kept under roof due to environmental issues (rain).

B.1.3 Maturity of Technology:

2.1 Is the process currently viable?
It is not currently viable. The former director of AVL is now doing lobbying for the plastic recycling industry. The aim is to achieve more standardization and better rules/laws in general to make the business more profitable.

2.2 What is the markup?

They only pay for the material, that they are able to recycle.

2.3 How many operations hours?

Now they do one 8h shift, they plan to make it 3 shifts per day after reassembling.

2.4 Is the process line based on other existing lines?

The process line is designed and built in-house.

2.5 What is the capacity of machines?
They do not know the right number yet.

2.6 how big is process reliability (running hours)?

They do not measure down time, but it they consider it negligible at the moment. But they have a system that monitors the whole production line.

2.7 Government funding?

They receive funding for doing new projects, but not for running the production lines. Also, they do research projects in collaboration with universities and other companies. Government funded building of the production line.

2.8 What is current investment in the production line?

They have developed or bought all machines for the production line. Further investment will be the reassembling of the line.

2.9 Are there any additives in production?
They have experimented with special type of additives, called compatibilizers, which could reduce the quality requirements. However, price is still too high in comparison to the results this additives provide.

2.10 How many operators per Machine? Which machines require operators?

They expect 1-2 workers to be able to handle the entire household plastic line, when it is moved to the hall. The only manual work needed for the line is the transport and cutting a wire before input. *1 operator per line, and he can work it part time, if the forklift drivers are not included.*

2.11 Are there any problems with waste from process?

They lose some plastic when moving it from hall to hall, the biggest issue with this was the local environmental hazard. There is waste in the extruding process. Impurities create waste of plastic. They also have a minor waste problem with waste in transport.

2.12 What are the main expenses for the post-consumer process line?

They don't know the exact numbers, but water and electricity are among the biggest expenses.

2.13 Some information about the ideas for new plant?

The household plastic is smelly, even after wash. The best way of removing this smell is by heated air, but they are looking into using heated water in the last washing to maybe remove the smell in a cheaper way (they avoid extra process step).

Odor removal from plastic: Heat water to washing at 80 degrees Celsius, heat air to 105 degrees Celsius. Their customers right now don't care about the smell.

Hall for new line is around 30x30m. The NIR Plastic sorter costs 1.7million.

They have problems with sand in their washing machines because it wears them down. They have partly solved it by washing it in another machine.

2.14 Existing documents, what can they get from them?

They can get info on the previous batches of household waste.

B.2 Resource Flow of Post-consumer Process Line

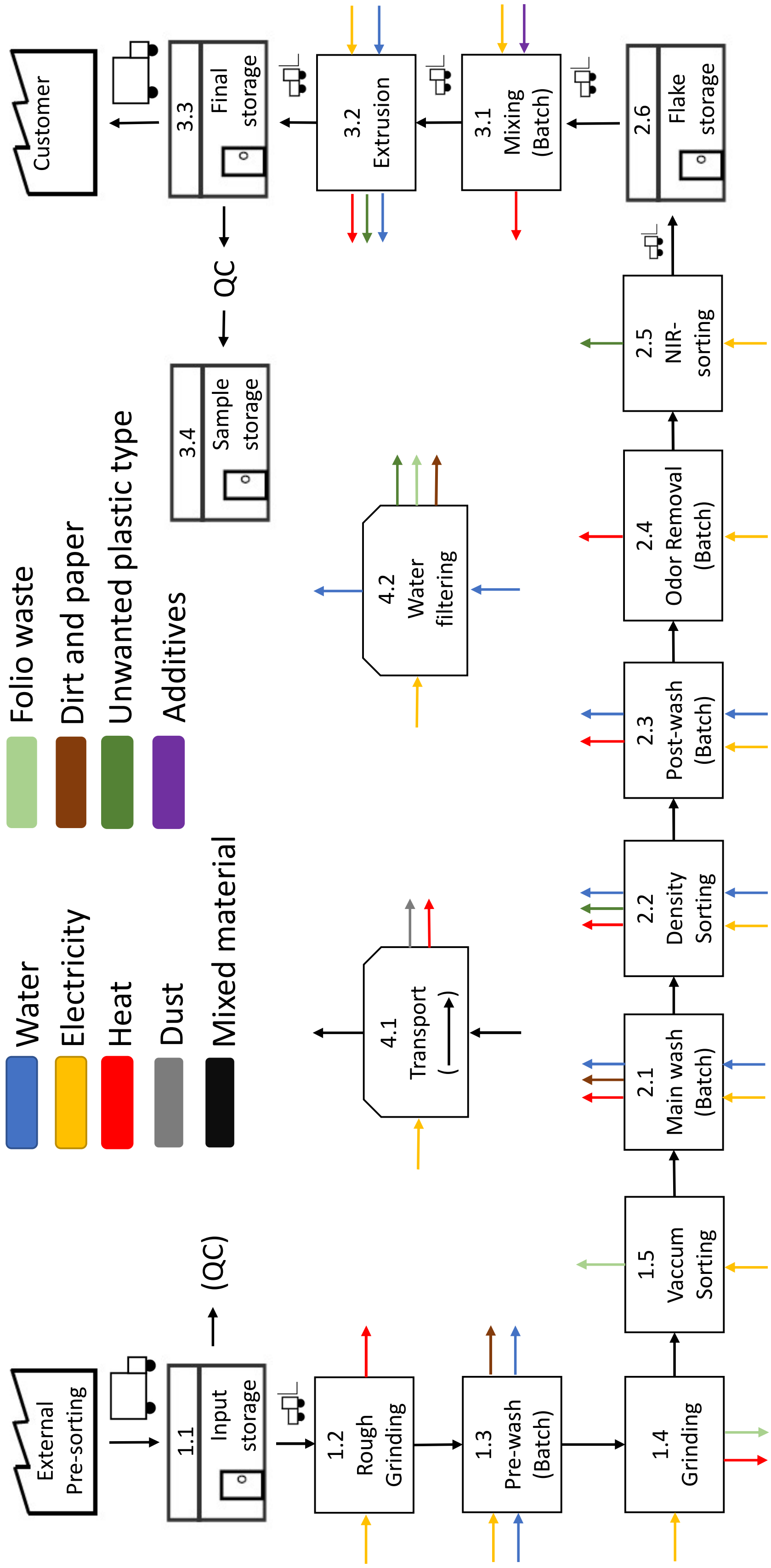

Figure B.1: Flowchart over the process at AVL, based on information provided by AVL. The color of the arrows represent flow of different resources and materials.

B.3 Spreadsheet from AVL's Test of the Production Line

Produktionsordre	**Proces**	Materiale	Indgangs kg.	Udgangs kg.	Timer	kg. pr. time	Kass. %
24669	Hal 26	PP	24240	14802	34	435	39
24805	Hal 26	PP	21060	13930	47	296	34
24890	Hal 26	PP	22360	15386	37.5	410	31
Sverige 25036	Hal 26	PP	8915	7050	15	470	21
24659	Hal 26	PE	12400	9640	28	344	22
24807	Hal 26	PE	23230	18847	41	460	19
Sverige 25038	Hal 26	PE	7935	6975	14	498	12
Anslået output pr. time ved spild på 30 %						450	Kg/time
Timer pr. uge 2 skift		71					
Timer pr. uge 3 skift		105					
KG. pr. uge 2 skift						31950	
KG. pr. uge 3 skift						47250	
Arbejdsuger 1 kvartal 2 skift		12				383400	Kg.
Arbejdsuger 2 kvartal 3 skift		11				519750	Kg.
Arbejdsuger 3 kvartal 3 skift		9				425250	Kg.
Arbejdsuger 4 kvartal 3 skift		10				472500	Kg.
I alt 2022						1800900	Kg.

Figure B.2: Data from the 7 test-batches, the values in at the top of the document are all for test hall 26, which corresponds to half of the process. The bottom values are general for the entire line. Spreadsheet provided by AVL.

Produktionsordre		Proces	Materiale	Indgangs kg.	Udgangs kg.	Timer	kg. pr. time	Kass. %	Ialt Indgangs kg.	I alt Udgangs kg.	Kass. %
	24683	Hal 19	PP	14802	13680	28	489	8	24240	13680	44
	24806	Hal 19	PP	13930	12370	30	412	11	21060	12370	41
	24891	Hal 19	PP	15386	12751	31.5	405	17	22360	12751	43
Sverige	25037	Hal 19	PP	7050	6226	13	479	12	8915	6226	30
	24684	Hal 19	PE	9640	9387	19	494	3	12400	9387	24
	24808	Hal 19	PE	18847	18420	42	439	2	23230	18420	21
Sverige	25039	Hal 19	PE	6975	6510	12	543	7	7935	6510	18

Figure B.3: Data from the 7 test-batches, the values are for test hall 19, which corresponds to the second half of the process line. The purity percentages are for the entire test-line.

B.4 Process Types and Output Purities EU Plastic Recyclers

B.4.1 Output Purities of Investigated EU MRF's and Plastic Recyclers

Table 3
Purity rates of the target output materials of the plants surveyed in the study. MRF: material recovery facility; REC: recycling plant; NA: not available.

Plant ID	PET	PP	PS	Films	HDPE
MRF1	NA				
MRF2	95.5%			82%	
MRF3	98%	98%	98%	98%	98%
MRF4	65%	92%	90%	92%	
MRF5	98%				98%
REC1				97%	
REC2	98%				
REC3	97%				
REC4	97%				
REC5	98%				
REC6	97%				
REC7	80%	80%			
REC8		95%	95%		85%

Figure B.4: Figure taken from Antonopoulos, Faraca, and Tonini, 2021

B.4.2 Technologigies Used by Investigated EU MRF's and Plastic Recyclers

Plant ID	Collection system*	Target polymer*	Technological setup
MRF1	LPW	PET, PP, PS, film, HDPE	Manual pre-sorting, sieve, ballistic separator (x2), NIR (x6), magnet, manual sorting, baler
MRF2	LPW	PET, HDPE, films	Manual pre-sorting, trommel, ballistic separator, vacuum (x3), film baler, magnet (x2), NIR (x5), manual sorting, Eddy current separator, baler
MRF3	LPW	PET, PP, films, PS, HDPE	Bag opener, trommel, ballistic separator, magnet (x2), vacuum, NIR(x5), HD camera, vibrating screener, Eddy current separator, baler
MRF4	LPW	PET, PS, HDPE, LDPE	Feed hoper, bag opener, drum screen, magnet (x3), air classifier, rotary feeder, NIR(x4), Eddy current separator, Manual sorting, baler
MRF5	LPW	PET, HDPE, films	Reception of inputs, bag opener, ballistic separator, magnet (x2), manual sorting (x2), Eddy current separator, baler
REC1	Household plastic films from MRF	PP, HDPE	Shredder, magnet, cascade screen NIR (x2), shredder, friction washer, dryer, extruder
REC2	PET from MRF	PET	Manual bale breaker, metering unit/hopper, manual sorting, flakes, baler
REC3	PET from MRF	PET	Bale opener, magnet (x2), Eddy current separator (x2), NIR (x2), sink/float separation, centrifuge, hot wash, centrifugal dryer, pelletizing
REC4	PET from DRS and MRF	PET, PP, HDPE	Bale opener, magnet, label remover, ballistic separator, Eddy current separator, NIR (x3), manual sorting, hot washing, sink/float separation, air classification, extruder (x2), flake sorter, baler
REC5	PET bottles from DRS & household mixed LPW from DRS	PET	Bale opener/hopper, manual sorting, grinding, hot wash and centrifuge (x2), density separator (x2), NIR (x3), bagging
REC6	Sorted bales of PP & HDPE from MRF	HDPE, PP	Hopper/shredder, magnet, air classifier, drum screen washing, density separator, extrusion, bagging
REC7	Mixed plastics packaging from bring banks & PET bottles from DRS	PET, HDPE, PP, film	Feed hopper, film splitter, trommel, air classifier, NIR (x5), wind sifter, manual sorting, baler, granulation, density separation (x2), turbo wash, centrifuge dryer, air filter, bagging
REC8	LPW from separate collections	HDPE, PP, PS	Feed hopper, trommel, air classifier, magnet, NIR (x3), baler, hot wash and centrifuge, density separator (x2), extruder, bagging

* Detailed information about the inputs and source of inputs are presented in the SI document.

Figure B.5: Figure taken from Antonopoulos, Faraca, and Tonini, 2021

B.5 Additives

Another challenge when using recycled plastics is additives, which can potentially be toxic and can negatively affect the properties of the recycled plastics. Additives are a natural part of plastic production and are present in all plastic products. They are added to achieve a wide range of different properties, for example: coloring, UV-resistance, mechanical properties, flame retardants or resistance towards oxidization. In recycled plastics, additives can also be used to control the unavoidable degradation of the polymer structure.

Colour agents are one of the most commonly used additive types. The benefit of using colour agents is that no post-production painting is needed, if the customer want a specific colour, as mentioned in Francis, 2016, Chapter 2. However, it is not possible to remove the coloring additives from the plastic mixture. This means that the plastic waste must also be sorted by color, if the resulting recycled plastic is to have another color than black or dark grey.

A special type of additives, called compatibilizers, can be added to reduce the purity requirements of the recycled plastic while still meeting the requirements for rheological, thermal and mechanical properties. The compatibilizers work by improving the compatibility between otherwise incompatible polymers. This means that the percentage of cross-contamination can be higher, allowing for less strict presorting. However, using compatibilizers can be costly. Many types of compatibilizers are available, and AVL have done some experimentation, but they have not yet found an additive which brings sufficient advantages compared to the cost of adding it.B.1 It is concluded that compatibilizers are a relevant additive type to be aware of when dealing with recycling of post-consumer plastics. And while the additive type might become a part of plastics recycling in the future, AVL consider none of the previously investigated products to be financially sound. (Francis, 2016, Chapter 2)

Leaching of additives can mean that an otherwise safe plastic becomes toxic. Even though the additives bounded in the polymer structure are normally not toxic, if they leach out, the material can become unstable and toxic. Furthermore, additives such as polymerization additives may reach the consumer. However, AVL generally do not consider toxic additives as being an issue, as the REACH regulation from 2006 (ECHA, 2021) has banned the use of most substances, that might cause issues. However, if AVL are to reach markets for higher quality products such as food packaging, medical equipment and packaging or cosmetics containers, a need for greater quality control and documentation might be necessary. This supports investigation of case 3 and case 11, as the NIR can detect some additives and trace chemicals. (Blastic, 2021)

B.6 Investigation of Plastic Recycling Capacity in EU Countries

Figure B.6 shows an overview of the plastic packaging waste recycling rates in the European Union. The Figure is based on numbers from 2017, which is the last time an official counting was conducted. It is seen, that most EU countries have yet to fulfill the recycling rate goal of 50% in 2025. And as the numbers also account for waste that is exported for recycling, a very large deficit in the European plastic recycling capacity seems to be present.

Figure B.6 indicates a tendency, that some Eastern European countries are quite good at recycling their plastic packaging waste. However, the accounting of plastic recycling rates was not sufficiently standardised, so the numbers must be taken with caution. Furthermore, scandals of illegal dumping and illegal burning of plastic waste have recently appeared in Romania, Bulgaria, Slovakia and Poland, suggesting that the plastic recycling industry is not well regulated in these countries. (Nuttall, 2020) (Statista, 2019)

According to Ravignan, 2020, estimates based on new counting rules indicate, that the overall European recycling rate could drop from 41% to 30% when the new statistics

Figure B.6: Recycling rates of plastic packaging waste in the EU Member States in 2017. (Eurostat, 2019)

arrive in 2022. When comparing the recycling rates to the amount of produced waste, it is seen that Bulgaria, Cyprus, Slovenia, Czech Republic, Slovakia have relatively low yearly plastic waste productions, as seen in the graph in Appendix B.7. Consequently, their actual plastic recycling capacities are quite small.

Germany has the largest plastic waste recycling capacity of 1.5 million tonnes while also being the biggest producer of plastic packaging waste by total volume, see Appendix B.7. Italy has between 1 and 1.5 million tonnes of capacity, while Spain, France, the Netherlands and the United Kingdom have between 0.5 and 1 million tonnes of capacity each, according to Waste Management World, 2021. In conclusion, cheap labour does not seem to be an important factor in the recycling of post-consumer plastic waste. This can be explained by the fact that the recycling processes are generally highly automated. Instead, factors such as the total plastic waste production and the general level of industrial development in the countries seem to correlate with high plastics recycling capacities. These trends are also reflected when looking at EuCertPlast certified companies, of which 30% are located in Germany, 12% in Italy, 11% in the Netherlands and 10% in France. (Waste Management World, 2021)

But the most important common factor in countries with highly developed plastic recycling industries is legislative initiatives. This includes plastic bottle deposit systems, standardized plastic collection systems and taxes and fees. An example of fee-based legislation is the principle of "polluter pays", which requires manufacturers to take responsibility of their packaging and waste. This was introduced in Germany in 1991, according to FTC, 2021, while being generally introduced in the European Union in 2004 (European Enviromental Agency, 2021).

B.7 Plastic Packaging Waste Generation in EU Member States

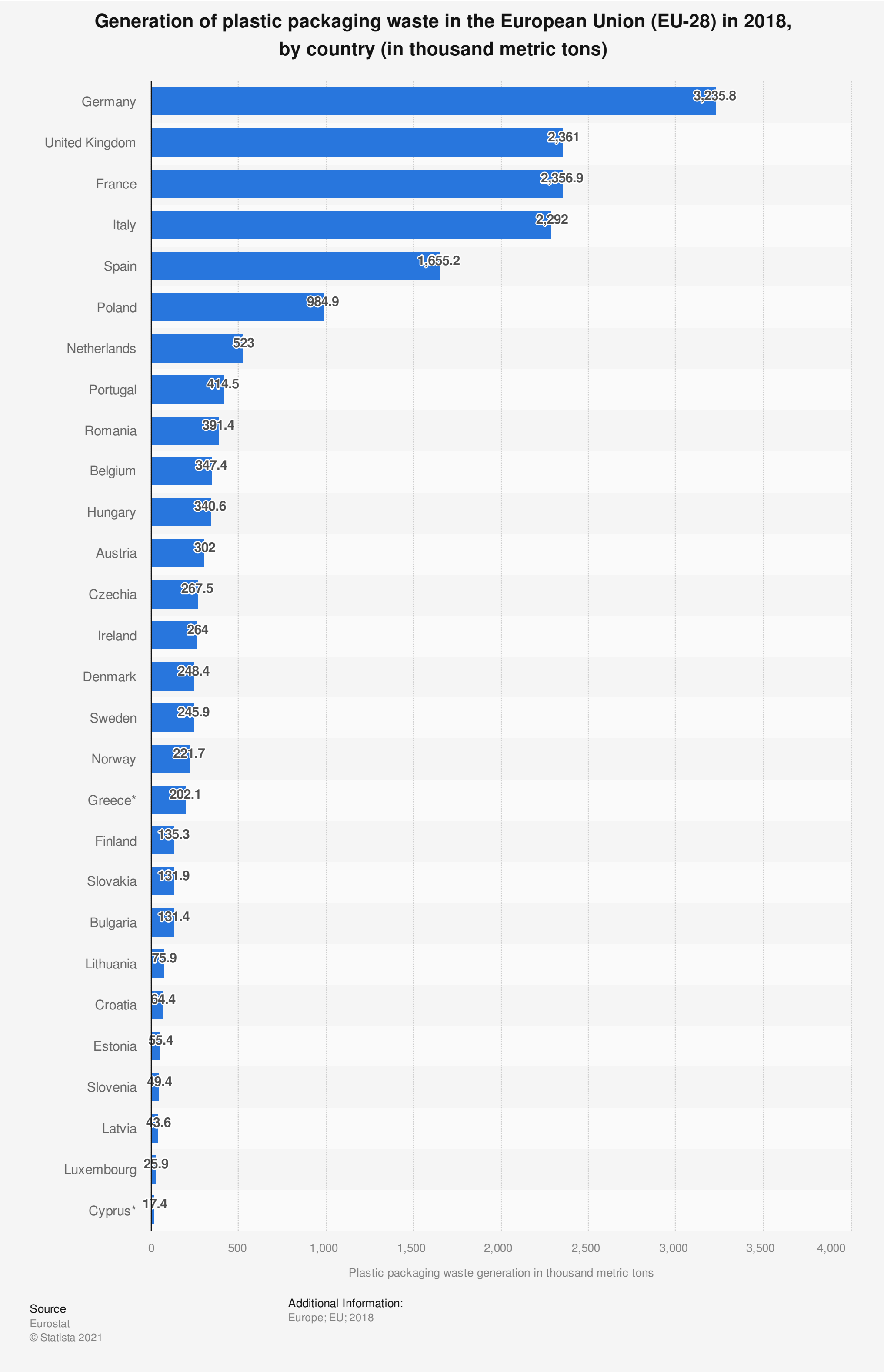

Figure B.7: Plastic packaging waste generation in EU member states (Statista, 2021a)

KEY PARTNERS
- Pre-sorting facilitys
- Municipality
- Government
- Consumers
- Customers
- Waste disposal companies
- Water treatment facilty
- REACH

KEY ACTIVITIES
- Ordering pre-sorted post-consumer waste
- Recycling
- Selling recycled granulate

KEY RESOURCES
- Municipal post-consumer pre-sorted waste
- Water for the wash
- Electricity
- Additives
- Recycled granulate

VALUE PROPOSITIONS
- Recycling post-consumer waste
- Center-part of the Danish circular-economy process
- Supplying the need for recycled plastics

CUSTOMER RELATIONSHIP
- Achieving high quality, low price recycled material, with a documentation for a low carbon footprint

CHANNELS
- Municipalities
- Advertisments
- Ecological projects
- Educational projects
- Danish circular-economy project
- Previously known costumers/suppliers

CUSTOMER SEGMENTS
- Surge in the need for high-grade recycled plastics by companies willing to pay the green premium

COST STRUCTURE
- Costs of water and electricity
- Costs of pre-sorted post-consumer plastics and additives
- Costs of development of the process line
- Employee saleries

REVENUE STREAMS
- Sale of recycled post-consumer plastics ganulate
- Technology (future)

Figure B.8: AVL business plan.

Appendices: Case A C

C.1 Influences on resource usage

The following subsections provides a list of the various factors, which might influence the resource usage at AVL, sorted after their expected influence level.

C.1.1 Large influence

1. **The setup of the washing, grinding, sorting, odour removal, mixing and extrusion processes at AVL:** The various process steps in the post-consumer process line all have significant power usage. Meanwhile, the washes, density sorting and extrusion processes all use water as well. The settings on each machine will influence their resource usage. Furthermore, cross-interactions are expected such that changing the parameters on one machine in the line might influence the resource usage of other machines down the line.
2. **Resources used at presorters:** A big part of the plastics recycling value chain lies at the presorting facilities. Thus, the resources used to recycle a kg of plastic will depend on the efficiency of the presorting facility as well. Some presorters might deliver material of very high quality compared to others. These presorters will expectedly have a higher resource consumption themselves, as they will have adopted a larger chunk of the value chain. Thus, the resource usage at AVL should be considered in relation to the resources spent at the presorting facilities.
3. **Presorted input quality:** The variance in the quality of the presorted plastics will inevitably influence the efficiency of the line at AVL. Batches of presorted waste with a low purity of target material will give a lower yield, resulting in a higher amount of resources spent pr. kg of recycled plastic. Furthermore, specific contaminants might influence the resource usage of the process line more than others. For example, folio can clog up some systems, while rocks and sand will wear down some parts in the washing processes.
4. **Transport between AVL and their suppliers/customers:** If AVL are to import presorted plastics from foreign countries, the emitted CO_2 from transportation could become significant. The same goes if AVL are to sell their finished granulate to foreign companies. Thus, transportation of pre-sorted waste and finished granulate can be a significant part of the total resource usage in the plastics recycling value chain. Granulate which is produced locally and is based on locally sourced presorted plastics will have the lowest transport-related CO_2 emissions.
5. **Plastic transport system:** The tubular air-pressure-based transport system is

expected to be responsible for a significant part of the total power consumption of the line. The power consumption of this system is dependent on factors such as pressure leakages, compressor efficiency, turbulence and the filters clogging up.

6. **Plastic waste legislation and consumer sorting:** The consumer sorting is not affecting the resource usage in a direct way, but it can hold a big and direct stake in the input quality of AVL's process line. And as mentioned earlier, the input quality influences the resource usage both within AVL and at the presorting facility; when consumers sort well, producing the recycled granulate of a specified quality becomes easier. Furthermore, the behavior of consumers is shaped by the legislation; a proper waste sorting system is necessary if the consumer is to improve his/her sorting. On the other hand, the consumers can have an influence on what legislation is passed in the municipality. Therefore, the resource usage is largely dependent on both consumers and legislators, which in turn can be influenced through better public information and greater standardization.

C.1.2 Small influence

7. **Forklift transport within AVL:** The electric forklifts demand energy as they move the batches around five different routes in the production line, as outlined in Figure B.2 on page 100. However, the energy consumption related to the transport is considered small compared to the above mentioned influences.
8. **Water circulation and filtering:** AVL implemented a water filtering unit into the new line with the aim of reducing water usage by reusing the same water between different processes (Appendix B.1). The actual water savings from doing this are unknown, and so is the electricity and chemical usage of the filtration and circulation system. Even though, the electricity usage of these processes is relevant when documenting the resource usage, it is considered to be of small influence on the total resource usage of the line, as the system has already been designed with the goal of reducing resource consumption.
9. **Maintenance-related issues:** Reducing the maintenance time of the processes without compromising their efficiencies can also result in lower overall resource consumption, as down time can lead to resource waste. Whenever the process line needs to be stopped due to some unplanned problems, the output of the line goes to zero. However, some machines will still be running idle, consuming power. On the other hand, other processes might unlock resource savings by increasing the amount of maintenance performed on them. Thus, good timing and planning of maintenance can reduce resource waste.
10. **Utilization rate:** As some of the processes in the line are batch-based while others are continuous, it might be hard to achieve a full utilization of all machine capacities at all times. It is expected, that some of the machines will be running idle some of the time or with a lower throughput rate, resulting in a waste of resources. As the resource usage is much smaller while the machines are idle, compared to when they are running, the influence of the utilization rate is considered small.

C.1.3 Very small influence

11. **Additives:** When mixing the plastic flakes before extrusion, certain additives are added. Resources are required to produce these additives, and some of the additives might influence the resource consumption of the extrusion process slightly. However, the amount of additives which are added is small compared to the amount of sorted flakes in the mix, so the overall influence of additives is considered as being very small.
12. **Customer needs:** Correlation between customer needs and resource consumption exists, because more resources are needed to produce recycled granulates with higher purities.
13. **Packaging:** A small part of the total energy usage goes into packing the final product and making it ready for delivery. The product is packed in big plastic bags that also need to be produced, which leaves a small influence on CO_2 consumption per bag of product.
14. **Facility expenses:** These are heating and electricity expenses needed for sustaining the offices and buildings in general.

C.2 North American Freight Emissions Factors

NORTH AMERICAN FREIGHT EMISSIONS FACTORS

Mode	Category	Functional Unit		Emission Factor	Greenhouse Gases Included	Source
Air	Longer flights (>3,700 km/ 2,300 miles)	grams per short ton-mile	Weight	868.3	CO2	A
	Shorter flights (<3,700 km/ 2,300 miles)	grams per short ton-mile	Weight	2,050.0	CO2	A
Barge	All	grams per short ton-mile	Weight	17.5	CO2	A
Ocean-Dry Goods	Asia to North America (east coast)	grams per TEU kilometer	Volume	68.1	CO2	B
	Asia to North America (west coast)	grams per TEU kilometer	Volume	59.1	CO2	B
	Mediterranean to North America (east coast)	grams per TEU kilometer	Volume	79.6	CO2	B
	Mediterranean to North America (west coast)	grams per TEU kilometer	Volume	76.8	CO2	B
	North America to Africa	grams per TEU kilometer	Volume	89.5	CO2	B
	North America to Oceania	grams per TEU kilometer	Volume	81.3	CO2	B
	North America to South America	grams per TEU kilometer	Volume	68.6	CO2	B
	North American (east coast) to Middle East and India	grams per TEU kilometer	Volume	77	CO2	B
	North Europe to North America (east and gulf)	grams per TEU kilometer	Volume	78.2	CO2	B
	North Europe to North America (west coast)	grams per TEU kilometer	Volume	69.6	CO2	B
Ocean-Refrigerated Goods	Asia to North America (east coast)	grams per TEU kilometer	Volume	95.3	CO2	B
	Asia to North America (west coast)	grams per TEU kilometer	Volume	87.9	CO2	B
	Mediterranean to North America (east coast)	grams per TEU kilometer	Volume	113.9	CO2	B
	Mediterranean to North America (west coast)	grams per TEU kilometer	Volume	112.4	CO2	B
	North America to Africa	grams per TEU kilometer	Volume	127.1	CO2	B
	North America to Oceania	grams per TEU kilometer	Volume	109.2	CO2	B

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Figure C.1: North American Freight Emissions Factors, taken from (Mathers et al., 2014).

Mode	Category	Functional Unit		Emission Factor	Greenhouse Gases Included	Source
Ocean-Refrigerated Goods (*Continued*)	North America to South America	grams per TEU kilometer	Volume	102.1	CO2	B
	North American (east coast) to Middle East and India	grams per TEU kilometer	Volume	101	CO2	B
	North Europe to North America (east and gulf)	grams per TEU kilometer	Volume	107.6	CO2	B
	North Europe to North America (west coast)	grams per TEU kilometer	Volume	98.2	CO2	B
Rail	All	grams per rail-car mile	Distance	1,072.0	CO2	A
	All	grams per TEU-mile	Volume	292.8	CO2	A
	All	grams per short ton-mile	Weight	22.9	CO2	A
Truck	All	grams per mile	Distance	1,700.0	CO2	C
	Dray	grams per mile	Distance	1,750.0	CO2	C
	Expedited	grams per mile	Distance	1,200.0	CO2	C
	Flatbed	grams per mile	Distance	1,800.0	CO2	C
	Heavy Bulk	grams per mile	Distance	2,000.0	CO2	C
	LTL Dry Vans	grams per mile	Distance	1,625.0	CO2	C
	Mixed	grams per mile	Distance	1,700.0	CO2	C
	Refrigerated	grams per mile	Distance	1,750.0	CO2	C
	Tanker	grams per mile	Distance	1,750.0	CO2	C
	Truck-load Dry Vans	grams per mile	Distance	1,700.0	CO2	C
	All	grams per TEU-mile	Volume	597.4	CO2	A
	All	grams per short ton-mile	Weight	161.8	CO2	A

Source: A. EPA SmartWay: Shipper Partner Tool: Technical Documentation, 2013
B. BSR. Collaborative Progress: Clean Cargo Working Group Progress. 2013
C. EPA SmartWay: Carrier Performance for Public Export, 2014 (data is the median of each class)

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Figure C.2: North American Freight Emissions Factors, taken from (Mathers et al., 2014). (continued)

C.3 Potential Ways of Decreasing Resource Usage at the Process Line

1. **The setup of the washing, grinding, sorting, odour removal, mixing and extrusion processes at AVL:** The resource consumption of each of the plastic-processing machines at the AVL line depends on its own specific parameter settings and general setup. Furthermore, cross-interactions will be present, meaning that the setup of machines at the beginning of the process line can influence the resource usage further down the line. Information about the resource usage of each machine is needed to get an initial understanding of the power and water usage of each machine. Meanwhile, more detailed data, coupled with other data types, is necessary to further get an understanding of the relationships within the process line. Other data types, that should be coupled with the resource usage of each machine and their respective parameter setting includes the quality of the presorted waste.

2. **Resources used at presorting facilities:** By decreasing the resource usage at the presorting facilities, lower CO_2 emissions can be achieved in the recycled granulate supply chain. If the presorting facility is not ready to act in that direction, providing them with help can profit both sides. Sharing information about the data collection implemented in the post-consumer process line at AVL, and proposing similar strategies to presorting facilities can lead to lower resource usage overall. This will be easier achieved at presorting facilities that have some level of automation at their line. Investing time, money and knowledge into having less resources used while getting the same output quality on presorting, would be beneficial for the entire downstream of the whole supply chain, as it would lower the life cycle emissions.

3. **Presorted input quality:** The resource usage at AVL get is expected to be lower when the presorted waste has a high purity. The key to lower the total emissions along the supply chain, would then be to find a balance between consumption in presorting and consumption at AVL, while keeping the same product quality. After implementing data collection in the AVL line, and at the same time benchmarking the resource usage and purity per batch at presorting facility, it could be researched how the resource usage at presorting facilities affect resource usage and quality at AVL. This would allow AVL and the presorters to find out how divide the supply chain between them, resulting in the same product quality while lowering the resource usage. For example, testing out process parameters in presorting, with an aim to spot and record an impact on the process line in AVL. The impact will be manifested as a lowered or enlarged resource usage in AVL, when keeping the product quality constant. This could lead to a case where a slightly enlarged resource usage at the presorting facility would lower the resource usage significantly at AVL's facility. The effect would furthermore be influenced by the purity dependency on the freight emissions; if the presorted waste has a higher purity, less CO_2 equivalents will be emitted in relation to the transport between presorter and AVL, as shown in Equation 4.3 on page 36. With better, smartly placed data collection in line, it will also be possible to differentiate how a change in quality/resource usage at presorters, affects some very specific parts of the process line. This would allow for resource

reduction solutions to go even deeper and other optimisation opportunities would most likely arise.

4. **Transport between AVL and their suppliers/customers:** If imported household waste has a better quality for the same price, of course it should be considered to import it. It is however important to also consider factors like CO_2 emissions in that process. Importing waste with higher purity might reduce emissions at AVL, but could thus increase the total emissions along the supply chain of the recycled granulate. However, calculations would need to be conducted in order to the determine the influence of the freight emissions. Generally, AVL should aim at getting their presorted waste from areas geographically close to them, only considering import if there is a shortage on the "nearby" market, or if the freight emissions seems reasonable compared to the price and quality of the imported presorted plastic. Future technology improvements in recycling and shipping, such as a transition towards green fuels, could decrease the transportation problem with CO_2. Then, the price and purity would be the two main factors to consider when buying presorted plastic material. Furthermore, AVL could consider investing in electric vehicles for closer range transports to customers.

5. **Plastic transport system:** A higher efficiency of the plastic transport system inside of the facility would likely result in a lower resource usage at AVL. Improving the transport system efficiency could make it run smoother and avoiding any stops due to blocked or clogged up pipes. Secondly, the efficiency can be improved by using less pressure, effectively slowing the line down. Choosing the right velocity for the process line transportation and machine workload is a way to find a balance between different parameters that affect the resource consumption overall. Slowing the process line down will increase the production costs. However, doing so might provide power savings which outweigh the additional costs, when compared to running the process as fast as it can be run, due to the highly non-linear behavior of turbulent air. Discrete event simulations of the process line provided with collected data could help trying out different solutions and searching for an optimisation opportunity.

6. **Plastic waste legislation and consumer sorting:** Making a change at the first step of recycled plastic supply chain, the consumer, could be a way to lower the consumption of every part of the supply chain and waste processing. The change can be achieved if consumers are taught to separate different kinds of plastic into different trash bins. Guiding and educating citizens to do more precise sorting, while providing the supply chain with needed equipment like deeper categorised trash bins and adapted waste collecting trucks, could be achieved with the help of the government. Overall awareness and knowledge about sorting and recycling can also be pushed by campaigns, in which citizens are informed and motivated to make a transition towards more precise sorting. As actions like these take time, and momentum to move people into new era of recycling builds up slowly, they are long term solutions. Even if the change in recycling habits of consumer is not yet tangible, and is expected to happen in long term, it still presents one of the most important factors in

the supply chain because of the potential it holds for the future recycling standards. However, changing the consumer habits starts with changes in the recycling systems.

7. **Forklift transport within AVL:** Making a better planned smart movement of forklifts through process line can save energy and time. Simulation softwares like Enterprise Dynamics can be used in figuring out which routes and timings are best for the utilization of the forklift transporters. However, the gains from doing so are expected to be quite incremental, while it would require a big restructuring of the work habits of the workers.

8. **Water circulation and filtering:** With the new water re-usage system implemented into the line, water resource consumption has already been reduced significantly. Electricity consumption of the circulation pumps and filters is present, but it is assumed to be much smaller, compared to using new water with every batch. Adjusting the parameters of the filtering machines could make a slight difference towards overall resources used. In order to make big savings in the water circulation and filtering system, a deep technical investigation would need to be conducted, to fully understand the systems and its potential/limitations.

9. **Maintenance-related issues:** By reducing the frequency of regular maintenance or avoiding unplanned maintenance, some savings in electricity usage can be achieved. The savings stem from reducing unnecessary idle time in conjunction with process line shut downs, while a machine is being maintained. However, the major savings potential, related to the maintenance of the machines, manifests in time savings. This will be elaborated when discussing process time management in Chapter 5.

10. **Utilization rate:** Due to similar reasons, as explained above, the utilization rate can also influence the resource usage of the line, through idle-time electricity waste. However, the major savings potential, related to the utilization rate of the machines, manifests in time savings. This will be elaborated when discussing process time management in Chapter 5.

C.4 Processes to measure electricity usage

The list below provides as discussion of the processes, at which the electricity usage should be measured in step resource reduction step 1:

- **The grinding and washing processes** include processes 1.2, 1.3, 1.4, 2.1 and 2.3. Some of these machines are developed by AVL in collaboration with universities and consultancy firms, while other machines are developed and produced entirely by other companies. The in-house developed machines are likely to have significant optimization potentials, which can be investigated if the resource consumption of some of them is big. Meanwhile, specific modifications to the machines developed by other companies would require more work. However, the machines have different process parameters, which can be adjusted. Thus, testing could be done on each of the most consuming processes to see if the parameter settings can be improved to reduce the electricity usage of individual processes while maintaining the quality of their output.

- **The sorting processes** includes processes 1.5, 2.2 and 2.5. While the vacuum sorting and NIR-sorting machines are designed and built by other companies, the density sorting is developed in-house. This means, that a lot of knowledge is available to AVL on the design of the density sorter. So if this process is among the biggest power consumers, it might make sense to look further into how its efficiency could be increased by modifying the design. Meanwhile, the two other sorting processes can be individually improved by testing parameter settings, if they turn out to consume a lot of power.
- **The odour removal process** 2.4 is not currently used at AVL, but is expected to be needed for future customers (Appendix B.1 on page 95). Thus, this machine should not be prioritized in step 1.
- **The mixing and extrusion processes** 3.1 and 3.2 are not developed by AVL. While the extrusion process is expected to consume a lot of electricity, the power usage of the mixing process is hard to predict. If it turns out to be significant, investigations on the needed amount of mixing could be done with the goal of reducing its electricity usage. Meanwhile, the efficiency of the extrusion process could be improved by adjusting process parameters or by looking at ways of re-using the heat generated in the process.
- **The water transport and filtering** 4.2 has been designed to filter and re-use the water from the processes. The overall layout of this system is described in the grey box, see Figure 4.2 on page 40. The rather complex layout of the water system means, that the water usage of each process can be hard to approximate. However, the power usage of the entire water transport and filtering system can be measured rather easily. To obtain this knowledge, watt meters should be installed at all circulation pumps and the filtration system motors. Distributing the power usage of the complete water system between the water-consuming processes requires knowledge of the water consumption of each machine. This will be covered in step 2.
- **The air transport and filtering** 4.1 is expected to have a significant power usage. The usage should however still be approximated to determine the magnitude, before any work is done to improve it. For example, the possibility of slowing down the line might greatly reduce the power usage of the transportation system, as air resistance is non-linear and the flow through the pipes is expected to be highly turbulent. Velocimeters can be used for measuring airflow and turbulence in the pipes to look for improvement opportunities.
- **Forklift transport** is expected to have a low power usage compared to the other processes. However, it would be relevant to get an idea about how much power is used. If step 2 in the emissions documentation has been completed, this knowledge has already been obtained.

Appendices: Case B D

D.1 OEE Calculation of TOMRA Innosort Flake

In this Appendix, the OEE of the TOMRA Innosort is calculated for HDPE and PP since they differ.

Used variables to calculate OEE

Variable	HDPE	PP	Source
Quality	98%	95%	Appendix B.1
Average Hourly Output [t]	0.492	0.446	(Appendix B.3)
Capacity of NIR [t]	4.5	4.5	(TOMRA, 2019)

Table D.1: Proposed priority of automatic data collection

OEE for Processing HDPE:

$$Quality = 0.98 \tag{D.1}$$

$$Performance = \frac{Output}{Capacity} = 0.109 \tag{D.2}$$

$$Availability = 1 \tag{D.3}$$

$$OEE = Quality \cdot Performance \cdot Availability = 0.107 \tag{D.4}$$

OEE for Processing PP:

$$Quality = 0.95 \tag{D.5}$$

$$Performance = \frac{Output}{Capacity} = 0.099 \tag{D.6}$$

$$Availability = 1 \tag{D.7}$$

$$OEE = Quality \cdot Performance \cdot Availability = 0.094 \tag{D.8}$$

D.2 TOC

Implementation of the Theory of Constraints can be done by following the Five Focusing Steps. Ways of implementing these steps are explained in the following tables.

- **Identify** - The first point is to identify the part of the process that acts like a constraint for the whole system or line.

Table D.2: Identify

ITEM	DESCRIPTION
Work in Process	By walking through the process line, a visual inspection may reveal a constraint due if a lot of inventory is accumulates in front of the bottlenecks.
Cycle time or capacity	Looking at the data in step 1 and finding the equipment piece with the longest average cycle time or lowest capacity. Time that the equipment is not working because of external factors, such as being blocked or starved by some other process, are not included.
Demand	It is also a good idea to ask the operators or worker where they think the constraint is located. The operators and worker are the ones who are knows by experience there the constraints are located.

- **Exploit** - Here the aim is to improve the throughput of the constraint, with available resources. This means that the cost of the improvement must keep low.

Table D.3: Exploit

ITEM	DESCRIPTION
Buffers	Creating a buffer in front of the constraint, so it keeps working regardless of the upstream process stopping. This is a way controlling the material flow and prevent blockades.
Quality	Checking the quality of the input before the constraint. Making sure only needed parts are processed.
Continuous Operation	Making sure the constraint is constantly available to work and to work overtime, for instance during breaks. Limiting the time spend doing change-overs is also a essential. Cross training the operators so there is available workforce to operate the constraint all the time.
Maintenance	By trying to keep regular maintenance outside of the production time.
Offload (Internal)	Off-loading by using other available machines.
Offload (External)	Off-loading production by outsourcing production to other companies.

- **Subordinate** - align the rest of the process to fit the improved constraint

Table D.4: Subordinate

ITEM	DESCRIPTION
Upstream	A buffer can agin be placed in front of the constraint, so it keeps working regardless of the upstream process stopping.
Downstream	Checking the quality of the input before the constraint. Making sure only needed parts are processed.

- **Elevate Performance** - if after exploiting, the constraint doesn't move, further actions are needed to "brake it". Process is considered over after the constraint is solved, sometimes capital investments are needed

Table D.5: Elevate Performance

ITEM	DESCRIPTION
Performance Data	The goal is to use the data from step 1, along with the quality to calculate performance of each machine this is called the Overall Equipment Efficiency (OEE). This will be explained more thoroughly in the following section.
Top Losses	Focusing on largest losses, one by one with a team.
Review	Implementing reviews on the plant floor, between the shifts.
Setup Reduction	Implementing a program that will reduce the setup time during the changeovers.
Updates/Upgrades	Looking into potential upgrades or updates for the constraint.
Equipment	Getting new equipment to improve the efficiency of the line.

- **Repeat** - the five steps are to be seen as a constantly iterative process, aiming toward improving the line one constrain at a time

Table D.6: Repeat

ITEM	DESCRIPTION
Constraint Broken	If the constraint is considered solved, repeat the process from step one and focus on a new constraint in the line.
Constraint Not Broken	If the constraint is not broken, further work is required and focus is again on the constraint.s

Appendices: Case C E

E.1 Step 1 Brainstorm

To generate different ideas of sampling, a brainstorm was performed, while using the process flowchart as the basis for discussion and inspiration. The following list contains a short description of each idea.

- **Sampling at mixing** Taking samples at the mixing process, for making a tensile tests, in order to test material properties before extrusion. If the quality is not sufficient, higher quality plastics can be added, to improve the quality.
- **Sampling after the rough grinding** Taken samples after rough grinding, can be used to determine the input quality. Would be used to test for amount of impurities such as dirt, rocks, metal and glass as well as the amount of unwanted plastic types. Furthermore, it can be used to adjust the first wash, according to how dirty the input is.
- **Sampling after the prewashing** Sampling after the Prewashing, can be used to see if the wash has been efficient at removing dirt, sand, glas, dirt and rocks.
- **Sampling after grinding** Sampling after the second grinding, to check whether the size of flakes is appropriate, and how much folio is in the flow? Furthermore the shape of flakes can be analysed to see if the grinder needs sharpening or maintenance.
- **Sampling the waste from Vacuum Sorter** Samples can be used to determine whether the folio is clean enough to be sold for recycling. Furthermore, it can be used to survey the efficiency of the vacuum sorter and the previous processes, by examining the contaminants in the sample.
- **Sampling before the density sorter** Samples from the density sorter can be used to check the amount of folio, as the density can not run satisfactorily if folio is present in its input material.
- **Sampling before and after odor removal** To check the efficiency of this process.
- **Tomra Insight** Is an app for the Tomra NIR sorter, which can be used to evaluate how good the previous process are at removing contaminates, especially if used in conjunction with sampling at the begin of the line, so the input distribution is known. Furthermore the information can be used to change the previous process, this change in process to fit the current batch will be delayed with the through-put time
- **Surveillance of the storage facility**, to make sure the plastic isn't degraded.
- **Water quality sampling**. This is probably already done. It could potentially be used to see if there is a correlation between the efficiency of the washes and the amount of particles in the water. It could be possible to measure the amounts of contaminants on the water filtering equipment.

A map of where each of the sample points are located on the line, can be seen in Figure E.1.

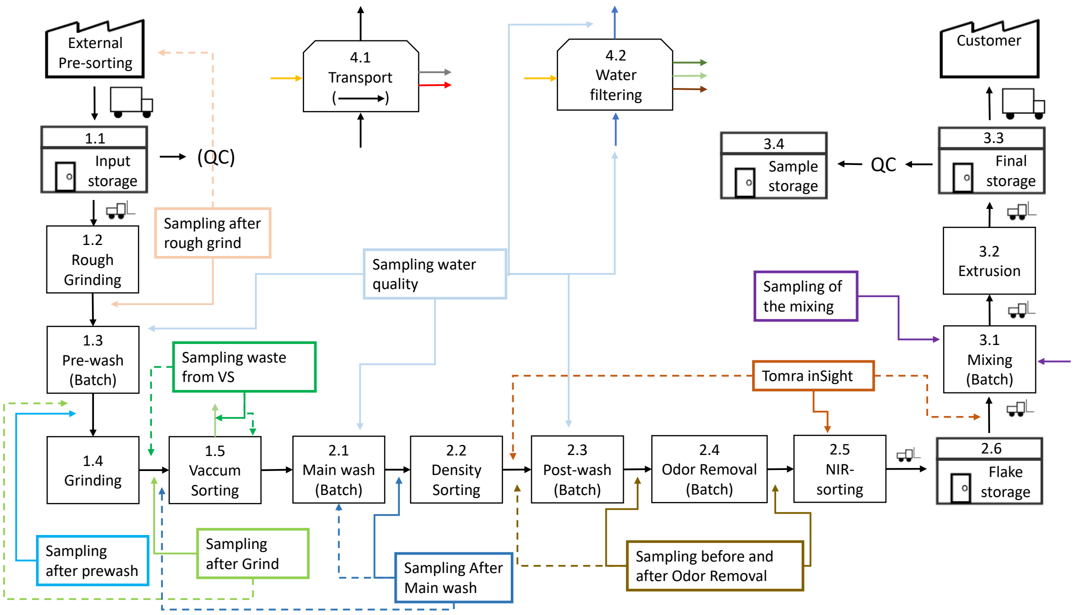

Figure E.1: Placement of the found sampling points.

- **Sampling after the density sorter** By sampling after the density sorter and looking for all contaminates, it is possible to gain knowledge about the previous washes efficiency, if they are sufficient at removing contaminates, the duration of the post-wash can be decreased.
- **Sample the temperature of the flowing flakes** Some of the processes are temperature dependent, so it might be possible to insulate the transport. To verify this idea, the temperature should be increasing or stable for all processes. If a process such as the vacuum sorter removes heat, this is probably not a valid idea.
- **Sample test of the pressure in the transportation** It might be possible to gain information about the amount of dust that has accumulated in the system. We need more knowledge about the current system to verify this idea.

Sample Rate
Similarly to the method of sampling method the rate can be standardized or random. There are benefits to doing random samples, as it is a way to avoid aliasing. For this project it is assumed that the mixture is random and not time depended therefore aliasing is unlikely. Furthermore, it is easy to insure that a line work takes sufficient samples if there is a standard interval.

E.2 Sample Rate

An explanation for the rating of the different sampling rates can be seen in the following list.

- **Time interval** is hard to define because it is vary dependent on the chosen time interval. But an increase in the amount of data will give a decrease in the available time for analysis. The convenience of the method is low for the worker, because it can be hard to fit in with other tasks. Lastly the quality of the data is dependent on how the sample is treated, thus there is a correlation between available time for analysis and the quality of the data.

- **Change of Batch** The amount of the data collected of this sample rate is low, because the shipments/batches are very large, and sometimes it will take more than 24 hours to finish a batch. This gives the worker a lot of available time for analysis in between gathering them. It can be done as a convenient part of pouring the first bale into the start of the line. The quality of the data will be low, because it would likely be gathered with the first bale, which could be an outlier of the shipment.
- **Input of Bale** The amount of data generated for this method is medium, and because it can be done in a convenient way, the available time for analysis is set to medium. The quality of the data is medium because it will give several data points per supplier, but because it will always be taken in the beginning of a bale, the sample could be different than the entire bale.
- **Specific Amount Per Day** As for the time interval it is hard to define the tendencies for this method. The amount of data is highly related to the specific amount of samples, therefore it can be both low and high. The available time of analysis is correlated with the amount date. If the amount of data is low, the available time of analysis is high. The convenience of the line work, is high, because they can fit the sampling in with other task. The quality of data is low-medium, because there is a chance of getting to many data samples in a too short period, and not enough in the end of a batch or end of the day, or vice versa.
- **During Breakdown** The amount of data of this method is low, therefore the available time for analysis is high. The convenience is medium, since the line is stopped, it would be easier to gather the sample. Though the worker would be working on getting the process line fixed, it might not be first priority to make a sample at this time. The quality of data for this method could be contaminated, because it would always be related to the breakdown. On the other hand it could give knowledge about the reasons for breakdowns. The final advantage for this method is that if it is only possible to get sample while stopping the process line, this method has the least impact on the OEE.
- **According to Previous sample results** This method is more complex than the others and will be described in the following. The newest sample should be compared to the previous sample, if there is a change in the amount of contaminants and/or the composition of the contaminants. If the change is small the time for the next sample is larger, because it can be assumed that the current sample rate is sufficient to capture the data correctly. If the change is large the time between the sample should be short. The amount of data is medium to high depending on the fluctuation of the contaminants. The available time for analysis will therefore vary according to the sample rate. The convenience for this method is low, since the time between sample is changing and hard to combine with other tasks.

Appendices: Final Implementation F

F.1 Financial Calculations of the Roll-out Plan

Price of Case A Step 1
In this step, an rough estimate of the CO_2 emissions should be calculated. Here a white collar work should find a relevant way to calculate the emissions and gather the data that were collected about the electricity and water usage of the entire line. Handling the data and doing the calculations could be done with in a week.

	Blue Collar Worker	White Collar Worker	Consultant	Total
Hourly wage	300 DKK	500 DKK	800 DKK	
Weeks of work		1		
Hours of work pr week		37		
Price		18 500 DKK		18 500 DKK

Table F.1: Case A Step 1 OPEX

Price of Case B Step 1
During this step a blue collar worker should test the capacity of all ten machines, it is expected that a work day of 8 hours a week is enough to find the capacity of a machine. After the information is collected a white collar worker should analyse the data and make decisions, a week should be sufficient to make informed decisions.

	Blue Collar Worker	White Collar Worker	Consultant	Total
Hourly wage	300 DKK	500 DKK	800 DKK	
Weeks of work	10	1		
Hours of work pr week	8	37		
Price	48 000 DKK	18 500 DKK		66 500 DKK

Table F.2: Case B Step 1 OPEX

Price of Case A Step 2
During this step, a blue worker should gather data about the electricity and water usage of the machines on the line. Once a week for a year should be sufficient to gather enough information for the white collar work to do an informed decision, a week for each resources is needed.

	Blue Collar Worker	White Collar Worker	Consultant	Total
Hourly wage	300 DKK	500 DKK	800 DKK	
Weeks of work	52	2		
Hours of work pr week	1	37		
Price	15 600 DKK	37 000 DKK		52 600 DKK

Table F.3: Case A Step 2 OPEX

CAPEX:
10 electric gauges are needed, these have been at, at a price of 1445 DKK/piece. Furthermore 4 water gauges are needed, these have been found at, for a price of 1000 DKK/piece.

CAPEX of Case A step 2 = 18 450 DKK

Price of Case C Step 1
In this step there is two OPEX cost. Firstly a white collar needs to define what specificly is sought and how to do it on the AVL line, this should be done in a week.

	Blue Collar Worker	White Collar Worker	Consultant	Total
Hourly wage	300 DKK	500 DKK	800 DKK	
Weeks of work		1		
Hours of work pr week		37		
Price		18 500 DKK		18 500 DKK

Table F.4: Case C Step 1 OPEX

And the education of the blue collar workers, to gather and analysing the material samples correctly.

	Blue Collar Worker	White Collar Worker	Consultant	Total
Hourly wage	300 DKK	500 DKK	800 DKK	
Weeks of work	8	1		
Hours of work pr week	8	1		
Price	2400 DKK	4000 DKK		6400 DKK

Table F.5: Case C Step 1 OPEX

CAPEX:
For this step a manual granulation sieve is necessary for the worker to measure the amount of flakes of different sizes. It is expected that this sieve can be manufactured for 3000 DKK.

CAPEX of Case C step 1 = 3000 DKK

Price of Case C Step 2
It is in case C step 2 expected that a external consultant is needed to create the data handling system. It is expected that the consultant can do this in 3 weeks of work. It is furthermore expected that a white collar worker will spend one hour every week to access

the collect data.

	Blue Collar Worker	White Collar Worker	Consultant	Total
Hourly wage	300 DKK	500 DKK	800 DKK	
Weeks of work		52	3	
Hours of work pr week		1	37	
Price		26 000 DKK	88 800 DKK	114 800 DKK

Table F.6: Case C Step 2 OPEX.

CAPEX:
For this step 2 automatic granulation sieves and 2 NIR sensors are needed. The automatic granulation sieves are expected to be produced in house at AVL, with a design cost of 20 000 DKK and a production cost of 30 000 DKK pr granulation sieve.

The price of the NIR sensors are based on Manolis Sherman, 2020, which states that in-line units are within the price range of 200 000 DKK. It is therefore assumed that the two NIR sensors can be bought for 400 000 DKK.

CAPEX of Case C step 2 = 480 000 DKK

Price of Case A Step 3
It assumed that a white collar worker would spend 2 weeks finding a correlation between resource usage and input quality of each process. Afterwards it is estimated that the white collar worker needs 2 weeks to find solutions for the problems.

	Blue Collar Worker	White Collar Worker	Consultant	Total
Hourly wage	300 DKK	500 DKK	800 DKK	
Weeks of work		4		
Hours of work pr week		37		
Price		74 000 DKK		74 000 DKK

Table F.7: Case A Step 3 OPEX

Price of Case B Step 2
It assumed that a white collar worker can calculate the OEE of the machines within 3 working days:

	White Collar Worker	White Collar Worker	Consultant	Total
Hourly wage	300 DKK	500 DKK	800 DKK	
Weeks of work		1		
Hours of work pr week		24		
Price		12 000 DKK		12 000 DKK

Table F.8: Case B Step 2 Calculation of OEE OPEX.

It is estimated that a white collar worker will use 8 hours every other week to use the theory of constraints:

	Blue Collar Worker	White Collar Worker	Consultant	Total
Hourly wage	300 DKK	500 DKK	800 DKK	
Weeks of work		8		
Hours of work pr week		26		
Price		104 000 DKK		104 000 DKK

Table F.9: Case B Step 3 Theory of Constraints iterative process OPEX.

Price of Case B Step 3

The price of implementing predictive maintenance is hard to estimate at present time. The choice of sensors are very dependent on which kind of maintenance that are observed in the line during the first couple of years. It is assumed the price of sensors will be ranging from 100 000 DKK to 750 000 DKK.

The development of the predictive maintenance system, including data analysis and scheduling system is also assumed to be ranging from 100 000 DKK to 750 000 DKK.

F.2 Proposed Updates to AVL's Business Plan

KEY PARTNERS
- Pre-sorting facilitys
- Municipality
- Government
- Consumers
- Customers
- Waste disposal companies
- Water treatment facilty
- REACH
- Foreign plastic recyclers

KEY ACTIVITIES
- Ordering pre-sorted post-consumer waste
- Recycling
- Selling recycled material (granulate)
- Data collection for line improvement
- Collaboration with key partners

KEY RESOURCES
- Municipal post-consumer pre-sorted waste
- Water for the wash
- Electricity
- Additives
- Recycled granulate
- Data

VALUE PROPOSITIONS
- Recycling post-consumer waste
- Center-part of the Danish circular-economy process
- Supplying the need for recycled plastics
- Influencing legislation and standardization
- Carbon credits
- Data and data-collection know-how

CUSTOMER RELATIONSHIP
- Achieving high quality, cheap price recycled material, with a documentation for a low carbon footprint
- Knowledge-exchange

CHANNELS
- Municipalities
- Advertisments
- Ecological projects
- Educational projects
- Circular economy projects
- Previously known costumers/suppliers
- Cunsultency

COSTUMER SEGMENTS
- Surge in the need for high-grade recycled plastics by companies willing to pay the green premium
- Other companies related to the plastics recycling value chain
- Industries looking to reduce their footprint through carbon credits

COST STRUCTURE
- Costs of water and electricity
- Costs of pre-sorted post-consumer plastics and additives
- Costs of development of the process line and improvement through data collection
- Employee saleries

REVENUE STREAMS
- Sale of recycled post-consumer plastics ganulate
- Technology (future)
- Data (future)
- Selling carbon credits
- Consulting pre-sorters, customers and foreign plastic recyclers

Figure F.1: Proposed updates of the AVL business plan (marked in red).