From Trash To Treasure

Design of a gripper for automated sorting of mixed aluminium scrap to create added value

Master Thesis
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From trash to treasure:
The design of a gripper for automated sorting of mixed aluminium scrap to create added value.
MSc thesis

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0 - Summary

Reukema is the biggest non-ferrous trader in the Netherlands. They want to investigate the possibility of sorting aluminium in a robotic system. Aluminium is one of the most used materials worldwide. Demands for aluminium are ever increasing. Recycling scrap is needed to keep up with the demand. An important step in the recycling process is the separation into different alloys, as sorting aluminium creates added value. Currently, the only way to sort the scrap is to have it done manually in low-wage countries such as China, Pakistan or India. This thesis describes the analysis of the problems which may occur implementing such a system. Three idea directions were generated based on the analysis executed. It was found that using a robotic arm with a robotic gripper would unwantedly increase the complexity of the sorting system. Simply pushing the scrap off a conveyor belt was found to be the best design. Based on this finding three different concepts were created, of which one, the concept in which material is fed into the system in a line, was selected. A pusher, perpendicular to the conveyor belt, pushes the material off the belt. Material is classified using a camera and a line scanner. The scrap is stored in a bunker under the sorting installation. In the last phase of this project the gripper was detailed. It was important to maximize the quality of sorting. Besides this, the reliability of the complete system needed to be maximized, while the cost per tonne should be minimized. The final design is a gripper which gives the pieces of scrap a parabolic trajectory before they land in the bunker for storing. The gripper is constructed out of steel and is 250 by 125 [mm]. A rib of 100 [mm] was added to lift pieces of scrap off the conveyor belt and decrease friction.

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1 - Introduction

Aluminium is one of the most used materials worldwide. Looking at the world wide volume, aluminium is ranked number two in terms of usage (aluminium leaders, n.d.). The material can be recycled with almost no quality loss. A crucial step in this process is the separation of the different alloys of aluminium for further processing.

Separation of the different alloys of aluminium is currently done by hand. Laborers in low-wage countries such as China, India or Pakistan, separate the metal scrap into the different categories for further processing, see figure 1.

Looking at the aluminium market in the Netherlands, we find Reukema. Reukema is the biggest non-ferro trader in the Netherlands. The company trades in Copper, Aluminium, Zinc, Lead, Stainless steel, Brass, Motors, Cables, Zorba and paper (Reukema, 2018). Reukema buys and sells around 2.000 tonnes of mixed aluminium scrap every month.

Reukema wants to investigate the possibility of creating added value by sorting aluminium in a robotic system. The first idea was to use a sensor module to scan the pieces of scrap. Based on this information a robotic arm will position a gripper in place. This gripper will grab the piece and place them in a designated bin for further processing on another location. Currently there is no off the shelf gripper able to pick the aluminium scrap Reukema wants to sort.

During this graduation project, I will research the possibility of automated sorting of the aluminum scrap. The focus of this project is on the design, prototyping and testing of a robotic gripper for the sorting. Based on this brief, the following design assignment was formulated:

Design, prototype, and test a robotic gripper for automated sorting of mixed aluminium scrap.

Figure 1 - Women sorting metal scrap by hand (Minter, 2008).

2 - Graduation Project

This thesis is the final work during the master Integrated Product Design, at the Delft University of Technology. This graduation project is divided into three sections; analysis, synthesis, and embodiment. An overview of the project can be found in figure 2. The original project brief, as approved by the Board of Examiners of the faculty of Industrial Design Engineering, can be found in appendix A. An overview of the planning of the project can be found in appendix B.

Analysis
During the analysis phase the goal is to analyse the problem and the context. This analysis phase is divided into different subsections. Firstly, a better understanding of the company and the concept is needed. In what context are they operating? Secondly material properties are investigated. What are the parameters of the material and what is it made off? Thirdly, an external analysis is needed of competing technologies and other sorting methods. Lastly, grippers are investigated. What is a gripper and how does a gripper function.

Synthesis
During the synthesis phase the conclusions from the analysis phase will be used as an input for design ideation. Besides this ideation, small prototypes will be generated to validate the ideas. At the end of this phase a concept design of a gripper for automated sorting will be created.

Embodiment
During the last phase, the concept design will be further detailed and embodied. Different tests will be conducted to validate and optimize the design.

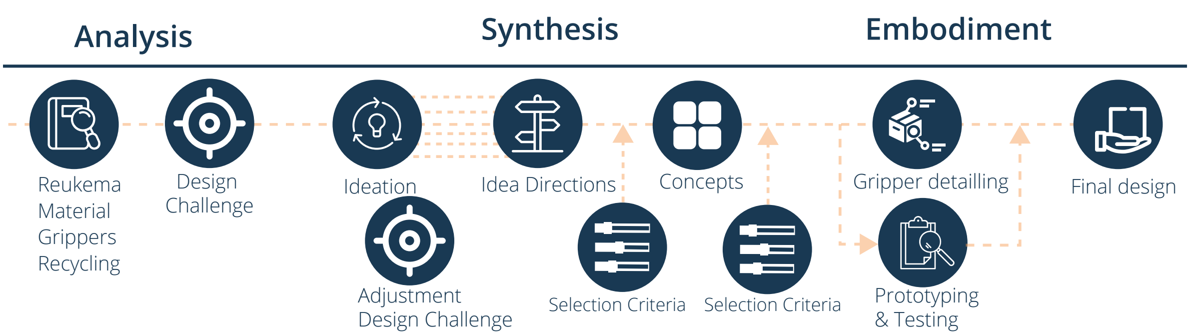


Figure 2 - Overview of the three phases of my graduation project: Analysis, Synthesis, and Embodiment.

Analysis

3 - Context

Aluminium is versatile in use and can be found in many different places. According to The International Aluminium Institute (2018) “around 35% is located in buildings, 30% in electrical cables and machinery and 30% within transport applications”. This chapter will dive deeper into the workings of the aluminium market, looking at the life-cycle of aluminium and market trends within the market.

3.1 - Aluminium

The global aluminium consumption is rising (figure 3) (UC RUSAL, 2018). This trend is expected to continue for the coming years (UC RUSAL, 2018; Fitch Solutions, 2017; Aluminium Leaders, n.d.). This growth in demand is due to the ever increasing world population (United Nations, 2017) combined with increasing wealth (The World Bank Group, 2019). Luckily, aluminium recycling is a really good option for the re-use of the material. It is estimated that three quarters of all the aluminium produced since 1880 is still in use (Sapa, 2014; The International Aluminium Institute, 2018). Due to the small quality loss during smelting, secondary aluminium scrap has a high economic value (980 [€/tonne] for secondary aluminium versus 2000 [€/tonne] for primary aluminium (The London Metal Exchange, 2019)). Besides, recycling of aluminium requires only 5% of the energy compared to producing primary aluminium (Sapa, 2014; European Aluminium, 2016b).

3.2 - Aluminium Lifecycle

In 2016, the European Union exported nearly 520 ktonne of aluminium scrap. Over 80% was exported to Asia, with 38% destined to China and 26% to India (European Aluminium, 2016a). Looking at the history of Europe, we have always been exporting scrap to other continents. Minter (2011) points out that this is due to the fact that Europe and the United States produce more scrap then they can consume. On the other hand, Asia consumes more than it throws away. Especially China needs cheap material due to their industrial boom (Minter & Flam, 2018). Hagelüken, Lee-Shin, Carpentier & Heron (2016) stress the importance of keeping scrap within the EU to “close the loop, and prevent Europe’s metals from being landfilled, incinerated, or exported without guarantee of high-quality treatment”.

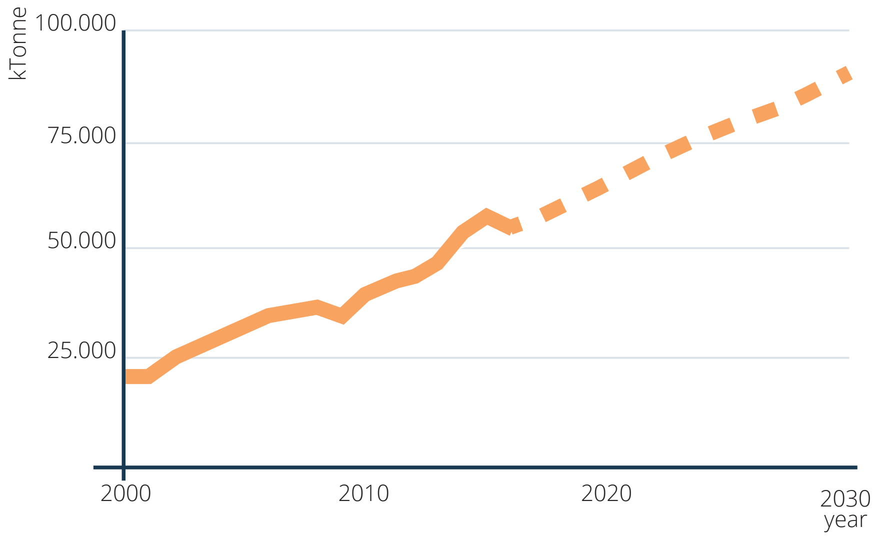


Figure 3 - Global consumption of Aluminium until 2016 and the forecasted consumption. (Based on: UC RUSAL, 2018; Fitch Solutions, 2017; Aluminium Leaders, n.d.)

Currently most of the scrap is transported to Asia. According to M. van de Poll (personal communication 18 October 2018), managing director at Reukema, 25% of the total smelting capacity of aluminium worldwide is located in China. The mixed aluminium[1] scrap consist of different alloys, each with their own material composition. Aluminium profile is made out of aluminium mixed with magnesium and silicon (6000-series), while aluminium sheet is made out of aluminium mixed with magnesium (5000-series), manganese (3000-series), or pure aluminium (1000-series). The material is shipped to China for "separation into higher-value scrap grades using low-cost labor for visual identification and sorting" (Spencer, 2005). The material is separated in China, remelted and casted into ingots and t-bars for further processing. During the smelting process, any plastic will eventually float to the surface of the molten aluminium where they will burn and char. This charred plastic, or slag, can be removed from the molten aluminium (Schmitz, 2006). Any iron on the other hand (e.g. bolts) form a contamination during the smelting process This degrades the alloy composition significantly (de Moraes, de Oliveira, Espinosa & Tenório, 2006). After smelting the aluminium scrap, the molten aluminium can be mixed with other metals to get the correct alloy. This means that the more contamination your material has in the beginning, the more elements you need to add to get the correct alloy in the end. Figure 4 gives an overview of the production of secondary aluminium compared to primary aluminium.

[1]Mixed Aluminium Scrap - Geslagen Aluminium
Old and new aluminium. Free of: Cu, Zn, cast alumnium, scoria, foils, and other alien substances. Tolerance of 2% for Fe and plastic. (Reukema Direct, 2018)

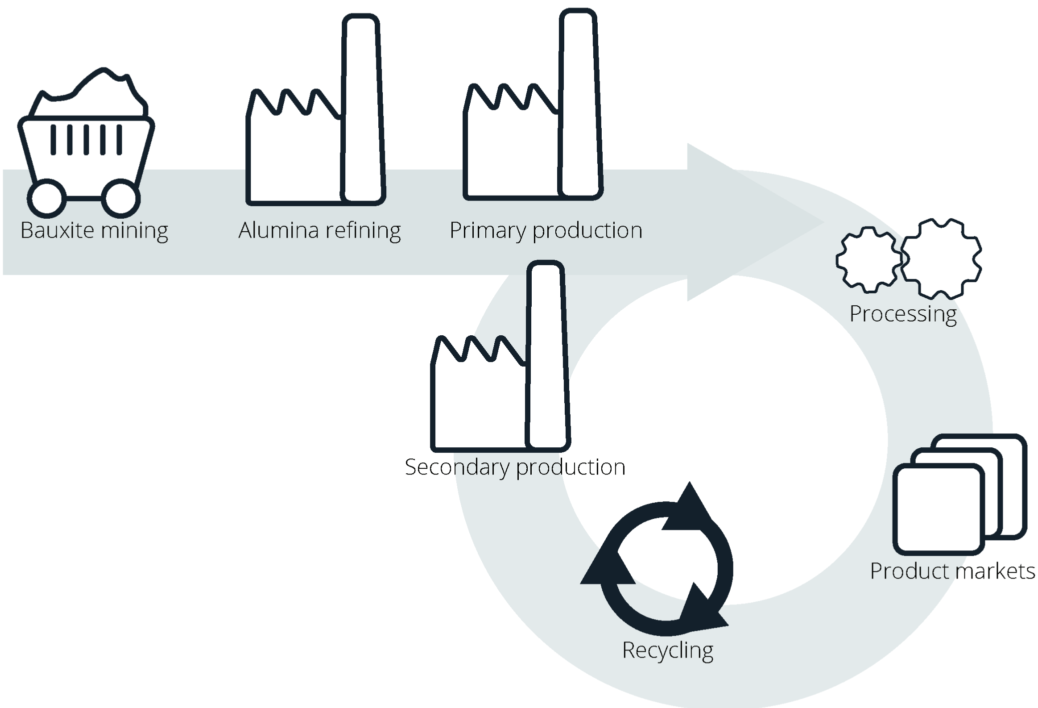


Figure 4 - Aluminium life cycle.

3.3 - Market Trends

To get a understanding of the context, a trend analysis (Buijs and Valkenburg, 1996) was performed. The most important trends were identified and are listed below.

3.3.1 - Increasing aluminium demand

The population of the world is still growing, besides this the wealth of all of these people is also growing (United Nations, 2017; The World Bank Group, 2019). The result is an ever increasing demand for aluminium. Increasing the recycling percentage can help match the growing demand. The expected increasing demand also means that Reukema is in a market in which the demand is ever increasing.

3.3.2 - More power for Recycling companies

More recycling companies are becoming the front of the production chain, instead of the end of it. Due to depletion of materials (Diederen, 2010), materials are getting scarce. Therefore there is an increasing need to recycle to keep up with our demand for materials (Aeternus, 2018). Aluminium is a nonrenewable natural resource and therefore an active recycling system should be inplace to keep all the aluminium in the loop. Due to increasing recycling rates, recycling companies are getting more and more power. They are becoming the producers of the material, instead of being the trashcans of the economy. They can use this power to force products to be design for recycling.

3.3.3 - More technology in Recycling

The recycling business is conservative by nature (Waste Management World, 2011), due to the unpredictable nature of the incoming material, the recycling industry heavily relied on a highly skilled workforce. Currently more and more recycling companies are adopting technology (e.g. automated sorting of C&D waste by the Finish company ZenRobotics). Using more technology for automated sorting can decrease costs (Lukka, Tossavainen, Kujala & Raiko, 2014), and make the recycling industry a safer and healthier place to work. Currently, working in the recycling industry can be dangerous (Chen, 2015).

3.3.4 - Stricter waste regulations

Increasing number of rules regarding waste regulation are being drawn up. The European Union wants to move towards a circular economy using matching laws. In addition, China is putting higher demands on the purity of the material entering the country for recycling (TOMRA sorting, n.d.; Rosengren, 2017; Recycling magazine, 2018). China is already sending ships back which do not comply with the rules. This poses a problem for companies exporting materials to China for recycling, because they need to pre-treat their material before sending it. Furthermore, transportation cost will rise due to increasing fuel prices (World Bank Group, 2019) & empty return ships. Normally ships would return with consumer goods, making the travel cost efficient. But because recycling materials are send to other countries, the two way travel can be less cost-efficient.
Regulation is targeted more towards the circular economy. In this way the urban mine is more and more becoming a reality. This means there are more rules regarding waste, but it is also a possibility for higher recycling grades. As much materials as possible should be kept inside the loop. This means more recycling, remanufacturing and refurbishing.

3.4 - Conclusion

Aluminium is one of the most used materials on the planet and the demand is still increasing. Recycling is a crucial element for accommodating this demand. Currently, most aluminium scrap is transported to Asia for further processing. But regulations on the imported waste is getting stricter and stricter. A chance is to keep the material within the European Union, to create the urban mine within Europe. In this way the strict rules of China can be avoided, while the material is still circulating in the EU. This however requires local separation of the material. Reukema aims to solve this issue by designing a system in which the material is sorted automatically. This idea will be discussed in chapter 4.

4 - Reukema

Figure 5 - Reukema buys material from 1.000 active suppliers within a radius of 250 km around Harderwijk, the material is sold mostly in Asia.

Reukema operates as the biggest trader of non-ferrous metals in the Netherlands (Reukema, 2018). The company has been in business for 100 years. Using the Business Strategies from Miles and Snow (Miles, Snow, Meyer & Coleman, 1978) to characterize the competitive strategy of Reukema, I concluded that Reukema is a combination of a Defender and an Analyzer. They defend the market and the business they are currently in and try to minimize risk on the one hand (buying and selling material to trusted parties). On the other hand they are looking into new business cases, such as automated sorting of aluminium, to be implemented into the company. At the same time, they are no front runners in the adoption of technology, as technical knowledge is lacking within the company. Therefore reducing complexity within the design would be beneficial for the company. Reukema is looking for a simple easy to operate solution. For this reason, the need for maintenance should be minimized.

4.1 - Material flow of Mixed Aluminium

Reukema handles different non-ferrous waste streams. These materials are sourced from suppliers within a radius of 250 km around Harderwijk, the Netherlands (T. Oudshoorn, personal communication, 12 October 2018). The material is transported to and collected in Harderwijk. The material is inspected and assessed by an inspector on site. The inspector assesses the received material by eye and takes some picture with his smart phone for documentation. Based on this visual inspection the supplier can get less money per tonne for the delivered material, for example when the material is heavily contaminated. The material is stored on site and shredded twice. For shredding the material, the company uses a Hammel (figure 9). This machine is designed for the forestry, but Reukema has adjusted it so it can be used to shred aluminium. During the shredding process, most iron parts are removed by the use of a belt magnet. After the second shredding step, the material is stored in a container and transported by boat to the harbour of Rotterdam for further shipping and separation by an external company. Figure 7 gives an overview of the steps as it is in the current situation compared to the envisioned future situation.

Currently the mixed scrap is sold to other companies for further processing. But Reukema wants to investigate the possibility of using a robotic system for automated sorting of this mixed aluminium scrap on site. The next section will discuss the aluminium material flow as it is currently present at Reukema and how the company envisions a new automated sorting system.

4.2 - Automated sorting of Mixed Aluminium

Currently separation of the mixed aluminium is done by external parties. Reukema envisions a new separation installation which can separate the material on site in Harderwijk. This section will discuss the aluminium separation concept which the company wants to implement.

Currently, the only way to have a high quality sorting result is using laborers to manually sort the mixed aluminium. Other separation techniques currently in use for separation of aluminium lack the quality or efficiency that handsorting offers. In appendix C the different techniques for sorting aluminium currently in use are discussed. There I discuss these techniques and conclude that there is no existing alternative to handsorting yet.

Reukema wants to develop an automated sorting installation which uses robotic arms for separating the incoming mixed material. Automated sorting can significantly lower costs per shift compared to hand sorting (Lukka, Tossavainen, Kujala & Raiko, 2014). Figure 6 illustrates the concept the company envisions. A line scan camera and a 3D laser scanner gather data. This data is used to classify the pieces using a neural network. The material is then transported by conveyor belts and picked by a robot which places it in the designated place for further processing. For Reukema this concept is interesting because of the created added value when you separate the material. The mixed aluminium is worth 980 [€/tonne], while the sorted category blank profile is worth 1820 [€/tonne]. This makes this project an interesting business case for the company. In confidential appendix B I will dive deeper into the added value that can be created by sorting the aluminium.

Firstly, Reukema wants to compete with the human sorting process in a cheap automated sorting system. By only using a camera and a line scanner, they aim to classify the material. As Meijneke, Kragten and Wisse (2011) point out: "to get the industry interested, there is a need of cheap, simple and robust solutions". Secondly, their goal is to sort 20 [tonne/hour]. This is the output a sorting facility in a low-wage country reaches. Thirdly, the cost per tonne for automated sorting should be lower than the cost of hand sorting. Reukema estimates the cost of hand sorting at 55 [€/tonne] including transport (T. Oudshoorn, personal communication, 4 October 2018). Lastly, the automated sorting system should be able to reach a sorting purity of 98 - 99 [%]. According to Reukema, handsorters are capable of reaching this level of sorting quality. Because the sorting purity of 100% are unreachable (Tempelman, Shercliff and Ninaber van Eyben, 2014), employees are needed to treate the unsortable materials. These unsortable materials should be hand sorted on site.

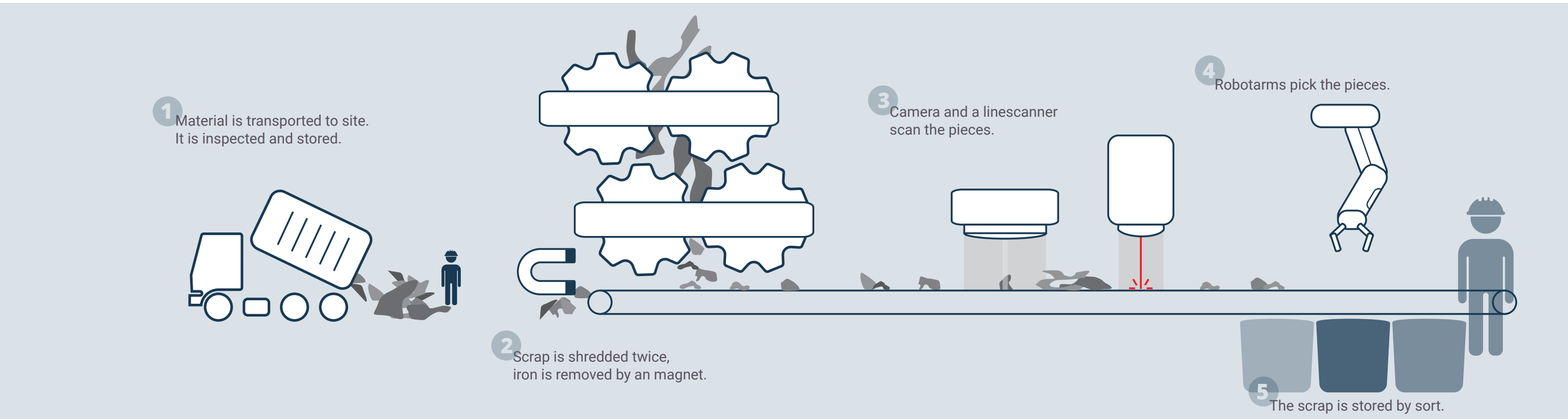


Figure 6 - Envisioned concept for separation of aluminium. The material is (1) transported, (2) shredded, (3) scanned, (4) picked and sorted by a robotic arm, and (5) sorted for further processing.

4.3 - Conclusion

The envisioned system can be divided into the following functions: input material, spread mix, acquire data, grab, move, release, store (figure 7). We can conclude that the system to be designed needs to be able to sort mixed aluminium automated. The quality or grade of the sorting is an important factor. Therefore we can conclude that the system should be reliable in the output and thus quality it delivers. During this project it is important that the precision of the sorting process is maximized. Besides, the cost for sorting should be lower than 55 [€/tonne] to be able to compete with hand sorting. There should be designed for minimized cost. Besides this, the system should be able to sort 20 [tonnes/hour]. To create the most added value, there should be designed for maximum throughput in the system. Lastly, the sortation purity of the system should be maximized. Reukema aims for purities of at least 98%.

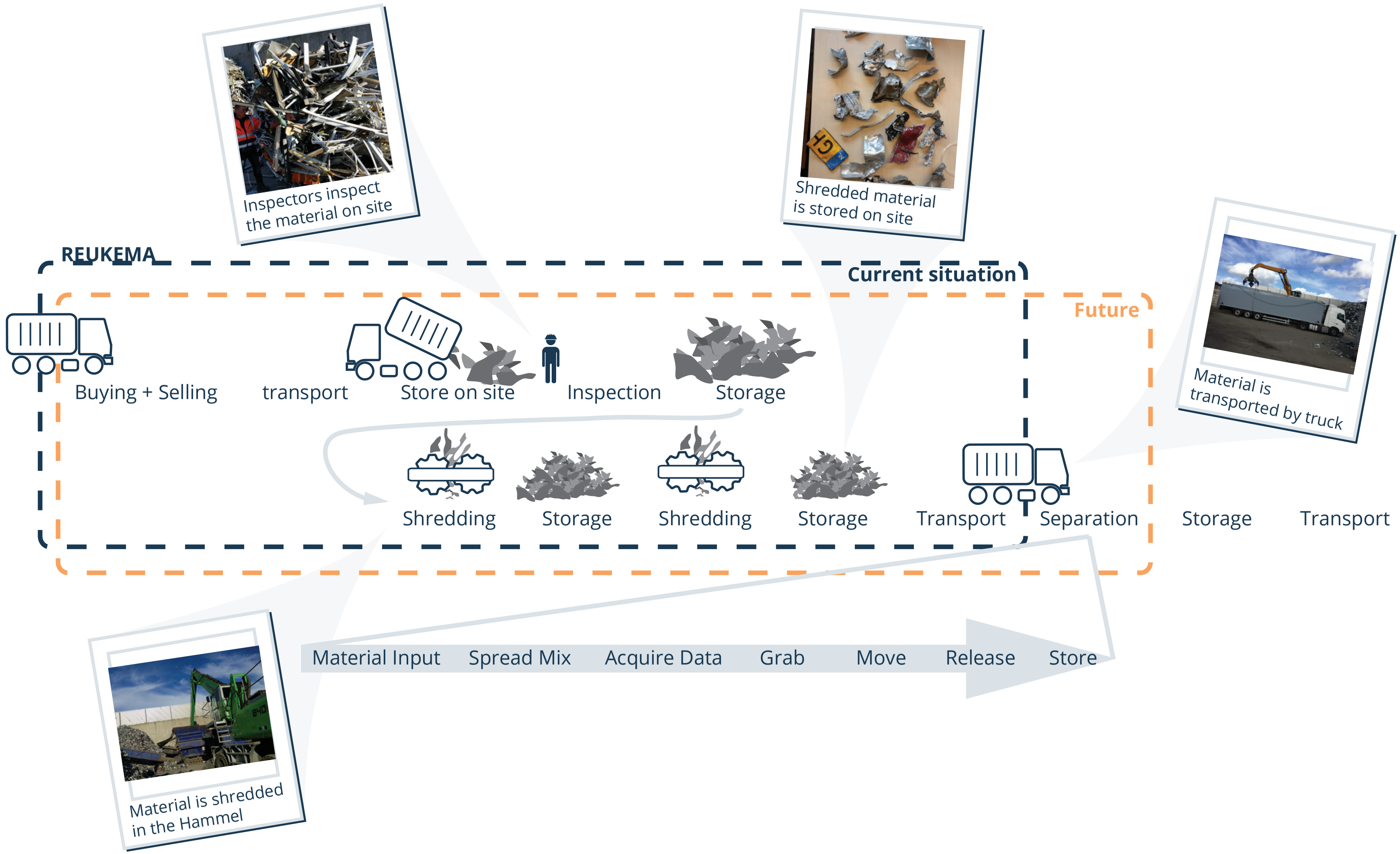


Figure 7 - Process flow as it is in the current situation, and the envisioned situation in the future.

5 - Recycling

As discussed earlier, recycling aluminium has economic and environmental benefits. It is therefore important to understand what recycling is, and how we can distinguish the different steps within the recycling process. According to Tempelman, Shercliff and Ninaber van Eyben (2014) four different steps can be distinguished within the recycling process. We can use these steps to clarify the recycling process at Reukema. This section will discuss the four steps off recycling and discuss the actions of Reukema per step.

1) Collection

Collection is the first step in the recycling process. Looking at Reukema, we can identify 1000 active suppliers from whom they buy the material. The mixed aluminium is coming from industry, construction, demolition and consumer products. Every month 2.000 tonnes of mixed aluminium scrap are transported to Reukema and stored at their facility in Harderwijk for further processing.

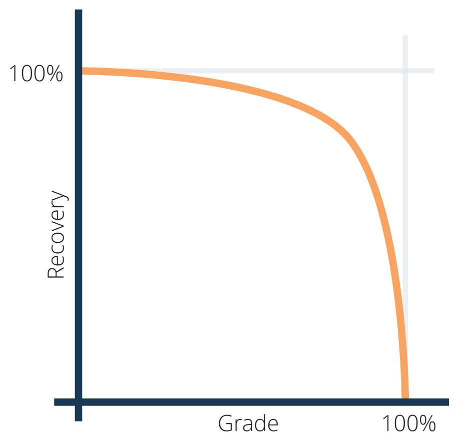


Figure 8 - The trade of recovery versus grade of the recycled material - "Idealized grade-recovery curve" (Tempelman, Shercliff & Ninaber, 2014).

2) Liberation

Secondly, the material is liberated. "Generally this means that the material is shredded or cut into smaller pieces, so each chunk consists of a single material" (Tempelman, Shercliff and Ninaber van Eyben, 2014; p. 253). In the ideal situation you get 100% recovery and a 100% purity of each material. In reality this is not possible, you will always have contaminations or a lack in recovery. Figure 8 illustrates this trade-off between recovery and purity.

Reukema liberates the aluminium by shredding the scrap in the 'hammel', see figure 9. The material is shredded twice to get a consistent mix size. This is originally done to get as much scrap into one container for transportation. During the shredding process, iron particles are removed as much as possible by the use of a belt magnet.

Figure 9 - Hammel; the shredding machine Reukema uses to shred the aluminium into smaller pieces. (Courtesy: https://www.hammel.de/index.php/en/unternehmen-en/uber-hammel-en)

3) Concentration

After liberation, the different categories of material need to be separated and concentrated per category.
At Reukema, we can see that after liberation they sell the material to other companies located all over the world. They mainly ship the liberated scrap to China, Pakistan, and India - low-wage countries. The material is shipped in 40 [ft] containers to Rotterdam from which they are transported to Asia. In Asia the material is sorted for further processing. This concentration step is done by hand sorting, mainly done by women. Figure 11 shows the handsorting in a factory in China. For concentration it is required that the pieces can be classified by the available sensors or employees.

4) Reprocessing

The last step in recycling is reprocessing. Aluminium is melted and used for the secondary production of aluminium. This smelting creates semi-finished products, such as ingots or t-bars for further processing into new products.
Reukema is not actively working in this last step of the recycling process.

Figure 11 - Concentration of metal parts by Chinese employees (Minter, 2011b).

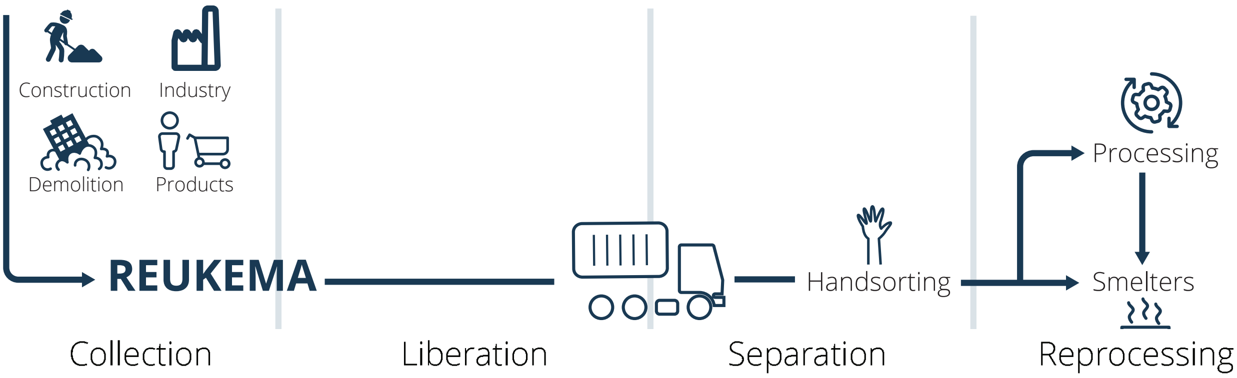


Figure 10 - Recycling process at Reukema.

5.1 - Conclusion

For the best separation results, it is required to classify the parts. Therefore, the used sensors in the design need to be able to classify the material.

6 - Material

The mixed aluminium is bought by Reukema to be sold to others buyers around the world. The buying and selling process heavily relies on trust from both parties. Quality checks can only be done partially. As M. van de Poll (personal communication 18 October 2018) puts it, "we buy chaos". Sellers are even ranked according to a trust system similar ones found in the financial world (C. Lisman, personal communication, 18 October, 2018). Reukema weighs an incoming truck and weighs it again when it leaves. Besides this, an inspector inspects the material by eye and takes pictures. Based on these two data streams, a decision will be made if the supplier will get a lower offer for the material brought to Harderwijk. This method only supplies the company with some information regarding the material. One percent change in purity of the material means the company loses its margin (M. van de Poll, personal communication 18 October 2018). So, there is a need for more data regarding the material bought from suppliers.

Material data is also important during the design phase of this project. How big are the pieces that need to be sorted? How large is the spread? How heavy can a piece be? This chapter aims to gather this data needed within the scope of this project. From two different samples, the weight, length and width are recorded. Secondly, the percentual mix of the material is investigated. How many piece of one specific category can be found in a tonne? The complete data set of the material parameters can be found in appendix D.

The requirements demand a sorting quality of 98% or higher. Therefor 3 standard deviations, or 3σ, were taken to quantify the upper boundary of the material parameters. This ensures that statistically 99,7% of all material falls within this range.

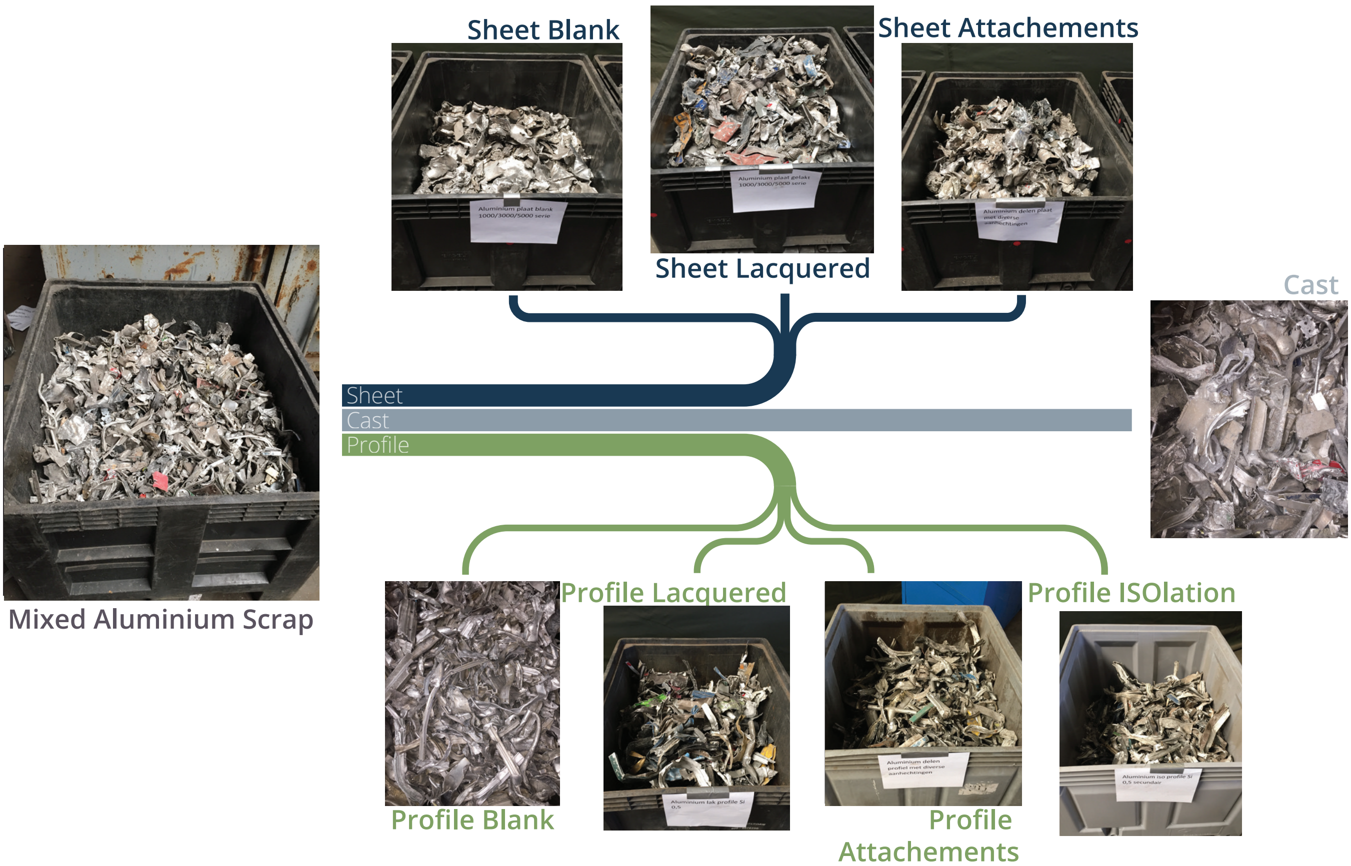


Figure 12 - Material mix, split into categories and groups.

6.1 - Material Mix

The incoming waste stream consists of a mix of different sorts of aluminium. Pictures of the different material groups can be found in figure 12*. The incoming mixed aluminium can be split up into 8 different groups, falling in 3 categories. The categories are: Sheet, Profile, and Cast. Cast cannot be subdivided further. Sheet can be divided into three different groups: blank, lacquered and with attachments. Blank is every piece of scrap which is completely blank. Within the group lacquered, you can find every piece which is lacquered or painted. Lastly, there is the group with attachments. These attachments can be anything from plastic, iron particles (e.g. bolts), stickers or any other foreign substance attached to it. Within the category profile the same groups as with sheet can be distinguished, in addition to one more: ISOlation. ISOlation profiles are profiles which can be found in door jambs for example. These profiles consist of aluminium, often with a layer of foam. Pieces of cast aluminium can also be found in the mix, these are tolerated by the buyer and seller, but are normally treated as a separate category.

*The value of each group in €/tonne can be found in the confidential appendix A.

There is no data available regarding the percentual mix of the mixed aluminum. To get an understanding of the percentual material mix, a random sample size was taken on two different days: October 18th (N= 84) and December 6th (N= 82). This sample (N= 166) was sorted into the 8 different categories. Figure 13 shows the results. We can see that the biggest groups are; Sheet Blank 24%, Sheet Lacquered 21% and Profile Blank 19%. The material mix is highly influenced by the suppliers and external factors (e.g. the demolition of a building). The sample taken during this graduation project gives an indication of the mix.

6.1.2 - Discussion

To validate the results of the sample size, more samples should be taken through time. It would be best to take random samples over the course of several months. In the restricted time of this graduation project, that is unfortunately not possible.I would recommend Reukema to continue gathering data regarding the percentual mix over the course of several months.

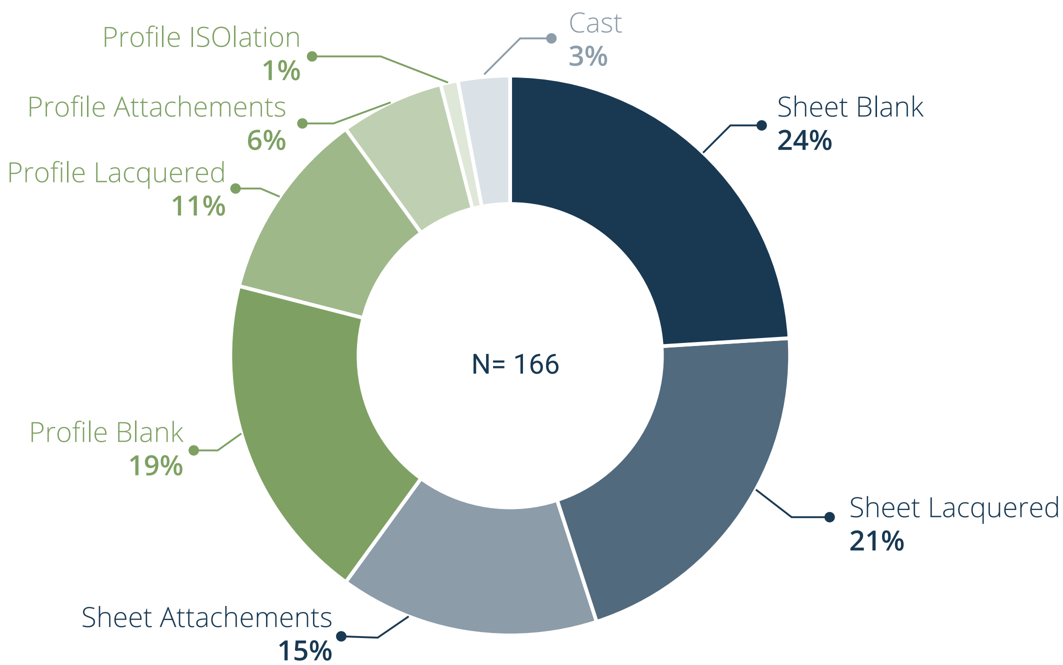


Figure 13 - Percentual material mix.

6.2 - Material Weight

Weight is one of the crucial factors in successfully gripping a piece by a robotic gripper (Monkman, Hesse, Steinmann & Schunk, 2007). To investigate the weight of the pieces from 7 different groups 20 samples were taken. The weight was noted for every sample. This experiment was conducted twice on October 18th and December 6th, which brings the total sample size to 280 samples. Figure 15 displays the distribution of the weight.

The maximum weight of a piece of scrap is 700 [g].

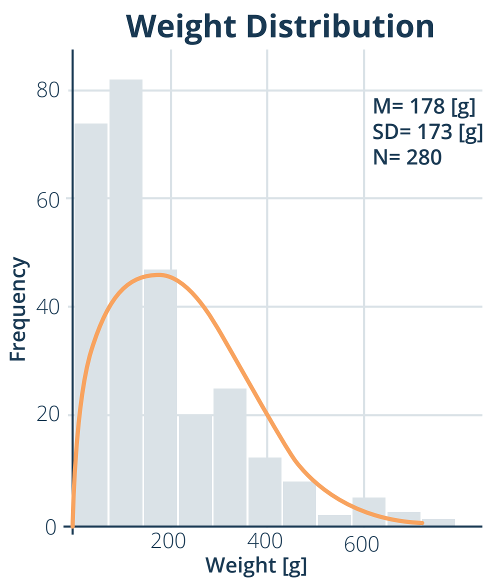


Figure 15 - Weight distribution of the complete sample size.

6.3 - Material Dimensions

The size of the gripper is influenced by the size of the pieces the gripper needs to grip. The same sample which was used to determine the weight, was used to measure the material dimensions. Every piece was placed on a blocked background with squares of 1 by 1 [cm]. The length and width were noted, based on a photograph made with a smart phone (Nexus 5X). By drawing a box around the piece, the length and width were determined (figure 14). The distribution of the length of the different pieces can be seen in figure 16. The distribution of the length of the different pieces can be seen in figure 17. The maximum length found was 514 [mm], and the maximum width was 261 [mm]. An overview of the material data can be found in table 1.

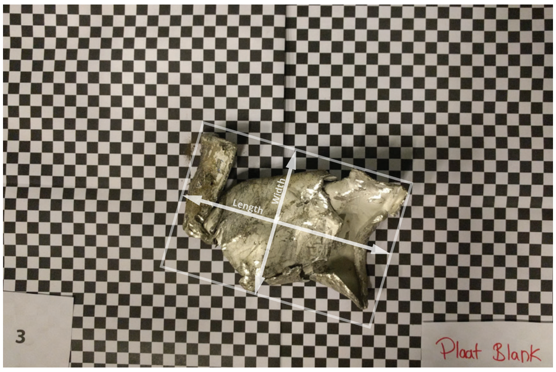


Figure 14 - Sample placed on a blocked background for dimension reference; a box is drawn around the piece of scrap to determine the length and width.

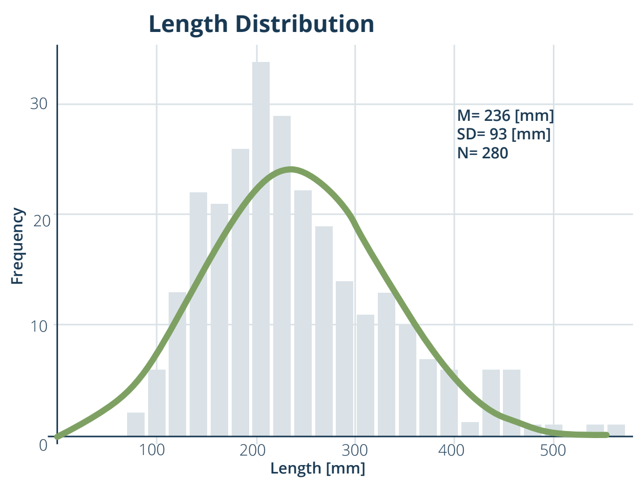


Figure 16 - Length distribution of the complete sample size.

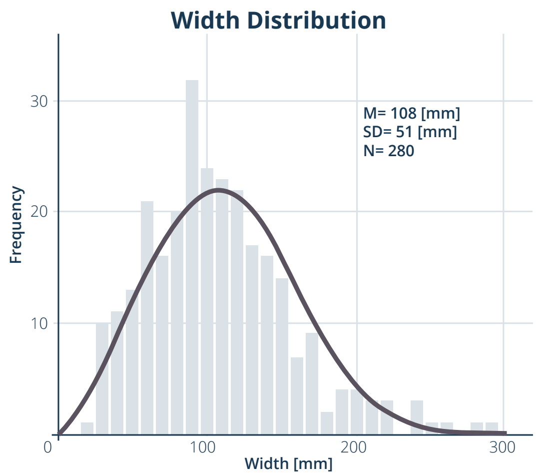


Figure 17 - Width distribution of the complete sample size.

Table 1 - Overview of the material parameters.

	Mean	Standard Deviation	Lower 99,7% Confidence Interval	Upper 99,7% Confidence Interval
Weight [g]	178	173	0	697
Length [mm]	236	93	0	514
Width [mm]	109	51	0	261

6.4 - Discussion

3 standard deviations were used to indicate the spread of the material data. Statistically 99,7% of all pieces of scrap fall within the upper and lower confidence interval. Looking at the lower confidence interval, we can observe that all parameters are zero. Although this may be true, I would recommend Reukema to include a step to sieve the scrap. This prevents really small particles to enter the system. This step is outside the scope of this project. During this project a minimum weight of 10 [g] was taken as a lower boundary for weight, 10 [mm] for length and width. Based on the experience of the designer these values were picked.

During the collection of the data, it was observed that the material is really dusty. This dirt poses a threat to the complete system. Therefor the system should be robust to be able to function in this dusty environment. Besides this, the variety in shapes is large, no piece is the same. Because every piece is different in shape, the behaviour is expected to be different as well. Therefore there should be designed to maximize the control over the objects, to minimize material behaviour spread and create the most predictable system possible.

The sample used (N= 280) to set the material dimensions was taken on two different days. Based on a confidence level of 95% and a margin of error of 5%, assuming the population is 10.000.000, we find an ideal sample size of 664 (based on https://www.qualtrics.com/blog/calculating-sample-size/). Increasing the confidence level of decreasing the margin of error results in a larger ideal sample size. We can conclude that the original sample size is not enough to have a representative data set. I would recommend Reukema to gather more data on different dates.

In confidential appendix B - “Added value of sorting”, different scenario’s can be found for sorting material groups. There it is showed that for each group sorted, added value is created.

Lastly, the distribution of the data is currently based on equal contributions of all material groups. But as was shown in this chapter, the percentual mix of all material groups is not equal. This may have resulted in a skewed image of the complete dataset. The current sample can therefore be used as an indication, but more data in the correct ratio is needed.

6.5 - Conclusion

Because every piece is different in shape, the behaviour is expected to be different. Therefore there should be designed to maximize the control over the objects. Besides this, it was observed that the material is really dusty. Therefore robustness of the system should be maximized. Lastly, the system should be able to handle pieces of 10 - 700 [g], with a length of 10 - 514 [mm] and width of 10 - 260 [mm].

7 - Competitors

Reukema wants to venture into a market in which they are not yet operating. Who are the competitors in this new market Reukema wants to enter? This chapter will discuss the different competitors in the current market.

7.1 - Handpicking

According to Spencer (2015), handpicking is the most used technique for sorting of metal scrap. One of the biggest companies doing this is S!GMA, based in China (figure 18). The cost of hand sorting are not transparent, but Reukema estimates the costs of hand sorting is €55,- per tonne. This cost includes transportation.
A human has a picking cycle of 7 to 12 seconds (Freyberg, 2011). This means that one person can sort 0.576 tonne of scrap per day (=(3600 [s] x 8 [h] / 10 [s]) x 200 [g]). A whole sorting plant can sort 20 tonnes per hour. This means that there are approximately 320 persons working in a sorting plant.

Figure 18 - Handsorting of aluminium scrap. Chinese workers are sorting aluminium scrap by hand. In large factory halls they are sorting 0.5 tonne per person per day. (Courtesy: Minter, 2011b; Bloomberg, 2009)

7.2 - ZenRobotics

ZenRobotics is a Finnish company specialized in robots for automated sorting (ZenRobotics, 2018a). The company has different grippers which can sort different materials. The ZenRobotics Heavy Picker (w, 2018b) resembles the idea Reukema envisions the most (figure 19). This robot can sort fractions from 50 till 500 [mm], with a maximum weight of 30 kg. This installation can do 2000 picks/h/arm, or 2 [s] per pick. The maximum speed of the conveyor belt for feeding the material is 0.5 [m/s].

Figure 19 - ZenRobotics sorting system for sorting different construction waste with a robotic system. The system can sort up to 8 ton/hour. (Courtesy: ZenRobotics, 2018b)

7.3 - Steinert

Steinert is a German company specialized in magnetic and sensor sorting solutions (Steinert, 2018a). The company has developed a system in which LIBS, laser-induced breakdown spectroscopy, is used to classify parts (Steinert, 2018b). Compressed air valves shoot the parts into different containers. The company states that an accuracy of up to 99.9% can be reached. The machine is optimized for particle with a width of 20 to 60 [mm] and a length of 60 to 150 [mm]. Conveyor belt speeds vary from 2 till 3 m/s. The machine can sort several tons an hour (Recycling Today, 2016). The exact sorting capacity is unknown.

Figure 20 - Steinert aluminium sorting system using LIBS. Steinert sorts small aluminium fractions using laser-induced breakdown spectroscopy for classification. The aluminium pieces are shot off the belt using air pulses (Courtesy: Baum Publications, 2019; Recycling Today, 2016; Steinert global, 2018).

7.4 - Vacuum grippers

Different companies operate in the vacuum gripper sorting market. Bollegraaf, AMP Robotics, SamurAI, MAX-AI & ZenRobotics all have a robotic sorting system which uses vacuum grippers. The robots sort plastics and drink cartons. They do this in co-production with humans. The robots can pick up to 60 picks per minute, 1 [s] per pick (AMP Robotics, 2018; Machinex Industrie, 2018; Max-AI, 2018). The robot picks small & light objects with a weight of under 1 [kg] and a width and length of 400 [mm] (ZenRobotics, 2018b).

Figure 21 - Vacuum grippers sorting light fractions of plastic and drinking cartons (Courtesy: AMP Robotics, 2018; Bollegraaf Recycling Machinery BV, n.d.)

7.5 - Conclusion

Looking at the market, there is no company which can automatically sort aluminium of the size Reukema wants to sort. Vacuum grippers need a flat surface and are specialised for light parts. Steinert sorts only small fractions, while ZenRobotics only sorts large fractions. The only competition currently able to sort aluminium, is hand sorting. Therefor, as discussed earlier, costs should be kept lower than 55 [€/tonne] to be competitive. Besides this, the sorting capacity should be 20 [tonnes/hour]. On the other hand, to be competitive with automated sorting installations, the pick cycle should be lower than 2 [s].

8 - Grippers

This section will discuss the robotic gripper. What is a gripper and which parameters are important in designing a gripper?

8.1 - Gripper overview

"A robot arm by itself can serve no purpose until a load or a tool is suspended from or attached to it" (Chen, 1982). This means that the gripper is an essential part of the system. Different definitions for what a gripper is can be found in the literature. The best definition for this graduation project is the definition by OMEGA engineering (2018): "A gripper is a device that holds an object so it can be manipulated. It has the ability to hold and release an object while some action is being performed".

If we look at the important parameters in designing a robotic gripper, four major factors that need to be considered in designing or selecting the correct gripper can be identified (MacKenzie & Iberall, 1994; OMEGA engineering, 2018):

1) Part shape, orientation, dimensional variation

What are the possible shapes that the gripper needs to pick? How large or small is the variance? A gripper that needs to grasp a round object compared to a squared object will be different in design.
In chapter 6 I examined the material parameters. The shape variation is large due to the way of shredding the pieces. Looking at the dimensional variation, we can conclude that 99,7% of all pieces have a length smaller or equal to 514 [mm] and a width smaller or equal to 261 [mm]. The orientation of the pieces depends on the way the material is fed into the machine and will be investigated in during the synthesis phase.
We can conclude that it is required that the sensors used in the system are able to measure the part shape and location.

2) Part weight

What is the weight of the parts the gripper needs to pick? The weight of the part has a big influence on the gripper design.
Looking at the aluminium mix, 99,7% of all pieces will have a weight of 700 [g] or less. We can conclude that the system should be able to sort pieces with a weight of 700 [g] or less.

3) Accessibility

Are parts accessible during an action? Gripping a ball from an flat surface compared to a ball placed in a container, requires different gripper designs and approach strategies.
The envisioned concept, as shown in figure 6 in chapter 4, will transport pieces of aluminium on a conveyor belt. The gripper should therefore be able to grab pieces from a moving conveyor belt to guarantee continuous sorting. It is required that the system can detect the velocity of the pieces. The top surface of a conveyor belt is flat. The accessibility of the pieces is heavily influenced by the way the pieces are fed into the system. This will be investigated further during the synthesis phase.

4) Environmental

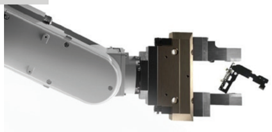
What are the conditions the gripper needs to work in? A gripper that needs to operate in a cleanroom has different requirements from a gripper that needs to work in a dusty recycling installation.
All aluminium pieces are dusty. By inputting the aluminium in a sorting system, more metal dust will be created because of the friction between pieces. Therefore it is important the the gripper is dust tight (at least IP6X). In addition, the installation will be placed in a indoor environment, but the aluminium may be stored outside. Therefore the system should be able to handle condensation (at least IPX2).

8.2 - Gripper classification

Grippers can be classified into 3 different groups (Chen, 1982): (1) mechanical finger types, (2) vacuum and magnetic types, and (3) universal grippers. Different grippers on the market were found and classified based on this system.

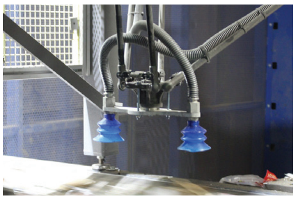
8.2.1 - Mechanical finger type

Most mechanical finger grippers consist out of two or three fingers. Companies such as RightHand Robotics (2019), Schunkz (2019), RobotIQ (n.d.), and ZenRobotics (2018b) manufacture mechanical grippers. According to a study by Muldau & Androiden, two fingers can grab 40% of the pieces a five finger gripper can handle. A gripper with three fingers can handle 90% of the objects, and four fingers can handle 99% of the objects a five fingered gripper can. More fingers mean more control and a complexer system, while it does not always result in a securer grip.



8.2.2 - Vacuum and magnetic

This category includes all grippers that are equipped with suction cups or magnetic force-exerting elements. In the recycling industry these robots are mostly used for picking up light fraction (<1 kg) such as plastic and drinking carton (ZenRobotics, 2018b). Companies such as Zenrobotics (2018b) and Festo group (n.d.a) fabricate vacuum type grippers.



8.2.3 - Universal grippers

Universal grippers are the group with inflatable fingers, soft fingers and grippers made of mouldable materials. Universal grippers are mostly used for grasping irregular or fragile object. Festo group (n.d.b) and Empire Robotics (n.d.) are examples of two companies manufacturing these types of grippers.

8.3 - Prehension Types

Based on Monkman, Hesse, Steinmann & Schunk (2007) and Wolf, Steinmann & Schunk (2005) 7 prehension types can be distinguished; reverse grip, form-fit, partial form fit, pure force closure, holding with vacuum, retention with a magnetic field, and the adhesive grip. Because we need to deal with waste aluminium which is highly contaminated with dust and other foreign substances. The adhesive prehension can be eliminated. The same goes for the magnetic prehension, simply because aluminium is not magnetic. Figure 22 gives an overview of the 5 prehension types which can be used for gripping the aluminium scrap.

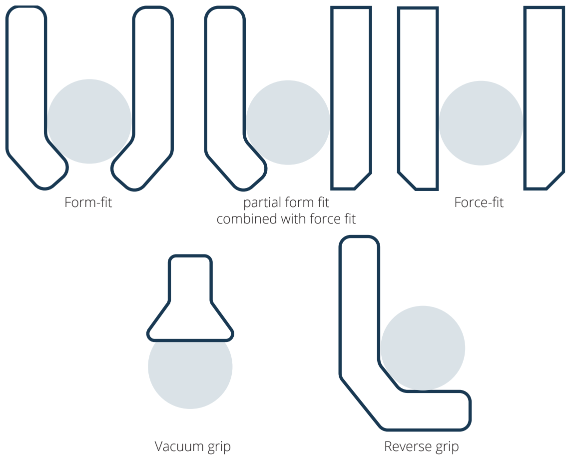


Figure 22 - 5 Possible prehension types to grasp the aluminium scrap (Based on Monkman, Hesse, Steinmann & Schunk, 2007; Wolf, Steinmann & Schunk, 2005).

8.4 - Design Guidelines

The major factors in designing a gripper were identified. Besides this, different gripper types and different prehension types were found. Lastly, we need design guidelines for the design of the gripper. Causey & Quinn (1998) divide design guidelines into two different categories: “those that improve the throughput of the system and those that improve the reliability of the system”. All design guidelines below are grouped according to these two categories.

8.4.1 Improve throughput of system

8.4.1.1 - Minimize the gripper footprint

The gripper footprint is “the three dimensional space which must be free of obstructions for a gripper to successfully grasp a part” (Causey & Quinn, 1998). This parameter is very relevant in a system in which a flexible feeding is used and in which spacing between parts is random and unknown. By minimizing the footprint, part collision can be prevented, and the throughput of the system can be maximized.

8.4.1.2 - Chamfer the exterior of gripper fingers

By chamfering the exterior of a gripper, the footprint of the gripper is decreased. Besides this, the chance that the gripper gets stuck behind a piece is decreased.

8.4.1.3 - Minimize the gripper weight

Heavier tooling causes larger overshoots. Besides this, minimizing the weight of the gripper allows the robot to accelerate quicker. This increases the throughput of the system.

8.4.2 Improve reliability of the system

8.4.2.1 - Prevent part deformation around the gripper

Part deformation is not an issue when the part deforms after it has been sorted. But if the part deforms around the gripper, problems with releasing the part could occur. This hinders the sorting process and is unwanted. Therefore, design solutions which deform the aluminium should be avoided. At the same time, it is important that the gripper does not deform. For this reason, it is required that the Youngs Modulus of the material out of which the gripper is constructed, is higher than that of aluminium (69 [GPa]).

8.4.2.2 - Put center of gravity at gripper centres (Eitel, 2010)

By putting the center of gravity of the scrap at the center of the gripper, the most secure grip and most predictable part behaviour can be reached. The gripper should be designed in such a way that it is possible to place the center of gravity in the center of the gripper.

8.5 - Conclusion

Four important factors for the design of the gripper where identified; part shape, part weight, accessibility and the environment. As discussed, the way of feeding the material into the system has an influence on the accessibility and should therefore be specified and investigated. In the synthesis phase this will be further explored.

The classification of different grippers and prehension types give inspiration which can be used during the synthesis phase. This inspiration can for example be used in a brainstorm. By using the 5 different prehension types identified, different gripper solutions can be generated. In the synthesis phase, this will be used to start the ideation.

Lastly, design guidelines were found in literature. Depending on the type of prehension, some design guidelines are not relevant. For example, part deformation is not a big issue when using the reverse grip, compared to using the force fit grip. It is important to design for a minimized gripper weight and a minimized gripper footprint. Placing the center of mass in the center of the gripper will result in the most predictable sorting result.

9 - Problem framing

To analyse where problems arise in the process, a process overview is created. This process overview was discussed in chapter 4. Material is stored on site for inspection. After this the material is shredded twice and then it is transported to an external location for separation. This graduation project focuses on a new concept in which Reukema separates the material on site, instead of selling it to an external party for separation.

At the beginning of this project, the aim of this project was around gripping, moving and releasing of an object. Taking a more critical view on these processes, made me realise that move is the main function and gripping and releasing can be seen as sub-functions of this function. This creates another solution space. This new solution space can be used in the synthesis phase to create designs which can move the scrap to sort it.

To conclude, we can say that the moving of an object is the main function of this assignment. How can a specific piece be moved in a designated bin for further processing? This question will be used in the synthesis phase as an input for a brainstorm.

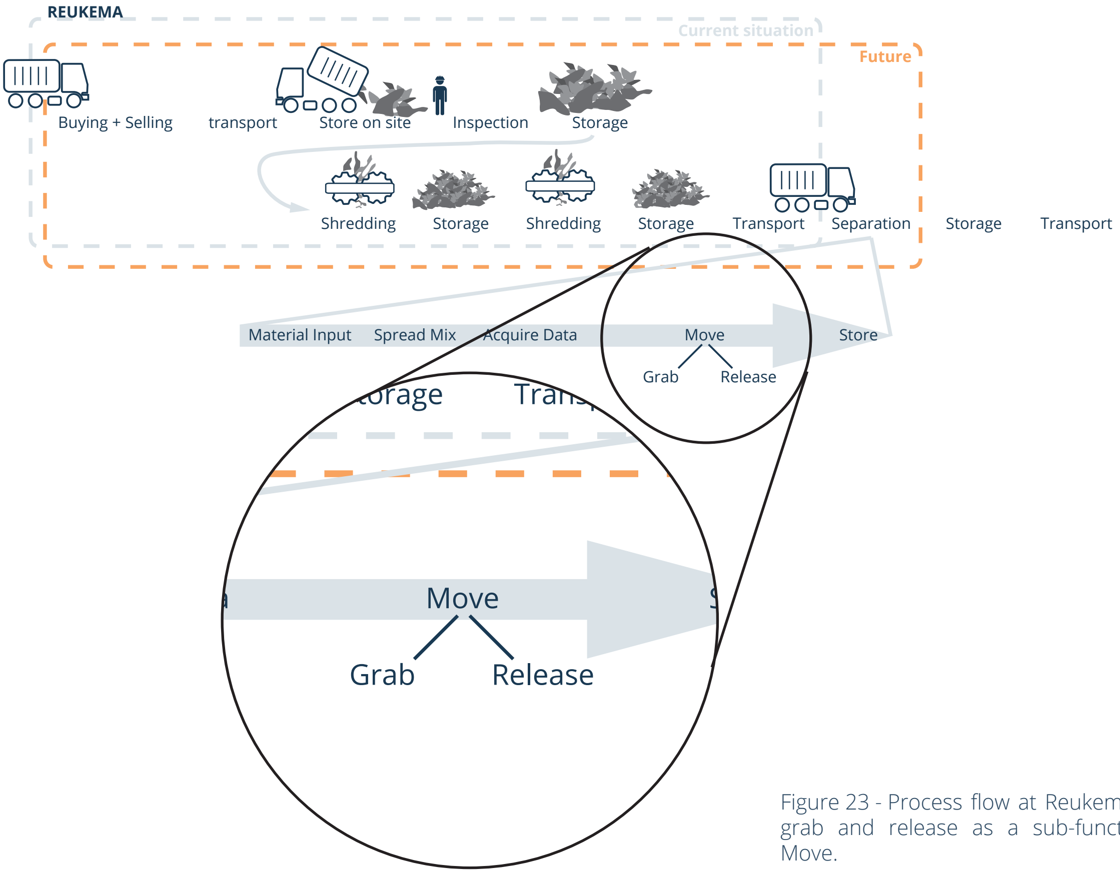


Figure 23 - Process flow at Reukema, with grab and release as a sub-function of Move.

10 - Selection Criteria

Throughout the analysis phase different Design Goals were formulated. These design goals can be used as selection criteria on which ideas and concepts can be scored in the synthesis and embodiment phase of this project. This section will discuss these selection criteria's.

Investment costs

Because the design needs to be constructed, investment costs will be made. These investment costs will be spread out over the lifetime of the system. As a result, they will have an influence on the cost per tonne. To create a profitable design, the investment costs should be minimized.

Operation costs

Reukema aims to build an automated sorting system which can function for multiple years. Operations costs have a direct impact on the cost per tonne. For this reason, teducing operation costs is important to be able to be competitive with other sorting techniques.

Feasibility

Reukema is looking for a design which is implementable within a short timespan. This means that the design should be feasible to execute within a year. It should not be a future vision for a sorting installation. The company aims to build a functioning prototype as soon as possible. Feasibility should therefore be maximized.

Precision

Maximizing the sorting purity is of importance for the quality of the sorted aluminium. The design moves pieces to the correct sorting place. This process should be precise to maximize the quality of the design.

Control over object

Object behaviour is an important parameter in the design. The accuracy of the movement of the pieces should be maximized. In other words, the control over an object should be maximized to increase sorting quality.

Simplicity

As Reukema is no front runner in technology, reducing complexity and creating a simple design is beneficial. Consequently, Simplicity in the design should be maximized.

Robustness

The system needs to handle dirty pieces of scrap metal. This means that it should be robust to be reliable. Pieces should be designed to be as robust as possible.

Maintenance

The system should demand as little maintenance as possible. Reukema is looking for an automated sorting system which can function with as little interference as possible. The design should aim for decreasing the need for maintenance. This increases the reliability of the system.

11 - Conclusion

Sorting aluminium scrap creates added value. As was shown, a valid business case can be created around the automated process of sorting aluminium scrap. Aluminium is one of the most used materials on the planet and the demand is still increasing. Recycling is a crucial factor for matching the ever increasing demand. Within the recycling process, sorting is an important step. Reukema aims to create an automated sorting system which can sort mixed aluminium scrap. Currently there is no solution on the market which is able to automatically sort mixed aluminium in the grain size Reukema wants to sort. As was shown, designing a reliable system is of great importance. This project focuses on the design of the gripper for the sorting of the aluminium scrap. The design challenge formulated is as following:

Design a gripper is able to move specific pieces of mixed aluminium scrap in a designated bin for further processing.

In the synthesis phase the conclusions and results from the analysis phase will be further used to design a system capable of sorting mixed aluminium scrap. The requirements which are set for the design can be found on the next page.

Because the company only has an idea of the complete design, and there is no concept yet. The synthesis phase will start broad. I will first work on designing a concept in which the gripper needs to function. As Stompff, Geraedts and Jansen (2008) put it: “it is impossible to design an element of a system without considering the entire system and how the elements interrelate”. After this the gripper can be designed in more detail.

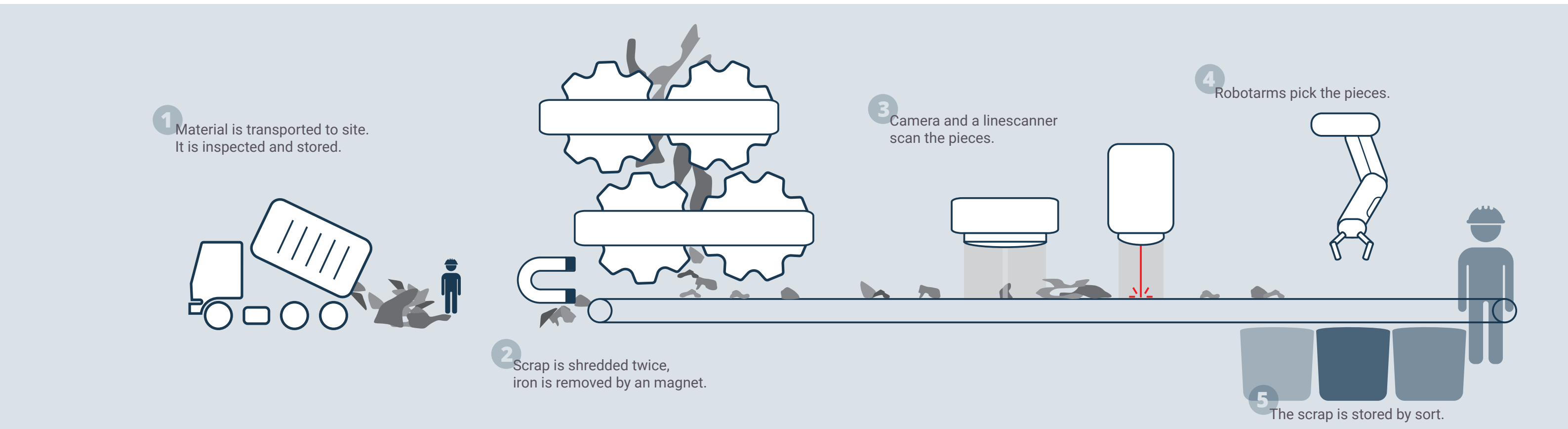


Figure 24 - Envisioned sorting system.

Overall requirements

- Sorting the aluminium scrap cost less than 55 [€/tonne] (investment and operation cost) (Ch. 4)
- The system sorts 20 [tonnes/hour] (Ch. 4)
- The system can sort 8 different groups of material (Ch. 6)
- Non sortable materials are collected for hand sorting by an employee (Ch. 4)
- The process of sorting can function continuously (Ch. 4)
- The material is transported through the system (Ch. 4)

Material input

- Shredded material can be inputted into the sorting system (Ch. 4)

Spread mix

- The mix of material is automatically spread out (Ch. 4)

Acquire data

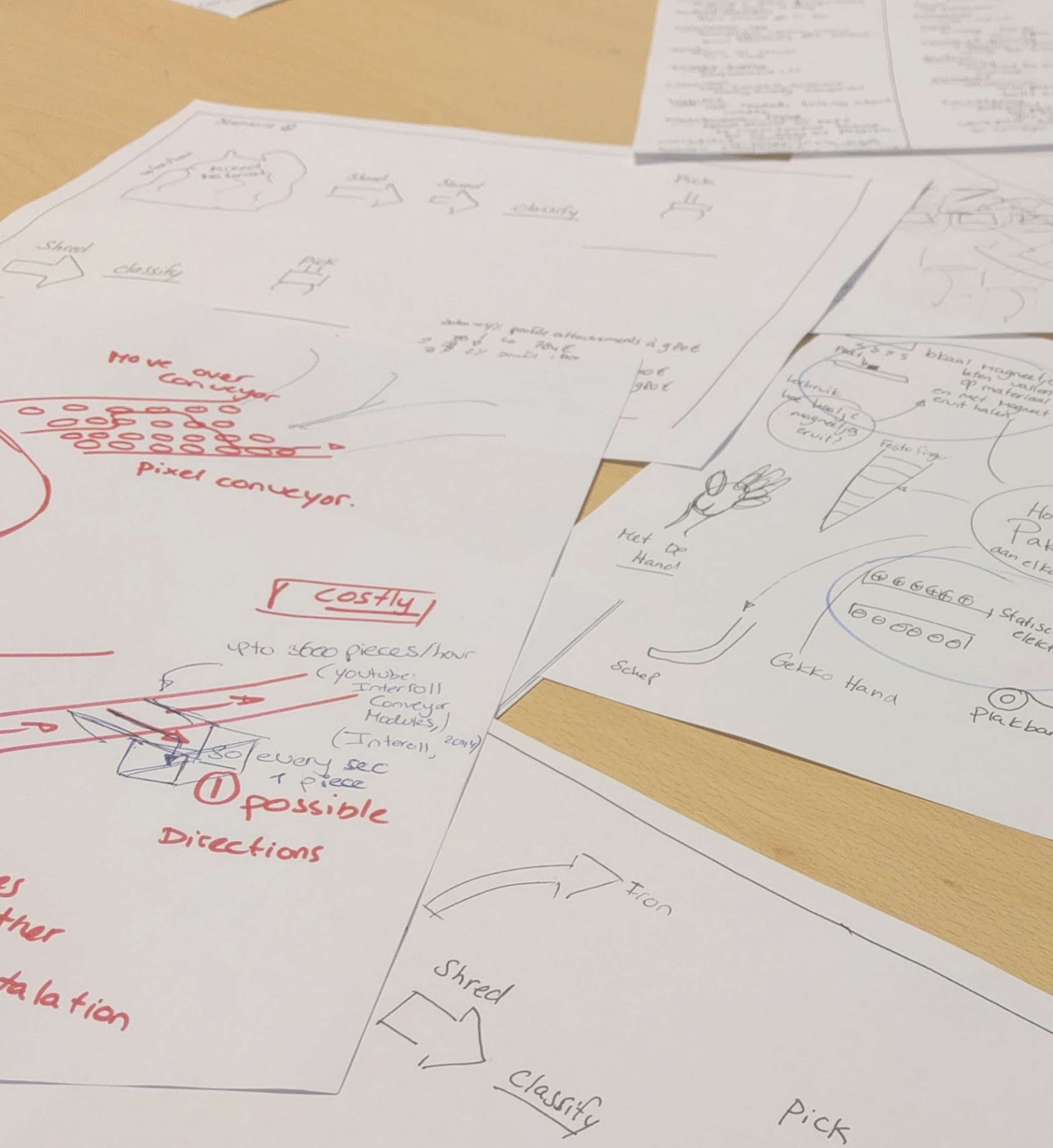
- X & y location of a piece of scrap is measured (Ch. 8)
- The velocity of the pieces of scrap is be measured (Ch. 8)
- The contour of the piece can be determined (Ch. 8)
- Pieces are classified based on the acquired data (Ch. 5)

Move

- The gripper is able to handle piece with a length of 10 - 514 [mm] (Ch. 6)
- The gripper is able to handle piece with a width of 10 - 261 [mm] (Ch. 6)
- The gripper is able to handle pieces with a weight of 10 - 700 [g] (Ch. 6)
- Grippers move 112.359 [pieces/hour] of aluminium scrap from a moving conveyor belt (20 [tonnes/hour] / 178 [g/piece]).
- 98% (or more) of the picks are successful (Ch. 4)
- The gripper has a pick cycle of 2 [s] or less (Ch. 7)
- The gripper is protected against dirt and condensation - IP62 (Ch. 8).
- The Young's Modulus of the material out of which the gripper is constructed is higher than 69 [GPa] (Ch. 8).

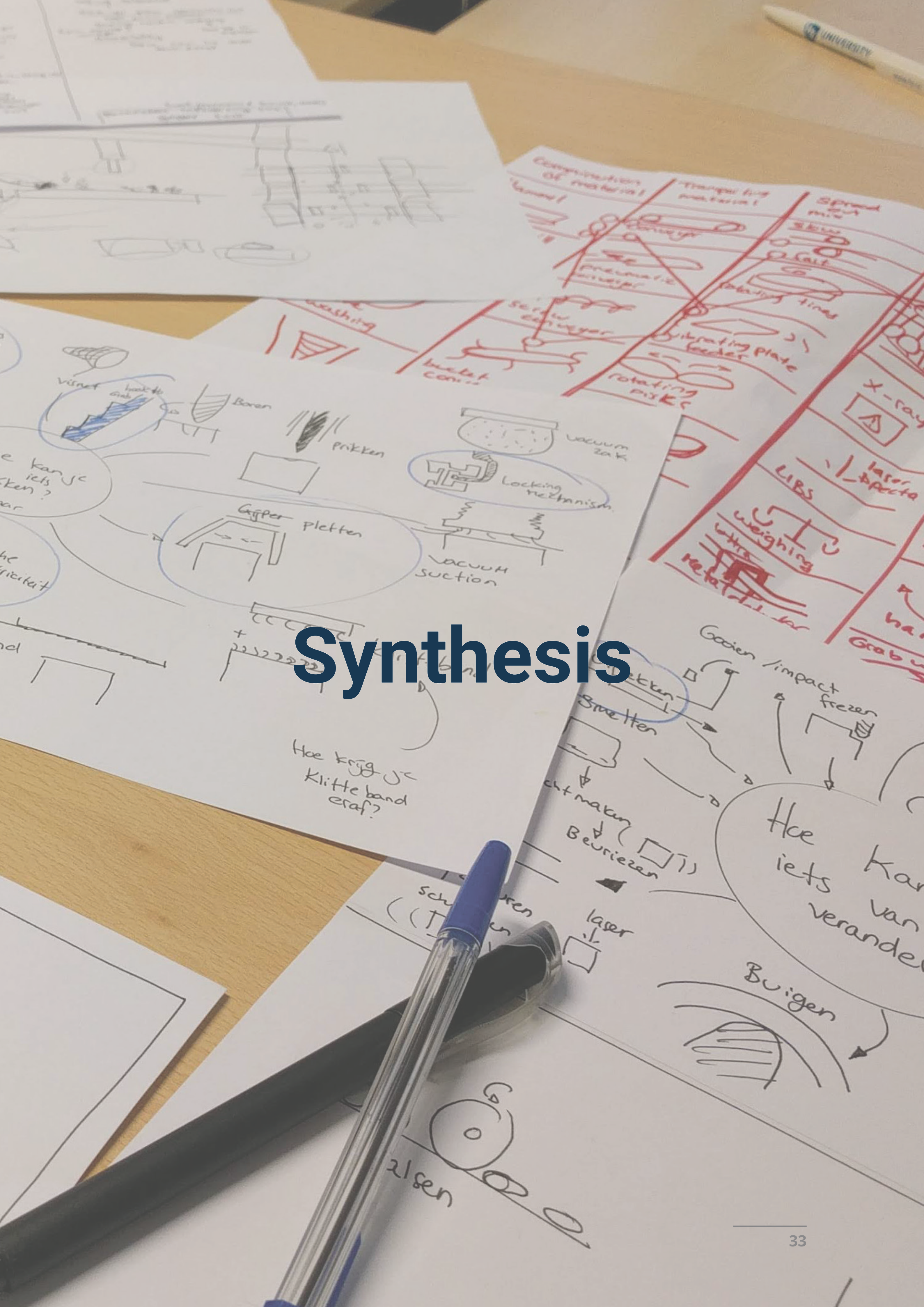
Store

- The sorted material is stored in such a way that the sorting process can continue continuously (Ch. 4)



In the synthesis phase the results and conclusions from the analysis phase will be used for idea generation and concept development. This section of this graduation report will discuss the ideation and concept development.

Synthesis


Boren
prikken
vacuum zak
Locking mechanism
pletten
vacuum suction
Hoe krijg je Klitteband eraf?
Gooien /impact
frezen
Beuriezen
laser
Buigen
weighing
LIBS

12 - Ideation

As discussed in chapter 9, the problem of this graduation project can be defined as 'How can material be moved in a designated bin for further processing?'. This question is used as input for the ideation. Although the focus of this graduation project is on the design of a gripper for sorting aluminium scrap, the gripper cannot be designed without considering the complete system in which it will function. Therefore the five different sub-functions, as identified in chapter 4, of the sorting system were used to generate concepts.

1 - Material input
Firstly, the material needs to be inputted into the sorting system. How will it be transported through the system? After shredding, this is the first step of the sorting installation.
2 - Spread Mix
To sort scrap, the pieces need to lie singulated so a gripper can manipulate them and move them in the correct storing bin. The incoming material mix needs to be spread out for successful sorting.
3 - Acquire Data
Data is needed to classify the pieces of scrap. Besides this, data regarding the location and velocity of the pieces is needed in order to successfully move them in the correct bin.
4 - Move
As was discussed in chapter 9, move can be considered as the main function with grab and release as subfunctions. A gripper needs to move material for succesful sorting. This gripper needs to move the pieces of scrap in the correct bin for further processing.
5 - Store
The last step in the sorting process is storing the pieces in a designated area in such a way that the sorting process can continue undisturbed.

Because the focus of this project is on the main function move - the design of a gripper - this function was used as the first input for a brainstorm. Different ideas to move the aluminium scrap were generated. The final design should be low in cost and high in feasibility. A C-Box (Tassoul, 2006) was used to select promising ideas. The C-Box can be found in figure 25. The ideas in the top left quadrant - low cost and easily feasible - were selected to developed out further in an idea direction.

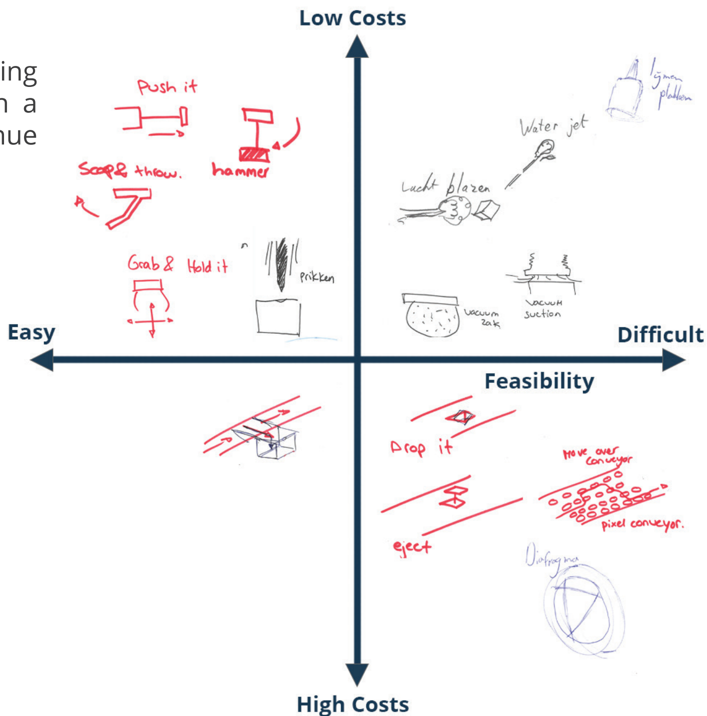


Figure 25 - C-Box; different ideas to move scrap rated on the feasibility and cost. The top left ideas - low cost and easily feasible - were selected for further detailling.

12.1 - Morphological Chart

The 5 different sub functions and their principle solutions were combined in a morphological chart (Roozenburg & Eekels,1998) to create a complete design solution. The morphological chart can be found in figure 26. The morphological chart helps to generate different design directions in an analytical and systematic way. Each column presents different principal solutions for a function. The most feasible principal solutions are shortly discussed below. For a complete overview of all the principal solutions, see appendix E.

12.1.2 Most feasible options per column

1 - Material input: Conveyor belts are a viable option to move material through the system. The technique of conveyor belts is widely used throughout the industry.

2 - Spread mix: Vibrating feeders are a robust solution for spreading material. This technique is seen in multiple sorting installations.

3 - Acquire data: Using a 3D scanner and a camera creates a low cost solution for acquiring data regarding the material that needs to be sorted.

4 - Move: A gripper gives a lot of control over the objects. Although for sorting, this is unnecessary because pieces do not have to be aligned in a specific position. The pusher is a low cost option which is expected to give a reliable sorting output.

5 - Store: Material stored under the installation in bunkers is the simplest option which does not obstruct the continuous sorting process.

The three most promising combinations of principle solutions were generated (figure 26). Three different idea directions were generated using the morphological chart. In the following sections the three idea directions will be discussed in more detail.

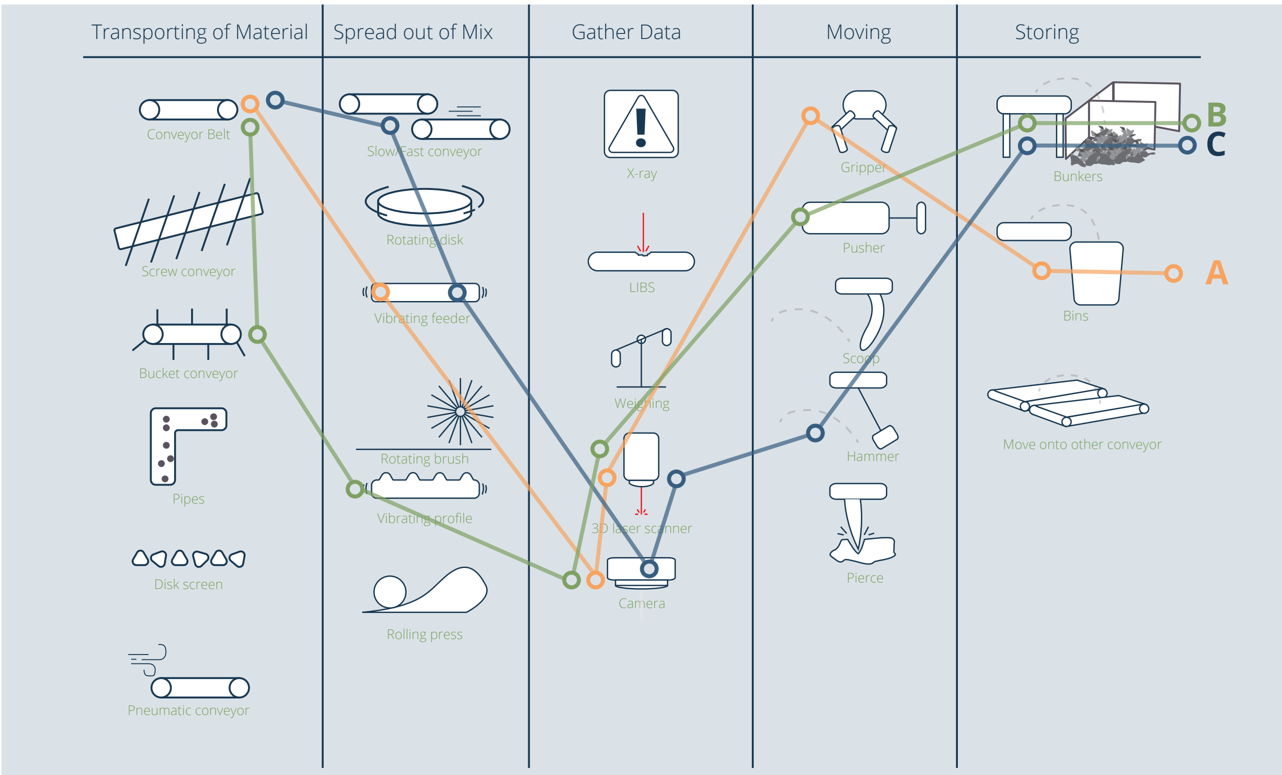


Figure 26 - Morphological Chart; overview of the sub-functions with their principle solutions. Three different feasible combinations were generated; A, B, C.

13 - Idea Directions

13.1 - A - Grab

Material is transported through the system using conveyor belts. To spread out the mix of scrap, a vibrating feeder is placed in line. Data is gathered by a camera and a 3D scanner. The 3D scanner creates a 3D surface based on which the material category can be determined. The camera facilitates in the distinction between blank and lacquered material. Koyanaka and Kobayashi (2009) validated this technique for the classification of metal scrap. Next, the material is grabbed by a mechanical gripper with fingers. The gripper grips the materials and removes them from the belt by lifting them - grab, move, release. The gripper releases the scrap to place it in a bin. The bin monitored remotely and manually removed when it is full. The idea is visualized in figure 27. The shredding of the material is included in the visualization.

13.1.1 - Scale

The requirements demand a system sorting 20 [tonne/hour]. This means that 112.359 [pieces/hour] need to be picked (20 [tonne] / 178 [g]). This results in 31,2 [picks/s]. Because a pick by a robot arm takes on average 2 [s] (Freyberg, 2011), this would require 63 robot arms to sort the aluminium scrap (31,2 [picks/s] * 2 [s/pick]).
Reukema set the width of the conveyor belt to 2 [m] as a starting point. Therefore the conveyor belt in this concept is also 2 [m] in width. This means that a robot arm should have a radius of at least 2 [m]. This results in a 120 [m] long sorting line, if placed in a single line.

13.1.2 - Investment Cost

According to the Key account manager of the Grip-it! group at Festo (Henrico van Zuilen, personal communication, 30 October, 2018), a Gantry costs approximately €25.000. Taking only the costs of the actuator into account, this leads to an investment cost of €1.575.000.

13.1.3 - Precision

A robotic gripper can precisely grip a piece of aluminium scrap (Wolf, Steinmann & Schunk, 2005; Monkman, Hesse, Steinmann & Schunk, 2007) and it can be controlled in great detail, however this is unnecessary in the sorting installation to be designed in this project. This adds costs and requires more computing power. An advantage of using a robot picker, is the ability to handle overlapping objects (Lukka, Tossavainen, Kujala & Raiko, 2014). However, using a robot picker does increase the complexity of the system drastically.

13.1.4 - Robustness

In a robotic arm are a lot of moving parts which can get damaged during the process. The robotic arm and gripper are sensitive to changes and can be considered to not be robust.

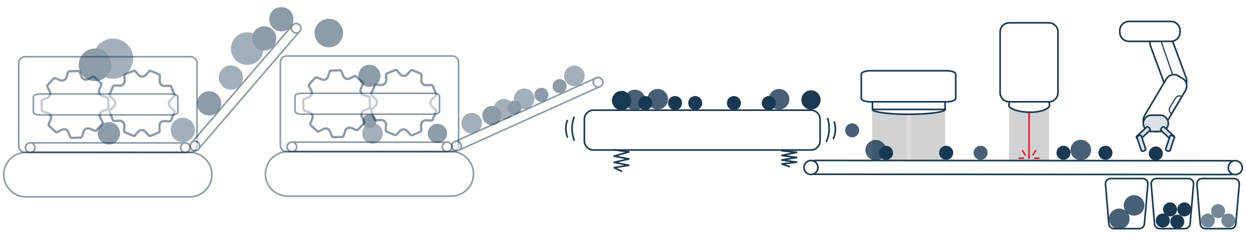


Figure 27 - Idea direction A: Gripper. (1) Material is transported by a conveyor belt and (2) spread by a vibrating feeder. (3) A camera and 3D line scanner gather data for the control of the (4) robotic gripper, which (5) stores the pieces of scrap in bins.

13.2 - B - Push

Material is inputted into the system and transported by a bucket conveyor and a conveyor belt. A vibrating feeder is used to spread the mix and place all the pieces in one line. This is necessary for the pusher to function correctly and sort one piece of scrap at the time. Data acquiring is done in the same way as in the previous idea direction; with a camera and a line scanner. The scrap is pushed off the conveyor belt for storing by a pusher. The scrap falls of the belt into a bunker below the sorting line, where employees can remove it manually or with the aid of a machine (e.g. shovel). The idea is visualized in figure 28.

13.2.1 - Scale

The maximum length of a piece of scrap found was approximately 500 [mm]. For the pusher it is essential that the pieces are positioned behind each other. This means that either the speed of the conveyor belt needs to be increased, or the number of conveyor belts need to increase, in order to sort 20 [tonnes/hour]. Placing all pieces on a conveyor belt in a line, would result in a speed of 15,6 [m/s]. Typically conveyors run at a maximum of 4,0 [m/s] (Fenner Dunlop, 2009). In other words, increasing the speed is no option.
Increasing the number of conveyor belts to 8 results in a conveyor belt speed of 2 [m/s] (=112.359 [pieces/hour] x 0.5 [m]), which is normal to use in a standard application (Ullamnn, n.d.). We can conclude that increasing the number of belts is a better option to reach the sorting quotation.
Using 8 belts means that there are 64 pushers needed to sort 8 different groups of material. Unsortable material is left on the belt and will flow into a container for further processing by hand.
For this idea direction, belts can be smaller compared to idea direction A. If we assume a belt width of 500 [mm] (the maximum length of a piece of scrap) and we would estimate that the opening of a storing bin is double this size, this would mean that we need a line of 64 [m].

13.2.2 - Investment Cost

A pneumatic linear actuator costs around €600 (RS Components, 2018). This means that this would result in an investment cost of €38.400 for 64 pushers.

13.2.3 - Precision

It is expected that the precision of pushing an object of a conveyor belt depends mainly on the timing of pushing. Compared to a robotic gripper, there is less control over the behaviour of the object. But less computing power is needed to perform the action, which makes it less complex.

13.2.4 - Robustness

For a pusher, a linear actuator needs to move forward and backward. There are less axis and motors which can get damaged compared to a robotic gripper. This means that a pusher is more robust compared to a robotic gripper.

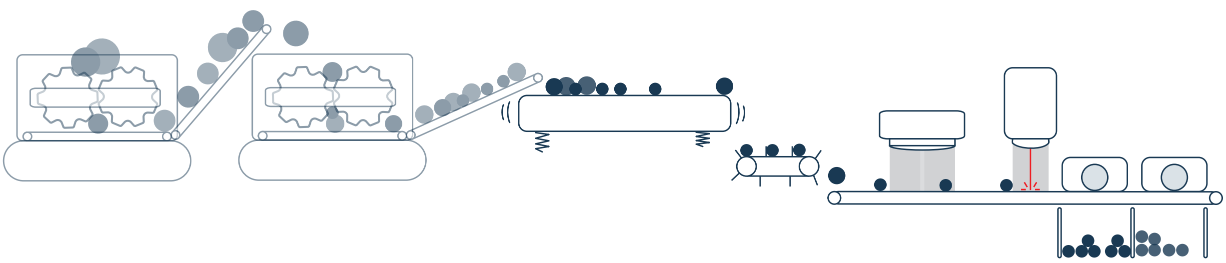


Figure 28 - Idea direction B: Pusher. (1) Material is transported through the system by a conveyor belt. (2) The material is spread by a vibrating feeder with a profile for alignment. A bucket conveyor makes sure material is inserted in controllable batches. (3) A camera and a 3D line scanner gather data, (4) which is send to a pusher to push the material of the belt in (5) bunkers situated under the conveyor belt.

13.3 - C - Smash

Pieces of scrap are transported by a conveyor belt. A vibrating feeder and a conveyor belt at a different speed spread the material. The data is acquired in the same fashion as in idea direction A & B; with a camera and a line scanner. The pieces are moved of the conveyor belt by a moving hammer. This hammer gives the pieces an impact force, which swings the pieces of the belt. The pieces are stored in a bunker under the conveyor belt (Figure 29)

13.3.1 - Scale

To move a hammer, a robot arm or gantry is needed. This would mean that a 'pick' would take approximately the same amount of time, compared to a robot arm with a gripper. So we can conclude that you would also need 63 robot arms

For the length of the complete system, we can compare this idea direction to the pusher. A hammer needs to swing perpendicular to the moving conveyor belt. The assumption is made that a bin with an opening of 1000 [mm] would be big enough to catch all pieces successfully. This means that this system would be 64 [m].

13.3.2 - Investment Cost

If a gantry costs €25.000 (Henrico van Zuilen, personal communication, 30 October, 2018), we can conclude that the investment costs of idea direction C are comparable to idea direction A; €1.575.000. Because a gripper is complexer compared to a hammer - more control is needed - it is expected that the investment of the hammer is slightly lower compared to a gripper.

13.3.3 - Precision

When an object is hammered or smashed of a conveyor belt, there is little control over the behaviour of the object. This means that the precision of sorting is decreased due to the unpredictable behaviour of the object. Compared to the robotic gripper there is less computation power needed, but more compared to the pusher.

13.3.4 - Robustness

Looking at the robustness of a hammer system, we can conclude that it is less robust compared to a pusher, but more robust compared to a robotic gripper. This simply has to do with the amount of axis and motors which can get damaged or broken.

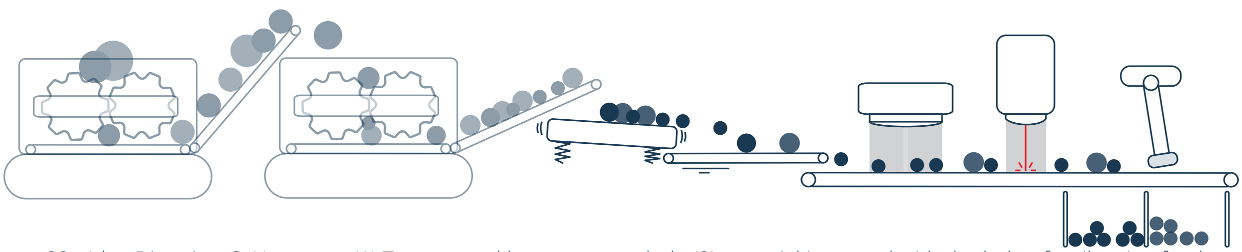
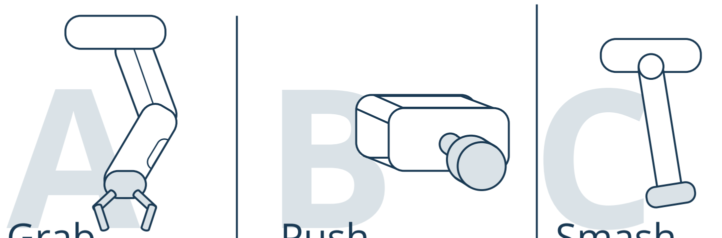


Figure 29 - Idea Direction C: Hammer. (1) Transported by a conveyor belt, (2) material is spread with the help of a vibrating feeder and a conveyor belt at a different speed. (3) A camera and a 3D scanner gather data, (4) which the Hammer uses to swing the pieces of a conveyor belt and (5) store them in bunkers below the system.

13.4 - Selection and Conclusion

The three idea directions are scored based on the selection criteria discussed in chapter 10 (figure 30). The selection criteria are scored as following: -- (very bad), - , +/-, +, ++ (very good), based on the gathered information and the designers experience.

Looking at figure 30, we can conclude that idea direction B has the most potential based on this scoring. Therefore this idea direction will be used to create concepts around and elaborate on. By selecting idea direction B, new design challenges arise. The following chapters will discuss the design challenges of idea direction B.



	A Grab	B Push	C Smash
Simplicity	-	+	+
Feasibility	+/-	++	+
Control over object	++	-	--
Maintenance	--	++	++
Robusteness	-	+	-
Price	--	+	+
Precision	++	+/-	--

Figure 30 - Three different idea directions rated according to selection criteria. The idea direction Push was rated best based on the selection criteria.

14 - Push: Design Challenges

The selected idea direction brings forward different design challenges. This chapter will shortly address these challenges.

Figure 32 gives an overview of the identified design challenges. Firstly, pieces of scrap need to be place in line in order to sort them. How can this be done? Section 14.1 discusses different methods currently in use for singulating pieces. Secondly, the in-feed of the system is important for the quality of sorting. Research was conducted to validate if it is possible to do this with a vibrating feeder. Section 14.2 discusses the results of this research. Thirdly, it is important to get an estimation of the center of mass. As discussed in chapter 8, puting the center of gravity at the grippers center will increase the sorting reliability (Eitel, 2010). Section 14.3 investigates possible ways to estimate the center of mass of a piece of scrap. Lastly, different linear actuators are discussed in section 14.4.

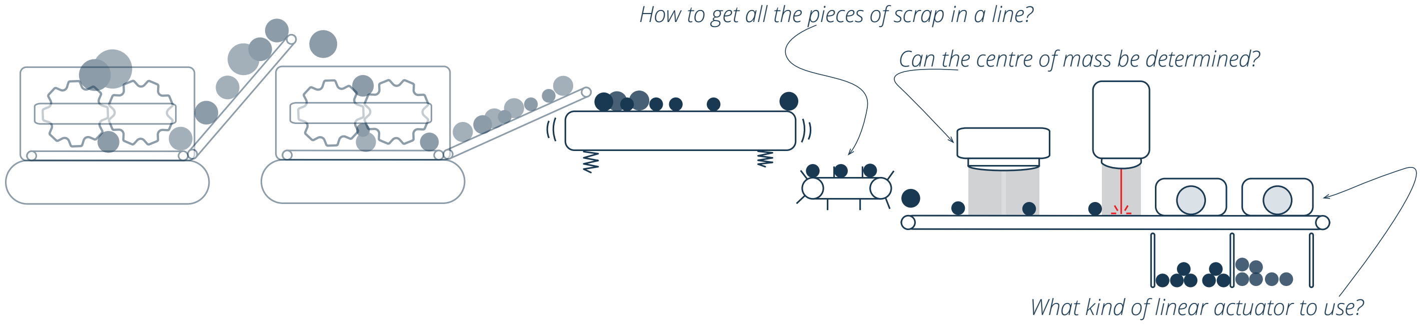


Figure 32 - Overview of the Design Challenges identified for the selected idea direction.

14.1 - Scrap in line - How to get all pieces behind each other?

Pushing pieces of scrap off a conveyor belt in this design, requires the pieces to be lined up behind each other. Because all pieces are different in shape and size it is a challenge to place the pieces in a single line on a conveyor belt. Market research was performed to identify systems currently in use to singulate products. The results are discussed below.

14.1.1 - Unscrambler

The unscrambler is a round machine which inputs products into a line, piece by piece. The products are rotated on a disk with an opening on one side. The opening is big enough to fit one product at a time

Figure 31 - Unscrambler; water bottles are transported into the machine in batches and exit in a line one at the time (Tomra, 2017).

14.1.2 - Vibrating ZigZag

The vibrating ZigZag feeder places every product in the correct orientation and behind each other. This is done by a vibrating movement, in combination with a zigzag pattern on the bottom of the vibrating machine. This machine is used for example in a production line for sausages (ABBRobotics, 2010).

Figure 33 - Vibrating ZigZag; sausages enter on the left and by vibrating a sharkteeth-like surface, the sausage align (ABBRobotics, 2010).

14.1.3 - Multilane singulator

A multi-lane singulator is a conveyor belt with a funnel at the end, see figure 34. Products are forced to form a line by the funnel shaped sides (Vande Berg Scales, 2014). To aid the singulation, the conveyor belts are controlled one by one.

14.1.4 - Vertical bar separator

The vertical bar separator separates pieces by forging them into a specific lane, by the placement of vertical bars.

14.1.5 - Form-fit singulator

A rotary disk with the negative shape of the product rotates and grabs products from a pile. This machine is used for example in the battery industry (Trimantec, 2014).

14.1.6 - Screw Unscrambler

A screw is used to control the in-feed. The screw rotates and thereby grabs a product at the time to feed it into the system. This machine is used for example in the wood industry for lifting single logs (Hein, 2015)

14.1.7 - Steinert Line Feeder

As discussed in chapter 7, Steinert is able to sort aluminium scrap using LIBS. To do this they line the scrap in order to scan it by laser. Figure 37 shows a snapshot of the architecture of the vibrating feeders used.

14.1.7 - Conclusion

Steinert is the only company which is able to place irregular shaped pieces in a line. By combining multiple vibrating feeders placed perpendicular to each other, the company can control the in-feed of material. It is not clear what the details of the installation are. More research is needed to investigate how the system works and if there are any constrains such as patents.

Another possibility to feed pieces one by one is using the vibrating ZigZag. If enlarged, it may be able to singulate pieces of aluminium scrap. By creating a profile in the vibrating feeder, pieces can be singulated and placed after each other. Testing is needed to test whether the vibrating zigzag is a working solution for the problem.

Figure 34 - Multilane singulator unscrambler ; packages enter on multiple conveyor lanes and are redirected to one lane by controlling the entering conveyors in sequence (waldropproducts, 2009).

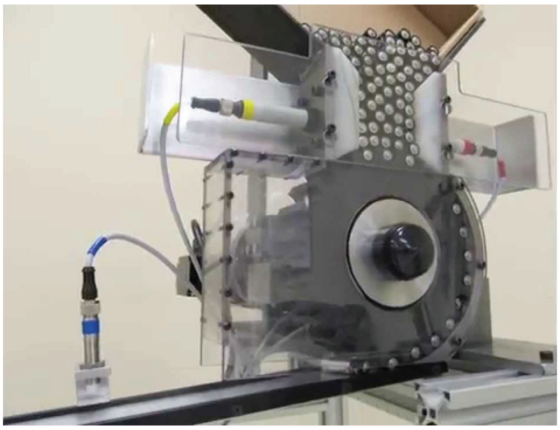


Figure 36 - Form-Fit singulator; batteries are inserted in the top and exit on the bottom one at the time (Trimantec, 2014)

Figure 35 - Screw unscrambler; Trees enter on the right while a screw is rotating. This screw scoops the trees up and transports them one by one upwards (Hein, 2015).

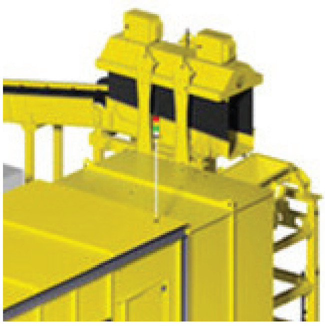


Figure 37 - Singulator for sorting aluminium scrap by Steinert. Scrap comes in from the left and is fed in a vibrating feeder (black), falls into a perpendicular vibrating feeder. (Steinert global, 2019)

14.2 - Vibrating feeder

To spread the incoming material feed in the design, a vibrating feeder is used to spread the mix. A test was conducted to validate the spreading of the vibrating feeder and the spreading. It is required that the pieces of scrap lie singulated. Secondly, it is necessary that the pieces are not positioned next to other, in order to able to push them off the belt. The aim of this test is to see whether it is possible to use a vibrating feeder to spread the mix equally over the belt and to get all pieces behind each other in a line. All data gathered during this test can be found in appendix

14.2.1 - Method

Four different batch sizes were inserted into the vibrating feeder: a full bucket (45 pieces), 20 pieces, 10 pieces and 10 pieces fed two pairs at one time. The pieces were selected randomly. The vibrating feeder was 480 [mm] in width, 1240 [mm] in length and has a slope of 6o. The output was filmed using a smart phone and later used for analysing the results (figure 38). The amount of pieces which were completely liberated were counted versus the amount of pieces which were lying on top of each other. Each test was conducted three times.

14.2.2 - Results

Table 2 shows that a smaller feeding portion leads to more pieces lying singulated on the belt. Feeding 10 pieces into the vibrating feeder in a small batches (2-3 pieces at a time), results in 90 % of the pieces being liberated. The analysis of the video shows that the falling of the material helps in liberating more pieces. When the pieces leave the vibrating feeder, they fall approximately 0.5 [m]. This fall helps in liberating pieces.
The analysis also showed that pieces were ending up besides each other. This means that by using this setup it is not possible to push pieces off with the use of a pusher. Some preliminary tests were conducted by narrowing the output of the vibrating feeder, see figure 39. This helped in outputting piece after piece, but also resulted in pieces getting stuck in the vibrating feeder.

14.2.3 - Conclusion

To conclude, we can say that a smaller batch size inputted in small portions provides the highest percentage of liberated pieces. Besides this, we can conclude that dropping the pieces helps to liberate even more pieces. Using a bucket conveyor helps in inputting the material in small portions. Secondly, using two vibrating feeders in serie can help to liberate more pieces. Material falls from the first into the second feeder. The fall facilitates in the extra liberation, and the first vibrating feeder in feeding the material in smaller batches.
It was observed that pieces were lying besides each other, which obstructs sorting. Using a vibrating feeder with a smaller opening is an interesting research topic, but also results in pieces getting stuck. Another option could be to place the vibrating feeder perpendicular to the conveyor belt - as in the sorting system of Steinert global (2018). Lastly, setting the speed of conveyor belt higher, causes the material to be more spreaded in the y-direction. This can facilitate in placing pieces more in line.

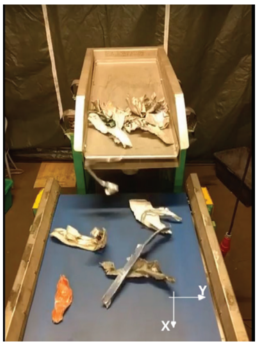


Figure 38 - Still of the video footage used for analysis; Scrap falls off the vibrating feeder onto the conveyor belt which moves in the positive x-direction.

Figure 39 - Using a wooden block to narrow the output of the vibrating feeder, in order to singulate pieces. Result: Pieces got stuck in the feeder.

Table 2 - Average amount of liberated pieces per batch size (3 repetitions per test).

	Full bucket	20 pieces	10 pieces	10 pieces in batches
Average amount of piece singulated [%]	31 SD= 6	40 SD= 5	66 SD= 11	90 SD= 10

14.3 - Centre of mass

The requirements demand that the gripper's center can be placed in line with the center of mass. This means that based on the data gathered, the center of mass needs to be determined. The difficulty of this design challenge is the balance between getting a fully detailed image of the pieces of scrap and the processing time. The more data you gather, the better you can estimate the center of mass, but this also leads to increasing costs and more processing time, which increases the overall complexity of the system. This chapter investigates how the center of mass can be determined based on the two data streams - a camera and a line scanner - in the design.

14.3.1 - Area Centroid

The 3D scanner outputs a point cloud which can be transformed into a surface. Based on this surface, the area centroid can be determined using Rhino.
The second method to determine the center of mass based on a surface, is by using a photograph. Based on the 2D camera image, the center of mass was determine by using a Matlab script created by Wells (2013). This showed that the center of mass in both methods was exactly the same. Therefore the area centroid was only based on the 3D surface scan.
A drawback of this method is the underestimation of the material. Overhangs limit the view on the complete part and thus result in an underestimation of the area of the piece of scrap (figure 40).

14.3.1 - Volume Centroid

The 3D line scanner outputs a point cloud of the top surface of a piece of scrap. This point cloud can be transformed into a surface. In Rhino this surface can be transferred into a 3D model by extruding the surface until the bottom plane (figure 40). In Rhino the center of mass was determined of 21 different samples, using the VolumeCentroid function. Using this method results in measurement errors, which is the exaggeration of material (figure 40) (Koyanaka & Kobayashi, 2010).

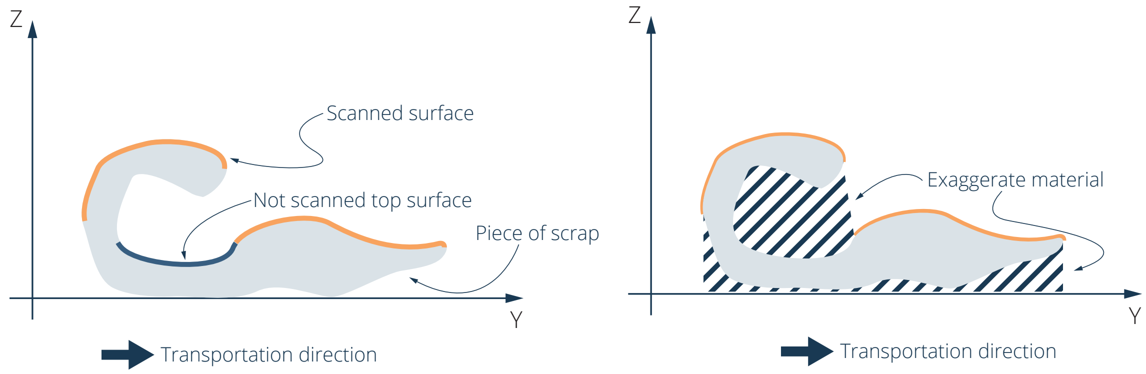


Figure 40 - Left: not scanned surface due to overhang. Right: exaggerated material when extruding 3D surface to a solid.

14.3.3 Conclusion

It is not possible to create a complete 3D scan of thin objects like sheet aluminium (B. Naagen, personal communication, 1 April, 2019). Therefore, the 3D surface scan is currently the best way to approach the center of mass of the objects.
Because the AreaCentroid underestimates the volume, and the VolumeCentroid overestimates the volume, it is expected that the center of mass lies between these two values. The pieces of scrap move in the y-direction along the pusher, this means that the y-location of the center of mass is the most important parameter for a successful sorting result. The difference between the AreaCentroid and the VolumeCentroid is 39 [mm] (99.7% CI). Because this difference can be on both sides of the center of a piece of scrap. We can conclude that the minimum width of the pusher needs to be 80 [mm], in order to ensure that the center of mass is aligned with the center of the gripper.

14.4 - Linear Actuator

Based on Dietrich (2017) and Rosenfeld (2017), there are three main linear actuator groups; Pneumatic, Hydraulic, and Electric. To move the pieces of scrap from a moving conveyor belt, one of these linear actuators is needed. This section will discuss the different actuator types, after which a selection will be made.

14.4.1 - Pneumatic

Pneumatic actuators are low-cost options within the rod-style actuators. A pump or external compressor moves a piston in a hollow cylinder.

Pneumatic actuators are energy inefficient (figure 41). A major disadvantage of pneumatic linear actuators is their "limited flexibility in performance and capability" (Dietrich, 2017). It is difficult to regulate speed, control multiple positions, or do mid-stroke positioning. Pneumatic actuators are noisy due to the need of compressors and the release of air from the system. Lastly, pneumatic actuators require an infrastructure to function.

14.4.2 - Hydraulic linear actuators

Hydraulic actuators are similar to pneumatic actuators. However, instead of air, a liquid is used to move the actuator. Hydraulic actuators are more expensive compared to pneumatic systems, but they can exert extremely high loads.

14.4.3 - Electric

Electric linear actuators can be fully programmed. This means motions can be tightly controlled. Operation costs are lower compared to pneumatic systems. However, initial investment costs are higher. Prices can range from 3 to 10 times higher compared to pneumatic systems.

Looking at installation, cabling from and to the drivers is needed. This increases costs and the footprint of the installation.

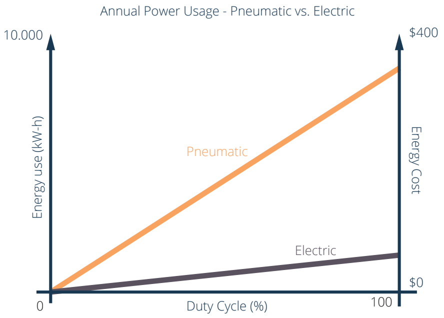


Figure 41 - Annual power usage versus energy cost for different duty cycles - pneumatic vs. electric linear actuators (Based on Dietrich, 2017).

Table 3 - Overview of different advantages and drawback of pneumatic hydraulic and electric linear actuators (Based on Rosenfeld (2017)).

	Pneumatic	Hydraulic	Electric
Price Investment	Low	High	High
Operating cost	Moderate	High	Low
Speed	High	Moderate	Moderate
Complexity	Simple	Moderate	Moderate
Position Control	Difficult	Difficult	Simple
Lifetime	Moderate	High	High
Load	High	Extremly high	High
Efficiency	Low	Low	High
Emergency stop	Hard	Hard	Easy

14.4.5 Conclusion

Table 3 summarises the advantages and disadvantages of the different actuator types. We find that the operation costs of electric linear actuators are low compared to the other groups. A drawback however are the high investment costs. Besides this, it is possible to easily control the position of an electric actuator. This is important for accurately pushing material of a conveyor belt. It is expected that lighter pieces should be pushed off with lower force compared to heavier objects. Lastly, electric actuators are safer to work with due to their short shut down time. Therefore, we can conclude that an electric actuator is the best options for the concepts.

After the concept selection the selection of an electric linear actuator will be discussed in more detail.

15 - Concepts

Three different concepts were generated based on the idea direction Push. This section will discuss the three different concepts generated.

15.1 - Push

Pushers push pieces off a moving conveyor belt. To do this, pieces of scrap are placed in a single line on a conveyor belt. Pieces are classified based on the sensor data of the 3D scanner and the camera.

15.1.1 - Specifications

Push is a concept in which 8 conveyor belts with a width of 0.5 m are stacked in two columns. Material is placed on the conveyor belt in a line. Pushers push the material off the side into a bunker under the installation. From here it can be removed using a manually operated shovel (2,3 [m] in width). Per conveyor belt 8 different materials can be sorted, so 8 pushers per conveyor belt are needed. Bringing the total amount of pusher to 64. Besides this, 8 sensor modules are needed for classification of the material.
The conveyor belt is set to move at 2[m/s]. To make sure all pieces fit on the belt, the belt needs to be 0,5 [m] in width. Because there are 8 belts, this means every belt should carry 14.044 [pieces/hour] or 4 [pieces/s]. This means that every 500 [mm] one piece should pass by. In other words, the pieces need to lie head to tail without any space between them. Therefore, space between the pieces is necessary for successful sorting. So we can conclude that this way of sorting is not feasible. Sorting 20 [tonnes/hour] can only be reached by scaling the system - increasing the number of conveyor belts.
The typical maximum acceleration of a belt driven linear actuator is 50 [m/s2] (Festo Group, n.d.c). This means that a minimum of 300 [mm] is needed between the pieces to facilitate sorting. When the space between pieces is 300 [mm], then every 814 [mm] (300 + 514) a piece comes along. Every 0,4 [s] a piece is moved over the belt (0,814 / 2). This means 9000 pieces in an hour (3600 / 0,4). Since we have 8 belts and an average weight of 178 [gr], this means that 12,8 tonnes of scrap is fed through the system in an hour.
To be able to sort the material using a pusher from the side, material needs to be aligned behind each other. The in-feed of the system needs to be in a line. As was seen in the sorting installation of Steinert global (2018), feeding scrap in one line is possible (chapter 7). But, more testing is needed to validate the use of vibrating feeder for the in-feed of the material.

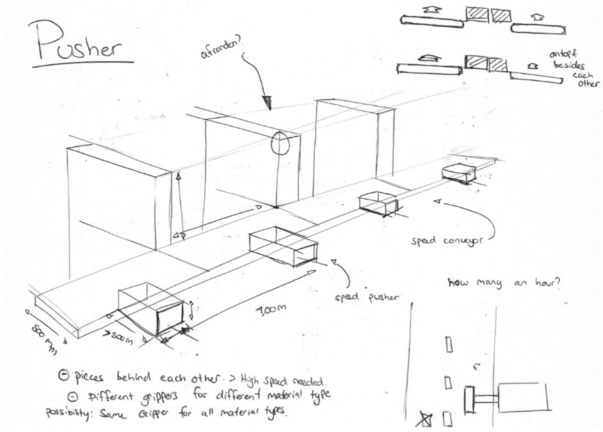


Figure 42 - Sketches of the concept Pusher.

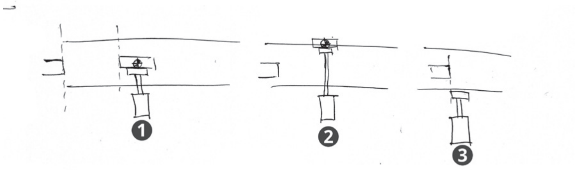


Figure 43 - Pusher steps; (1) Touch material (2) Push material off belt (3) Return to starting position before new piece enters.

15.1.2 - Feasibility test

The feasibility of the concept was tested using three different wooden prototypes (figure 44). 20 random pieces of scrap were pushed manually to test the feasibility of pushing scrap with a pusher. Based on the results (figures 45 till 47) we can conclude that it is possible to push material into a designated area with the help of a wooden prototype. The prototype which was yawed under an angle of 30°, pushed the material into a groups which was 15° off the centerline. More structured testing is needed to validate the design further.

15.1.3 - Cost

An estimation of the investment costs was made. The complete calculation can be found in appendix H. It is estimated that the concept pusher will cost € 1,6 million in investment costs for the complete system. To exacute the concept, it is estimated that 5 operators are needed to handle the machine (1 for overview of the system, 1 for removing sorted material, 2 for over viewing the conveyors and solving problems, 1 shift manager). The energy consumption is based on the consumption of the conveyor belt and the actuator. Energy consumption and employment costs combined, brings the variable cost at € 9.355 per week.

15.1.4 - Gripper Design

To prevent the gripper from deforming when pushing aluminium scrap off the belt, the selected material should have a higher Young's modulus and Hardness compared to the scrap. In addition it is required, from a environmental perspective, that the material of the gripper can be recycled. Besides this, the material should have a high fracture toughness. Using CES (Granta Design Limited, 2018) different materials were investigated. Steel was found to be harder and cheaper compared to aluminum. Designing the gripper out of steel will create a low cost and low maintenance gripper.

The maximum length of the pieces is 514 [mm]. The aim is that the pusher pushes the material in a line with the center of mass. By creating a pusher which is half the maximum length of a piece, the pusher head is big enough to push pieces off the conveyor belt. The height of the pusher head is set to 125

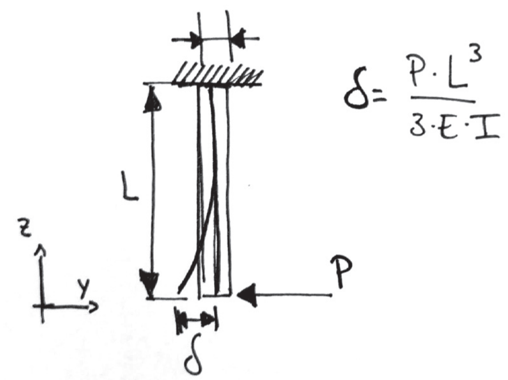


Figure 49 - Deflection of the pusher, when a load P is exerted on the corner and the top is clamped. The pusher is made out of steel (E= 210 GPa), and is 0.25 * 0.125 * 0.002 [m. The deflection is 6,5*10^-4 [mm].

[mm], half the width of the pusher. When the heaviest piece is pushed by the system with an acceleration of 50 [m/s2], the pusher deflects 6,5 *10^-4 [mm] (figure 49). This deflection can be neglected, meaning that the pusher is stiff enough.

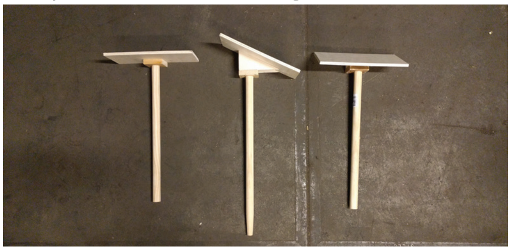


Figure 44 - Wooden prototype pushers to validate the feasibility of the concept; straight, yawed, pitched.

Figure 45 - Result of straight pusher; pieces being pushed forward and aligned around the center of the pusher.

Figure 46 - Result of pitched pusher; pieces are on line with the center of the pusher.

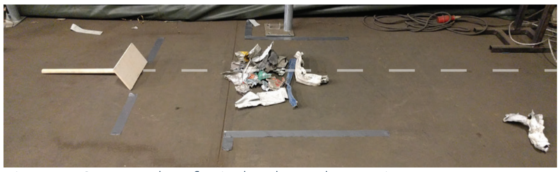


Figure 48 - Result of pitched pusher; pieces are on line with the center of the pusher.

Figure 47 - Result of yawed pitcher; pieces are approximately 15 degrees off center when pushed with a pusher under an angle of 30 degrees.

PUSH

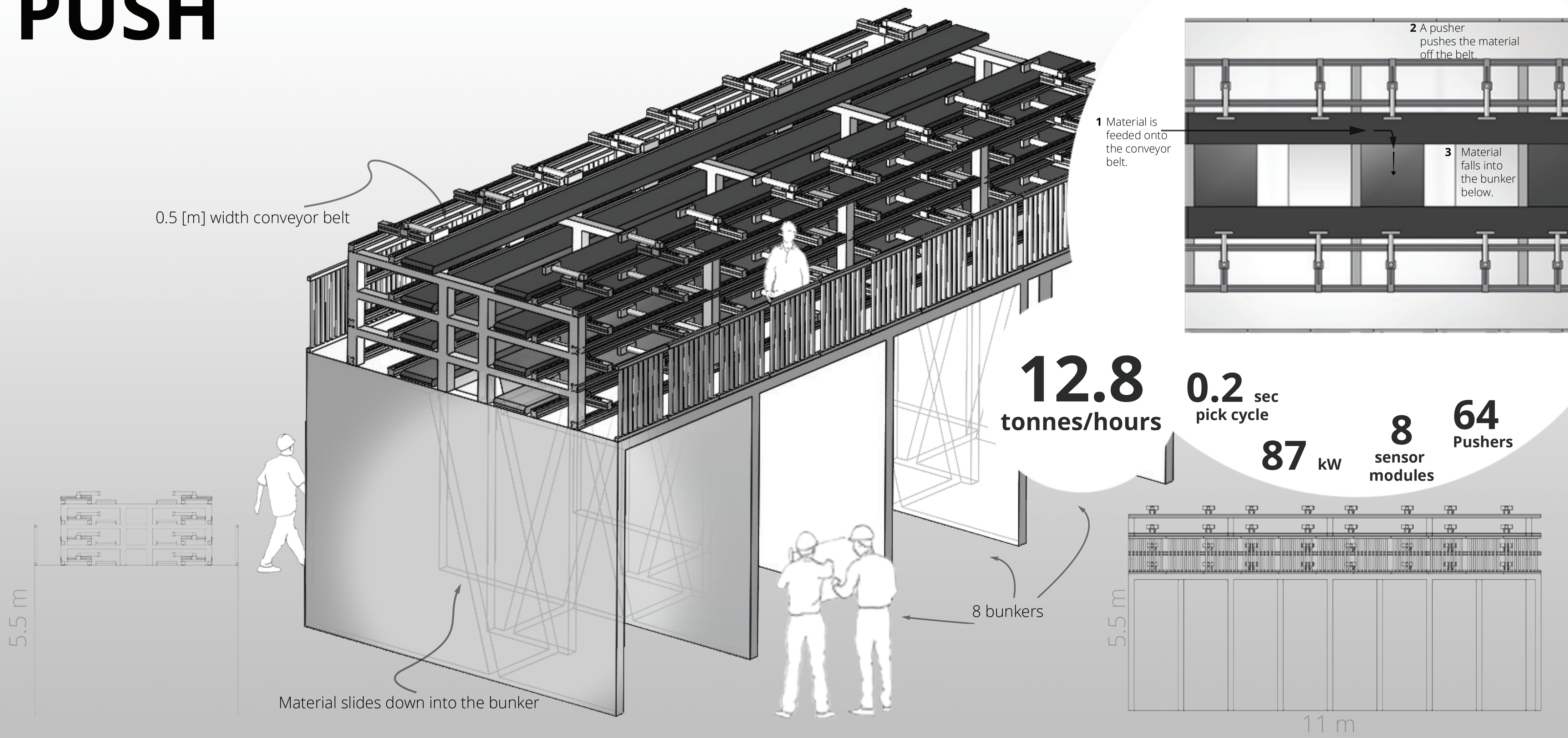


Figure 50 - Concept Pusher overview.

15.2 - Pull

Another concept is Pull. A hook pulls pieces off a conveyor belt. The conveyor belt moves the pieces into the hook and the hook pulls these pieces off the belt. The hooks remove scrap from the outside of the belt inwards. This means that the last hook needs to move further compared to the first hook.

In this concept a conveyor belt with a width of 2 [m] feeds the material into the system. Pieces of scrap are scattered over the conveyor belt. The hook moves outwards onto the belt. Secondly, material is moved into the hook by the moving conveyor belt. Lastly, the hook pulls the material off the belt and the material falls down into the bunker located under the installation (figure 51).

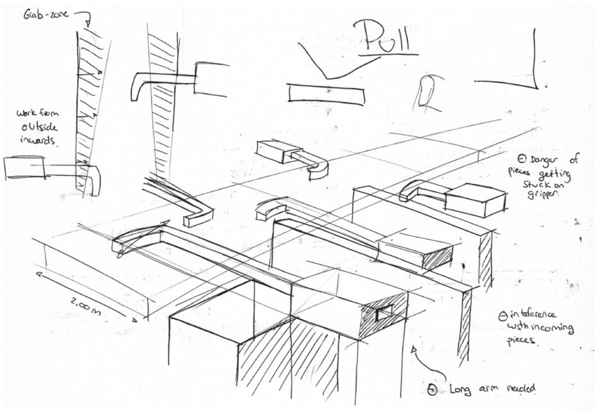


Figure 51 - Sketches of the concept Pull.

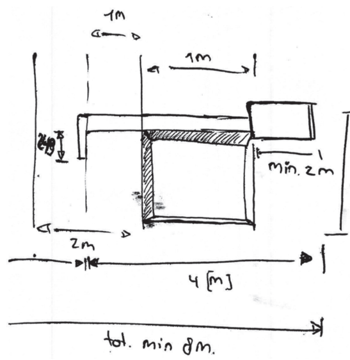


Figure 52 - Rough dimensions of the concept

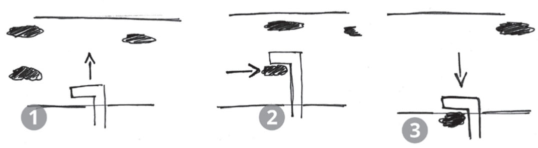


Figure 53 - Overview of sorting process; 1) Hook moves into the field to catch a piece. 2) Piece of scrap moves into the hook. 3) The hook pulls the piece of the conveyor for sorting.

Material should stay in the hook and not rotate out off it due to the moving conveyor belt. To prevent this, the arm of the hook needs to be bigger than half the maximum length of the incoming pieces.

The maximum width of incoming pieces is 261 [mm]. We assume that the hook needs 100 [mm] of free space around the piece to grab it. This means that there can be 5.5 pieces in the width of the conveyor belt (2 / (0.26 + 0.10). So we can say that there are roughly 6 zones from which material needs to be grabbed. Because there are 8 different material groups which need to be sorted, this concept needs 48 grippers (8 x 3 x 2). There is a chance that the hooks distort the field of material when they grab a piece. If the hook touches other pieces on the belt, the real location and the digital location of the pieces do not match anymore. This effect should be prevented to be able to have a high sorting quality. To check the location of the pieces, after 8 hooks, a new sensor module will be placed. Bringing the total number of sensor modules to 3.

15.2.1 - Specifications

If we assume a margin of 0,1 [m] around the pieces of scrap. We find that in theory 5,5 pieces can lie side by side on the conveyor belt (2 [m] / (0,26 [m] + 0,1 [m])). This means that every 0,6 [m] (=0,514 + 0,1), 5,5 pieces pass by. A speed of 3,4 [m/s] for the conveyor belt is needed to reach 20 [tonnes/hour]. Because the footprint of this gripper is bigger, this is sorting goal cannot be reached. The hook needs to move into the field, which means open space is needed to do so.

If the hook needs to move to the middle of the belt - furthest possible position of a piece - then it needs to travel 1 [m]. Assuming that the belt moves at 2 [m/s], and the hook accelerates with 50 [m/s/s] (Festo Group, n.d.c), then it takes 0,28 [s] to travel to the middle of the belt. In this time the conveyor belt moves 0,56 [m]. This means that the distance between pieces needs to be 0,56 [m]. So every 1 [m] (= 0,56 + 0,514) 5.5 pieces are moved through the system. This brings the theoretical sorting output to 6,8 [tonne/hour]. This sorting result can only be reached of 100% of the pieces are sorted.

15.2.2 - Feasibility test

To test the feasibility of the concept a test with a wooden prototype was conducted. The material was placed on a conveyor belt and pulled off with the wooden prototype. Based on this we can conclude that it is possible to pull pieces off a moving conveyor belt. When this concept is selected, more testing is needed.

15.2.3 - Cost

An estimation of the investment costs was made. The complete calculation can be found in appendix H. The concept Pull will cost € 1,3 million in investment costs. To operate the concept, it is estimated that 6 employees are needed (1 for over viewing the system, 2 for over viewing the conveyor belt & grippers, 2 for removing material, and 1 manager). The energy consumption is based on the consumption of the conveyor belt and the actuator. This brings the variable cost at € 10.991 per week.

15.2.4 - Gripper Design

We assume that the center of mass is at half the maximum length of a piece - 248 [mm]. To ensure the hook can grab a piece securely, without the piece rotating out of the hook, the width of the hook needs to be bigger than half the maximum length of a piece of scrap. A safety factor of 1.5 is used to create a secure grip. This means the gripper needs to be 375 [mm]. The height of the pull gripper will be the same as the pusher, 125 [mm]. The complete length of the arm of the gripper needs to be at least 1000 [mm] to be able to reach the middle of the conveyor belt. The pull gripper will be made out of steel due to its higher hardness and higher Young's modulus compared to aluminium.

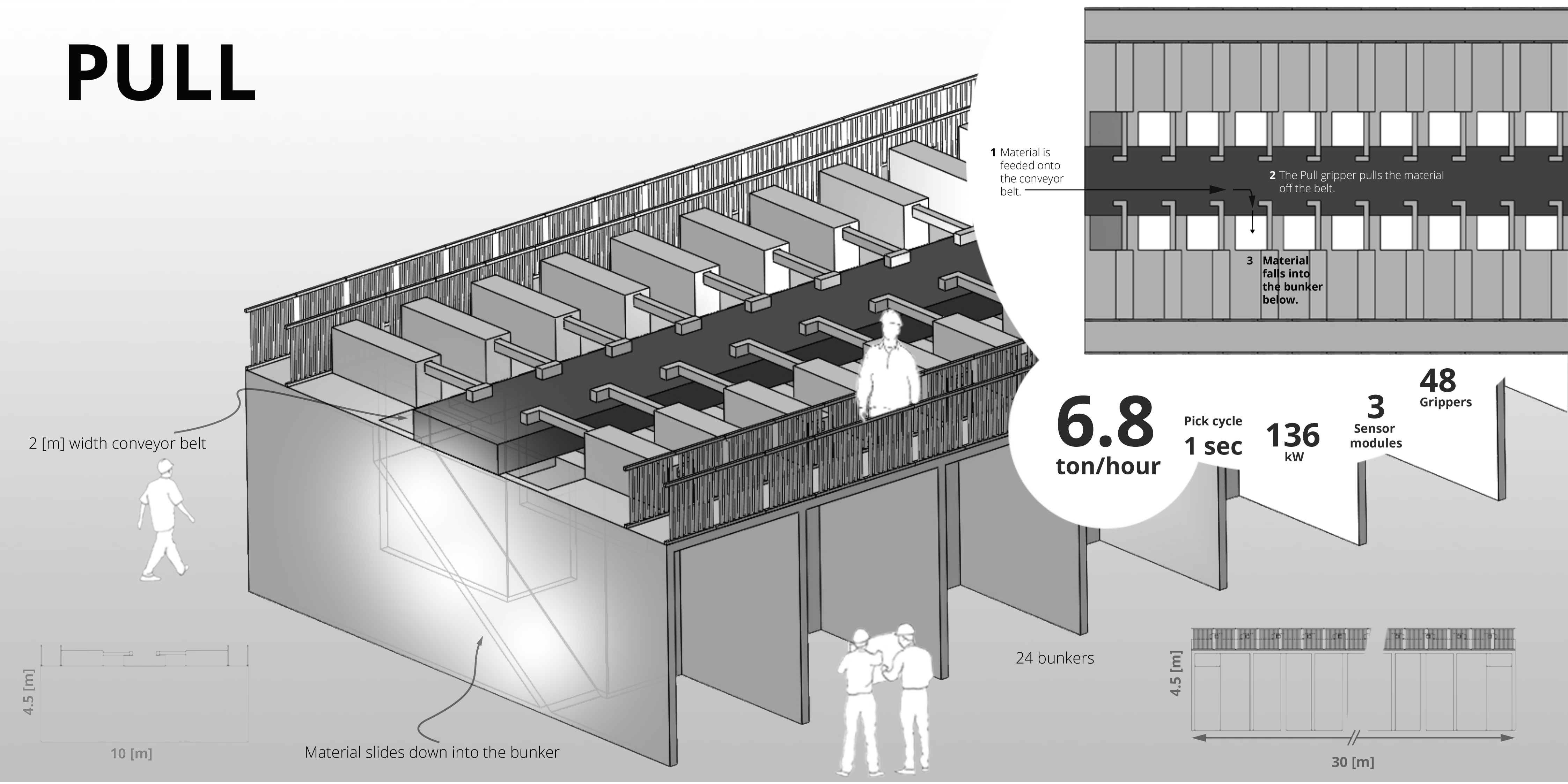


Figure 54 - Concept Pull overview.

15.3 - Direct

The last concept is Direct. Pieces are fed in the system using a conveyor belt. The scrap is scattered over the belt in x and y direction. The pusher moves in the z direction and acts as a direction changer for the pieces of scrap. By redirecting the piece from its original movement trajectory, the piece is redirected off the conveyor belt to either side of the belt. Pushers in the beginning are smaller compared to pusher at the end of the belt. In this way the pushers work from the outside of the belt to the inside to prevent unwanted part collisions and wrong sortation.

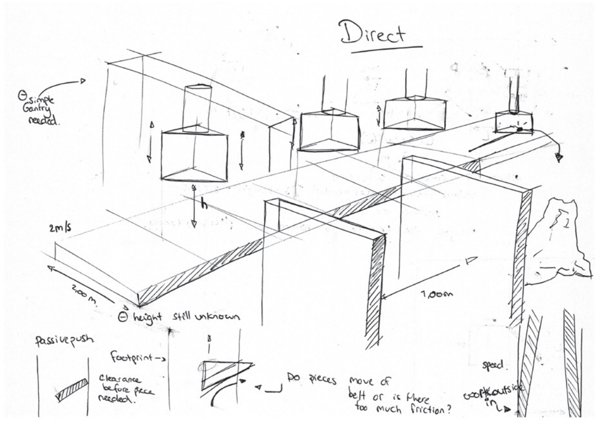


Figure 55 - Sketches of the concept Direct.

15.3.1 - Specifications

A conveyor belt moves the material through the system. The belt is 2 [m] in width and moves at a speed of 2 [m/s]. The longest distance a piece needs to travel is when it is moving in the middle of the belt. If we assume that the speed of the pieces in the x direction is constant, so vx= 2[m/s]. And a piece will be moved with a pusher which is under a 60 degree angle. The length the piece needs to travel L is 1,73[m] (1 * tan(60). The maximum piece length is 514 [mm]. This means that the distance between pieces needs to be 2,2 [m] when pieces are pushed from the middle of the belt. If a piece is grabbed from the side of the belt, the distance is smaller. Using the same approach angle and the maximum width of a piece, we find that the distance between pieces needs to be 0,45 [m] (0.26 * tan(60)). Using the smallest needed space between pieces - 0,45 [m] - we find that this concept can sort 7,4 [tonne/hour].

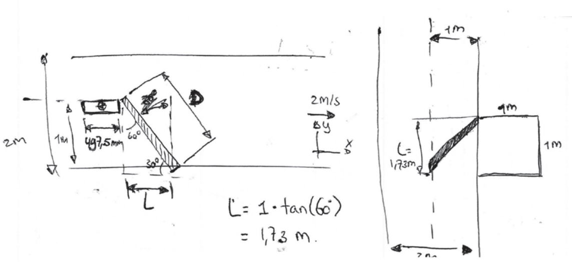


Figure 56 - Rough dimensions of concept direct

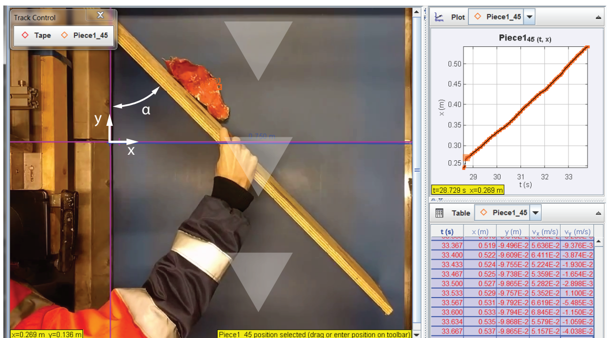


Figure 57 - Screenshot of Tracker, the analysis software for video.

15.3.2 - Feasibility test

To test the feasibility of the concept a test with a wooden prototype was conducted. The material was placed on a conveyor belt and directed to the side using a wooden plate. The angle α was changed to test the influence: 30, 45, and 60 degrees. Using Tracker, video analysis and modelling tool, the speed of the pieces was measured (figure 57). Looking a the video result it turns out that it is possible to direct the pieces to the side using a wooden plate. Figure 58 gives an overview of speed in the x direction and the angle under which the plate was placed.

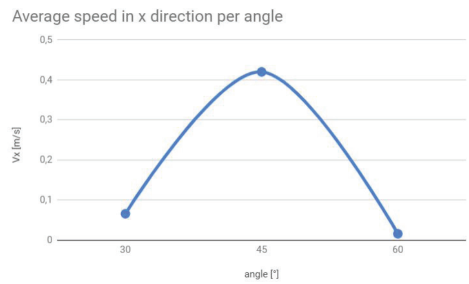


Figure 58 - Average speed in x direction per incoming angle, where a gripper under an angle of 45 degrees result s in the highest speed.

A plate under an angle of 45 degrees results in the highest speed in the x-direction. If this concept is selected, more testing is needed.

15.3.3 - Costs

An estimation of the investment costs was made. The complete calculation can be found in appendix H. The concept Direct will cost € 1,3 million in investment costs. To operate the concept, it is estimated that 6 employees are needed (1 for over viewing the system, 2 for over viewing the conveyor belt & grippers, 2 for removing material, and 1 manager). The energy consumption is based on the consumption of the conveyor belt and the actuator. This brings the variable cost at € 10.599 per week.

15.3.4 - Gripper Design

The direct gripper needs to be able to reach the middle of the belt. Because this gripper is placed under 45 [°], the length of the longest gripper needs to be 1414 [mm] (1000 / sin(45)). For the thickness we use the standard steel plate thickness of 4 [mm]. The height of the gripper will be 150 [mm]. The smallest gripper has a length of 471 [mm] (1000/3)/sin(45)) , and the medium gripper has a length of 942 [mm] ((1000/□) / sin(45)).
The direct gripper will be made out of steel due to its higher hardness and higher Young's modulus compared to aluminium.

DIRECT

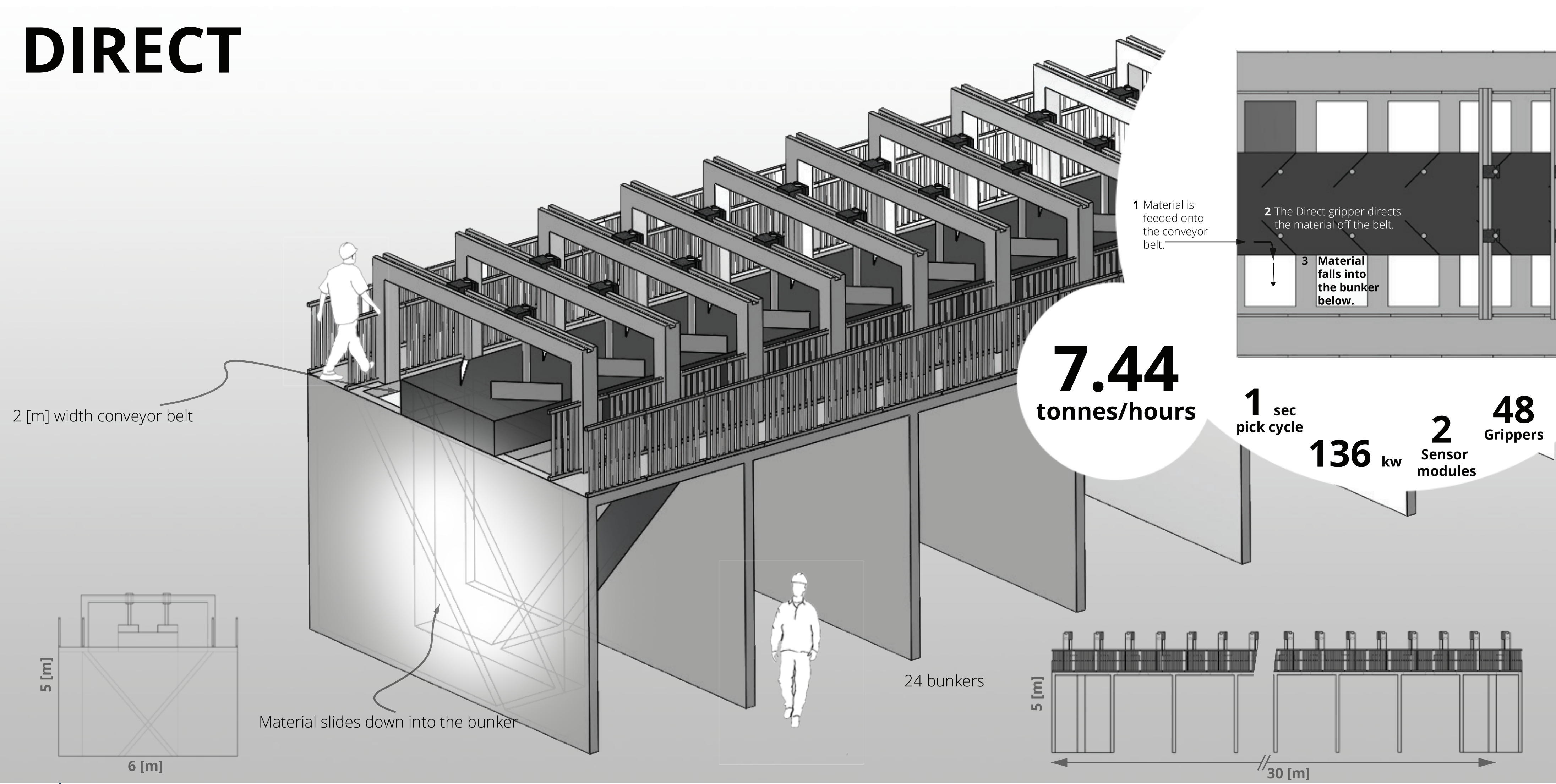


Figure 59 - Concept Direct overview.

15.4 - Discussion

In chapter 4 it was set that the design is required to sort 20 [tonne/hour]. During the design process it was found that this is target is too high for a first version of a sorting system. None of the created concepts are able to sort 20 [tonne/hour]. Sorting this amount of scrap requires a short pick cycle, or a high number of actuators which in their turn increase cost. All concepts can increase in capacity by increasing the number of conveyor belts and grippers. However, the concept Push is the easiest to scale. Conveyor belts can be stacked on top of each other. The requirement to sort 20 [tonne/hour] was removed from the list of requirements.

15.5 - Cost per tonne

Using the investment cost and the variable costs, the costs per tonne can be determined. It is assumed that the complete system lasts 15 years, and that it runs for 52 weeks a year, 5 days a week, 8 hours a day. Using the throughput in tonnes an hour, the cost per tonne was calculated for each concept. Figure 60 shows the different costs per tonne for each concept compared to hand sorting. The total costs are almost equal for each concept. In contrast, the sorting capacity differs per concept. This explains the large difference in cost per tonne for the concept Push (€22,35) versus the concept Pull (€46,48) and Direct (€41,45).
We can conclude that the concept Push is the most preferred concept, only looking at the factor cost. The complete cost estimation can be found in appendix H.

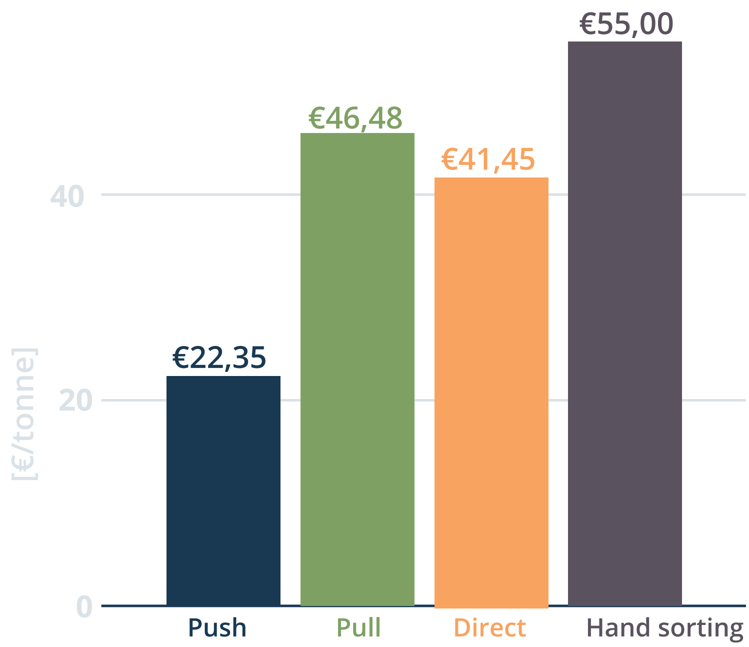


Figure 60 - Costs per tonne for each concept, compared to handsorting.

15.6 - Concept selection

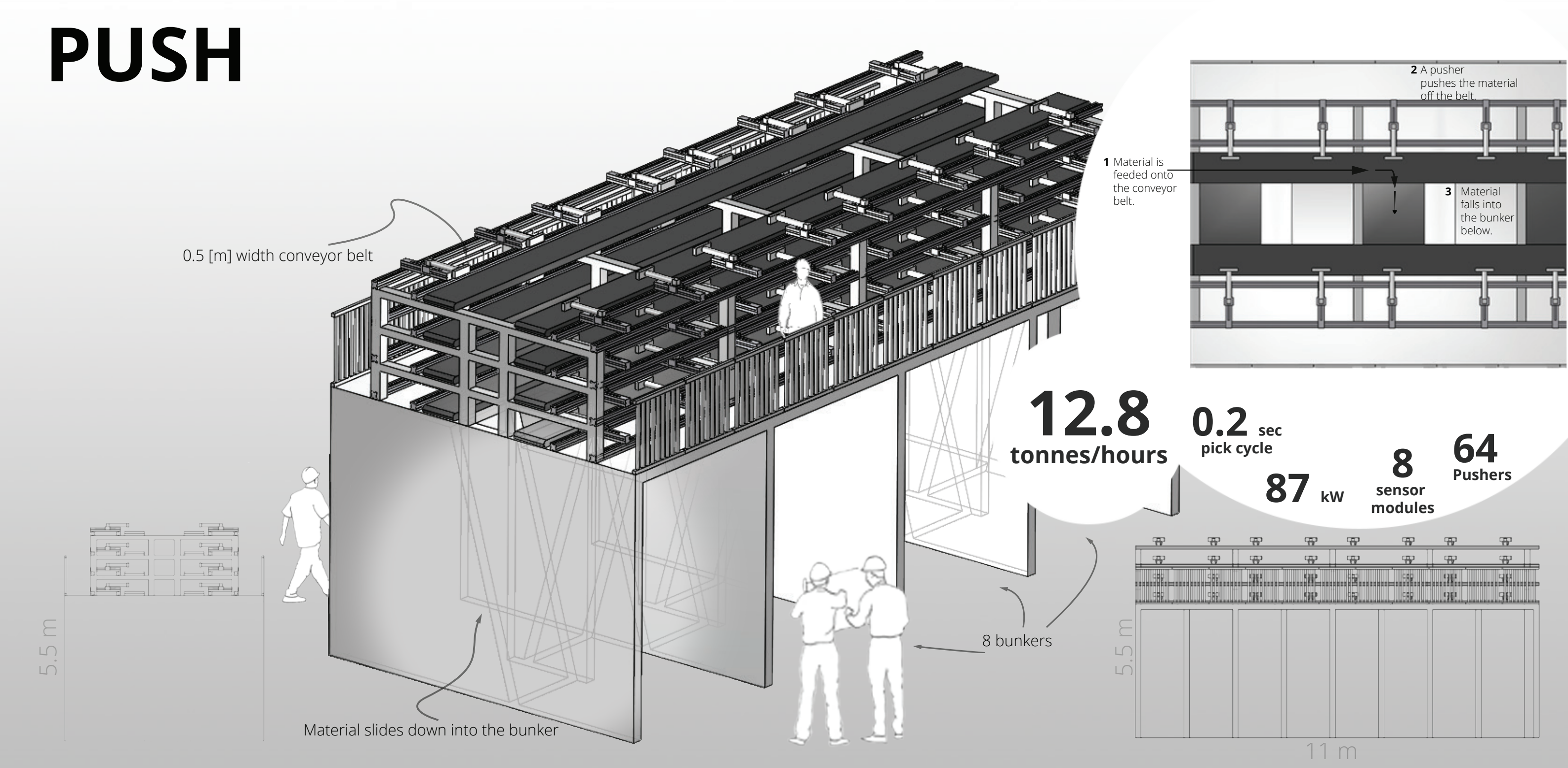
Based on the selection criteria as described in chapter 10, the concepts were rated using the weighted objectives method (Roozenburg & Eekels,1998). The selection criteria were coupled in three categories: Price (Investment and operation cost), Quality (Feasibility, Precision and Control over Object) and Reliability (Simplicity, Maintenance, Robustness). The quality of the system is the most important factor. Therefor the summed weight of the category Quality is set to 50. The summed weight for Price is set to 20 and the summed weight for Reliability is set to 30.

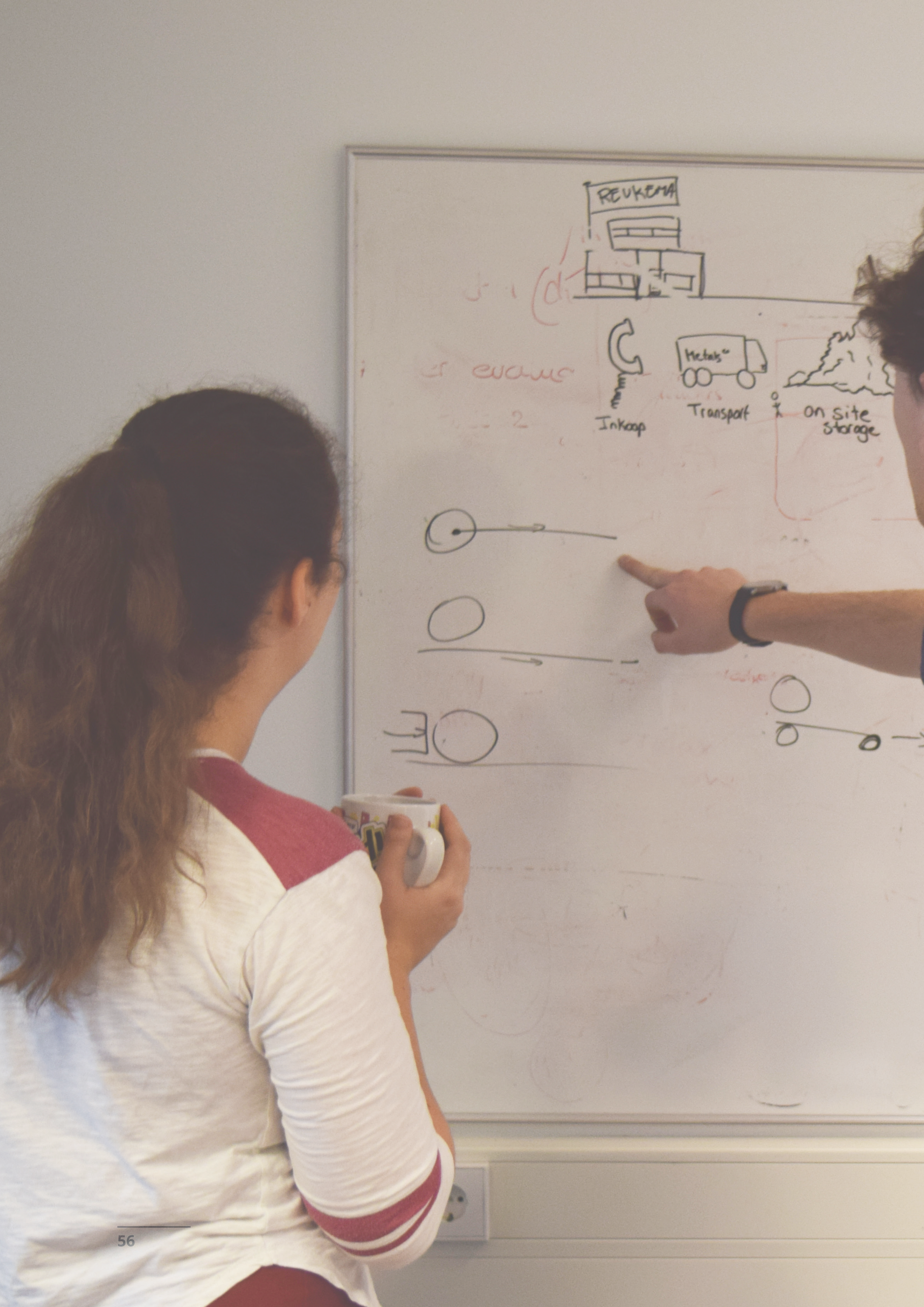
The concepts were rated using scores of 9 (excellent), 6 (medium) and 3 (poor) (Table 4). All concept score comparable on Price and Quality. In contrast, Push scores higher on reliability because of its simple design, low maintenance and high robustness. We can conclude that the concept Push is the preferred concept to be detailed during this project. An updated version of the list of requirements can be found in appendix G.

Table 4 - Scoring the three concepts using the weighted objectives method.

		Weight	Push		Pull		Direct	
			Score	Total	Score	Total	Score	Total
Price	Investment costs	5	9	45	6	30	6	30
	Operation costs	15	6	90	6	90	6	90
Quality	Feasibility	10	9	90	6	60	6	60
	Precision	15	9	135	9	135	9	135
	Control over object	20	3	75	6	150	3	75
Reliability	Simplicity	10	9	90	3	30	6	60
	Maintenance	10	9	90	6	60	3	30
	Robustness	10	9	90	3	30	6	60
	Total			**705**		**585**		**540**

Figure 61 - Selected concept Push.

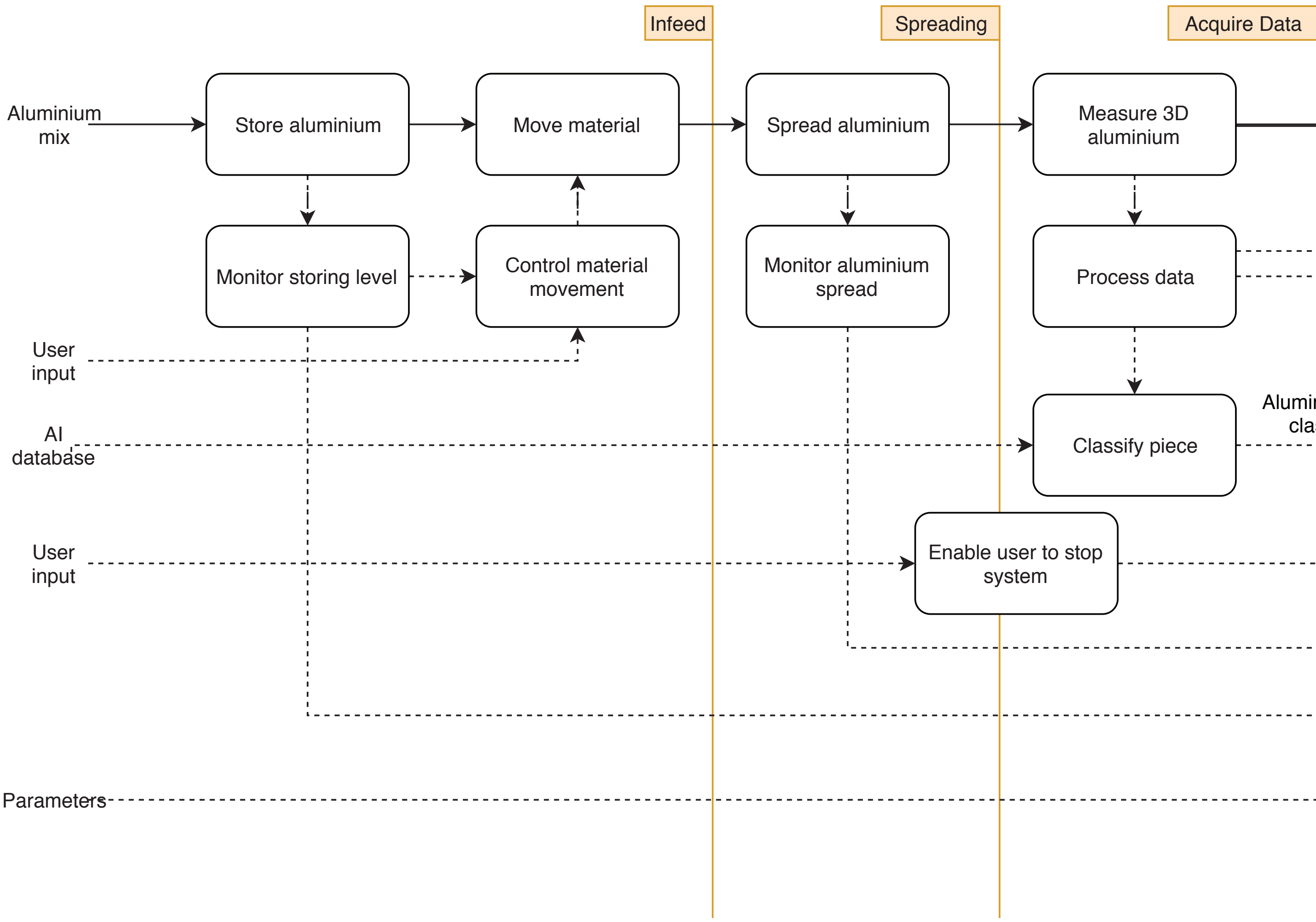


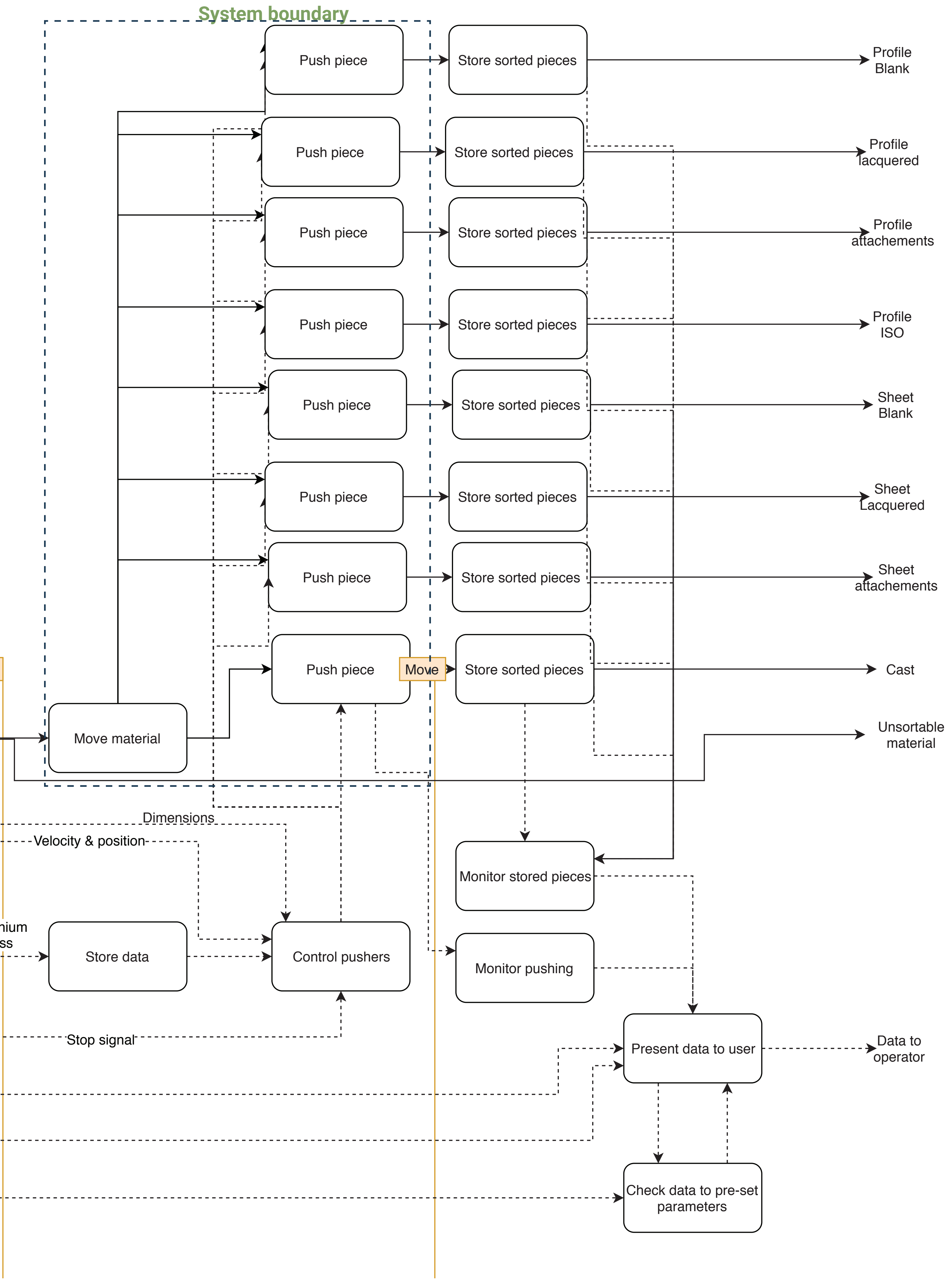

REUKEMA
Inkoop
Transport
on site
storage

Detailing

16 - Concept overview

During the synthesis phase a cocept was designed. On this page the complete system with al its elements and the relation between them can be found. During the embodiment phase there will be a focus on the Gripper. Therefore the system boundary is place around the Gripper & moving the material.





System boundary
Push piece
Store sorted pieces
Profile Blank
Push piece
Store sorted pieces
Profile lacquered
Push piece
Store sorted pieces
Profile attachements
Push piece
Store sorted pieces
Profile ISO
Push piece
Store sorted pieces
Sheet Blank
Push piece
Store sorted pieces
Sheet Lacquered
Push piece
Store sorted pieces
Sheet attachements
Push piece
Move
Store sorted pieces
Cast
Move material
Unsortable material
Dimensions
Velocity & position
Monitor stored pieces
nium
ss
Store data
Control pushers
Monitor pushing
Stop signal
Present data to user
Data to operator
Check data to pre-set parameters

17 - Actuator selection

As discussed in chapter 14, an electric actuator would be the best choice for the design. Within the group electric linear actuators there are different groups which can be distinguished. This section discusses different possibilities for an electric linear actuator for the design. The requirements demand a linear actuator with a stroke length of 500 [mm]. It should be able to exert a minimal force of 7 [N] and should have a minimal acceleration of 2 [m/s2] in order to have a pick cycle shorter than 2 [s]. Lastly, the actuator should be protected against dust and condensation; IP62 or higher.

17.1 - Belt Driven

Belt driven actuators can reach high speeds and long strokes (Collins, 2016). Speeds can reach up to 15 [m/s] (Macron Dynamics Inc., 2019) with a maximum stroke length of 5625 [mm]. They can exert a maximum load of 15.000 [N] (Parker, 2016). In comparison to linear motors, they produce a lot of force per volume (DC linear Actuators Maxon precision motor, n.d.).

17.2 - Lineair motors

Linear motor actuators are capable of long travel lengths. They can reach high-precision and highly dynamic motions (Collins, 2016). Linear motors can reach high speeds with outstanding acceleration rates . Besides this they have a relatively high life span, due to the fact that there is no gearing and the only friction points are the required linear guides. Linear motors do however draw a lot of current, and have a low force speed gradient (Maxon precision motors, n.d.)

17.3 - Solenoid

Solenoids have a small stroke length, typically 25 [mm] (Jouaneh, 2012), but linear transmission are an option to increase the stroke length. Forces are however limited to 600 [N] (Kendrion, 2019). Besides this, service life is limit to 1.000.000 strokes (LISK, n.d.). Which means that the duty cycle is an important selection parameter. This service life would lead to switching an old solenoid for a new one every 23 days.
So we can see that solenoids are no feasible option for the design.

17.4 - Conclusion

Two different linear actuators were selected; a belt driven system (OSPE-E.BHD) and a Rod style linear Actuator (ETT).The specifications of the two actuators can be found in table 5.
We find that only the ETT meets the requirement, as the belt driven system is not protected against dust and condensation. The ETT is superior in acceleration, service life and power consumption. We can therefore conclude that the ETT is the best option for the design.

Table 5 - Comparison of a BeltDriven lineair actuator (LCB) (Parker Hannifin Corporation, 2019) and a Rod Style Linear Actuator (ETT) (Parker Hannifin Corporation, 2017).

	LCB	ETT
max stroke [mm]	7.000	720
max trust force [N]	3.120	118,5
max speed [m/s]	8	5,8
max acc. [m/s²]	20	339
protection	IP30	IP67
Price [€]	2370[1]	3186[2]
Service life	5.000 [km]	500 mil. [cycles][3]
Power supply [VAC]	360[4]	230
Peak current [A]	12,4[4]	7,4

[1]E. Hogervorst, sales manager at VarioDrive (personal communication, 23 January, 2019)
[2]E. Hogervorst (personal communication, 14 January, 2019)
[3]Y. Hynderick, Parker Hannifin Benelux (personal communication, 27 March, 2019)
[4]Based on EMME-AS servomotor: https://www.festo.com/cat/nl_nl/products_EMME_AS

Figure 62 - ETT Rod Style Linear Actuator; selected linear actuator.

18 - Gripper Design

The gripper is an essential part of the sorting installation. This gripper will be designed, prototyped, and evaluated. The following sections discuss the design, prototyping and evaluation of the gripper.

A gripper was designed which fits the design as presented in chapter 15 (figure [xx]). In essence, the gripper is a flat metal plate. As a starting point the width of the gripper was set to half the maximum length (250 [mm]). The height was set to 125 [mm]. The thickness of the gripper is 1,5 [mm].

Reukema is looking for a system which needs as little human interference as possible. Maintenance should be minimized as much as possible. Sorting aluminium by shifting it off a conveyor belt can create damage to the system. The conveyor belt is subjected to friction. By pushing the pieces of scrap off the belt in a parabolic flight, friction is minimized. This ideal material behaviour has an influence on the design of the gripper. This will be discussed in sections 18.1, 18.2 and 18.3.

It is important to understand the effect that the conveyor belt has on the sorting quality. Pieces are moving with a constant speed in the x-direction, and a pusher pushes them off the belt in the y-direction. Will the velocity in the x-direction influence the sorting precision? This will be discussed in section 18.6.

Lastly, as discussed in chapter 8, minimizing the gripper footprint has an influence on the throughput of the complete sorting system. Because the sorting output should be maximized, it is important to optimize the gripper footprint. Can a smaller gripper have the same control over the object and precision as a bigger gripper? This is the research question which will be discussed in section 18.7.

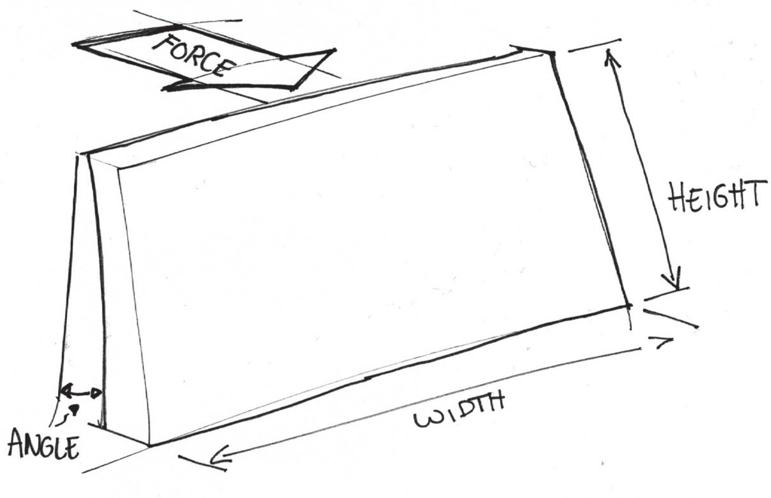


Figure 63 - Gripper overview; What is the influence of the width on the spread of material? How does changing the angle chang the lifting of material? What is the needed force to move the scrap?

18.1 - Dynamic model

Pieces of scrap need to be pushed off perpendicular to a moving conveyor belt. It is required that the pieces are pushed off the belt, which is 0,5 [m] in width. Besides this, it is required that after 0,2 [s] the piece is moved off the conveyor belt to prevent collision with the next piece of scrap. This means that the actuator needs to accelerate at 50 [m/s2]. Assuming that the pusher follows a triangular motion profile, only half off the stroke length actually creates an impulse force. This means that only 0,1 [s] a force is exerted on the piece of scrap.
The pusher exerts a force in the x-direction (Fx) on the piece of scrap. Due to friction, a negative air drag and friction force in the x-direction are acting on the piece of scrap. The free body diagram of a piece of scrap can be seen in figure 64. The sum of forces in the x-direction is as following:

$$\Sigma Fx := Fx - Ffriction\_x - Fairdrag\_x = mass\left(\frac{d^2}{dt^2}\,sx(t)\right)$$

In which the airdrag is equal to:

$$Fairdrag\_x := 0.5\left(\frac{d}{dt}\,sx(t)\right)^2 \rho\, Cd\, A$$

Cd was set to 1, ρ to 1,204 [kg/m^3], and A to 0,0257 [m^2] (0,236 x 0,109 [m]). Using the sum of forces in the x-direction, the position of the pieces of scrap after time (t) can be found. We can conclude that a minimum force of 30 [N] is needed to push the heaviest piece of scrap 0,5[m] in 0,2[s] (figure 65). With a force of 30 [N] a piece with a mean weight moves 0,5 [m] in 0,08 [s]. The lightest piece (0,010 [g]) moves this distance in 0,0165 [s].

Pieces are sliding over the conveyor belt when pushed for sorting. The friction which is created by this movement, shortens the lifetime of the conveyor belt. This leads to a need for more maintenance to repair the conveyor belt, which in turn leads to increased costs. To minimize the maintenance, the friction force should be kept to a minimum. Friction force is dependent on the neutral force (N) and the frictioncoëfficient (μ):

$$Ffriction\_x := N\,\mu$$

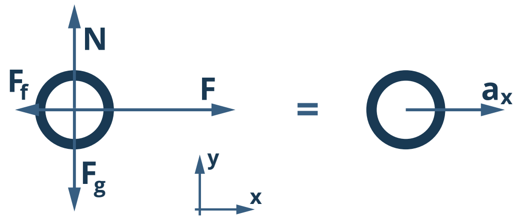


Figure 64 - Free Body Diagram of the Gripper with all the forces acting on the piece of scrap.

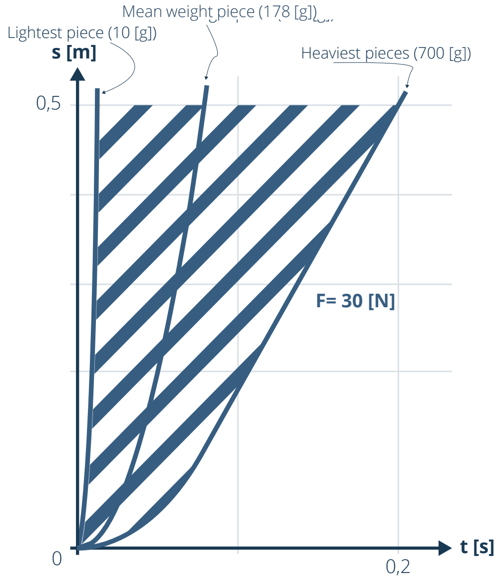


Figure 65 - Distance travelled when the pieces of scrap are pushed with a force of 30 [N]. Results show the displacement in the x-direction for the heaviest piece, mean weight piece and the lightest piece.

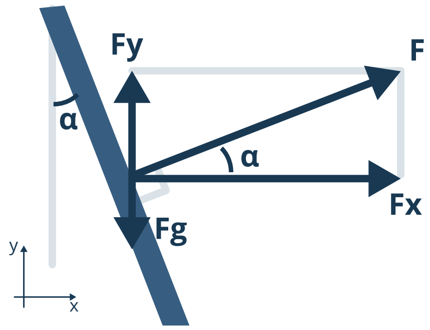


Figure 66 - Free Body Diagram of a gripper under angle alpha.

The frictioncoëfficient is dependent on the material and can only be changed by adding a third material like a lubricants (e.g. oil). This would however increase cost and maintenance, and is therefore not preferred. Reducing the normal force can decrease or even remove friction between the belt and the scrap. The gripper can be designed in such a way that it lifts the piece of scrap from the conveyor belt. By placing the gripper under an angle, a force in the y direction is exerted on the pieces of scrap, resulting in a parabolic flight. The free body diagram of the gripper when placed under an angle can be found in figure 66. It is required that the heaviest piece lifts off the belt and lands after 0,5 [m]. If the heaviest piece lifts off, the other pieces will also lift off.
The relation between the force in the y-direction and x-direction is:

$$Fy := \frac{Fx \sin(\alpha)}{\cos(\alpha)} = Fx \tan(\alpha)$$

Based on the dynamic model created in Maple, it was found that an angle of 10 [°] was enough to lift the pieces of scrap off the conveyor belt. The complete dynamic model can be found in appendix K. In figure 67 the trajectories of a piece of scrap for different forces in the x-direction can be found. We can conclude that an angle of 10 [o] and an external force in the x-direction of 42 [N] are required to meet the requirements. After 0,14 [s], the heaviest piece has traveled 0,5 [m] in the x-direction.

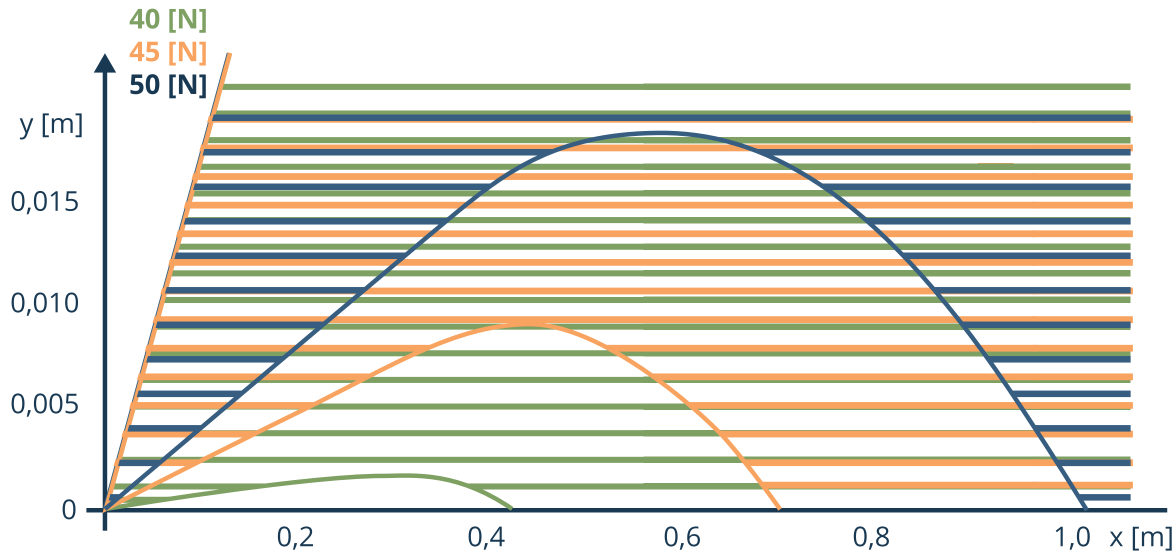


Figure 67 - Trajectory spread for different pushing forces (40, 45, 50 [N]) when the pusher is placed under an angle of 10 degrees. Indicated here are the trajectories of the heaviest piece (700 [g]) and the lightest piece (10 [g]). We can conclude that a minimum force of 42 [N] is needed to give the heaviest piece a trajectory after which it lands at 0,5 [m] in the x-direction.

18.2 - Gripper prototyping and evaluating

The dynamic model showed that placing the gripper under an angle of 10 [º] lifts the pieces off the belt. This section discusses the prototyping and evaluating of the gripper.

The gripper was prototyped using sheet metal (figure 69). 20 different scrap samples were selected for testing. The mean weight is 470 [g], mean length 336 [mm], and the mean width 171 [g]. The test sample is compared to the material sample as used in chapter6 (figures 70 - 72). As can be seen, the test sample consists of multiple heavy pieces, which means that the test sample represents extreme cases. The width and length were on average slightly larger compared to the reference sample. The data of the 20 test samples can be found in appendix I.

The actuator used to move the gripper was an LHRF-ELGA-RF-120, with an EMMS-AS-100-S-HS-RS servomotor. The stroke length was set to 500 [mm]. Because the weight of the gripper and the arm was approximately 3 [kg], the acceleration was set to 15 [m/s2]. Pieces of scrap were placed on a rubber surface. Each push was captured using a smart phone Nexus 5X, filming at 120 [fps]. These videos were used to analyse how many pieces had a parabolic flight. The movement profile was kept constant during the testing.

18.2.1 - Results

The number of pieces lifting off versus the number of pieces sliding over the rubber mat were counted. The results can be found in table 6. 23% of the pieces had a parabolic flight, and thus were lifted from the belt, while 77% of the pieces was sliding over the belt.

It is interesting to investigate why some pieces were flying and why others were not. Therefore a correlation test was conducted to investigate the relation between the parameter lifting, and the parameters weight, length and width. Table 7 shows the results of a Pearson Correlations test. Only a significant correlation was found between the number of pieces lifting and their weight. Figure 68 shows a Scatter plot representing the relation between the times lifting and the weight of the pieces.

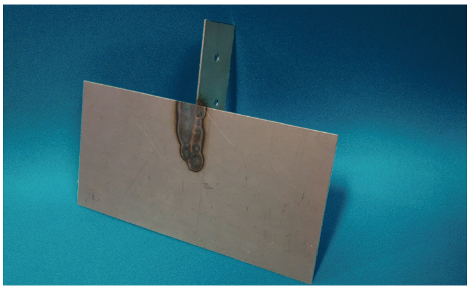


Figure 69 - Prototype of the gripper constructed out of 1,5 [mm] sheet metal. Dimensions: 250 by 125 [mm].

Table 6 - Number of pieces flying and not flying using a gripper under an angle of 10 degrees.

	Pieces (%)
Lifting	14 (23%)
Sliding	46 (77%)
Total	**60 (100%)**

Table 7 - Pearson Correlations between Lifting and Weight, Length, Width for the Grippper(1).

	Lifting
Weight	-0,459*
Length	-0,265
Width	-0,242

* Correlation is significant at the 0.05 level (2-tailed)
Note: For every piece the number of times lifting was summed, which results in the variable lifting from 0 to 3 with a sample of N=20.

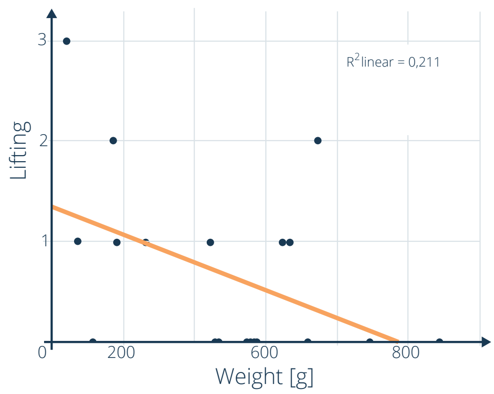


Figure 68 - Scatterplot of the summed lifting compared to the Weight of the the piece.

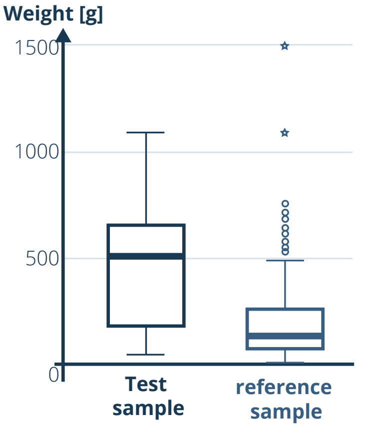


Figure 70 - Boxplot of the distribution of weight [g] of the test sample in comparison to the reference sample.

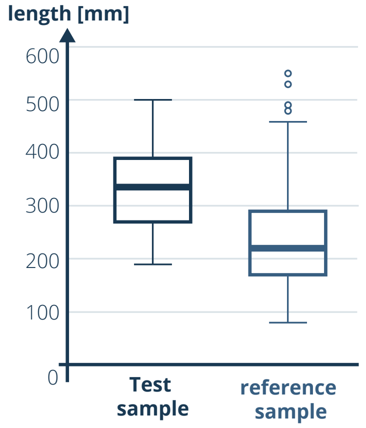


Figure 71 - Boxplot of the distribution of length [cm] of the test sample in comparison to the reference sample.

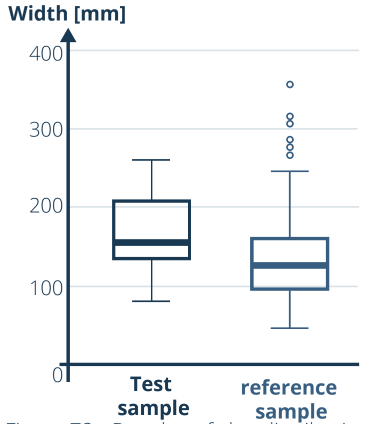


Figure 72 - Boxplot of the distribution of width [cm] of the test sample in comparison to the reference sample.

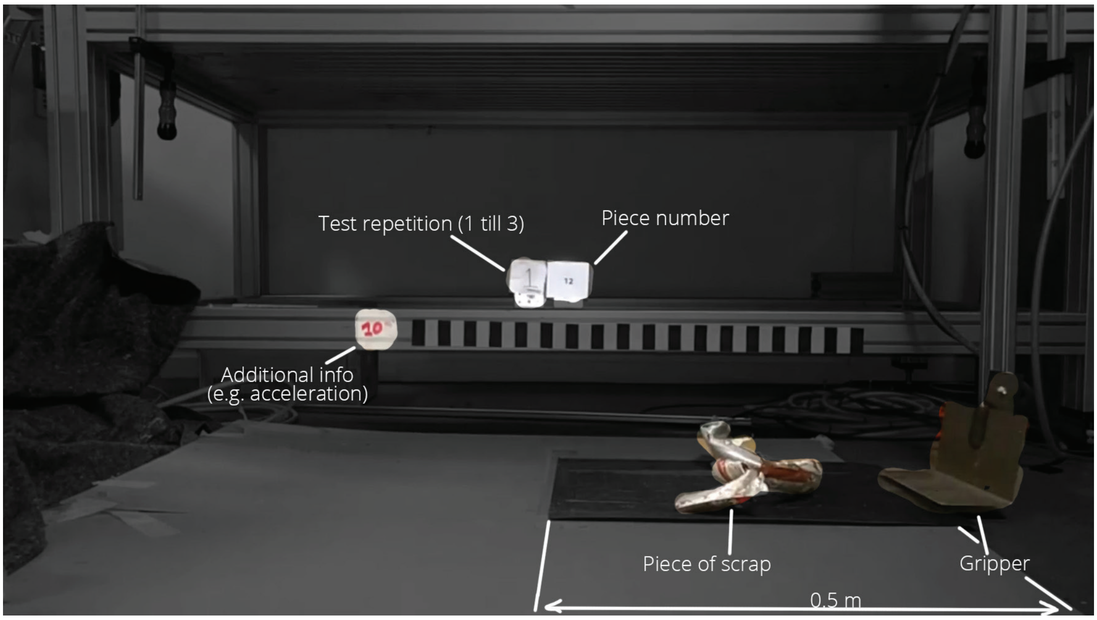


Figure 73 - Test setup overview; A piece of scrap is placed on a rubber surface of 0,5 [m] in width. The gripper moves towards it and pushes it to the side. The piecenumber and test repetition are recordeed.

18.2.2 - Conclusion

As can be seen in table 6, only 23% of the pieces did not slide of the belt. To optimize for minimal maintenance, the number of pieces sliding should be further minimized. Therefore a new prototype of a gripper was created. An improved design is needed to minimize the amount of pieces sliding over the belt. In the following sections two iterations on the design of the gripper and testing the gripper will be discussed.

18.3 - Gripper prototyping and evaluating

As described in the previous section, the first version of the gripper was able to lift 23% of the pieces. This section aims to improve this number by improving the design of the gripper. Based on observations of the video recordings, it was found that the most of the pieces were pushed off in a straight line. The first contact point pushed them off, instead of lifting them off into the air. By adding a small rib, the idea is to rotate the pieces so they will be lifted by the plate placed under an angle of 10 degrees. Figure 74 gives an illustrations off the intended effect. Besides this rotating effect, the added rib lifts the pieces of a couple of millimeters which will be helpful in creating a lifting effect.

Two tests were conducted iteratively. The method was unchanged in comparison to testing the first version of the gripper - Gripper1. Based on the results of testing the second version of the gripper, Gripper2, a new design was prototyped and tested, Gripper3 (figure 76). Figure 75 illustrates these basic design activities.

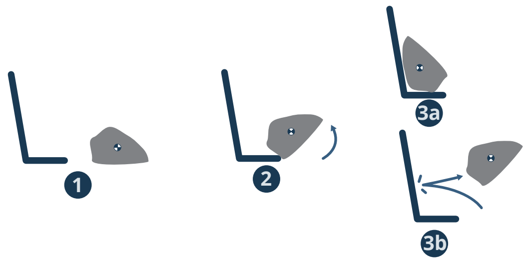


Figure 74 - Demonstration of the intended effect when adding a rib to the gripper. (1) The first contact point is below the center of mass, (2) this will make the piece rotate, (3a) the pieces is shoveled by the gripper or (3b) the piece hits the plate and will be lifted and launched off the conveyor belt.

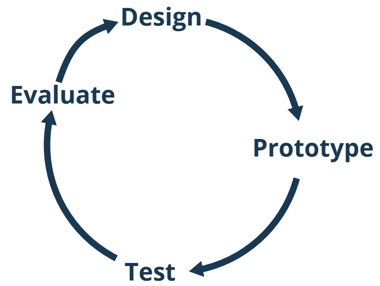


Figure 75 - Basic design activities for the design, prototyping, testing and evaluating of the gripper. Three different designs of the grippers were designed.

16.3.1 - Results

As can be seen in table 8, the gripper with the biggest rib, Gripper3, was able to create the most lift. 82% off the pieces were lifted off the belt. Table 9 shows that there is one significant correlation; between the summed lifting and the weight for Gripper3.

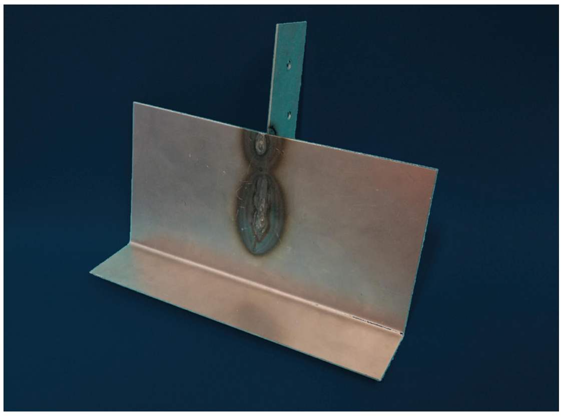


Figure 76 - Prototype of Gripper2; constructed from a sheet of metal of 1,5 [mm]. Dimensions: 250 by 125 [mm]. The rib is 50 [mm]. For Gripper3 the rib is 100 [mm].

Table 8 - Number of pieces lifting off for three different grippers.

	No Rib Gripper1	Rib 50mm Gripper2	Rib 100mm Gripper3
Lifting	14 (23%)	39 (65%)	49 (82%)
Sliding	46 (77%)	21 (35%)	11 (18%)

Gripper1 vs Gripper2: χ(1)= 21,1, p< 0,01
Gripper2 vs Gripper3: χ(1)= 4,26, p= 0,04
Gripper1 vs Gripper3: χ(1)= 40,9, p< 0,001

18.3.2 - Conclusion

The Gripper with the biggest Rib was able to lift the most pieces off the conveyor belt. This means that for minimizing the friction on the conveyor belt to increase service life, the best design is a Gripper under an angle of 10 [°] with a Rib of 100 [mm].
During the tests conducted, the motion profile and thus the impact force, was kept constant for all testing cases. The following chapter will investigate the effect of the motion profile on the number of pieces lifting.

Table 9 - Pearson Correlations between Lifting and Weight, Length, Width for the Grippper2 & Gripper3.

	Lifting Gripper2	Lifting Gripper3
Weight	0,020	0,387
Length	0,208	0,471*
Width	-0,426	0,001

* Correlation is significant at the 0.05 level (2-tailed).
Note: For every piece the number of times lifting was summed, which results in the variable lifting from 0 to 3 with a sample of N=20.

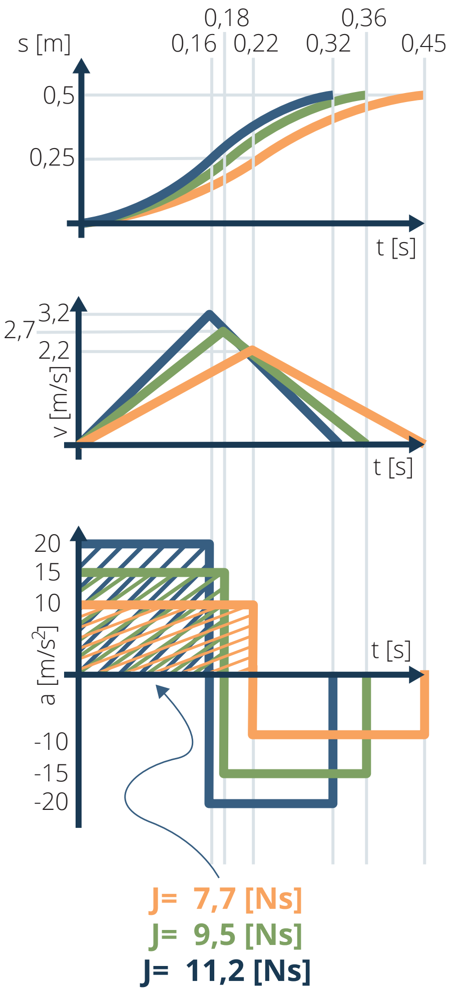


Figure 77 - Overview of the three different motion profiles for three different accelerations (10, 15 and 20) and the impulse resulting from the acceleration.

18.4 - Optimization of Motion Profile

During the optimization of the Gripper, the motion profile was kept constant for all test cases. As described in section 18.1, it is expected that the motion profile has an influence on the behaviour of the scrap when pushed of a conveyor belt. This chapter aims to optimize the motion profile.

The motion profile influences the force that is exerted on the piece of scrap, based on the first law of Newton: Force is the product of mass and acceleration. It is expected that the more force exerted on a piece of scrap, the higher the change it will lift off the conveyor belt and thus the friction is reduced. To reduce the number of parameters to be tested, it was decided to only change the acceleration and deceleration. The stroke length was kept constant at 500 [mm]. During the previous test the design was validated. Pieces were pushed by the gripper and no pieces were getting stuck. Therefore it was decided to keep the form of the motion profile constant.

Three different accelerations were use to test the influence on the behaviour of the pieces. The motion profiles and the impulse forces can be found in figure 77. The acceleration and deceleration were set to the same value; 10 [m/s2], 15 [m/s2] and 20 [m/s2]. The weight of the arm and the Gripper is approximately 3,5 [kg]. The Impulse was calculated using the following formula:

$$J := F\,\Delta t$$

$$J := m\,a\,\Delta t$$

Table 10 shows the number of pieces lifting for the different impulse forces.

Table 10 - The number of pieces lifting and sliding, for different Impulses.

	7,7 [Ns] 10 [m/s^2]	9,5 [Ns] 15 [m/s^2]	11,2 [Ns] 20 [m/s^2]
Lifting	39 (65%)	49 (82%)	54 (90%)
Sliding	21 (35%)	11 (18%)	6 (10%)

$\chi(1)$= 4,3, p= 0,039 $\chi(1)$= 1,7, p= 0,191

$\chi(1)$= 10,7, p= 0,001

The biggest Impulse force gives the best results, in terms of most pieces lifting. This was also found based on the dynamic model created in maple.
Firstly, the more pieces that lift off the conveyor belt, the less friction is created, thus minimizing maintenance. Secondly, the quicker the motion can be executed, the shorter the cycle time is. By decreasing the cycle time, the theoretical throughput of the complete system can be optimized. We can conclude from table 10 that the acceleration should be set to [20 m/s2]. Due to the time restrictions during this graduation project, there were only three different motion profiles tested. Based on the dynamic model, we can conclude that in theory even more pieces would lift if the impulse is increased.

18.5 - Effect of stiffness in system

During observations of the video material, it was found that the gripper wobbled due to the long arm. This section investigates if this wobbling behaviour has a negative effect on the pieces lifting off.

The method of testing the wobbliness was kept constant in comparison to the previous tests. The arm of the gripper was changed from 1.000 [mm] to 500 [mm]. Table 11 gives an overview of the results. There was no significant difference observed concerning the number of pieces lifting. We can assume that the movement that is caused by the length of the arm has no effect on the amount of pieces lifting or sliding.

Table 11 - The number of pieces lifting for different arm lengths, for Gripper3 (rib of 100 [mm]) and with an impulse of 11,2 [Ns].

	1.000 [mm]	500 [mm]
Lifting	54 (90%)	52 (87%)
Sliding	6 (10%)	8 (13%)

$\chi(1)= 0,3$, $p= 0,57$

18.6 - Effect of conveyor belt on material spread

In the final design, pieces of scrap will be transported on a conveyor belt and pushed off for sorting by a gripper. During the testing previously described, all pieces were pushed in a static situation. This section will discuss the effect the conveyor belt has on the spread of the material.

To create a testing situation as close to reality as possible, a conveyor belt was needed. At first there was no conveyor belt available to conduct test on, therefore different conveyor belts were prototyped to mimic the real situation. In appendix J an overview of the different prototypes of a conveyor belt can be found. At the end of the project I was able to conduct tests at the testing facility of ARCO solutions. Together with ARCO, Reukema had build a first testing setup for their concept (figure 78). Using this setup, the spread of the material was tested. With a camera mounted above the piece of scrap, the trajectory was captured and analysed, see figure 79.

Figure 78 - Testing setup built at ARCO solutions for Reukema. One large conveyor belt (blue) transports scrap. The material is pushed off the belt to a perpendicular belt, from which it is pushed on one of the trog conveyor belts.

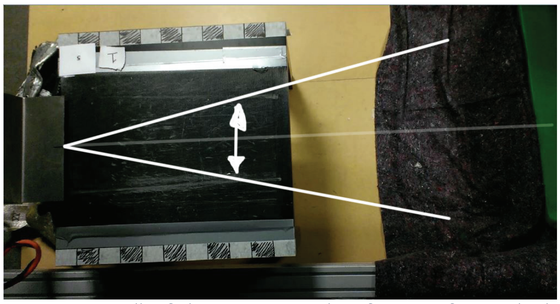


Figure 79 - Still of the topview video footage from which the trajectory of the pieces can be determined. The angle measured was taken with as origin the middle of the pusher at the starting position.

18.6.1 - Results

Figure 80 shows the results of the spread of material when the material is pushed off a conveyor belt moving at 0,4 [m/s] versus when it is pushed from a static position. The direction (negative or positive) for the pieces pushed from a static position is arbitrary and can also be switched around. The difference in angle for the static situation (M= -0,9) and moving the pieces on a conveyor belt (M= 1,7) is significant; t(114)=-2,419, p= 0,017.

18.6.2 - Conclusion

Moving the pieces off a conveyor belt and pushing them perpendicular to the movement of the conveyor belt, results in a slight change in angle. Besides this, the spread increases slightly.

18.6.3 - Discussion

The pieces of scrap were moved on a conveyor belt with a speed of 0,4 [m/s]. This is not the speed required for the design. Due to the time restriction in the graduation project, it was not possible to increase the speed of the conveyor belt within the limited time. It is recommended that more tests are conducted which an increased conveyor speed.

The two velocities of the material can be considered as two vectors; one in the x-direction and one in the y-direction. Therefore I expect that the mean angle of the direction of the pushed material has a linear correlation with the conveyor belt speed. I expect that the trend seen with the two data points (static and conveyor belt at 0,4), continues at higher speeds.

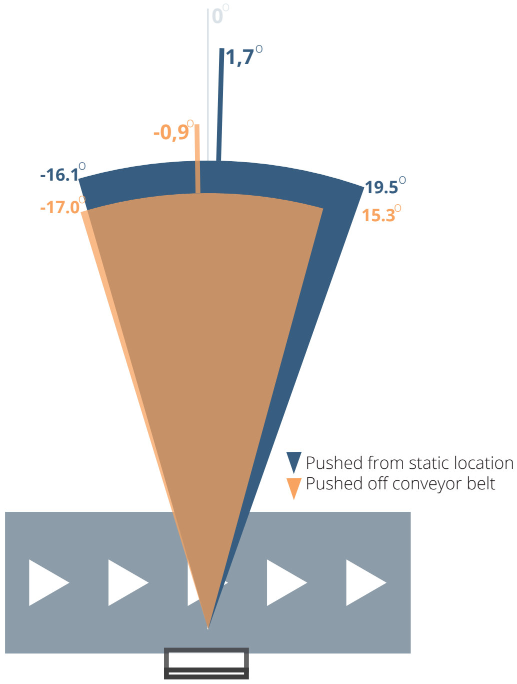


Figure 80 - Spread of material when pushed by a gripper from a static situation compaired to when pushed off a moving conveyor belt. Indicated are the mean angle, the 99,7% lower and upper confidence interval.

18.7 - Minimizing footprint of the gripper

As discussed in chapter 8, minimizing the footprint of a gripper is beneficial for the throughput of the complete system. This section will discuss the optimization steps taken to minimize the footprint of the gripper. The goal of this experiment is to find the effect of minimizing the gripper footprint on the spread of material and the reliability of the system. It is expected that by decreasing the footprint of the gripper, the spread of material becomes larger and the reliability decreases.

In chapter 14 it was set that the minimal required width of a gripper is 80 [mm] to ensure alignment of the center of the gripper with the center of mass of the piece of scrap. In the previous tests a gripper with a width of 250 [mm] was tested. A third gripper was added, which had a width which was in the middle of the two other gripper; 160 [mm] (figure 82). All dimensions, except the width, were kept constant for each gripper. 20 pieces of scrap - the same sample as in the previous tests - were placed on a running conveyor belt with a speed of 0.4 [m/s]. From the top view, the angle of ejection was recorded using a Nexus 5x. From the front view the number of pieces lifting were noted, using a HTC desire 601.

16.7.1 - Results

Table 12 gives an overview of the test results. Trajectory angle was noted, together with the number of pieces lifting off. Besides this, by observing the video footage, the number of correct pushes was noted. Some pieces were not pushed off the belt correctly, as they were getting stuck behind, or under the gripper. This effect is unwanted and should be avoided.

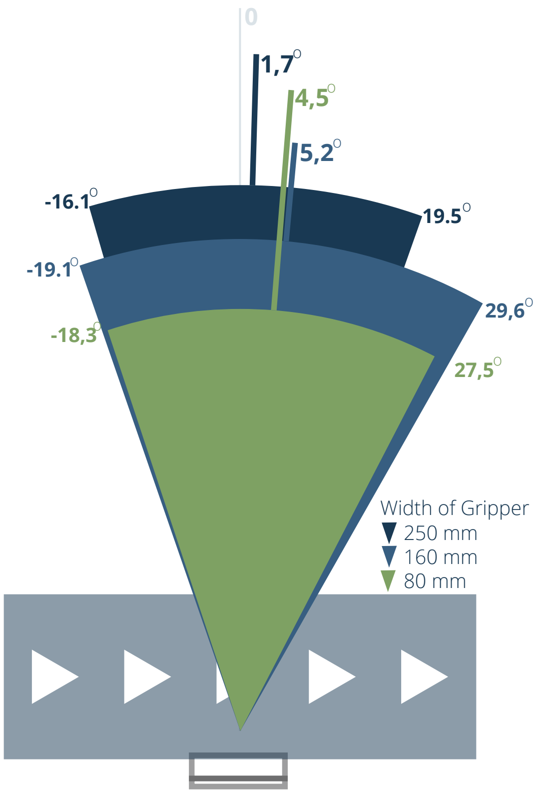


Figure 81 - Spread of material for different gripper width; 250, 160 and 80 mm. Indicated are the mean angle, 99,7% upper and lower confidence interval.

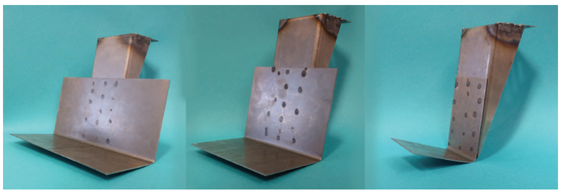


Figure 82 - Three different Gripper prototypes with three different widths. Left: Gripper with a width of 250 [mm]. Middle: Gripper width: 160 [mm]. Right: Gripper widht: 80 [mm].

Table 12 - Overview of the results of the different gripper widths as tested.

	Mean angle [o]	Upper 99,7% CI [o]	Lower 99,7% CI [o]	Correct push [%]	Lifting [%]	Throughput[2] [tonne/hour]
250 [mm]	1,68	19,5	-16,1	96,5	72,4[1]	14,7
160 [mm]	4,55	27,4	-18,3	96,4	73,7	15,7
80 [mm]	5,23	29,6	-19,1	82,5	43,9	16,7

1 During testing the gripper landed on top of a piece of scrap, this slightly deformed the Rib of the Gripper, possibly explaining the low lifting percentage.
2 Based on a conveyor belt with a speed of 2 [m/s], a width of 0,5 [m], and an average weight of 178 [g] for the pieces of scrap.

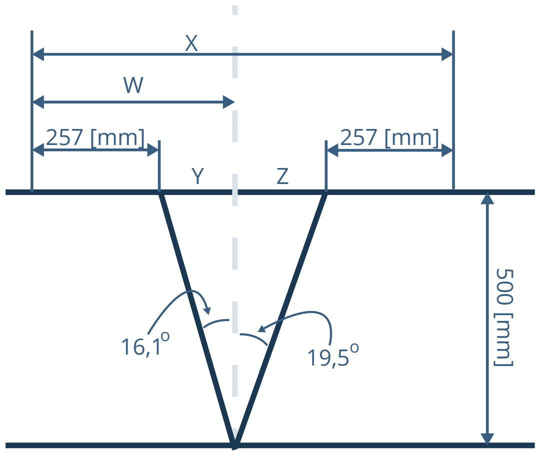
18.7.3 - Discussion

A smaller gripper leads to less correct pushes. In chapter 14 the minimum width of a gripper was found based on the location of the center of mass. The form factor was not taken into account. During testing it was observed that the shape has an equally important role in a reliable sorting quality as the alignement of the centre of mass. The center of mass can be aligned with the surface of the gripper, but if the contact point of the piece of scrap is not in line with the center of mass, it starts rotating. Figure 84 demonstrates this behaviour. This means that a gripper with a larger width is preferred because there is a higher change that there are two contact points, with the center of mass in between these two points creating a secure push.

18.7.2 - Conclusion

Looking back at the selection criteria, we can see that reliability is more important than throughput. If you are not able to correctly sort the pieces, the sorting speed does not matter. This means that the number of correct pushes should be maximized. Besides this, by minimizing the spread of material, the reliability of the system can be increased (parts are more predictable in a smaller spread) and costs can be decreased (the complete system can be designed smaller and construction costs can be lower). The Gripper 250 [mm] has the highest number of correct pushes. Besides this, the spread of material is the smallest of all Grippers. Therefore I conclude that it is best to continue with the gripper of 250 [mm] because of the high reliability for sorting. It is true that the throughput is lower compared to the other grippers. But there is a trade off in the correct sorting and the speed of sorting. When you want more speed, this has a negative effect on the sorting quality.
In the previous test the travelling distance of the actuator was kept constant at 500 [mm]. Because this system has a dynamic output mechanism, this stroke length could not be kept constant over the complete test. The stroke length was affected by the bounding box drawn around the pieces of scrap. Because this is currently only based on an image from the line scan camera, some bounding boxes were not drawn correctly. The system is sensitive to reading errors.

The opening of the bunker was set to 1000 [mm] in chapter 15. Using the data gathered in this section, we can conclude that an opening of 850 [mm] is enough to catch all the pieces of scrap. The center of the gripper should be positioned 400 [mm] from the start of the bunker, see figure 83. With these dimensions, 99,7% of all the pieces will be pushed into the bunker.



Y = 500·tan(16,1) = 144 [mm]
Z = 500·tan(19,5) = 177 [mm]
X = 257·2 + Y + Z = 835 [mm]
W = Y + 257 = 401 [mm]

Figure 83 - Dimensions of the opening of the bunker and the location of the center of the pusher.

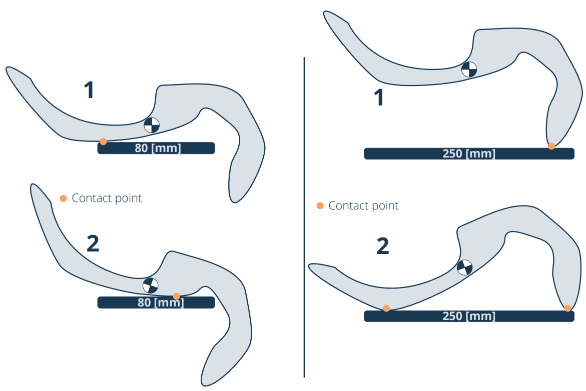
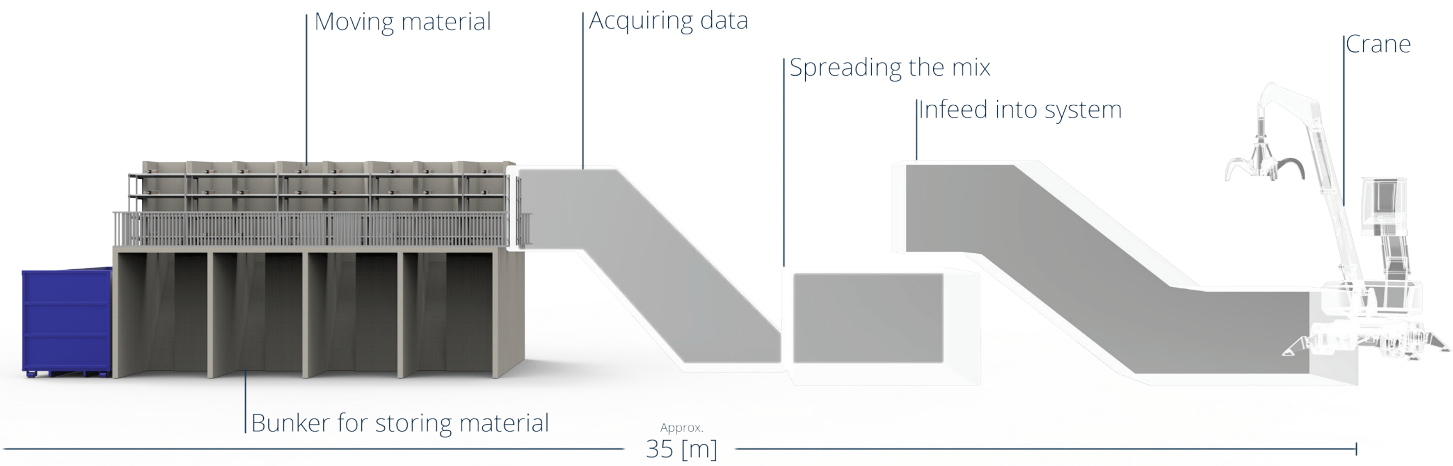
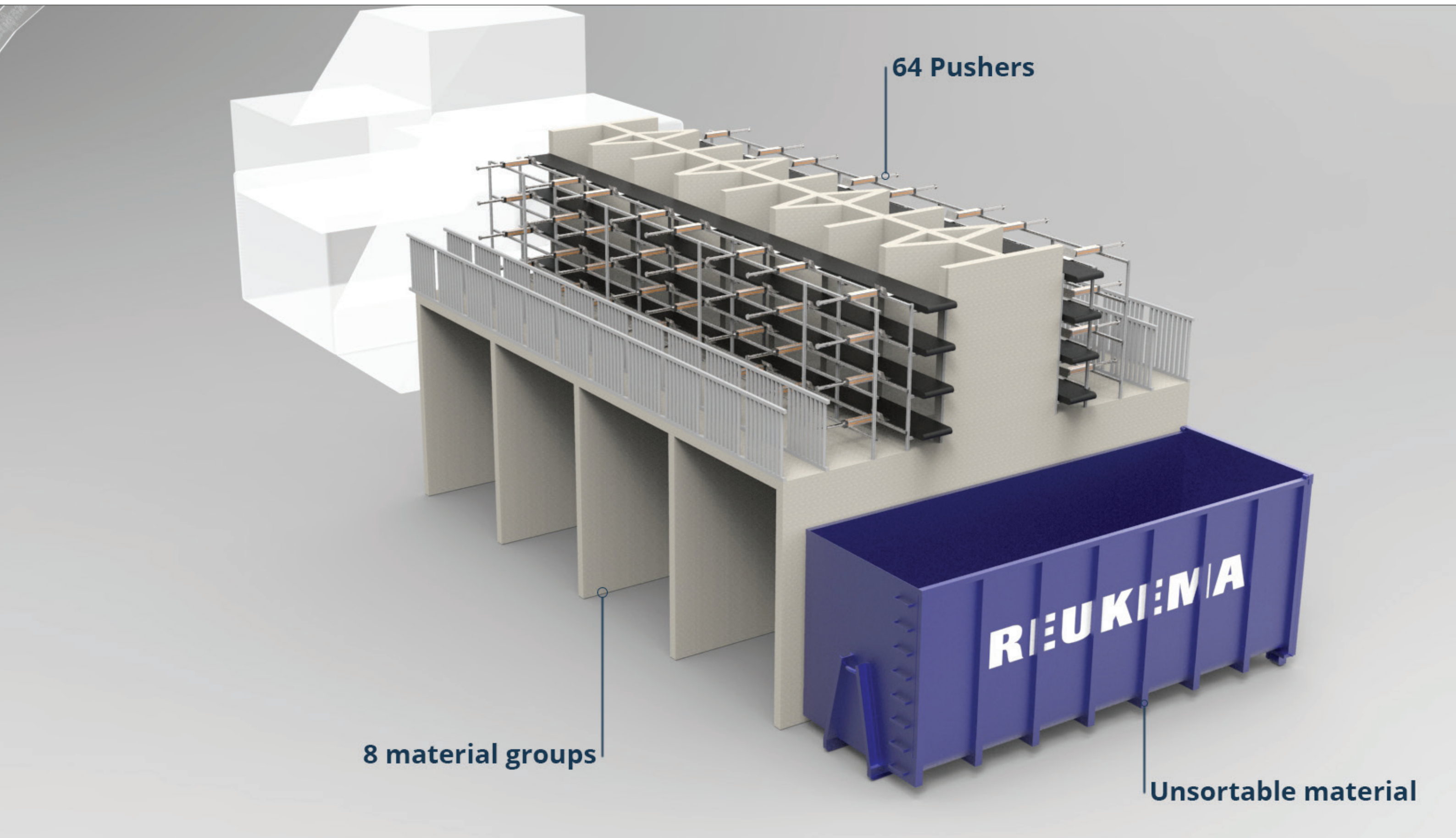


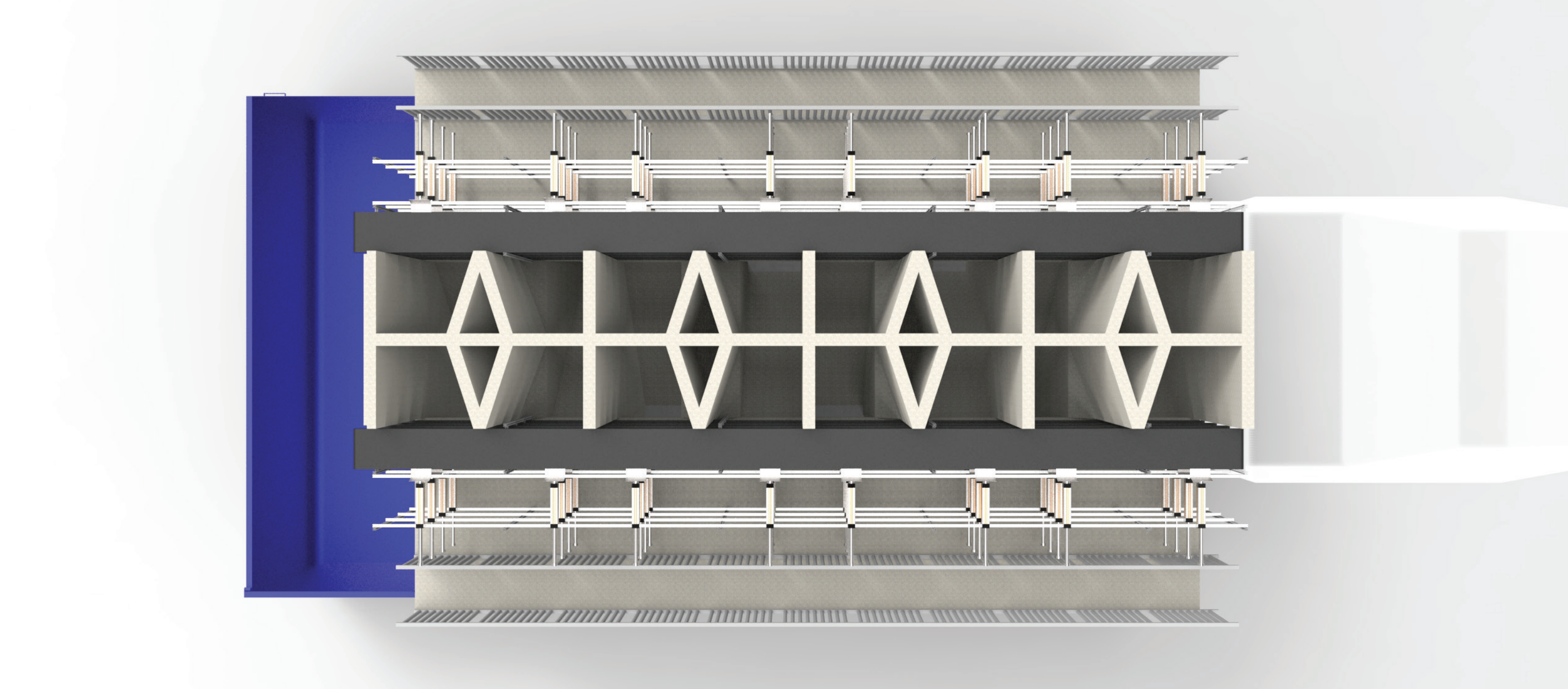
Figure 84 - Center of mass can be aligned with the gripper, but this does not guarantee a succefull push. On the left a 80 [mm] pusher; because there is only one contact point, the piece starts rotating and ends up behind the pusher. On the right a 250 [mm] pusher. Because the surface of the gripper is bigger, there are two contact points in the end. This leads to a secure push.

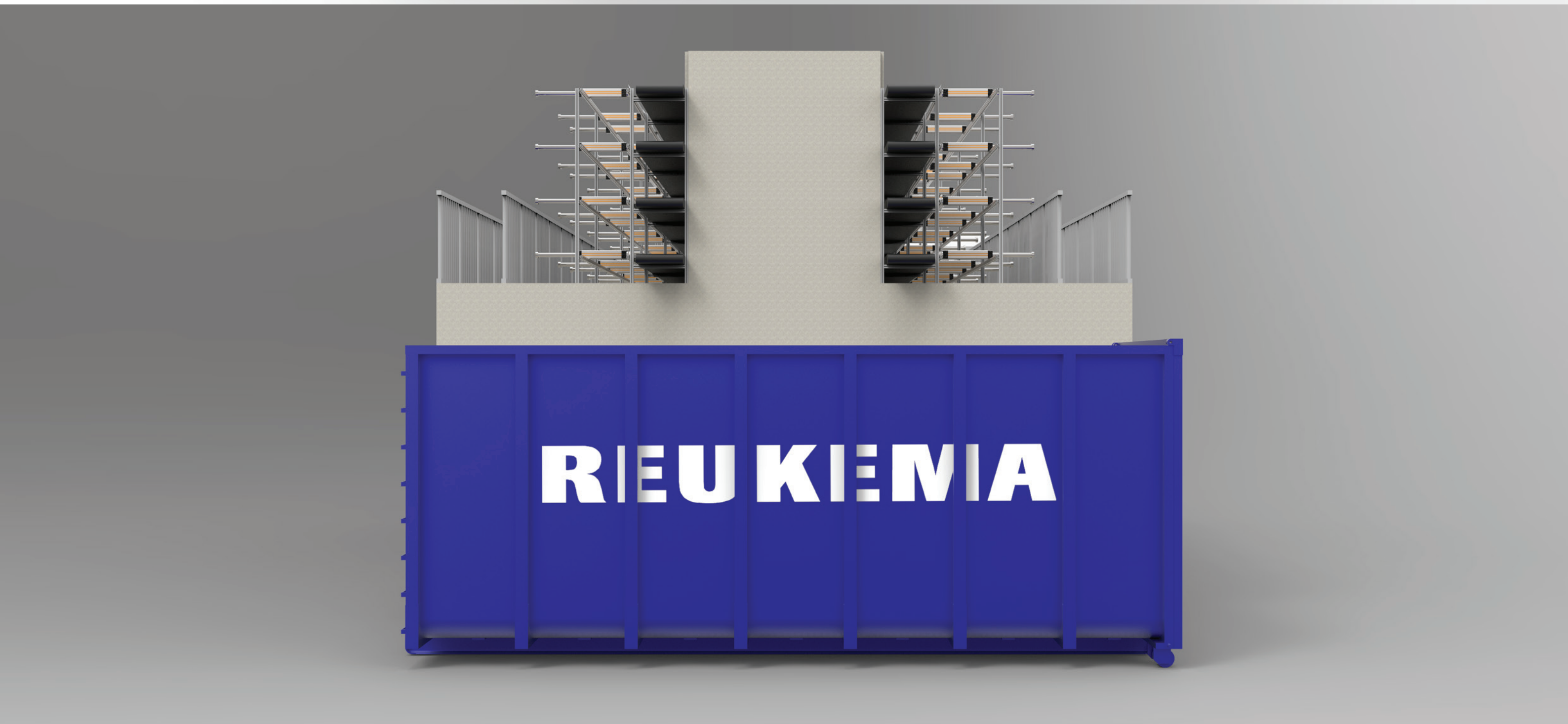
19 - Complete Design

Using the data gathered during this project, a final design was created. This chapter gives an overview of the final design.





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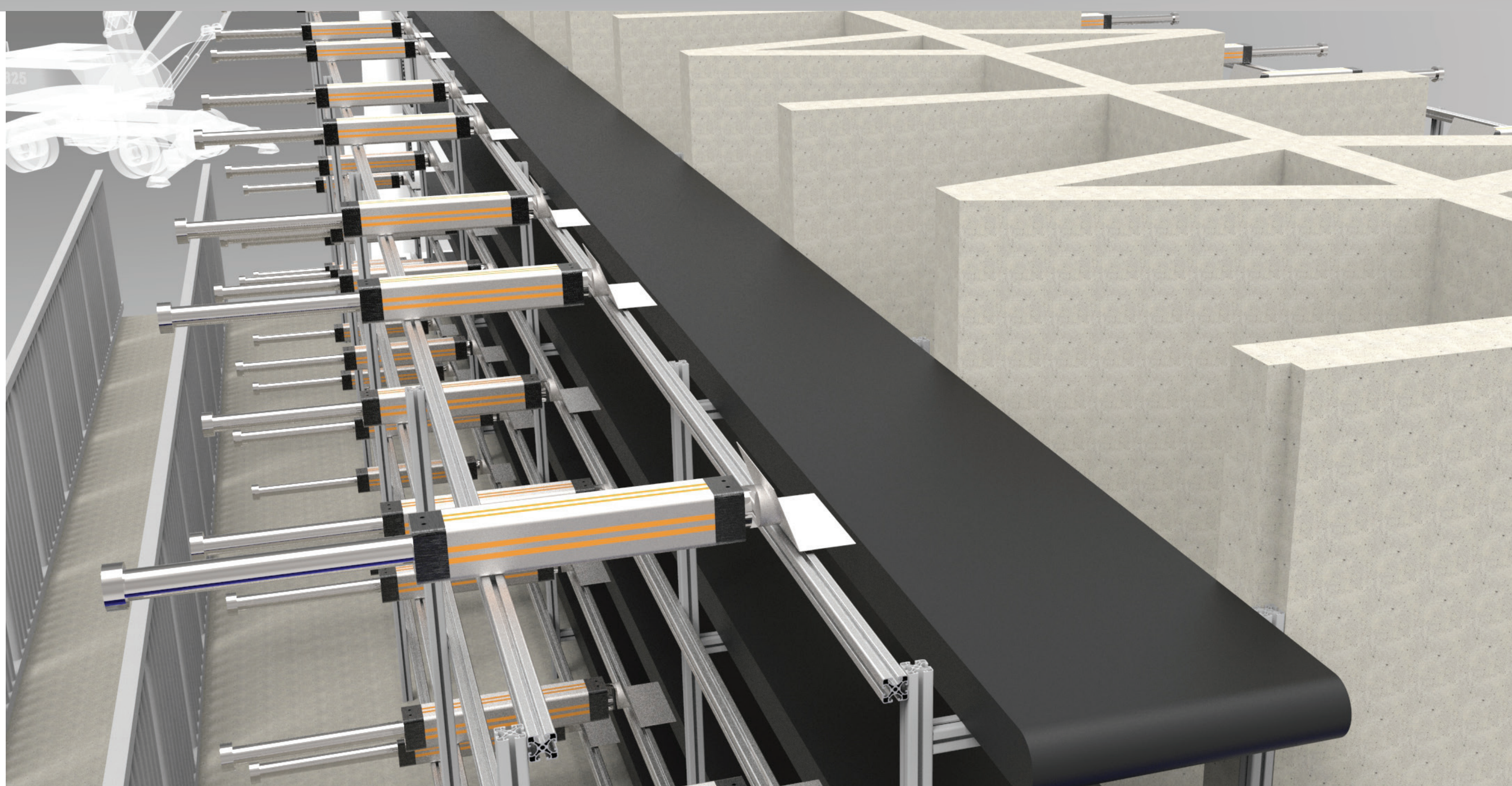

20 - Discussion

In confidential appendix B it is discussed that this design can create added value. In chapter 7 we discussed that there is currently no other company able to sort the mixed aluminium scrap Reukema wants to sort. This means that the design is rare. However, if Reukema does not have a patent, the design can be easily copied. The VRIO analysis (Mullins, Walker, Boyd & Larréché, 2013), shows that the design gives the company a temporary advantage. To sustain the competitive advantage, the company needs to make sure the design is inimitable.

Sorting aluminium scrap using a gripper which pushes them off a conveyor belt in a parabolic flight is new and innovative. This means that the gripper plus the effect of a parabolic flight can be patented. If the company patents this way of sorting, the design is inimitable for competitors.

During the design process, it was proven that the design is feasible. The gripper was prototyped and validated. Still there are elements in the design which require additional validation. Firstly, the in-feed of the material needs to be validated. The variety in shapes of the aluminium is big. Shapes can lock into each other, making it more difficult to singulate them. It is also important to research the spread of the material. As was demonstrated, a minimum distance between pieces is needed for successful sorting. More testing and validating is needed to research the possibilities for singulating material. Secondly, the classification of material using a 3D scanner and a camera needs to be validate for the design. In the literature it was found that using a 3D scanner can be used to classify aluminium (Koyanaka and Kobayashi, 2009). The material Reukema wants to classify is different from the material used in the literature. Besides this, external effects such as dirt, external light or vibrations, have an influence on the classification quality. Thirdly, tests were conducted in a test setup at Festo and ARCO solutions. These test setups were constructed in such a way that they represent reality as close as possible. Tests were focused on parts of the design. Therefore it is important to conduct a test with the complete system running.

A limitation during this design project is number of tests conducted. For each parameter which was optimized, 3 different options were tested (eg. 3 rib lengths, 3 accelerations, 3 gripper widths). This was done because of the limit time available in a graduation project. Besides this, while testing the gripper a random sample size of 20 pieces was used. As was shown, we can see these pieces as extreme cases. The form factor was however not taken into account. A bigger more diverse testing sample would have increased the reliability of the testing results. Besides this, it would have been better to truly optimize one factor, instead of picking 3 values and testing these and continuing with the best possible option.

Looking back at the design process, it can be identified that there are a lot of selection criteria which should be minimized or maximized. There was no upper or lower boundary set for these criteria. This would for example mean that 3 concepts with prices ranging from 500 million to 600 million were also acceptable if the concept of 500 million was selected. Hence, there was optimized for minimized price. We can say that this is a limitation of this graduation project. Earlier on in the project clear requirements should have been set for these selection criteria.

21 - Recommendations

In-feed

Feeding the material into the sorting system is crucial for the sorting quality. During this thesis some small tests were conducted with a vibrating feeder. I would recommend the company to continue testing and designing the in-feed of the material. Currently, the space between the pieces is theoretically determined, but not validated. Because some pieces can behave differently and may disrupt the field, I advise the company to test this. I would also recommend to design a dynamic feeding system in which the distance between pieces can be controlled. This way the effect of different spacing could be evaluated. Besides this, the form factor of the scrap is of great importance. The complexity of this project is mainly due to the fact that no piece is the same. This complexity is not only present at the sorting step, but also at feeding the material.

Pre-treatment material

Looking at the design, we can see that there is no pre-treatment step implemented. I would recommend to include a sieving step in the process. As discussed in chapter 4, statistically there are pieces which have a weight of 1 [g]. Because every piece takes the same sorting time, sorting small pieces is not cost effective. Consequently, I would advise Reukema to investigate what the lower limit should be. What are the smallest pieces the system should be able to sort? As a result, Reukema will end up with a lot of small pieces of aluminum. A solution for these small pieces could be to incinerate them. However, this is not a sustainable practice. There should be attention for this problem, and how to deal with it. Maybe these small pieces of scrap are not suitable for recycling, but can be used to create another product. Creating a circular product from these small pieces of scrap can be a new design project.

Prototype, Test, Evaluate

The tests conducted during this graduation project were conducted as precisely as possible. Still, the tests were not placed in context. Test were conducted as if they were loose elements. I would recommend Reukema to conduct more tests in series. Place the designed elements in their context and test the complete sorting system. See where adjustments are needed and adjust. One of the issues that needs to be solved, is with pieces which falling outside the 99,7% confidence interval. The dimensions for the system were based on three times the standard deviation. This means that 99,7% of all pieces fit into the data used. This means that from every 1.000 pieces, 3 pieces of scrap will behave differently. A possible solution would be to have employees overview the process, and manually remove too heavy or too large pieces. If these pieces are not removed, I expect that the pieces can create damage to the system which should be prevented.

Keep it simple

Reukema is a trading company by nature. As discussed, the company lacks the technological knowledge to design a complete sorting system. External companies are helping Reukema in the design and building of this new sorting system. Personally I found that the solutions these external companies are proposing are overly complex. I want to recommend Reukema to look into simple designs. Start by building a small setup and work from here. They should also be critical about every element in the system: ask what the function is and asses whether it could be simpler. This will help to create a solution which fits the profile of the company in the most optimal way.

22 - Conclusion

This thesis described the process of detailing a gripper for sorting mixed aluminium scrap. During the analysis phase the requirements for the system were drawn up. The goal of the thesis was to design a reliable sorting system with as little maintenance as possible.

In the synthesis phase the conclusions from the analysis phase were used to generate three different idea directions; grab, push, and smash. The idea direction push was selected to be developed into a concept. From this idea directions three different concepts were generated: push, pull and direct. The concept push was selected to be worked out further. The concept consists of a conveyor belt which feeds the material into the system. A pusher pushes the material perpendicular to the conveyor belt into a bunker which is located under the conveyor belts. Material is classified based on a camera and a 3D line scanner.

In the detailing phase different prototypes of the pusher were constructed, tested and evaluated. It was found that a pusher with a rib of 100 [mm] was optimal for lifting pieces off the conveyor belt to reduce fricition and as a result decrease damaging of the system. Besides this, the spread of material was minimized by using a gripper with a width of 250 [mm] and a height of 125 [mm].

In conclusion, the insights gathered and the design presented in this thesis can help Reukema built the first automated sorting system for mixed aluminium scrap.

22 - Personal reflection

This thesis is the final step towards becoming an engineer. When embarking on this journey, I was enthusiastic and motivated to work on the project Reukema had offered. At first, I saw the world of Recycling as a stream of material coming in and going out. But quite soon I understood that the context of recycling scrap is complex. During the project it was sometimes difficult to handle this complexity, but I personally think I have managed to create a feasible design within this complex context.

During this project I aimed to improve my competence to manage the design process. Looking back at the process, I can see that I struggled to work on my own. During the master program I enjoyed working in groups, exchanging ideas and co-creating with others. In my graduation project I learned that I am not the person who can work alone for a long time. Although, the other graduation students were of great help during the process, I learned that for a well-designed product I need a team of designers, users and experts.

Designing is a multidisciplinary activity. I often found myself working on multiple aspects of the design at the same time, which gave me the feeling of needing to rush forward. A personal pitfall is the striving for more and more, instead of improving what is already there. As my supervisors framed it "stop moving forward, and look back at what you have done". Intuitively I made the right design choices, but I was not able to clearly explain the reasoning behind the selection to others. Because I kept running forward, reporting was pushed off till late in the project. Starting earlier with documenting can help in building a more solid reasoning behind my choices, which enables me to explain my choices to others.

During the project the company started working with professional parties on solving the same problems as discussed in this thesis. Sometimes this gave me the feeling of doing unnecessary work. It felt like I needed to compete with professionals. Although this felt like a drawback, I also learned that as an indepent designer you can truly design a solution which fits the company or client. You are not restricted to company rules, toolboxes or specific knowledge. I tried my best in designing the best solution for Reukema. My design is not perfect, but it is simpler in design compared to the solutions the professionals propose, which I believe fits Reukema better.

Overall, the graduation project has been a rollercoaster. I am proud of the result presented in this thesis and I am ready for the next challenge.

23 - Acknowledgement

I would like to express my gratitude to a few people who helped me during my graduation project.

Firstly, I would like to thank Jo Geraedts, Zoltán Rusák and Tijmen Oudshoorn for their supervision the past six months. Your feedback helped me to constantly improve my project and take a critical look at my work.

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Thirdly, I want to thank Ludo & Micha for their critical proofreading skills. Your editing skills helped me in creating a better thesis.

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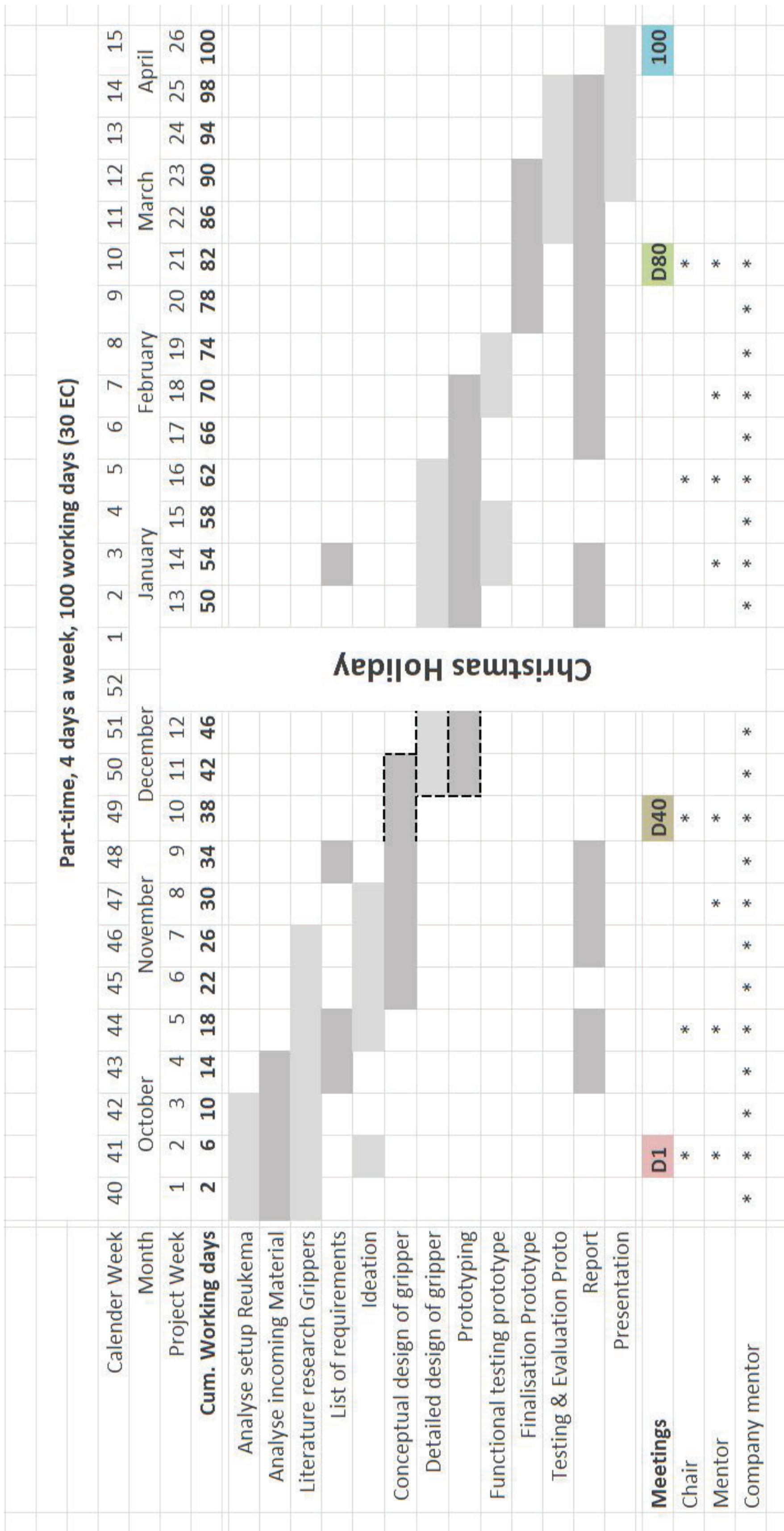
Appendix B - Planning



Appendix C - Different sorting Techniques

Looking at the Handbook of Aluminium Recycling (Schmitz, 2006), different techniques are currently in use to separate aluminum. This section will discuss these techniques.

Magnetic Sorting

Non-ferrous metals can be separated from ferrous metals based on the magnetic properties of the material. Figure 85 gives a graphic overview of the process. This technique is widely used across the industry for separation of ferrous metals from other waste.

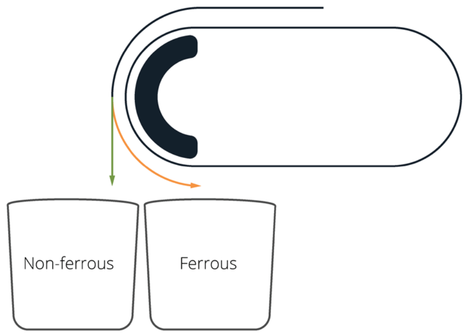


Figure 85 - Magnetic sorting.

Eddy Current Separator

After ferrous-metals are removed from the incoming material, non-ferrous metals can be separated from the organic waste. This technique relies on the electrical conductivity of the material. Materials which conduct electricity are thrown off the belt, due to opposite magnetic fields. Figure 86 gives a graphical overview.

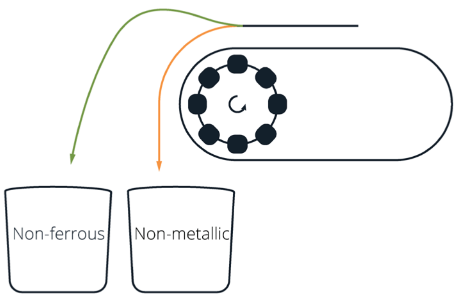


Figure 86 - Eddy current separator.

Air Flow Separator

The air flow separator uses the difference in gravity force on objects. A flow of air is pushed upwards, picking up pieces which have a lower settling velocity compared to the air speed. Using this principle, aluminium can be separated from lighter fractions like paper or plastic. Figure 87 gives a graphical overview.

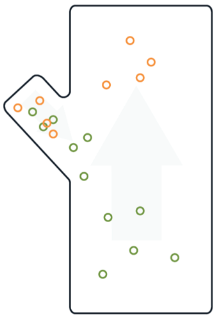


Figure 87 - Air flow separator.

Cyclone separation

The cyclone separation uses the inertia of the different pieces of waste. Heavier objects are spinned outwards, while lighter object stay in the middle. This is mostly used to separate big particles from dust. Figure 88 gives a graphical representation of this technique.

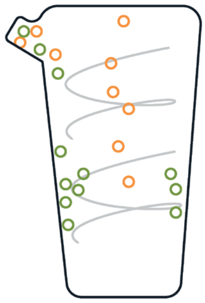


Figure 88 - Cyclone separation.

Sink float separation

The sink float separation technique is used to separate particle with different densities. Figure 89 gives an overview of this technique. Particle should be shredded finely to prevent air trapped in the material. Separation of different alloys of aluminium is possible in theory, but gives a low separation quality (Schmitz, 2006; Weiss, 2014).

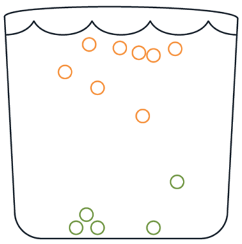


Figure 89 - Sink float separation.

Handpicking

The most used technique to sort different kinds of aluminium alloys from each other is handpicking (Schmitz, 2006; Minter, 2011; Weiss, 2014). Manual sorting is the most reliable process currently available on an industrial scale. In low-wage countries the material is sorted, the work is mainly done by woman (M. van de Poll, personal communication 18 October 2018). Figure 90 gives a graphical overview of the process.

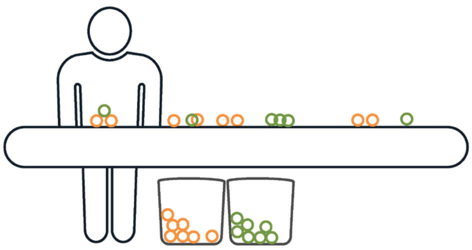


Figure 90 - Handpicking.

Conclusion

Looking at the different separation techniques, there are only two techniques able to sort aluminium alloys; sink float separation and handpicking. The sink float separation gives a low separation quality, while handpicking is labor intensive. Weiss (2014) points out that the use of sensor-based sorting systems is a good alternative to manual or density sorting.

Appendix D - Dataset material

Category	Subcatego	number	Weight	LengthCM	WidthCM	Ratio_LW	Ratio_WL	Group
Plaat	Blank	1	333	48	15	3	0	1.00
Plaat	Blank	2	184	27	14	2	1	1.00
Plaat	Blank	3	196	36	14	3	0	1.00
Plaat	Blank	4	78	16	11	2	1	1.00
Plaat	Blank	5	42	31	3	11	0	1.00
Plaat	Blank	6	446	29	21	1	1	1.00
Plaat	Blank	7	52	13	11	1	1	1.00
Plaat	Blank	8	170	18	12	2	1	1.00
Plaat	Blank	9	154	19	16	1	1	1.00
Plaat	Blank	10	1496	49	28	2	1	1.00
Plaat	Blank	11	14	24	8	3	0	1.00
Plaat	Blank	12	48	21	8	3	0	1.00
Plaat	Blank	13	94	12	9	1	1	1.00
Plaat	Blank	14	228	36	16	2	0	1.00
Plaat	Blank	15	78	18	11	2	1	1.00
Plaat	Blank	16	58	16	11	2	1	1.00
Plaat	Blank	17	30	26	10	3	0	1.00
Plaat	Blank	18	306	25	20	1	1	1.00
Plaat	Blank	19	356	18	12	2	1	1.00
Plaat	Blank	20	36	9	6	2	1	1.00
Plaat	Gelakt	1	112	20	16	1	1	2.00
Plaat	Gelakt	2	52	10	10	1	1	2.00
Plaat	Gelakt	3	100	33	12	3	0	2.00
Plaat	Gelakt	4	338	35	16	2	0	2.00
Plaat	Gelakt	5	638	42	29	2	1	2.00
Plaat	Gelakt	6	322	22	12	2	1	2.00
Plaat	Gelakt	7	94	31	16	2	1	2.00
Plaat	Gelakt	8	108	17	14	1	1	2.00
Plaat	Gelakt	9	470	43	17	3	0	2.00
Plaat	Gelakt	10	340	25	14	2	1	2.00
Plaat	Gelakt	11	282	20	11	2	1	2.00
Plaat	Gelakt	12	88	19	12	2	1	2.00
Plaat	Gelakt	13	42	11	8	1	1	2.00
Plaat	Gelakt	14	42	17	8	2	0	2.00
Plaat	Gelakt	15	162	22	21	1	1	2.00
Plaat	Gelakt	16	50	17	12	2	1	2.00
Plaat	Gelakt	17	82	19	10	2	1	2.00
Plaat	Gelakt	18	32	16	9	2	1	2.00
Plaat	Gelakt	19	42	13	8	2	1	2.00
Plaat	Gelakt	20	40	19	9	2	0	2.00
Plaat	div. aanhe	1	752	37	17	2	0	3.00
Plaat	div. aanhe	2	104	14	14	1	1	3.00
Plaat	div. aanhe	3	46	28	6	4	0	3.00
Plaat	div. aanhe	4	574	38	26	2	1	3.00
Plaat	div. aanhe	5	98	20	9	2	0	3.00
Plaat	div. aanhe	6	388	24	20	1	1	3.00
Plaat	div. aanhe	7	396	26	22	1	1	3.00
Plaat	div. aanhe	8	56	12	9	1	1	3.00
Plaat	div. aanhe	9	302	40	22	2	1	3.00

Plaat	div. aanhe	10	98	14	9	2	1	3.00
Plaat	div. aanhe	11	304	23	15	2	1	3.00
Plaat	div. aanhe	12	120	14	7	2	1	3.00
Plaat	div. aanhe	13	204	19	12	2	1	3.00
Plaat	div. aanhe	14	30	17	13	1	1	3.00
Plaat	div. aanhe	15	624	23	19	1	1	3.00
Plaat	div. aanhe	16	78	15	9	2	1	3.00
Plaat	div. aanhe	17	276	22	10	2	0	3.00
Plaat	div. aanhe	18	108	18	10	2	1	3.00
Plaat	div. aanhe	19	120	21	10	2	0	3.00
Plaat	div. aanhe	20	96	12	11	1	1	3.00
Profiel	Blank	1	60	25	3	9	0	4.00
Profiel	Blank	2	208	31	9	3	0	4.00
Profiel	Blank	3	112	23	20	1	1	4.00
Profiel	Blank	4	146	20	9	2	0	4.00
Profiel	Blank	5	56	31	4	7	0	4.00
Profiel	Blank	6	292	43	9	5	0	4.00
Profiel	Blank	7	130	28	8	4	0	4.00
Profiel	Blank	8	108	22	6	4	0	4.00
Profiel	Blank	9	12	25	5	5	0	4.00
Profiel	Blank	10	258	20	10	2	1	4.00
Profiel	Blank	11	60	14	11	1	1	4.00
Profiel	Blank	12	110	33	7	5	0	4.00
Profiel	Blank	13	72	21	11	2	1	4.00
Profiel	Blank	14	354	35	11	3	0	4.00
Profiel	Blank	15	80	19	12	2	1	4.00
Profiel	Blank	16	118	18	5	4	0	4.00
Profiel	Blank	17	436	26	8	3	0	4.00
Profiel	Blank	18	102	22	12	2	1	4.00
Profiel	Blank	19	30	22	6	4	0	4.00
Profiel	Blank	20	46	19	6	3	0	4.00
Profiel	Gelakt	1	304	32	17	2	1	5.00
Profiel	Gelakt	2	58	21	14	2	1	5.00
Profiel	Gelakt	3	86	16	15	1	1	5.00
Profiel	Gelakt	4	318	38	12	3	0	5.00
Profiel	Gelakt	5	272	32	6	5	0	5.00
Profiel	Gelakt	6	104	27	9	3	0	5.00
Profiel	Gelakt	7	204	35	14	2	0	5.00
Profiel	Gelakt	8	38	23	3	8	0	5.00
Profiel	Gelakt	9	184	29	13	2	0	5.00
Profiel	Gelakt	10	280	33	24	1	1	5.00
Profiel	Gelakt	11	546	35	15	2	0	5.00
Profiel	Gelakt	12	1086	45	24	2	1	5.00
Profiel	Gelakt	13	86	19	10	2	1	5.00
Profiel	Gelakt	14	84	37	2	17	0	5.00
Profiel	Gelakt	15	44	14	6	2	0	5.00
Profiel	Gelakt	16	38	10	4	3	0	5.00
Profiel	Gelakt	17	20	12	7	2	1	5.00
Profiel	Gelakt	18	26	23	10	2	0	5.00
Profiel	Gelakt	19	150	26	9	3	0	5.00

Profiel	Gelakt	20	118	15	8	2	1	5.00
Profiel	div. aanhe	1	58	19	11	2	1	6.00
Profiel	div. aanhe	2	369	43	19	2	0	6.00
Profiel	div. aanhe	3	252	24	17	1	1	6.00
Profiel	div. aanhe	4	340	35	12	3	0	6.00
Profiel	div. aanhe	5	482	32	24	1	1	6.00
Profiel	div. aanhe	6	90	17	9	2	1	6.00
Profiel	div. aanhe	7	68	34	10	3	0	6.00
Profiel	div. aanhe	8	116	26	11	2	0	6.00
Profiel	div. aanhe	9	352	21	19	1	1	6.00
Profiel	div. aanhe	10	410	25	11	2	0	6.00
Profiel	div. aanhe	11	76	36	7	5	0	6.00
Profiel	div. aanhe	12	312	34	7	5	0	6.00
Profiel	div. aanhe	13	66	17	7	2	0	6.00
Profiel	div. aanhe	14	466	32	13	2	0	6.00
Profiel	div. aanhe	15	80	20	12	2	1	6.00
Profiel	div. aanhe	16	316	24	9	3	0	6.00
Profiel	div. aanhe	17	182	24	8	3	0	6.00
Profiel	div. aanhe	18	134	8	6	1	1	6.00
Profiel	div. aanhe	19	90	24	6	4	0	6.00
Profiel	div. aanhe	20	282	26	13	2	1	6.00
Profiel	ISO profiel	1	176	29	11	3	0	7.00
Profiel	ISO profiel	2	400	44	9	5	0	7.00
Profiel	ISO profiel	3	682	46	18	3	0	7.00
Profiel	ISO profiel	4	302	39	19	2	0	7.00
Profiel	ISO profiel	5	172	30	9	3	0	7.00
Profiel	ISO profiel	6	196	26	4	6	0	7.00
Profiel	ISO profiel	7	190	25	20	1	1	7.00
Profiel	ISO profiel	8	180	34	6	6	0	7.00
Profiel	ISO profiel	9	146	19	4	5	0	7.00
Profiel	ISO profiel	10	348	39	15	3	0	7.00
Profiel	ISO profiel	11	272	26	16	2	1	7.00
Profiel	ISO profiel	12	366	40	11	4	0	7.00
Profiel	ISO profiel	13	172	31	11	3	0	7.00
Profiel	ISO profiel	14	374	30	12	3	0	7.00
Profiel	ISO profiel	15	302	37	15	3	0	7.00
Profiel	ISO profiel	16	30	14	3	5	0	7.00
Profiel	ISO profiel	17	232	29	14	2	1	7.00
Profiel	ISO profiel	18	36	16	6	3	0	7.00
Profiel	ISO profiel	19	152	23	6	4	0	7.00
Profiel	ISO profiel	20	150	16	11	1	1	7.00
Plaat	Blank	1	194	20	14	1	1	1.00
Plaat	Blank	2	388	20	13	2	1	1.00
Plaat	Blank	3	250	19	14	1	1	1.00
Plaat	Blank	4	58	17	9	2	1	1.00
Plaat	Blank	5	28	16	6	3	0	1.00
Plaat	Blank	6	112	14	9	2	1	1.00
Plaat	Blank	7	94	17	13	1	1	1.00
Plaat	Blank	8	94	21	15	1	1	1.00
Plaat	Blank	9	180	25	13	2	1	1.00

Plaat	Blank	10	40	22	7	3	0	1.00
Plaat	Blank	11	118	19	16	1	1	1.00
Plaat	Blank	12	100	30	17	2	1	1.00
Plaat	Blank	13	160	28	14	2	1	1.00
Plaat	Blank	14	20	18	7	2	0	1.00
Plaat	Blank	15	34	20	14	1	1	1.00
Plaat	Blank	16	60	22	12	2	1	1.00
Plaat	Blank	17	202	14	10	1	1	1.00
Plaat	Blank	18	16	23	7	4	0	1.00
Plaat	Blank	19	12	13	4	3	0	1.00
Plaat	Blank	20	46	14	9	2	1	1.00
Plaat	Gelakt	1	162	22	11	2	1	2.00
Plaat	Gelakt	2	68	19	12	2	1	2.00
Plaat	Gelakt	3	104	31	15	2	0	2.00
Plaat	Gelakt	4	92	17	7	2	0	2.00
Plaat	Gelakt	5	710	31	22	1	1	2.00
Plaat	Gelakt	6	156	22	21	1	1	2.00
Plaat	Gelakt	7	76	24	9	3	0	2.00
Plaat	Gelakt	8	70	20	10	2	1	2.00
Plaat	Gelakt	9	616	31	17	2	1	2.00
Plaat	Gelakt	10	172	28	15	2	1	2.00
Plaat	Gelakt	11	74	21	8	3	0	2.00
Plaat	Gelakt	12	18	13	7	2	1	2.00
Plaat	Gelakt	13	194	10	10	1	1	2.00
Plaat	Gelakt	14	408	27	15	2	1	2.00
Plaat	Gelakt	15	132	16	9	2	1	2.00
Plaat	Gelakt	16	150	34	13	3	0	2.00
Plaat	Gelakt	17	94	27	12	2	0	2.00
Plaat	Gelakt	18	68	18	9	2	1	2.00
Plaat	Gelakt	19	4	13	5	3	0	2.00
Plaat	Gelakt	20	2	11	3	3	0	2.00
Plaat	div. aanhe	1	280	16	14	1	1	3.00
Plaat	div. aanhe	2	178	17	11	2	1	3.00
Plaat	div. aanhe	3	106	15	14	1	1	3.00
Plaat	div. aanhe	4	106	17	12	1	1	3.00
Plaat	div. aanhe	5	102	20	12	2	1	3.00
Plaat	div. aanhe	6	120	20	10	2	1	3.00
Plaat	div. aanhe	7	156	24	13	2	1	3.00
Plaat	div. aanhe	8	118	21	9	2	0	3.00
Plaat	div. aanhe	9	78	16	8	2	1	3.00
Plaat	div. aanhe	10	64	18	10	2	1	3.00
Plaat	div. aanhe	11	128	15	10	2	1	3.00
Plaat	div. aanhe	12	60	13	13	1	1	3.00
Plaat	div. aanhe	13	304	24	15	2	1	3.00
Plaat	div. aanhe	14	100	20	9	2	0	3.00
Plaat	div. aanhe	15	62	19	12	2	1	3.00
Plaat	div. aanhe	16	134	12	11	1	1	3.00
Plaat	div. aanhe	17	160	19	15	1	1	3.00
Plaat	div. aanhe	18	76	16	15	1	1	3.00
Plaat	div. aanhe	19	400	22	13	2	1	3.00

Plaat	div. aanhe	20	136	14	8	2	1	3.00
Profiel	Blank	1	312	38	18	2	0	4.00
Profiel	Blank	2	284	46	13	4	0	4.00
Profiel	Blank	3	106	22	3	7	0	4.00
Profiel	Blank	4	368	45	12	4	0	4.00
Profiel	Blank	5	92	24	5	5	0	4.00
Profiel	Blank	6	244	53	12	4	0	4.00
Profiel	Blank	7	56	31	4	9	0	4.00
Profiel	Blank	8	194	20	13	2	1	4.00
Profiel	Blank	9	436	26	7	4	0	4.00
Profiel	Blank	10	64	13	9	1	1	4.00
Profiel	Blank	11	72	27	4	7	0	4.00
Profiel	Blank	12	62	24	8	3	0	4.00
Profiel	Blank	13	40	13	7	2	1	4.00
Profiel	Blank	14	164	29	3	9	0	4.00
Profiel	Blank	15	220	11	8	1	1	4.00
Profiel	Blank	16	160	13	5	2	0	4.00
Profiel	Blank	17	348	29	10	3	0	4.00
Profiel	Blank	18	72	17	5	3	0	4.00
Profiel	Blank	19	168	19	9	2	0	4.00
Profiel	Blank	20	50	15	10	2	1	4.00
Profiel	Gelakt	1	180	21	13	2	1	5.00
Profiel	Gelakt	2	60	27	4	6	0	5.00
Profiel	Gelakt	3	32	16	3	5	0	5.00
Profiel	Gelakt	4	94	11	7	2	1	5.00
Profiel	Gelakt	5	80	22	4	5	0	5.00
Profiel	Gelakt	6	82	26	9	3	0	5.00
Profiel	Gelakt	7	178	45	17	3	0	5.00
Profiel	Gelakt	8	118	17	11	2	1	5.00
Profiel	Gelakt	9	76	23	3	7	0	5.00
Profiel	Gelakt	10	106	23	11	2	0	5.00
Profiel	Gelakt	11	334	35	33	1	1	5.00
Profiel	Gelakt	12	28	22	7	3	0	5.00
Profiel	Gelakt	13	66	15	6	2	0	5.00
Profiel	Gelakt	14	306	20	10	2	1	5.00
Profiel	Gelakt	15	110	12	8	2	1	5.00
Profiel	Gelakt	16	82	18	5	4	0	5.00
Profiel	Gelakt	17	38	9	6	2	1	5.00
Profiel	Gelakt	18	76	13	8	2	1	5.00
Profiel	Gelakt	19	28	20	3	7	0	5.00
Profiel	Gelakt	20	22	13	5	3	0	5.00
Profiel	div. aanhe	1	614	37	25	2	1	6.00
Profiel	div. aanhe	2	174	16	6	3	0	6.00
Profiel	div. aanhe	3	66	35	8	4	0	6.00
Profiel	div. aanhe	4	90	21	11	2	1	6.00
Profiel	div. aanhe	5	118	39	9	4	0	6.00
Profiel	div. aanhe	6	444	45	15	3	0	6.00
Profiel	div. aanhe	7	288	28	14	2	0	6.00
Profiel	div. aanhe	8	284	24	11	2	0	6.00
Profiel	div. aanhe	9	112	18	13	1	1	6.00

Profiel	div. aanhe	10	260	23	8	3	0	6.00
Profiel	div. aanhe	11	108	11	9	1	1	6.00
Profiel	div. aanhe	12	48	26	9	3	0	6.00
Profiel	div. aanhe	13	40	22	4	6	0	6.00
Profiel	div. aanhe	14	60	18	13	1	1	6.00
Profiel	div. aanhe	15	84	30	4	7	0	6.00
Profiel	div. aanhe	16	168	22	8	3	0	6.00
Profiel	div. aanhe	17	150	8	10	1	1	6.00
Profiel	div. aanhe	18	254	43	5	9	0	6.00
Profiel	div. aanhe	19	44	12	6	2	1	6.00
Profiel	div. aanhe	20	60	13	5	2	0	6.00
Profiel	ISO profiel	1	488	55	17	3	0	7.00
Profiel	ISO profiel	2	156	22	6	4	0	7.00
Profiel	ISO profiel	3	216	20	13	2	1	7.00
Profiel	ISO profiel	4	28	22	9	2	0	7.00
Profiel	ISO profiel	5	48	19	6	3	0	7.00
Profiel	ISO profiel	6	529	40	17	2	0	7.00
Profiel	ISO profiel	7	182	34	5	7	0	7.00
Profiel	ISO profiel	8	152	17	12	1	1	7.00
Profiel	ISO profiel	9	216	21	6	3	0	7.00
Profiel	ISO profiel	10	156	16	5	3	0	7.00
Profiel	ISO profiel	11	128	26	10	3	0	7.00
Profiel	ISO profiel	12	402	44	10	4	0	7.00
Profiel	ISO profiel	13	82	27	7	4	0	7.00
Profiel	ISO profiel	14	168	27	14	2	1	7.00
Profiel	ISO profiel	15	126	30	10	3	0	7.00
Profiel	ISO profiel	16	34	28	8	4	0	7.00
Profiel	ISO profiel	17	118	15	10	2	1	7.00
Profiel	ISO profiel	18	102	11	6	2	1	7.00
Profiel	ISO profiel	19	122	18	9	2	1	7.00
Profiel	ISO profiel	20	34	9	5	2	1	7.00

CategoryN	Area	Date	Reukema
1.00	720.00	1.00	1.00
1.00	378.00	1.00	1.00
1.00	504.00	1.00	1.00
1.00	176.00	1.00	1.00
1.00	93.00	1.00	1.00
1.00	609.00	1.00	1.00
1.00	143.00	1.00	1.00
1.00	216.00	1.00	1.00
1.00	304.00	1.00	1.00
1.00	1372.00	1.00	1.00
1.00	192.00	1.00	1.00
1.00	168.00	1.00	1.00
1.00	108.00	1.00	1.00
1.00	576.00	1.00	1.00
1.00	198.00	1.00	1.00
1.00	176.00	1.00	1.00
1.00	260.00	1.00	1.00
1.00	500.00	1.00	1.00
1.00	216.00	1.00	1.00
1.00	54.00	1.00	1.00
1.00	320.00	1.00	1.00
1.00	100.00	1.00	1.00
1.00	396.00	1.00	1.00
1.00	560.00	1.00	1.00
1.00	1218.00	1.00	1.00
1.00	264.00	1.00	1.00
1.00	496.00	1.00	1.00
1.00	238.00	1.00	1.00
1.00	731.00	1.00	1.00
1.00	350.00	1.00	1.00
1.00	220.00	1.00	1.00
1.00	228.00	1.00	1.00
1.00	88.00	1.00	1.00
1.00	136.00	1.00	1.00
1.00	462.00	1.00	1.00
1.00	204.00	1.00	1.00
1.00	190.00	1.00	1.00
1.00	144.00	1.00	1.00
1.00	104.00	1.00	1.00
1.00	171.00	1.00	1.00
1.00	629.00	1.00	1.00
1.00	196.00	1.00	1.00
1.00	168.00	1.00	1.00
1.00	988.00	1.00	1.00
1.00	180.00	1.00	1.00
1.00	480.00	1.00	1.00
1.00	572.00	1.00	1.00
1.00	108.00	1.00	1.00
1.00	880.00	1.00	1.00

1.00	126.00	1.00	1.00
1.00	345.00	1.00	1.00
1.00	98.00	1.00	1.00
1.00	228.00	1.00	1.00
1.00	221.00	1.00	1.00
1.00	437.00	1.00	1.00
1.00	135.00	1.00	1.00
1.00	220.00	1.00	1.00
1.00	180.00	1.00	1.00
1.00	210.00	1.00	1.00
1.00	132.00	1.00	1.00
2.00	75.00	1.00	1.00
2.00	279.00	1.00	1.00
2.00	460.00	1.00	1.00
2.00	180.00	1.00	1.00
2.00	124.00	1.00	1.00
2.00	387.00	1.00	1.00
2.00	224.00	1.00	1.00
2.00	132.00	1.00	1.00
2.00	125.00	1.00	1.00
2.00	200.00	1.00	1.00
2.00	154.00	1.00	1.00
2.00	231.00	1.00	1.00
2.00	231.00	1.00	1.00
2.00	385.00	1.00	1.00
2.00	228.00	1.00	1.00
2.00	90.00	1.00	1.00
2.00	208.00	1.00	1.00
2.00	264.00	1.00	1.00
2.00	132.00	1.00	1.00
2.00	114.00	1.00	1.00
2.00	544.00	1.00	1.00
2.00	294.00	1.00	1.00
2.00	240.00	1.00	1.00
2.00	456.00	1.00	1.00
2.00	192.00	1.00	1.00
2.00	243.00	1.00	1.00
2.00	490.00	1.00	1.00
2.00	69.00	1.00	1.00
2.00	377.00	1.00	1.00
2.00	792.00	1.00	1.00
2.00	525.00	1.00	1.00
2.00	1080.00	1.00	1.00
2.00	190.00	1.00	1.00
2.00	74.00	1.00	1.00
2.00	84.00	1.00	1.00
2.00	40.00	1.00	1.00
2.00	84.00	1.00	1.00
2.00	230.00	1.00	1.00
2.00	234.00	1.00	1.00

2.00	120.00	1.00	1.00
2.00	209.00	1.00	1.00
2.00	817.00	1.00	1.00
2.00	408.00	1.00	1.00
2.00	420.00	1.00	1.00
2.00	768.00	1.00	1.00
2.00	153.00	1.00	1.00
2.00	340.00	1.00	1.00
2.00	286.00	1.00	1.00
2.00	399.00	1.00	1.00
2.00	275.00	1.00	1.00
2.00	252.00	1.00	1.00
2.00	238.00	1.00	1.00
2.00	119.00	1.00	1.00
2.00	416.00	1.00	1.00
2.00	240.00	1.00	1.00
2.00	216.00	1.00	1.00
2.00	192.00	1.00	1.00
2.00	48.00	1.00	1.00
2.00	144.00	1.00	1.00
2.00	338.00	1.00	1.00
2.00	319.00	1.00	1.00
2.00	396.00	1.00	1.00
2.00	828.00	1.00	1.00
2.00	741.00	1.00	1.00
2.00	270.00	1.00	1.00
2.00	104.00	1.00	1.00
2.00	500.00	1.00	1.00
2.00	204.00	1.00	1.00
2.00	76.00	1.00	1.00
2.00	585.00	1.00	1.00
2.00	416.00	1.00	1.00
2.00	440.00	1.00	1.00
2.00	341.00	1.00	1.00
2.00	360.00	1.00	1.00
2.00	555.00	1.00	1.00
2.00	42.00	1.00	1.00
2.00	406.00	1.00	1.00
2.00	96.00	1.00	1.00
2.00	138.00	1.00	1.00
2.00	176.00	1.00	1.00
1.00	280.00	2.00	1.00
1.00	260.00	2.00	1.00
1.00	266.00	2.00	1.00
1.00	153.00	2.00	1.00
1.00	96.00	2.00	1.00
1.00	126.00	2.00	1.00
1.00	221.00	2.00	1.00
1.00	315.00	2.00	1.00
1.00	325.00	2.00	1.00

1.00	154.00	2.00	1.00
1.00	304.00	2.00	1.00
1.00	510.00	2.00	1.00
1.00	392.00	2.00	1.00
1.00	126.00	2.00	1.00
1.00	280.00	2.00	1.00
1.00	264.00	2.00	1.00
1.00	140.00	2.00	1.00
1.00	161.00	2.00	1.00
1.00	52.00	2.00	1.00
1.00	126.00	2.00	1.00
1.00	242.00	2.00	1.00
1.00	228.00	2.00	1.00
1.00	465.00	2.00	1.00
1.00	119.00	2.00	1.00
1.00	682.00	2.00	1.00
1.00	462.00	2.00	1.00
1.00	216.00	2.00	1.00
1.00	200.00	2.00	1.00
1.00	527.00	2.00	1.00
1.00	420.00	2.00	1.00
1.00	168.00	2.00	1.00
1.00	91.00	2.00	1.00
1.00	100.00	2.00	1.00
1.00	405.00	2.00	1.00
1.00	144.00	2.00	1.00
1.00	442.00	2.00	1.00
1.00	324.00	2.00	1.00
1.00	162.00	2.00	1.00
1.00	65.00	2.00	1.00
1.00	33.00	2.00	1.00
1.00	224.00	2.00	1.00
1.00	187.00	2.00	1.00
1.00	210.00	2.00	1.00
1.00	204.00	2.00	1.00
1.00	240.00	2.00	1.00
1.00	200.00	2.00	1.00
1.00	312.00	2.00	1.00
1.00	189.00	2.00	1.00
1.00	128.00	2.00	1.00
1.00	180.00	2.00	1.00
1.00	150.00	2.00	1.00
1.00	169.00	2.00	1.00
1.00	360.00	2.00	1.00
1.00	180.00	2.00	1.00
1.00	228.00	2.00	1.00
1.00	132.00	2.00	1.00
1.00	285.00	2.00	1.00
1.00	240.00	2.00	1.00
1.00	286.00	2.00	1.00

1.00	112.00	2.00	1.00
2.00	684.00	2.00	1.00
2.00	598.00	2.00	1.00
2.00	66.00	2.00	1.00
2.00	540.00	2.00	1.00
2.00	120.00	2.00	1.00
2.00	636.00	2.00	1.00
2.00	124.00	2.00	1.00
2.00	260.00	2.00	1.00
2.00	182.00	2.00	1.00
2.00	117.00	2.00	1.00
2.00	108.00	2.00	1.00
2.00	192.00	2.00	1.00
2.00	91.00	2.00	1.00
2.00	87.00	2.00	1.00
2.00	88.00	2.00	1.00
2.00	65.00	2.00	1.00
2.00	290.00	2.00	1.00
2.00	85.00	2.00	1.00
2.00	171.00	2.00	1.00
2.00	150.00	2.00	1.00
2.00	273.00	2.00	1.00
2.00	108.00	2.00	1.00
2.00	48.00	2.00	1.00
2.00	77.00	2.00	1.00
2.00	88.00	2.00	1.00
2.00	234.00	2.00	1.00
2.00	765.00	2.00	1.00
2.00	187.00	2.00	1.00
2.00	69.00	2.00	1.00
2.00	253.00	2.00	1.00
2.00	1155.00	2.00	1.00
2.00	154.00	2.00	1.00
2.00	90.00	2.00	1.00
2.00	200.00	2.00	1.00
2.00	96.00	2.00	1.00
2.00	90.00	2.00	1.00
2.00	54.00	2.00	1.00
2.00	104.00	2.00	1.00
2.00	60.00	2.00	1.00
2.00	65.00	2.00	1.00
2.00	925.00	2.00	1.00
2.00	96.00	2.00	1.00
2.00	280.00	2.00	1.00
2.00	231.00	2.00	1.00
2.00	351.00	2.00	1.00
2.00	675.00	2.00	1.00
2.00	392.00	2.00	1.00
2.00	264.00	2.00	1.00
2.00	234.00	2.00	1.00

2.00	184.00	2.00	1.00
2.00	99.00	2.00	1.00
2.00	234.00	2.00	1.00
2.00	88.00	2.00	1.00
2.00	234.00	2.00	1.00
2.00	120.00	2.00	1.00
2.00	176.00	2.00	1.00
2.00	80.00	2.00	1.00
2.00	215.00	2.00	1.00
2.00	72.00	2.00	1.00
2.00	65.00	2.00	1.00
2.00	935.00	2.00	1.00
2.00	132.00	2.00	1.00
2.00	260.00	2.00	1.00
2.00	198.00	2.00	1.00
2.00	114.00	2.00	1.00
2.00	680.00	2.00	1.00
2.00	170.00	2.00	1.00
2.00	204.00	2.00	1.00
2.00	126.00	2.00	1.00
2.00	80.00	2.00	1.00
2.00	260.00	2.00	1.00
2.00	440.00	2.00	1.00
2.00	189.00	2.00	1.00
2.00	378.00	2.00	1.00
2.00	300.00	2.00	1.00
2.00	224.00	2.00	1.00
2.00	150.00	2.00	1.00
2.00	66.00	2.00	1.00
2.00	162.00	2.00	1.00
2.00	45.00	2.00	1.00

Appendix E - Overview Principal solutions

Screw conveyor
A screw rotates and grabs every time a bit of material. Similar screws can be seen for the transport of water from one level to another.
Pipes
Pipes transport the material like a sewage system.
Disk screen
Rotating disk sieve the material and transport it forward.
Pneumatic conveyor
Material is blown forward.

Slow/Fast conveyor
Two conveyor belts moving at different speeds spread the material. The first conveyor belt moves slow. Material falls onto a faster moving conveyor, resulting in a spread out mix.
Rotating disk
Material is put on a rotating disk. By spinning around, the material is spread.
Vibrating feeder
A vibrating bucket vibrates the pieces so they lie singulated.
Rotating brush
A rotating brush facilitates in feeding material in batches.
Vibrating profile
A vibrating bucket with an internal profile, cause pieces to be lined up in the profiles an lie singulated.
Rolling press
A heavy rolling press presses the material, which causes it to deform and spread out.

LIBS
Lasers burn a little bit of material. The spectrogram of the flame is analyzed and the material is classified.

Pierce
Pushing a sharp object in the pieces of scrap, just like piercing paper with a stick

Appendix F - Vibrating feeder test

The influence of the vibrating feeder was tested. Material was inserted 3 times per test. Afterwards using video, it was analysed how many piece were laying freely on the conveyor belt and how many pieces were still laying on each other. The aim of this research is to find the best in-feed to get as many free pieces on the conveyor belt as possible.

Fully loaded

	#	%
Free	15	30
on each other	35	70

	#	%
Free	15	37.5
on each other	25	62.5

	#	%
Free	12	25
on each other	36	75

Average amount of liberated pieces 30.8%

20 pieces

	#	%
Free	8	40
on each other	12	60

	#	%
Free	7	35
on each other	13	65

	#	%
Free	9	45
on each other	11	55

Average amount of liberated pieces 40%

10 pieces

	#	%
Free	8	80
on each other	2	20

	#	%
Free	6	60
on each other	4	40

	#	%
Free	6	60
on each other	4	40

Average amount of liberated pieces 66%

10 pieces inputted by hand in serie

	#	%
Free	8	80
on each other	2	20

	#	%
Free	9	90
on each other	1	10

	#	%
Free	10	100
on each other	0	0

Average amount of liberated pieces 90%

Appendix G - List of Requirements

Overall requirements

- Sorting the aluminium scrap cost less than 55 [€/tonne] (investment and operation cost) (Ch. 4)
- The system can sort 8 different groups of material (Ch. 6)
- Non sortable materials are collected for hand sorting by an employee (Ch. 4)
- The process of sortation can function continuously (Ch. 4)
- The material is transported through the system (Ch. 4)

Material input

- Shredded material can be inputted into the sorting system (Ch. 4)
- Shredded material is transported by the system on a conveyor belt (Ch. 13)

Spread mix

- The mix of material is automatically spread out (Ch. 4)
- Pieces are positioned by the system in a line (Ch. 13)
- There is a minimum distance between the center of each piece of 300 [mm] (Ch. 15)

Acquire data

- X & y location of a piece of scrap is measured (Ch. 8)
- The velocity of the pieces of scrap is be measured (Ch. 8)
- The contour of the piece can be determined (Ch. 8)
- Pieces are classified based on the acquired data (Ch. 5)

Move

- The gripper is able to handle piece with a length of 10 - 514 [mm] (Ch. 6)
- The gripper is able to handle piece with a width of 10 - 261 [mm] (Ch. 6)
- The gripper is able to handle pieces with a weight of 10 - 700 [g] (Ch. 6)
- Grippers move 112.359 [pieces/hour] of aluminium scrap from a moving conveyor belt (20 [tonnes/hour] / 178 [g/piece]).
- 98% (or more) of the picks are successful (Ch. 4)
- The gripper can exert 7 [N] or more
- The gripper has a pick cycle of 2 [s] or less (Ch. 7)
- The gripper is protected against dirt and condensation - IP62 (Ch. 8).
- The Youngs Modulus of the material out of which the gripper is constructed is higher than 69 [GPa] (Ch. 8).
- The center of the pusher is positioned 400 [mm] from the opening of the bunker (Ch. 18)
- The actuator has a minimal acceleration of 2 [m/s2] (for s=0.5, t=1s, because pick cycle should be shorter than 2 [s]).
- The actuator has a stroke of 500 [mm]
- The actuator can exert a minimum force of 0,7 [N]
- The gripper is constructed out of steel (Ch. 15)
- The gripper is 250 [mm] in width (Ch.18)
- The gripper is 125 [mm] in height (Ch.18)
- The gripper has an rib of 100 [mm] (Ch.18)
- The back plate of the gripper is place under an angle of 10 [degrees] (Ch.18)

Store

- The sorted material is stored in such a way that the sorting process can continue continuously (Ch. 4)
- The opening of the storing location is 850 [mm] (Ch. 18)
- The opening of the bunker is at least 2300 [mm] so a can remove the material (Ch. 15).

Overview (Ch.15)

- One operator overviews the process of the automated sorting
- Two operators are standing next to the conveyor belts
- One operator removes the material from the bunkers using a shovel
- One site manager is present per shift

Appendix H - Cost estimaton

Concepts

Push — Fixed Costs

	Price [€]	Quantity	Total [€]	*Sources*
Hammel	€ 68.365,00	1	€ 68.365,00	*https://www.werk*
Conveyor belt (infee	€ 500,00	50	€ 25.000,00	*Reukema*
Sensor modules	€ 30.000,00	8	€ 240.000,00	*Reukema*
Walking floor storage			€ 30.000,00	*Reukema*
Vibrating feeder	€ 4.500,00	16	€ 72.000,00	*https://www.aliba*
Sif			€ 33.000,00	
Installation			€ 50.000,00	
Certification			€ 15.000,00	
Conveyor belt (in sy	€ 500,00	64	€ 32.000,00	*https://www.aliba*
Concrete bunker	€ 550,00	36	€ 19.800,00	*https://hansonsilc*
Concrete Floor			€ 30.000,00	*Reukema*
Fence	€ 120,00	44	€ 5.280,00	*https://www.hom*
Stairs			€ 30.000,00	*Reukema*
Control cabinet	€ 20.000,00	2	€ 40.000,00	*Reukema*
Push gripper	€ 750,00	64	€ 48.000,00	
Linear actuator	€ 2.500,00	192	€ 480.000,00	
Frame aluminium 2	€ 35,64	176	€ 6.272,64	*http://www.stapp*
Control software			€ 20.000,00	
Engineering of all parts			€ 75.000,00	*Reukema*
Footing			€ 30.000,00	*Reukema*
Conveyor belt 1m (a	€ 1.000,00	140	€ 140.000,00	*Reukema*
Bunkers			€ 10.000,00	
Storage	€ 550,00	180	€ 99.000,00	*https://hansonsilc*
Project management			€ 20.000,00	*Reukema*
Testing of system			€ 10.000,00	*Reukema*
			€ 1.628.717,64	

Push — Variable Costs

	Price [€/hour]	Hours/week	Total	
Operator	25	160	€ 4.000,00	*https://www.proc*
Manager	50	40	€ 2.000,00	*https://www.proc*
Crane operator including crane			€ 2.884,62	*150.000€/ jaar (*
		kWh/week		
Energy	0,2	2352	€ 470,40	*https://www.engi*
			€ 9.355,02	
		kW		
		58,8		

Pull — Fixed Costs

	Price	Quantity	Total [€]	*Sources*
Hammel	€ 68.365,00	1	€ 68.365,00	*https://www.werk*
Conveyor belt (infe	€ 2.000,00	50	€ 100.000,00	*Reukema*
Sensor modules	€ 30.000,00	2	€ 60.000,00	*Reukema*
Walking floor storage			€ 30.000,00	*Reukema*
Vibrating feeder	€ 6.000,00	4	€ 24.000,00	*https://www.aliba*
Sif			€ 33.000,00	
Installation			€ 50.000,00	
Certification			€ 15.000,00	
Conveyor belt (sys	€ 2.000,00	30	€ 60.000,00	*Reukema*
Concrete bunker	€ 550,00	280	€ 154.000,00	*https://hansonsilc*
Concrete floor			€ 30.000,00	*Reukema*
Fence	€ 120,00	120	€ 14.400,00	*https://www.hom*
Stairs			€ 30.000,00	*Reukema*
Control cabinet	€ 20.000,00	2	€ 40.000,00	*Reukema*
Pull gripper	€ 750,00	48	€ 36.000,00	
Linear actuator	€ 2.500,00	144	€ 360.000,00	
Control software			€ 20.000,00	
Engineering of all parts			€ 75.000,00	*Reukema*
Footing			€ 30.000,00	*Reukema*
Conveyor belt 1m	€ 1.000,00	300	€ 300.000,00	*Reukema*
Bunkers			€ 10.000,00	*Reukema*
Storage	€ 550,00	180	€ 99.000,00	*https://hansonsilc*
Project management			€ 20.000,00	*Reukema*
Testing of system			€ 10.000,00	*Reukema*
			€ 1.288.400,00	

Pull — Variable Costs

	Price [€/hour]	Hours/week	Total	
Operator	25	200	€ 5.000,00	*https://www.proc*
Manager	50	40	€ 2.000,00	*https://www.proc*
			€ 2.884,62	
		kWh/week		
Energy	0,2	5532	€ 1.106,40	*https://www.engi*
			€ 10.991,02	
		kW		
		138,3		

Direct — Fixed Costs

	Price	Quantity	Total [€]	*Sources*
Hammel	€ 68.365,00	1	€ 68.365,00	*https://www.werk*
Conveyor belt (in	€ 2.000,00	50	€ 100.000,00	*Reukema*
Sensor modules	€ 30.000,00	2	€ 60.000,00	*Reukema*
Walking floor storage			€ 30.000,00	*Reukema*
Vibrating feeder	€ 6.000,00	4	€ 24.000,00	*https://www.aliba*
Sif			€ 33.000,00	
Installation			€ 50.000,00	
Certification			€ 15.000,00	
Conveyor belt (sy	€ 2.000,00	30	€ 60.000,00	*Reukema*
Concrete bunker	€ 550,00	180	€ 99.000,00	*https://hansonsilc*
Concrete floor			€ 30.000,00	*Reukema*
Fence	€ 120,00	120	€ 14.400,00	*https://www.hom*
Stairs			€ 30.000,00	*Reukema*
Control cabinet	€ 20.000,00	2	€ 40.000,00	*Reukema*
Direct gripper	€ 750,00	48	€ 36.000,00	
Gantry	€ 10.000,00	48	€ 480.000,00	*https://www.aliba*
Control software			€ 20.000,00	*Reukema*
Engineering of all parts			€ 75.000,00	*Reukema*
Footing			€ 30.000,00	*https://hansonsilc*
Conveyor belt 1n	€ 1.000,00	300	€ 300.000,00	*Reukema*
Bunkers			€ 10.000,00	*Reukema*
Storage	€ 550,00	180	€ 99.000,00	*https://hansonsilc*
Project management			€ 20.000,00	*Reukema*
Testing of system			€ 10.000,00	*Reukema*
			€ 1.353.400,00	

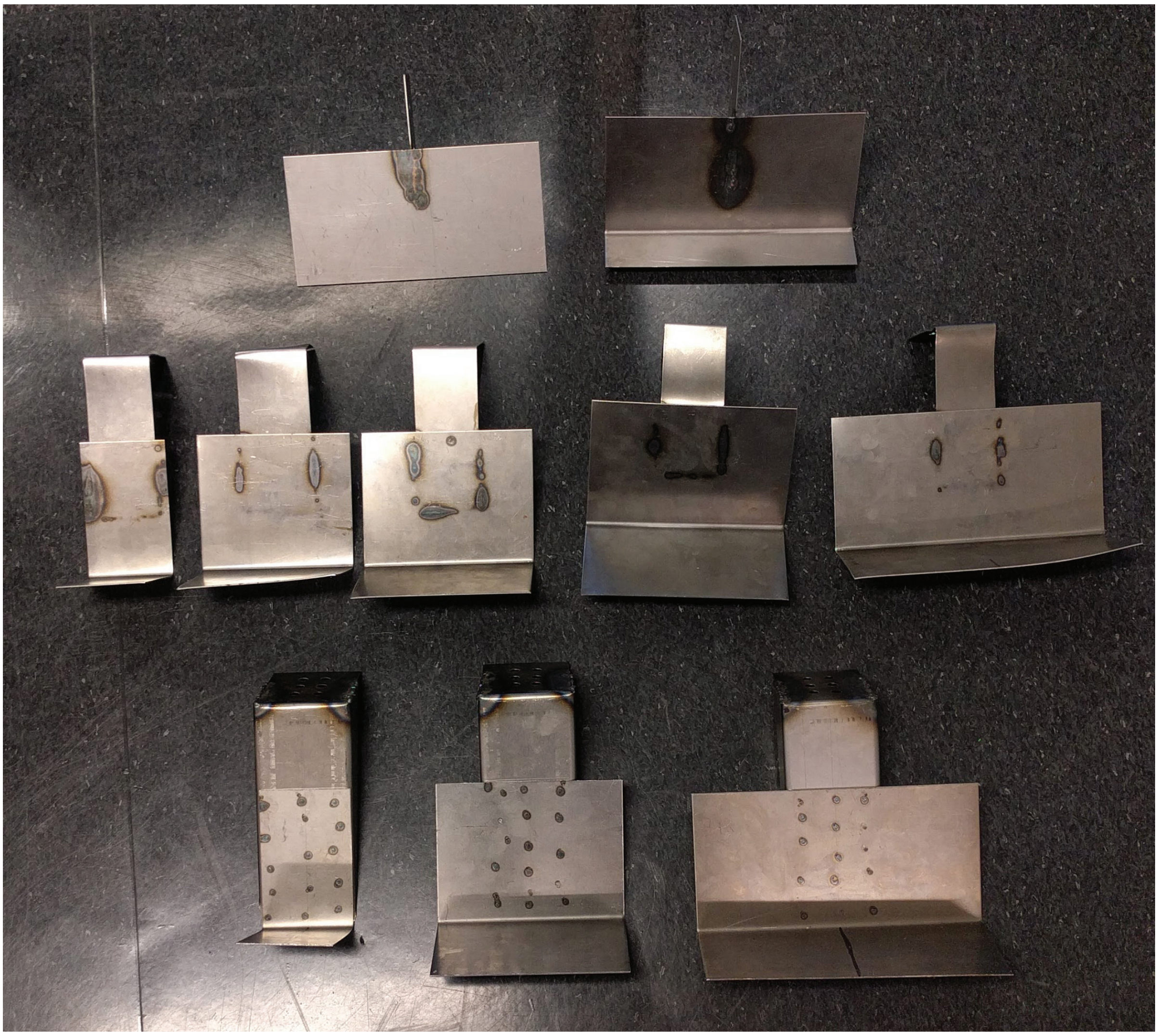
Direct — Variable Costs

	Price [€/hour]	Hours/week	Total	
Operator	25	200	€ 5.000,00	*https://www.proc*
Manager	50	40	€ 2.000,00	*https://www.proc*
			€ 2.884,62	
		kWh/week		
Energy	0,2	3572	€ 714,40	*https://www.engi*
			€ 10.599,02	
		kW		
		89,3		

Appendix I - Test sample material data

Piece Number	Weight	Length	Width
1	576	376	188
2	114	272	190
3	647	500	140
4	1088	383	260
5	547	346	148
6	444	272	198
7	745	420	185
8	559	346	252
9	718	346	82
10	41	185	111
11	184	260	148
12	458	445	223
13	891	297	260
14	179	297	111
15	263	396	148
16	172	247	235
17	71	322	99
18	667	420	161
19	567	260	148
20	468	322	131

Appendix J - Prototypes overview



Appendix K - Dynamic model

```
> restart; with(plots) : with(Statistics) :
> ΣFx := Fx - Ffriction_x - Fairdrag_x = mass · diff(sx(t), t$2);
  ΣFx_heavy := Fx - Ffriction_x_heavy - Fairdrag_x_heavy = mass_max · diff(sx_heavy(t), t
    $2);
  ΣFx_light := Fx − Ffriction_x_light - Fairdrag_x_light = mass_min· diff(sx_light(t), t$2);
```

$$\Sigma Fx := Fx - Ffriction\_x - Fairdrag\_x = mass\left(\frac{d^2}{dt^2}sx(t)\right)$$

$$\Sigma Fx\_heavy := Fx - Ffriction\_x\_heavy - Fairdrag\_x\_heavy = mass\_max\left(\frac{d^2}{dt^2}sx\_heavy(t)\right)$$

$$\Sigma Fx\_light := Fx - Ffriction\_x\_light - Fairdrag\_x\_light = mass\_min\left(\frac{d^2}{dt^2}sx\_light(t)\right) \quad (1)$$

```
> ΣFy := Fy − Fgravity − Fairdrag_y = mass · diff(sy(t), t$2);
  ΣFy_heavy := Fy − Fgravity_heavy − Fairdrag_y_heavy = mass_max · diff(sy_heavy(t), t$2);
  ΣFy_light := Fy − Fgravity_light − Fairdrag_y_light = mass_min · diff(sy_light(t), t$2);
```

$$\Sigma Fy := Fy - Fgravity - Fairdrag\_y = mass\left(\frac{d^2}{dt^2}sy(t)\right)$$

$$\Sigma Fy\_heavy := Fy - Fgravity\_heavy - Fairdrag\_y\_heavy = mass\_max\left(\frac{d^2}{dt^2}sy\_heavy(t)\right)$$

$$\Sigma Fy\_light := Fy - Fgravity\_light - Fairdrag\_y\_light = mass\_min\left(\frac{d^2}{dt^2}sy\_light(t)\right) \quad (2)$$

$$> Fx := piecewise\left(0 \le t \le \frac{1}{10}, 42, t > \frac{1}{10}, 0\right) :$$

$$> angle := 10\cdot\left(\frac{3.1415}{180}\right);$$

$$angle := 0.1745277778 \quad (3)$$

```
> Fy := Fx·tan(angle);
```

$$Fy := 0.1763216733\left(\begin{cases} 42 & 0 \le t \le \frac{1}{10} \\ 0 & \frac{1}{10} < t \end{cases}\right) \quad (4)$$

```
> evalf(tan(angle));
```

$$0.1763216733 \quad (5)$$

```
> Fairdrag_x := 0.5 · (diff(sx(t), t))^2·ρ ·Cd·A :
  Fairdrag_x_light := 0.5 · (diff(sx_light(t), t))^2·ρ ·Cd·A :
  Fairdrag_x_heavy := 0.5 · (diff(sx_heavy(t), t))^2·ρ ·Cd·A :
> Fairdrag_y := 0.5·(diff(sy(t), t))^2·ρ ·Cd·A·Heaviside(diff(sy(t), t)) :
  Fairdrag_y_heavy := 0.5·(diff(sy_heavy(t), t))^2·ρ ·Cd·A·Heaviside(diff(sy_heavy(t), t)) :
  Fairdrag_y_light := 0.5·(diff(sy_light(t), t))^2·ρ ·Cd·A·Heaviside(diff(sy_light(t), t)) :
```

> $Cd := 1:$
$A := 0.000277:$
$\rho := 1.204:$

>

> $mass := 0.178:$
$mass\_max := 0.178 + (0.173 \cdot 3):$
$mass\_min := 0.010:$

> $Ffriction\_x := N \cdot \mu;$
$Ffriction\_x\_light := N\_min \cdot \mu:$
$Ffriction\_x\_heavy := N\_max \cdot \mu:$

$$Ffriction\_x := N\mu \quad (6)$$

> $N := mass \cdot g:$
$N\_min := mass\_min \cdot g:$
$N\_max := mass\_max \cdot g:$

> $Fgravity := mass \cdot g:$
$Fgravity\_heavy := mass\_max \cdot g:$
$Fgravity\_light := mass\_min \cdot g:$

> $g := 9.81:$

> $\mu := 0:$

> $\Sigma Fx;$
$\Sigma Fx\_heavy;$
$\Sigma Fx\_light;$

$$\left(\begin{cases} 42 & 0 \le t \le \frac{1}{10} \\ 0 & \frac{1}{10} < t \end{cases}\right) - 0.0001667540 \left(\frac{d}{dt} sx(t)\right)^2 = 0.178 \frac{d^2}{dt^2} sx(t)$$

$$\left(\begin{cases} 42 & 0 \le t \le \frac{1}{10} \\ 0 & \frac{1}{10} < t \end{cases}\right) - 0.0001667540 \left(\frac{d}{dt} sx\_heavy(t)\right)^2 = 0.697 \frac{d^2}{dt^2} sx\_heavy(t)$$

$$\left(\begin{cases} 42 & 0 \le t \le \frac{1}{10} \\ 0 & \frac{1}{10} < t \end{cases}\right) - 0.0001667540 \left(\frac{d}{dt} sx\_light(t)\right)^2 = 0.010 \frac{d^2}{dt^2} sx\_light(t) \quad (7)$$

> $\Sigma Fy;$
$\Sigma Fy\_heavy;$
$\Sigma Fy\_light;$

$$0.1763216733 \left(\begin{cases} 42 & 0 \le t \le \frac{1}{10} \\ 0 & \frac{1}{10} < t \end{cases}\right) - 1.74618 - 0.0001667540 \left(\frac{d}{dt}\right.$$

$$sy(t)\Big)^2 \text{Heaviside}\left(\frac{d}{dt}\, sy(t)\right) = 0.178\, \frac{d^2}{dt^2}\, sy(t)$$

$$0.1763216733 \left(\begin{cases} 42 & 0 \le t \le \frac{1}{10} \\ 0 & \frac{1}{10} < t \end{cases}\right) - 6.83757 - 0.0001667540 \left(\frac{d}{dt}\right.$$

$$sy\_heavy(t)\Big)^2 \text{Heaviside}\left(\frac{d}{dt}\, sy\_heavy(t)\right) = 0.697\, \frac{d^2}{dt^2}\, sy\_heavy(t)$$

$$0.1763216733 \left(\begin{cases} 42 & 0 \le t \le \frac{1}{10} \\ 0 & \frac{1}{10} < t \end{cases}\right) - 0.09810 - 0.0001667540 \left(\frac{d}{dt}\right. \tag{8}$$

$$sy\_light(t)\Big)^2 \text{Heaviside}\left(\frac{d}{dt}\, sy\_light(t)\right) = 0.010\, \frac{d^2}{dt^2}\, sy\_light(t)$$

```
> ics_x := sx(0) = 0, D(sx)(0) = 0 :
  ics_x_light := sx_light(0) = 0, D(sx_light)(0) = 0 :
  ics_x_heavy := sx_heavy(0) = 0, D(sx_heavy)(0) = 0 :
> ics_y := sy(0) = 0, D(sy)(0) = 0 :
  ics_y_heavy := sy_heavy(0) = 0, D(sy_heavy)(0) = 0 :
  ics_y_light := sy_light(0) = 0, D(sy_light)(0) = 0 :
> solx := dsolve({ΣFx, ics_x}, type = numeric, output = listprocedure) :
> solx_heavy := dsolve({ΣFx_heavy, ics_x_heavy}, type = numeric, output = listprocedure) :
> solx_light := dsolve({ΣFx_light, ics_x_light}, type = numeric, output = listprocedure) :
> soly := dsolve({ΣFy, ics_y}, type = numeric, output = listprocedure);
  soly_heavy := dsolve({ΣFy_heavy, ics_y_heavy}, type = numeric, output = listprocedure);
  soly_light := dsolve({ΣFy_light, ics_y_light}, type = numeric, output = listprocedure);
```

soly := [t = **proc**(t) ... **end proc**, sy(t) = **proc**(t) ... **end proc**, $\frac{d}{dt}$ sy(t) = **proc**(t)

...

end proc]

soly_heavy := [t = **proc**(t) ... **end proc**, sy_heavy(t) = **proc**(t) ... **end proc**, $\frac{d}{dt}$ sy_heavy(t)

= **proc**(t) ... **end proc**]

soly_light := [t = **proc**(t) ... **end proc**, sy_light(t) = **proc**(t) ... **end proc**, $\frac{d}{dt}$ sy_light(t) = **(9)**

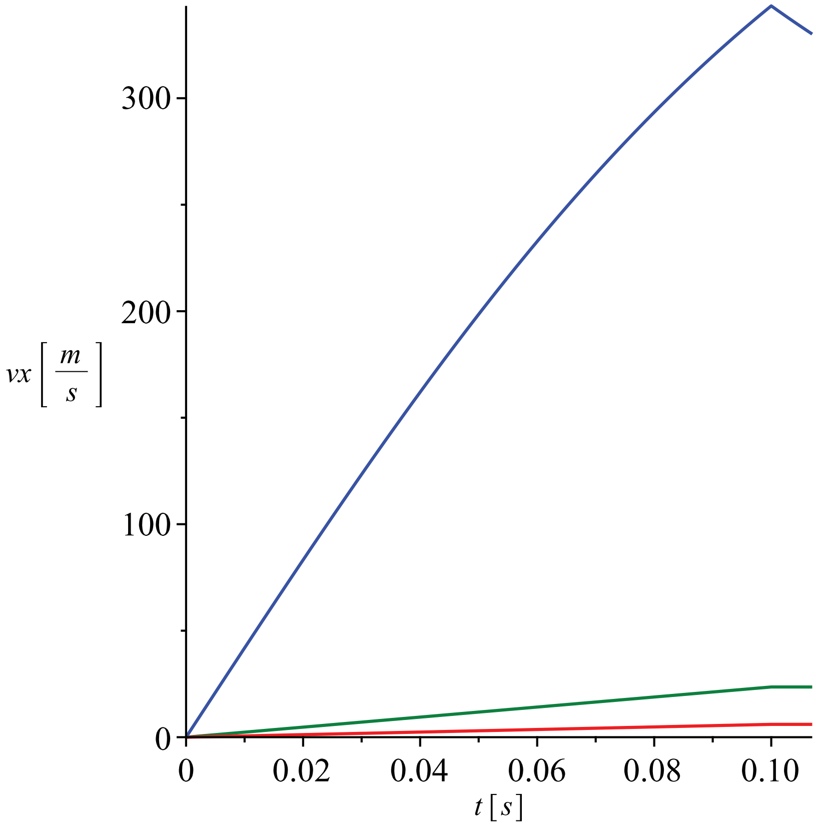
proc(t)

...

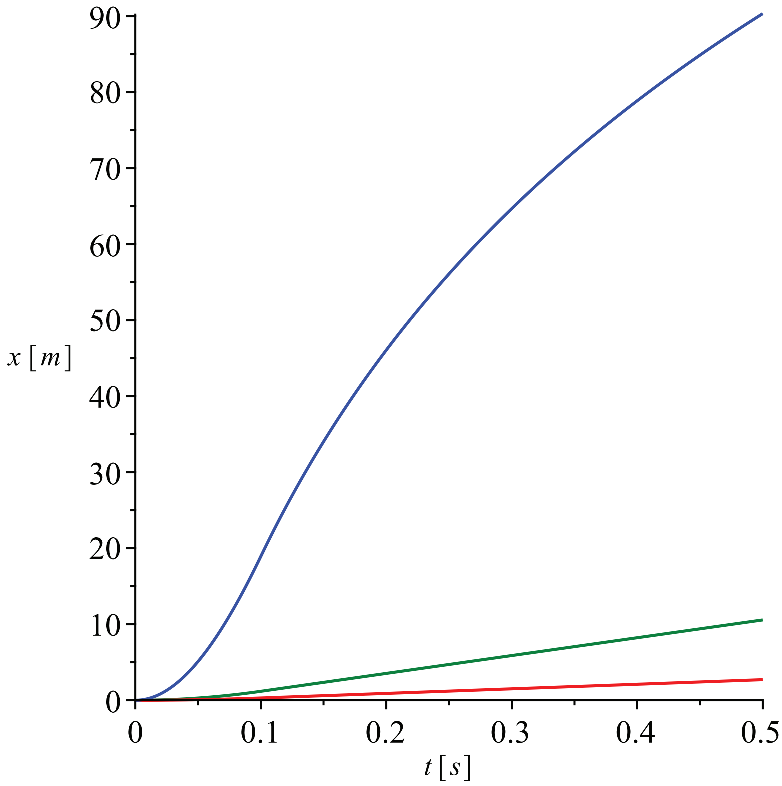
end proc]

```
> Distance_x := rhs(solx[2]) :
```

```
Speed_x := rhs(solx[3]) :
> Distance_x_heavy := rhs(solx_heavy[2]) :
  Speed_x_heavy := rhs(solx_heavy[3]) :
> Distance_x_light := rhs(solx_light[2]) :
  Speed_x_light := rhs(solx_light[3]) :
> Distance_y := rhs(soly[2]) :
  Speed_y := rhs(soly[3]) :
> Distance_y_heavy := rhs(soly_heavy[2]) :
  Speed_y_heavy := rhs(soly_heavy[3]) :
> Distance_y_light := rhs(soly_light[2]) :
  Speed_y_light := rhs(soly_light[3]) :
> plot({Speed_x(t), Speed_x_heavy(t), Speed_x_light(t)}, t = 0 ..0.107, labels = ['t' [s],'vx
  ' ['m'/s]], color = ["Green", "Red", "Blue"]);
```




```
> plot({Distance_x(t), Distance_x_light(t), Distance_x_heavy(t)}, t = 0 ..0.5, labels = ['t' [s],'x' [
  'm']], color = ["Green", "Red", "Blue"]);
```



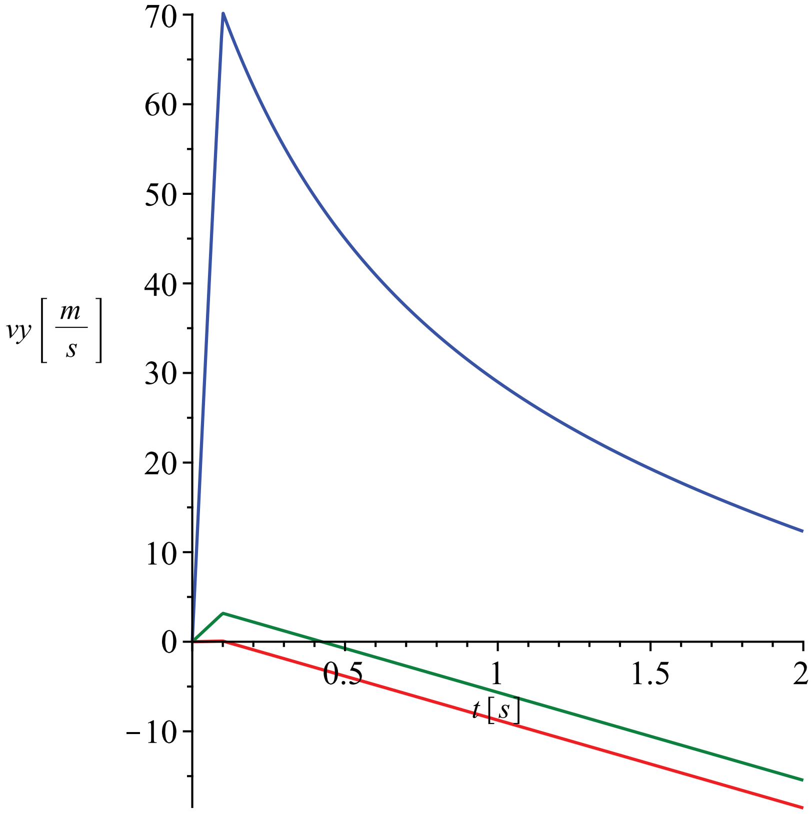
> *Distance_x_heavy*(0.14);
Distance_x(0.08);
Distance_x_light(0.0165);

0.542297695624168
0.754878216341020
0.569917316129880 **(10)**

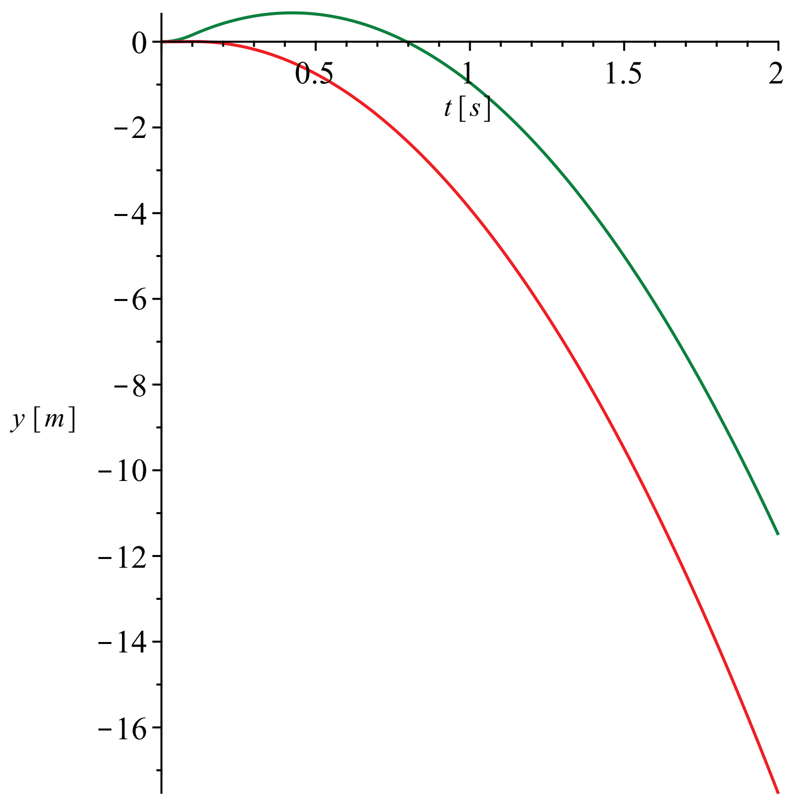
> *Speed_y_heavy*(0.1);

0.0814831924148151 **(11)**

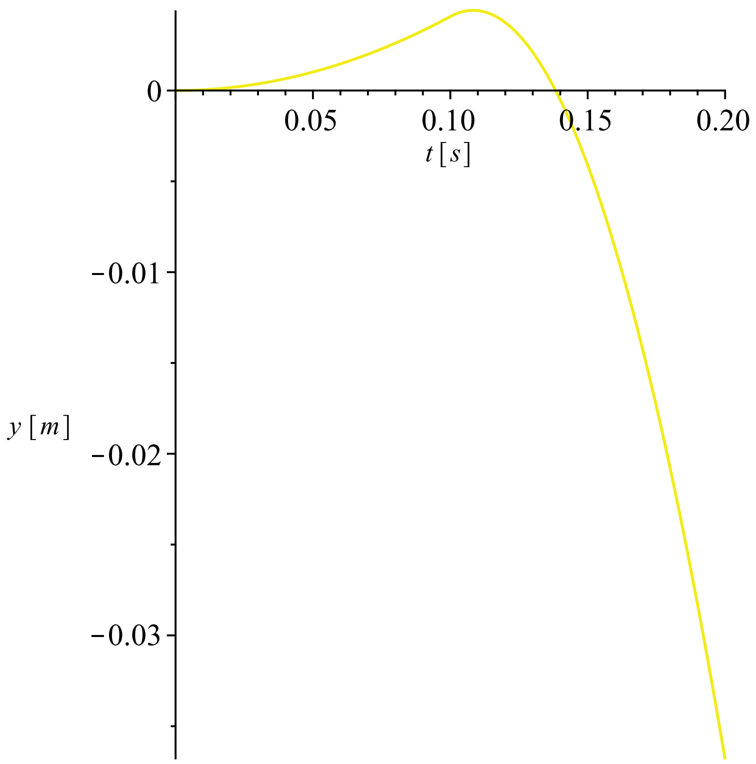
> $plot\left(\{Speed\_y(t), Speed\_y\_heavy(t), Speed\_y\_light(t)\}, t = 0..2, labels = \left['t'\ [s], 'vy'\left[\frac{'m'}{s}\right]\right], color = ["Green", "Red", "Blue"]\right);$



> *plot*({*Distance_y*(*t*), *Distance_y_heavy*(*t*) }, *t* = 0 ..2, *labels* = ['*t*' [*s*],'*y*' ['*m*']], *color* = ["Green", "Red", "Blue"]);



> *plot*({*Distance_y_heavy*(*t*) }, *t* = 0 ..0.2, *labels* = ['*t*' [*s*],'*y*' ['*m*']], *color* = ["Yellow"]);



> *Distance_x_heavy*(0.1);
Distance_y_heavy(0.1);

0.301284009202198
0.00407417571068922 **(12)**

> *Distance_x_heavy*(0.25);
Distance_y_heavy(0.25);

1.20501368484750
−0.0940658412188373 **(13)**

>

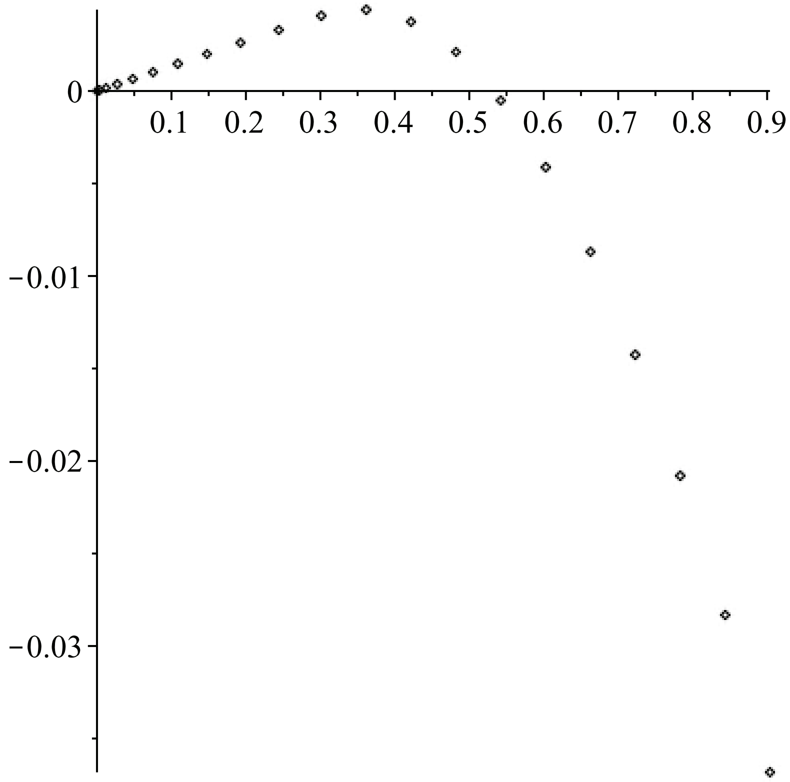
>

> $points\_heavy := \left\{ seq\left(\left[Distance\_x\_heavy\left(\frac{t}{100} \right), Distance\_y\_heavy\left(\frac{t}{100} \right) \right], t = 0 ..20 \right) \right\}:$

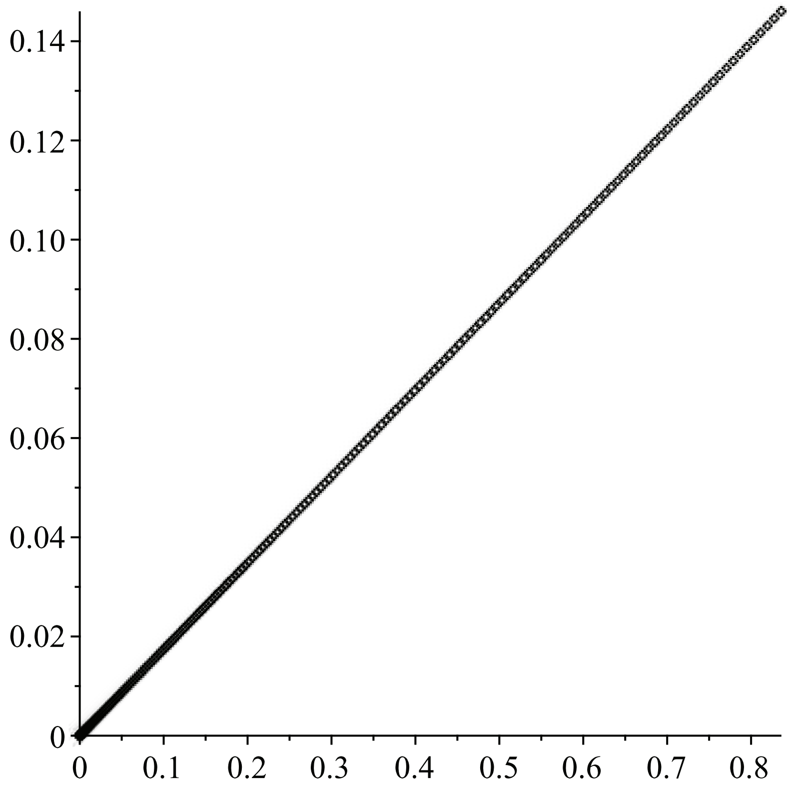
$points := \left\{ seq\left(\left[Distance\_x\left(\frac{t}{100} \right), Distance\_y\left(\frac{t}{100} \right) \right], t = 0 ..20 \right) \right\}:$

$points\_light := \left\{ seq\left(\left[Distance\_x\_light\left(\frac{t}{10000} \right), Distance\_y\_light\left(\frac{t}{10000} \right) \right], t = 0 ..200 \right) \right\}:$

> *pointplot*(*points_heavy*);



> *pointplot*(*points_light*);



>

>

L - Prototyping of conveyor belt

In the final design, pieces of scrap will be transported on a conveyor belt and pushed off for sorting by a gripper. During the testing described in earlier chapters, all pieces were pushed from a static situation. A conveyor belt was needed to create a testing situation as close to reality as possible. By talking to the electronic expert from our faculty (M. Verwaal, personal communication, 8 February, 2019) I concluded that setting up a conveyor belt on the test facility would take a lot of time. This would mean that only setting up the conveyor belt would consume a lot of valuable project time. Therefore I decided to mimic the behaviour of a conveyor belt by building a prototype. This chapter describes the process of prototyping the movement of a conveyor belt.

Car-based

To prototype a way to mimic the behaviour of a conveyor belt, different ideas were generated. An impression of the small brainstorm can be seen in figure 92.

Figure 91 gives an overview of the cart sliding over two aluminium L-profiles. The cart is pushed forward by a remote controlled car. On top of the cart the piece of aluminium can be placed.

Testing

Issue with timing
Problem: feedback is lacking. There is no feedback, so the speed is not constant for the different weights of pieces of scrap.

Lessons learned: Timing is important, This can be seen in figure 93.
But it is also promising, it can be correct, see figure 94 in which the piece is pushed off in a straight line.

Figure 92 - Brainstorming on different methods to move pieces of scrap forward.

Figure 91 - Moving pieces of scrap on a cart sliding over two L-profiles, pushing it forward by a remote controlled car.

Figure 93 - Testing the sliding cart propelled by a remote car. (1) The piece is moved forward (upwards in the figure), (2) the Gripper moves sideways but moves too early, (3) the piece is moved sideways but not enough and will be moving back onto the gripper.

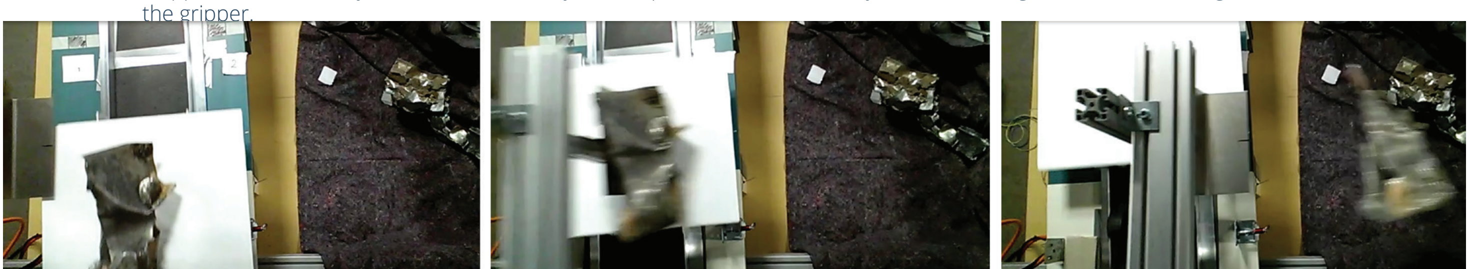


Figure 94 - A piece of scrap is pushed of the white cart and moves perpendicular to the moving direction of the cart.

M - Comminution

Comminution or shredding is the process of reducing the size of particles. This is common practice in the recycling industry. By reducing the size of each piece, materials can be liberated from each other. In this process energy and size reduction of the particles is crucial. According to Michaud (2015) the largest cost in comminution are due to energy consumption. The second largest reason for cost is due to wear and tear of the material of the comminution machine. More energy is required when a smaller grain size is needed. This is illustrated in figure 95. Therefore there is an optimal in the grain size, particle mass and grain size.

Currently Reukema uses the Hammel, which can be seen in figure 9, in their comminution step. This machine is based on the shearing principle to reduce the particle size. But other solutions for reducing the size of the material are available on the market. This chapter will discuss these techniques. A conclusion will be drawn on what techniques is most suited for the comminution of the mixed aluminium.

Based on Veasey (1989), Rumpf (1965) and Pahl (1993), four different types of loads can be identified to be applied on a particle of shredding. These four types will be discussed and different examples will be given.

- Compression
Compression is a technique in which two surfaces are pressed against each other to exert an external force on a particle.
Example: Rolling

- Grinding
Two surfaces move in opposite direction which create internal stress causing the particle to break into smaller pieces. In grinding there are a lot of different types which can be distinguished. Most of these techniques are used in the mineral industry.
Example: Jaw crusher, cone crusher, mineral sizer

- Impact
Principle: By creating a large force on two surfaces, you can reduce the size of an object. You can compare it to throwing a plate on the ground. In impact crushing there are two types which can be distinguished; gravity and dynamic. In gravity impact crushing, the gravity is used to create the force between the two objects. In dynamic impact crushing, the object is given a velocity with an external device.
Examples: Ball Mill, Impact crusher

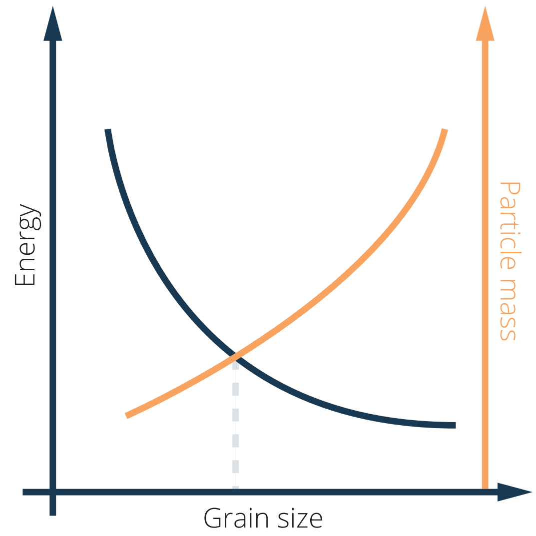


Figure 95 - Energy & particle mass versus Grain size.

- Shearing
Shearing is the process of creating shear stresses in the particle, which will ultimately shred a piece in smaller parts.
Example: Hammel

Conclusion
Aluminium has a high fracture toughness compared to stone. This makes it difficult to crush, but more suitable for shearing or shredding. This means that the best suitable for comminution of aluminium is shearing. Because the Hammel is already used in the process and uses the principle of shearing, comminution is placed outside the system boundary of this graduation project.

N - FEM analysis