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Conceptualizing an automated sorting system for the recycling of plastic-floors

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Abstract

Background
Tarkett AB Ronneby (Sweden) is a flooring solutions company, recognized for the manufacturing and recycling of homogeneous plastic flooring. Tarkett AB recycles mainly installation spill and manufacturing defects. However, Tarkett AB is considering widening its recycling capabilities to include old and torn plastic floors which may contain impurities and banned substances or plastic floors of competing brands. To accomplish this, Tarkett is considering a completely new recycling line with an automated sorting process instead of the current manual process. Thus, Tarkett proposes a dissertation to conceptualize a new automated sorting system with added capacity and increased functionality.

Purpose
This work aims to investigate the current sorting process and introduce conceptual solutions for a new automated sorting process capable of identifying and separating plastic floors according to the manufacturer, type, condition, and external waste by using existing technology.

Method
The methods and tools used in this work are mainly based on a modified product development process. Starting with data collection of the current sorting process, performing a need-finding, and extracting requirements for an automated sorting process, investigating relevant technology, evaluating technology based on scientific literature and tests. The testing was conducted in collaboration with two companies. Near-infrared scanners were tested with Holger AB, while pattern recognition systems were tested with Vision-Geek. Finally, three concepts for the automated sorting process were developed and shown through flow charts and 2D-3D illustrations.

Results
The results of this work showed that it was possible to use near-infrared and pattern recognition for the separation of plastic floors. Besides, three conceptual solutions for an automated sorting process were generated and showcased with schematic graphs and 2D-3D illustrations. The concepts describe how the sorting process functions and what technology is used for each step of the process. Concept 1 and Concept 2 used both pattern recognition and spectroscopy methods. While Concept 3 only used spectroscopy methods. Moreover, spectroscopy methods were used to sort plastic floors by content while pattern recognition by appearance.

Conclusions
Recycling of torn and old plastic flooring can be beneficial for both the environment and the recycling industry. Yet, it presents some challenges relating to reliable, fast, and nondestructive identification for sorting and separation purposes. New and proven technology such as near-infrared hyperspectral imaging and pattern recognition can be used. However, high-quality pattern and spectrum libraries of multiple plastic floors have to be created for optimal and reliable reference models. Furthermore, pattern recognition and near-infrared methods need to be tested further at an industrial scale.

Keywords: Plastic floor recycling, Automated plastic floor sorting, Near-infrared Spectroscopy, X-ray, Hyperspectral Imaging, Pattern recognition

Sammanfattning

Bakgrund
Tarkett AB Ronneby (Sverige) är ett golvlösning företag, erkänt för tillverkning och återvinning av homogent plastgolv. Tarkett AB återvinner huvudsakligen installations spill och tillverkningsfel. Tarkett AB överväger dock att utvidga sina återvinnings förmågor till att omfatta gamla och sönderrivna plastgolv som kan innehålla föroreningar och förbjudna ämnen eller plastgolv från konkurrerande varumärken. För att åstadkomma detta överväger Tarkett en helt ny återvinnings linje med en automatiserad sorteringsprocess istället för den aktuella manuella processen. Således föreslår Tarkett ett examensarbete för att konceptualisera ett nytt automatiserat sorteringssystem med ökad kapacitet och ökad funktionalitet.

Syfte
Detta arbete syftar till att undersöka den nuvarande sorterings processen och introducera konceptuella lösningar för en ny automatiserad sorteringsprocess som kan identifiera och separera plastgolv efter tillverkare, typ, skick och externt avfall med befintlig teknik.

Metod
De metoder och verktyg som används i detta arbete är huvudsakligen baserade på en modifierad produktutvecklingsprocess. Vilket börja med datainsamling av den aktuella sorterings processen, hitta behov och extrahera krav för en automatiserad sorteringsprocess, undersöka relevant teknik, utvärdera tekniken baserad på vetenskaplig litteratur och tester. Testningen genomfördes i samarbete med två företag. Nära-infraröda skannrar testades med Holger AB, medan mönsterigenkänning system testades med Vision-Geek. Slutligen utvecklades tre koncept för den automatiserade sorterings processen och visades genom flödesscheman och 2D-3D-illustrationer.

Resultat
Resultaten av detta arbete visade att det var möjligt att använda nära-infraröd och mönsterigenkänning för separering av plastgolv. Dessutom genererades tre konceptuella lösningar för en automatiserad sorteringsprocess och visades med schematiska grafer och 2D-3D-illustrationer. Begreppen beskriver hur sorterings processen fungerar och vilken teknik som används för varje steg i processen. Koncept 1 och Koncept 2 använde både mönsterigenkänning och spektroskopi metoder. Medan Koncept 3 bara använde spektroskopi metoder. Spektroskopi metoderna användes för att sortera plastgolv efter innehåll medan mönsterigenkänning efter utseende.

Slutsats
Återvinning av sönderrivna plastgolv kan vara fördelaktigt för både miljön och återvinningsindustrin. Dock finns det några utmaningar med anknytning till pålitlig, snabb och icke-förstörande identifiering för sorterings- och separation ändamål. Ny och beprövad teknik som nästan infraröd hyperspektral avbildning och mönsterigenkänning kan användas. Emellertid måste mönster- och spektrum bibliotek av hög kvalitet av flera plastgolv skapas för optimala och pålitliga referens-modeller. Dessutom måste mönsterigenkänning och nära-infraröda metoder testas vidare i industriell skala.

Nyckelord: Plastgolv Återvinning, Automatiserad plastgolv sortering, Nära-infraröd spektroskopi, Hyperspektral avbildning, X-ray, Mönsterigenkänning

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Abbreviations

BTH	Blekinge technical university
PVC	Polyvinyl Chloride
TPU	Thermoplastic polyurethane (TPU)
HE	Heterogeneous
HO	Homogeneous
HETF	Heterogeneous Tarkett flooring
HOTT	Homogeneous Tarkett flooring
LWM	Low molecular weight Phthalates
HWM	High molecular weight Phthalates
DEHP	Di(2-ethylhexyl) Phthalate
DBP	Dibutyl Phthalate
BBP	Benzyl Butyl Phthalate
DINP	Diisononylphthalate
DIDP	Diisodecylphthalate
DNOP	Di-n-octyl Phthalate
DINCH	1,2-Cyclohexane dicarboxylic acid diisononyl ester
TPS	Toyota Production System
JIT	Just-In-Time
NIR	Near-infrared
MIR	Mid-infrared
FIR	Far-infrared
SWIR	Shortwave infrared
MWIR	Midwave infrared
LWIR	Longwave infrared
NIRs	Near-infrared spectroscopy
MIRs	Mid-infrared spectroscopy
ATR	Attenuated total reflection
FTIR	Fourier Transform IR spectroscopy
HSI	Hyperspectral imaging
NIR-HSI	Near-infrared Hyperspectral imaging
XRT	X-ray transmission spectroscopy
XRF	X-ray fluorescence spectroscopy
AI	Artificial intelligence
NN	Neural networks
ML	Machine learning
DNN	Deep neural networks
ANN	Artificial neural networks
DL	Deep Learning
CNN	Convolutional Neural Network

1.Introduction

The thesis is a proposal from Tarkett, a flooring solutions company, globally recognized for a broad flooring offering in all major types of floor coverings and surface segments (excluding ceramics). Their offerings include heterogeneous and homogeneous vinyl, laminate, wood, carpet rolls and tiles, linoleum, artificial grass, and tracks. However, Tarkett AB in Ronneby manufactures and recycles homogeneous plastic floors only. These floors are used in hospitals, schools, sports facilities, elderly homes, and other public environments worldwide [1], [2].

Tarkett AB is currently looking to improve its recycling capabilities by adding a new source of recycling material. This new and additional source of the material consists of old used plastic floors. To accomplish this, Tarkett is considering a new production line for the recycling of this said source. This thesis will focus on the first step in the recycling line, the sorting system. A large portion of the current sorting system is conducted manually. There is no existing automatic sorting system that can identify and classify different types of plastic flooring.

There is a demand for an automation sorting system, for sorting mainly plastic flooring. The sorting system is expected to follow Lean production principles and working methods. It is also of interest to discuss safety aspects in the sorting system. The main task is to find existing technologies that can be further modified according to the organizational needs and properties of the material to be sorted. This dissertation will involve an illustration of a solution in how technologies are modified and implemented. Also, how the sorting system can be formed/structured to handle the incoming material.

1.1 Background

A new automated recycling line is planned to be built in the future. For this to be achieved, each sub-process in the line must be studied, for an increased understanding of the context of the entire recycling process. It is also important that the sorting of plastic flooring is automated first, as it is the first step in the line. More importantly, the focus will be on the sorting system. The sorting system needs to be adapted to the properties of the plastic floor as well as Tarkett's special needs for it to work in the best possible way.

Plastic floors

There are different variants of plastic flooring for different purposes. Plastic flooring has various ingredients that determine their properties, color, and appearance. Tarkett manufactures plastic flooring in different appearances and for different uses. There are homogeneous and heterogeneous plastic floors. Homogeneous plastic floors have the same pattern on both the front and back. The floor is considered suitable in, among other things, hospital and school corridors where lots of people and equipment pass daily, where the floor is subject to severe wear. While heterogeneous plastic floors do not have the same pattern on the front and back (in most cases). Heterogeneous plastic floors are constructed in several different layers, including the decorative layer, which consists of a printed sheet, and is available in many designs [3].

1.1.1 The current recycling line

The collection of torn plastic floors and installation spill at Tarkett Ronneby was introduced in 1996 with the aim of plastic floor recycling. Floor suppliers joined the system a few years later and now the entire flooring industry collects its waste via Tarkett in Ronneby under the name "GBR Floor

Recovery". Since 1999, the system for recycling waste installation has been taken over by the flooring industry. GBR takes care of the installation waste from large suppliers from all over Sweden. GBR commands the flooring companies, which install the floor, to collect all waste and send it to Tarkett Ronneby. Today, Tarkett Ronneby also receives installation spills from Tarkett products throughout the Nordic region [4], [5].

The recycling department is divided into two different departments. One department handles plastic flooring with effects that come from Tarkett's homogeneous plastic flooring factory. The other department handles torn plastic and installation spills. In the second department, there are different types of plastic flooring, homogeneous, and heterogeneous, as well as the competitors' plastic flooring. The different departments in the recycling process go through different processes due to their different processing needs and conditions (see Figures 1, 2, and 3). The various stages in the recycling department are, sorting of plastics flooring, granulation, sieving, washing, drying, removal of the plasticizers, and mixing (see Table 1 and 2).

Table 1: Recycling of defect plastic flooring.

Recycling of defect plastic flooring	
Sorting of defect plastic flooring	The first step in recycling the plastic floor. The input source for this stage consists of faulty homogenous plastic floors and shredded spill from the production line at the same location i.e. Tarkett Ronneby. Plastic flooring that doesn't meet the intended quality, coloring, and or consistency are sent to the recycling facility. They are rolled up to 2-meter-long cylinders (rolls) with an average weight of 200kg and wrapped in a thin transparent protective plastic film. The shredded plastic pieces arrive in metal containers while the rolled plastic flooring cylinders arrive vertically mounted and chained, both stored near the granulation machine. They are sorted into groups mainly depending on their content. Other sorting grapples are by color and family name.
Granulation	The second step in recycling, where the plastic floor is granulated into small parts. The granulation machine (or rather a line) used for processing production waste and faulty plastic flooring is called A805 and consists of a manually operated lifting arm, two feeding mechanisms, conveying belt, and the granulation machine itself. Also, the granulation machine is capable of sieving the granulates from dust and other particles that may affect the reusability of the recycled material. With the help of a manually controlled lifting arm, an operator lifts the vertically mounted plastic cylinders one at a time and places them horizontally on a lifting mechanism connected to a ramp. The plastic flooring rollers have to be oriented so that the exposed edge (the end) is facing the feeding mechanism. The lifting ramp is connected to a metal conveying belt, acting as a buffering zone for the first feeding mechanism. Before entering the buffering zone, the operator removes the transparent protective plastic film. This procedure is performed for each plastic cylinder until filling the buffering/loading zone. Then, the rollers are transported into the feeding mechanism via the buffered zone. The feeding mechanism is capable of detecting and grabbing the edge of the rolled plastic cylinders if placed correctly in the beginning. Furthermore, the feeding mechanism processes the rolled cylinder into smaller strips. The shredded production spills stored in metal containers inter the second feeding mechanism, the container is lifted and tilted until emptied. Both feeding mechanisms out the processed plastic flooring onto a conveying belt transporting the strips and spills to the granulating machine. The granulation machine

	crushes plastic floors to smaller granules, and which are later stored in metal containers ready for mixing.
Mixing	The mixing (Forberg mixer-A802) process is performed to neutralize and balance the coloring and material consistency of the recycled plastic. The mixture is performed per laboratory and production request. The recycling team receives an order for a new patch with clear instructions and measurements for color and flooring type. When the mixing process is complete, a sample is sent to the laboratory for testing and preparation. The mixing process itself is straight forward, the granulated homogeneous plastic flooring is mixed according to type, condition, and if possible, by color. However, the mixing of used and demolished homogenous plastic floors is performed at a very low scale due to impurities that will require intensive cleaning before mixing other sources. Homogenous plastic flooring is the main ingredient and is mixed according to the type of filler and plasticizers present in the material. For example, homogenous plastic floors consisting of 40% plasticizers are granulated and stored separately from those with 60% plasticizers and or from those with different fillers. Furthermore, the metal containers storing the granulated plastic floors are manually transported to a docking station, one at time. At the docking station, a lifting mechanism empties the content off into a suction system feeding the mixer. The mixer utilizes six metal containers with a horizontal rotary mixing blade for additional mixing. These containers are connected to the mixer via a second suction/bump docking station. First, the mixer pumps and stores the granulated plastic into the six metal containers, equally distributed. Thereafter, the mixer sucks equally large portions from each of the six-metal containers and mixes them into one final patch stored in an ordinary metal container placed underneath the mixer.
Placed in a metal container	Finally, the various bonds are placed in metal containers, waiting to be used in the production of homogeneous plastic floors.

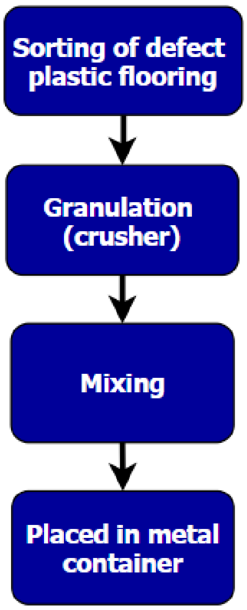


Figure 1: Recycling of defect plastic flooring.

Table 2: Recycling of torn plastic and installation spill.

Recycling of torn plastic and installation spill	
Sorting of all torn plastic and installation spill (part 1)	Spills that arise from the installation of plastic flooring, of which about 10% are flawless flooring, can be recycled. When collecting spills, they are placed in recyclable plastic bags (installation wastes from different suppliers are advised not to be mixed). The plastic bags must indicate who the current supplier of the plastic flooring is. When the bags are closed, they are placed in a special pallet container (different suppliers can be mixed). The bags are transported to Tarkett in Ronneby by truck. At Tarkett, the contents of the bags are sorted into a recycling facility. Each supplier is responsible for its installation spill and is sent to them as soon as the torn and spill flooring is identified [4], [5]. When the waste first arrives at Tarkett, they are placed in the recycling facility pending sorting. The bags may have to wait from a few hours to a few years depending on the sorting speed. Also, how many bags arrive and how much it is expected to recycle in the recycling department. It occurs that the plastic floors are placed outdoors when there is not enough room indoors, where they are affected by different types of weather. The sorting process starts with sorting Tarkett's homogeneous plastic flooring from other suppliers' plastic flooring. The sorting is done manually (by hand), where each bag is opened and emptied of the contents. Despite the clear rules about what the bags may contain, it often occurs that large variations of different plastic floors are placed in a bag from different suppliers as well as other materials such as knives, scalps, brushes, glue, paper tape, transparent tape, red tape, etc. Due to the large variety of materials and tools found in the bags, the sorting of the contents of the bags is very accurate, so that nothing is included in the recycling process except the plastic floors. When different suppliers' plastic floors are separated from Tarkett plastic floors, they are shipped to the respective manufacturer. When other materials and tools have been removed, the sorting plastic floors begin. Tarkett's heterogeneous plastic flooring is placed in a metal container and later shipped to other Tarkett factory for heterogeneous plastic flooring. Unknown plastic floors that cannot be identified are placed in a GBR metal container and sent to energy combustion through incineration.
Sorting of homogeneous plastic flooring (part 2)	The different types of homogeneous plastic flooring are distinguished by appearance, by the same pattern on front and back and by the properties of the surface (from both front and back). All homogeneous plastic floors that are Tarkett's and don't have glue on them are mixed. Floors that cannot be mixed are Safe T and IQ-One. Flooring with glue cannot proceed in the recycling process, because there is not yet a flawless removal process of the glue, they are sent to the energy combustion. Other floorings that go to energy consumption are plastic flooring with polyester on the back as well as bad and old floors that can't be recycled. The foam that is collected from some plastic floors is recycled at Tarkett's; it is mixed in their crush boxes until the amount is large enough to be recycled. The homogeneous plastic floors that have been identified are sent directly to the granulation process [6].
Granulation (part 2)	The input source consists of installation waste and removed plastic flooring. Torn plastic floors are not recycled at a large scale due to the presence of impurities such as

	glue, concrete, and spackle. Tarkett Ronneby recycles only homogenous plastic flooring. Moreover, homogenous plastic flooring free of impurities is sorted by present filler materials and granulated separately from impurities infected homogenous plastic flooring. The granulation is performed on a smaller granulation machine connected to a feeding conveyor belt operated manually. Currently, three workers manage the sorting, granulation, and logistics of the incoming plastic flooring waste. Two workers operate the granulation and ordering logistics and the third manages the inhouse logistics and transportation of container waste. Homogenous plastic floors with prohibited plasticizers, plastic floors of bad and unrecyclable conditions, polyester, and some floors with foam backing are shredded in a large granulation/shredding machine capable of processing wood and metal. The granulate is then sent to incineration for energy recovery.
Mixing (part 2)	The same process as in the defect plastic flooring recycling
Placed in a metal container (part 2)	The same process as in the defect plastic flooring recycling

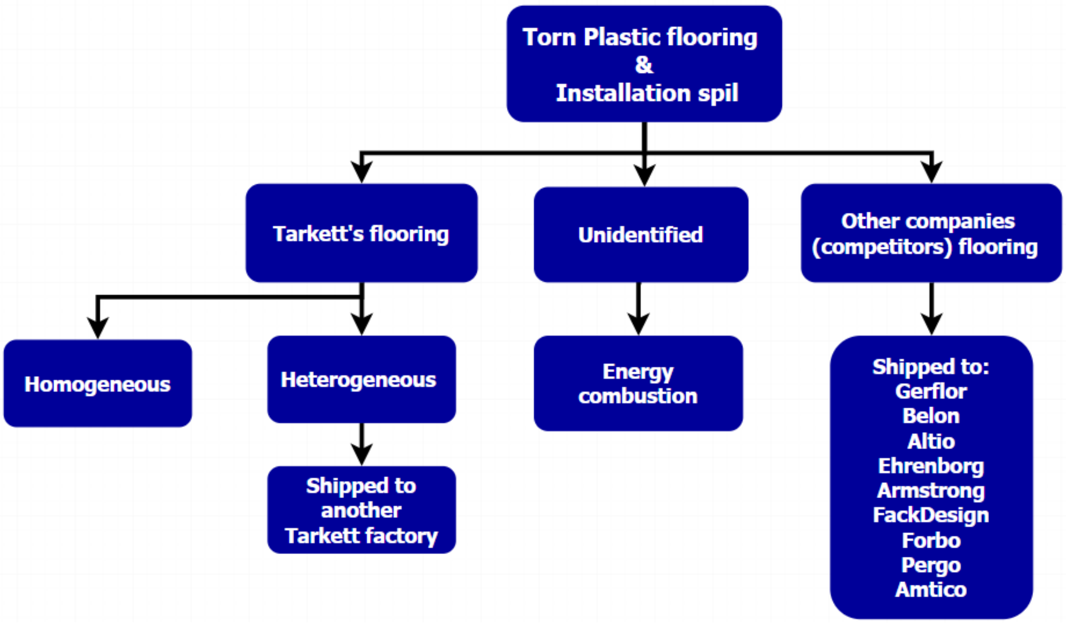


Figure 2: Part 1: Sorting of torn plastic and installation spill.

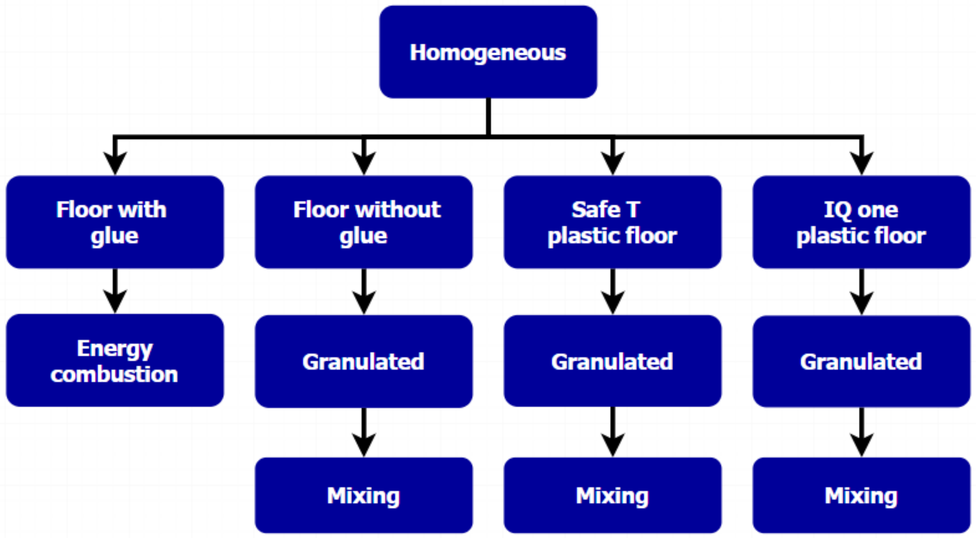


Figure 3: Part 2: Recycling of torn plastic and installation spill.

1.2 Project goal

The purpose of this project is to conceptualize an automated sorting system for recycling plastic floors with existing technology and evaluation of mechanical solutions. Also, the conceptual sorting system should meet a list of requirements set by Tarkett. Tarkett can then use these concepts as the first step towards an automated sorting system for the recycling of plastic floors.

1.2.1 Research questions

To achieve the goals, three research questions were asked:

RQ1. How can plastic flooring be distinguished by manufacturers and from external contaminants using existing technology and how can these technologies be applied in an automated sorting line?

RQ2. How can Homogeneous plastic flooring be distinguished from Heterogeneous flooring using existing technology and how can these technologies be applied in automated sorting lines?

RQ3. How can Homogeneous plastic flooring be distinguished by type and surface contamination using existing technology and how can these technologies be applied in an automated sorting line?

1.5 Limitations of work

The current recycling line consists of several processes, but one of the very first and most important processes is the sorting and separation of plastic flooring and external waste. The sorting quality and capacity will affect and dictate the remaining processes of the recycling line. Thus, this thesis work will mainly focus on the conceptualization of a new automated sorting process and evaluation of current technology that can be implemented for said process in a new automated recycling line. No additional sub-processes of the recycling line will be evaluated or analyzed other than the sorting process.

The safety, implementation of Lean, costs, dimensions, and performance estimations of the proposed concepts will be vaguely discussed as it is very difficult to calculate and or predict these parameters without testing at an industrial scale.

Testing and experimentation have been limited due to the lack of available instrumentations, physical restrictions, and closing of public institutions imposed by the current pandemic COVID 19. Consequently, no self-made experiments or testing were conducted. Instead, limited collaborative testing was performed with selected companies.

2. Theory

Under this section, technologies and methods will be described for further use when conceptualizing solutions.

2.1 Lean production and safety

Under this heading section, lean production and safety will be presented, for further use. The information under this section is the basis for implementing Lean.

2.1.1 Lean production

Lean production was developed by the car company Toyota in Japan. It is a mindset based on business-based philosophy that is based on "human knowledge" and "human motivation". The founder is Taiichi Ohno, who founded "The Toyota Production System" (TPS) which is now known as Lean production. The purpose of Lean production is to identify and eliminate waste factors (also known as "Muda" in Japanese) in a production process that does not create value for the end customer. The idea is to create more value for less work. It is based on developing leaders, creating teams in a functioning culture in a constantly learning organization that can formulate a strategy and build relationships with suppliers. Fourteen principles are divided into four departments, which are followed in lean. They stand for: philosophy, process, employees and partners, problem-solving. These four sections are illustrated in a pyramid which can be seen in figure 4 [7].

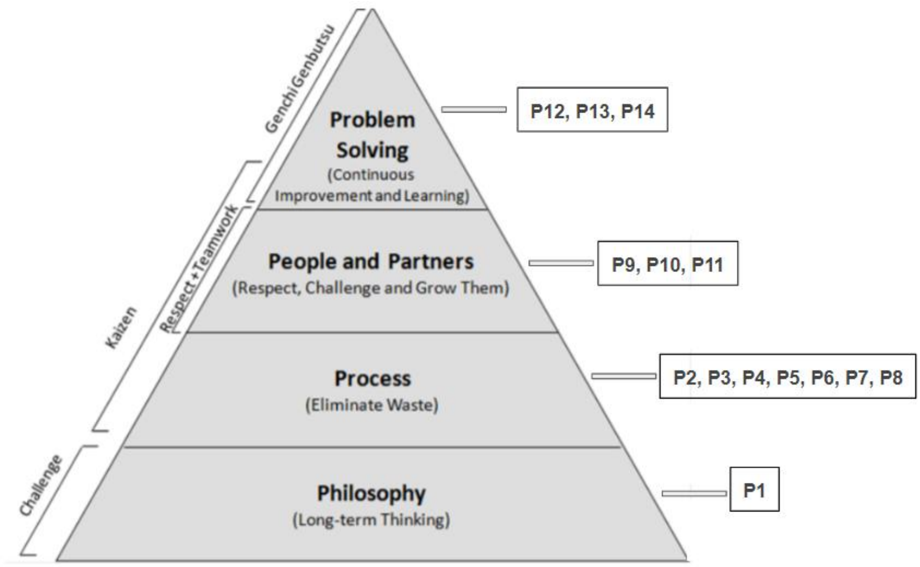


Figure 4: The four departments for the Fourteen principles.

Principle 1: "*Base management decisions on long-term thinking, even if it is at the expense of short-term financial goals*"

It is about aiming the organization towards a common goal and development, where philosophy lies with the basic principles of the organization. It is important to generate value for the customer, society, and the economy by increasing the value of the product and improving working methods within the organization.

Principle 2: "*Create continuous process flows that bring the problems to the surface*"

Create flow by linking different workflows to make it easy to move materials and information. People who can work together should be linked to create quick feedback and better control of processes. In this way, the problems that arise during production are clarified by the employees assisting with continuous improvements and development of the product in the various processes. The problems that arise should be solved immediately. The idea of creating a flow is also to remove unnecessary time that is spent when the work is at rest or moving.

Principle 3: "*Let demand control to avoid overproduction*"

By producing after the customer request, overproduction and inventory are reduced. In this way, a pulling system is created by the production based on the customer's request. That is the basic principle of *just-in-time*. Production should be regulated based on daily changes.

Principle 4: "*Workload equalization (heijunka)*"

The goals are to eliminate *Muda* (the eight types of waste), *muri* (people overload and equipment), and *mura* (irregularities in the production process). Machines, equipment, and people should not be overworked; therefore, the production schedule must be evened out. In other words, equalize the workload in all production processes.

Principle 5: "*Build a culture where the process stops to solve problems so that the quality is right from the start*"

Support systems should be built so that problems can be addressed quickly. The support system must be able to detect problems, stop itself, and be able to alert personnel if a machine or process needs to be addressed. This system Jidoka, which is a combination of human intelligence and automation, is said to be the foundation of quality. Such a system requires the organization to strive for modern and quality-assured methods, to improve productivity in the long term.

Principle 6: "*Use standardized work methods for continuous improvement and staff participation*"

It involves using stable and repetitive methods to maintain a predictable process, timing, and regular outflow. The organization should standardize the best working methods and gather knowledge about different processes to make the work more efficient. Participation should be allowed by creative and individual participation to improve the standard quality.

Principle 7: "*Use visual control so that no problems remain hidden*"

To help workers see if they are working according to a standard, simple and visible indicators can be created. Visual systems can be set up where the work is done to support the flow and the pulling system. It is said that visual control systems should be able to increase productivity, reduce errors, save time, facilitate communication, increase security, reduce costs, and give operators more control over the workplace.

Principle 8: "*Only use reliable, well-proven technology that supports staff and processes*"

Good technology should support people in the organization, not replace them. It's about eliminating waste by improving technology without threatening the stability, flexibility, and reliability of production. It is recommended to test new technology practically before it first enters a business process, manufacturing system, or products. New technology can be a threat to the flow because it is often unreliable and difficult to standardize. Clear advances must be seen in the new technology when it is evaluated so that it can be used in new work processes.

Principle 9: "*Develop leaders who truly understand the work, live by the company's philosophy and teach it to others*"

This principle supports the development/training of leaders within the organization rather than hiring someone outside the company. The leader should be able to be the role model for the organization's philosophy and business model and teach it in the best way.

Principle 10: "*Develop outstanding people and teams that follow the company's philosophy*"

The purpose is to teach individuals and teams according to the company's philosophy. Teamwork must be taught for teams to work towards common goals. To improve the quality and productivity of the teams, several skills need to be put together into one team. This creates a stable flow where complex problems can be solved.

Principle 11: "*Respect the expanded network of partners and suppliers by challenging them and helping them improve*"

To achieve set goals, the organization must support its partners and suppliers. The organization's parties and suppliers should be treated as an extension of the business. Appreciating them can help them grow and develop.

Principle 12: "*Go and see with your own eyes to understand the situation (genchi genbutsu)*"

To solve problems and improve processes, it is considered wiser to verify the information yourself. The sources of information should be examined based on personally verified information. This provides a deeper understanding of different data and situations.

Principle 13: "*Make decisions slowly, and by consensus, carefully consider all options and execute quickly*"

Before the decision is made, all alternatives must be considered, when the choices are well made, they must be implemented quickly but cautiously. *Nemawashi* is a process that recommends that problems and potential solutions be discussed with all concerned to gather ideas.

Principle 14: "*Become a Learning Organization by Reflecting Infinitely (hansei) and Constantly Improving (kaizen)*"

Stable working methods should be established that require minimal storage, this makes wasting easier to detect, as time and resources are visible to all concerned. Employees should be able to develop a process to achieve improvement (*kaizen*) and eliminate waste. Reflection (*hansei*) should be used at reconciliation times after a project is completed. In this way, deficiencies are detected in the process and can be corrected so that the same mistake is not made again. The organization should be able to standardize its working method and not reinvent the wheel [7].

The TPS-House

To facilitate the understanding of TPS, a simple illustration was made by Fujio Cho (Taiichi Ohno's pupil) in the form of a "TPS-House". The house was shaped with a foundation, roof, and two pillars (see figure 5). In the roof the goal is written, which is to achieve the highest quality, lowest cost, shortest lead time, achieve the best safety, and have a high work ethic. The pillars contain *just-in-time* (JIT) and *jidoka*, which means that an error must never pass to the next workstation/process. The building's foundation consists of several blocks, which are equalization of production (*heijunka*), stabilization and standardization of working methods, and the Toyota way philosophy [7].

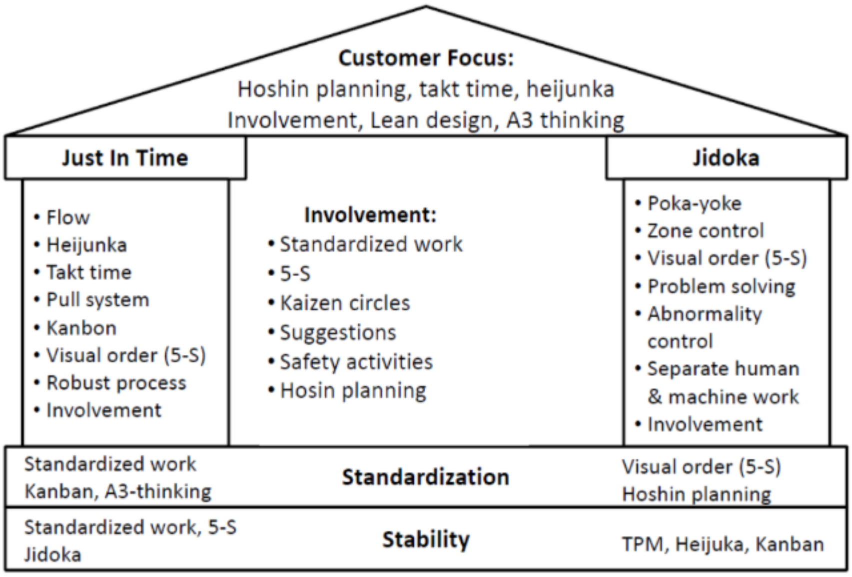


Figure 5: The TPS-House.

Muda (elimination of waste)

Eight major types of non-value-creating waste are mentioned (see Table 3). These main types of waste can affect different processes in an organization and not just production. Other processes that can also be affected are product development, order registration, and administration. Overproduction was the most serious waste because it caused most of the other waste [7].

Table 3: Muda, [7].

The eight main types of waste		
1	**Overproduction**	To produce without a request/order. It contributes to unnecessary inventory, personnel, and transport costs.
2	**Waiting**	Waiting for something that is not available when needed, leading to large costs as well as delayed processes and downtime.
3	**Unnecessary transport or transfers**	long-distance transport, inefficient transport, moving material, for example, moving materials/components out and in from storage.

4	**Over-processing or error processing**	Inefficient processes such as unnecessary work steps and poor tools that cause defects in production. It is considered a waste when the customer is provided with more value than he/she is willing to pay for.
5	**Overstock**	It includes damaged goods, transportation and storage costs, excess raw materials, which can be caused by poor production planning.
6	**Unnecessary work steps**	Any unnecessary movement that an employee must perform during their job such as reaching for tools. Stacking is also counted as waste.
7	**Defects**	Includes the production of defective parts or improvement. Repair or disposal, including inspection, leads to a waste of time and work.
8	**Unutilized creativity of employees**	By not allowing employees to have their voices heard, the business risks losing valuable and decisive ideas, improvements, and skills.

2.1.2 Safety and security

With the help of Lean, the workplace can be made safer. A safe work environment needs to be in order with work routines. With the help of 5S, a tool used in lean production, it may be possible to create a structured way of working in the workplace. The method 5S is in five steps, sort, set in order, shine, standardize and sustain (English version) [8]. It is a method that describes how to achieve and maintain order in a systematic way in the workplace. The method leads to time savings, increased efficiency, and collaboration, as well as a safer work environment. According to lean, reliable, well-proven technology should support personnel and processes. The technology should support people in the workplace for increased safety. According to “Prevent” (which is an environmental knowledge distributor for companies), a stable work environment must be safe and contribute to good workers' health and organizational profitability. Different types of solutions can prevent accidents depending on the work environment that needs to be made safe. A safe working environment creates security for employees and visitors, also, promotes the organization in the long term [7], [9].

Methods for setting up a safe and secure work environment:

-Emergency Stop

The purpose is to stop the machine immediately. It can be equipped with emergency brakes; it should not be used when the machine is switched off when workers have stopped working. A regular test must be performed to ensure that the emergency stop is working. It is highly appropriate that there is a clear sign showing the location of the emergency stop. The used color marking of the emergency stop is red with a yellow plate behind [9].

- Security stop

It stops machines if someone enters a hazard area, such as getting too close to a machine, tool, or opening. There are various types of safety stops, such as light rays that stop the machine if the light ray is cut. A contact mat as a mechanical stop, for example, through a contact strip when detecting touch. It should be made impossible to pass into the risk area. A regular test must be performed to ensure that the stop works [9].

- Breaks

Machines should be equipped with manual or automatic brakes (switched on when the machine is switched off), which can stop the machine completely under safe conditions. At a stop, accumulated energy should be blocked or relieved. When locating machines with a long roll-out time, the brake must be activated by the actuator, the workers must not be put in the risk zone. On old machines may have pedals or buttons for braking, they should be marked. The function should be tested regularly to ensure that it works [9].

- Machine protection
The shielding must be constructed in such a way that it is not possible to access machinery risk areas. The purpose is also to protect against materials and tools with the risk of being tossed out. It shall prevent the opening of sealed openable covers and passages. This applies both when machines are in motion and stationery. Also, it should not work to start a machine if a passage is open [9].

There are three types of shielding:

- Fixed protection as an obstacle by example, access to rotating machine parts/shaft end in a lathe. This type of protection should be firmly fixed and can only be opened or removed with the help of a tool.
- A movable shield that protects against cutting tools and moving parts in machines. The sealed shielding's should be able to stop the machine if it is opened or removed.
- Adjustable shielding is self-adjusting and prevents contact with the machine's various moving parts. These should be fixedly stable, easy to set, and can only be removed with tools [9].

2.2 Polyvinyl chloride (PVC)

Aside from PET and PP, Polyvinyl Chloride (PVC) and other chlorine containing-polymers are one of the most widely applied thermoplastic polymers in the world [10], [11]. PVC has been around for a long time, it was created in 1872 and commercialized in 1920, and unlike other heavily featured carbon-hydrogen polymers, PVC consists of around 57% Chlorine (by weight) as well as carbon and hydrogen [12], [13]. Polyvinyl Chloride resin is derived from the polymerization of Vinyl Chloride Monomer molecules which is in turn made from the combination of chlorine (by electrolysis of saltwater) and ethylene (by extraction from crude oil) [14]. The repeating chemical structure of PVC is shown in figure 6.

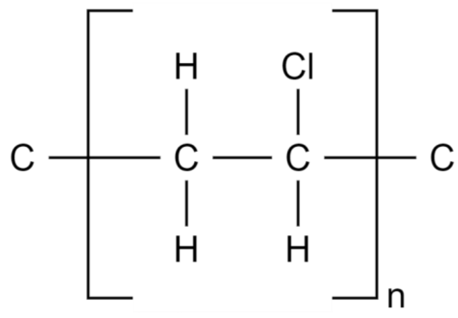


Figure 6: The repeating unit of Polyvinyl Chloride (PVC).

PVC is produced as a white powder, the powder is then mixed with other ingredients to formulate different properties that are suitable for different products and needs [12]. Pure manufactured PVC without any additives is brittle and white-colored, moreover, PVC is usually manufactured into two variants; rigid and flexible. The rigid PVC and unplasticized (U-PVC) is durable and hard [15]. One of the main applications of rigid PVC can be seen in the construction industry as pipes, window profiles, sidings, floor, and roof coverings [10]. Other applications of rigid PVC can be seen in healthcare applications and as fiber threads for clothing [11]. Flexible or plasticized PVC (P-PVC) is achieved with the addition of plasticizers to the main ingredient [10]–[12], [14], [15]. Flexibility is achieved through the interspersing of organic molecules (plasticizers) in between the PVC chains, thus, breaking the natural crystallinity of PVC chains [16]. Flexible PVC applications can also be found in the construction industry as indoor flooring, electrical insulation, and wires. Also, in medical and food products such as blood storage bags and food packaging [10], [14].

PVC has many preferable properties such as high flame and electrical conductivity resistance, high additive compatibility, and relatively small carbon-fingerprint, which makes it one of the most used thermoplastics today [10], [11]. However, this implies large amounts of waste and environmental pollution will be produced during and after its use. Energy recovery of polymers is still practiced on a large scale and widely considered as a prominent recycling method. Regardless, this presents a problem when considering the high chlorine content in PVC and the harmful HCl gases that can be released during incineration. It is therefore of economic and environmental interest to recycle PVC waste.

2.2.1 PVC Additives

Unlike other commodity polymers, PVC is not entirely made from oil, 57% of the molecular weight is derived from salt, thus, more effective usage of raw and nonrenewable materials. Moreover, the presence of chlorine creates strong polar regions which in turn enables a wider range of additive compatibility, thus making PVC the most modified polymer [16]. Also, the presence of chlorine gives the polymer increased flame-resistance properties [13], [14], [16]. PVC and polymer additives in general range from flame retardants to light and heat stabilizers, pigments, plasticizers, and fillers. Besides protecting and giving certain properties to the desired polymer, additives aid in the manufacturing process through lubrication and heat withstanding. Furthermore, some additives have multiple functions (multi-functional-additives), e.g. Carbon black can act as a coloring agent as well as Ultra Violet (UV) protection and electrical conductivity component [17].

Fillers

Fillers are optional additives and not necessary for the integrity of the chemical compound. Predominantly, fillers have been used to increase the bulk of the plastic while lowering material costs. Minerals like calcium are generally used as fillers in PVC due to the added bulk volume while keeping relatively low value (compared with PVC). However, nowadays fillers are used to offer positive attributes to the compound while still increasing the volume and lowering material costs. For example, fillers can be used for added strength and stiffness, improvement in processing and end of life, pigment replacement, heat, and light stabilizers. Primarily, fillers are inorganic minerals like calcium, talc, mica, silica, and Wollaston [17], [18]. However, there are organic alternatives like tree bark flour, nut flours, and rice husks. Modern plastics are often composed of fillers and can reach up to 70% of the plastic volume [18].

Plasticizers

Plasticizers are used to make the plastic flexible and soft for easier handling during manufacturing and application. Plasticizers consist of organic molecules that are somewhat polar therefore compatible with PVC. Plasticization is achieved when the interspersing of organic molecules (plasticizers) in between the PVC chains, thus, breaking the local crystallinity of PVC chains. The polar attraction between the plasticizers and polymer (PVC) binds them together, thus keeping the plasticized PVC matrix simple [16]. Plasticizers have been used for many years, early examples include water for softening of clay and oil for waterproofing ancient boats made from the pitch. More than 30 000 different substances have been evaluated for their plasticizing properties only 50 of which are commercially available today.

Today, 1.35 million tons of plasticizers are consumed every year in Europe, out of which approximately 85% corresponds to flexible PVC applications. Furthermore, 25% of all consumed plasticizers in Europe (2017) corresponds to wire and cable applications while 20% to flooring and wall covering applications [19]. Ortho-phthalates (phthalates) are the most commonly used plasticizers today [14], [16], [19], they are organic molecules derived from alcohol and acid [20]. Furthermore, phthalates are divided into two groups; low and high molecular weight (LMW & HLM) [14], [19], [20]. Phthalates containing eight or fewer carbon atoms in their chemical backbone are classified as LMW. These are, DEHP, DBP, DIP, and BBP. Phthalates containing 7-13 carbon atoms in their chemical backbone are classified as HMW. These are, DINP, DIDP, DPHP, DIUP, and DTDP [14]. DEHP and DINP, DIDP and DPHP account for more than 75 % of all PVC plasticizers used in the world [21]. However, new and stronger phthalates regulations in both Europe and the US have limited the use of some LMW and HMW phthalates to specific amounts and applications due to health concerns, [14], [21]. Although, safer and commercially available alternatives to Ortho-phthalates exist. These include (to name a few), Terephthalates (DOTP), Cyclohexanooate di-esters (DINCH), Trimetallites (TOTM) and Citrates (ATBC) [20], [22].

Other additives

Other additives include heat and light stabilizers, coloring-pigments, anti-slip agents, electrically conductive fillers, and flame-retardant fillers. Flame retardants are very important fillers from a safety aspect against fire and smoke build-up. Moreover, the presence of the chlorine atom in the PVC chemical structure enhances the polymers' flame resistant [13], [14], [16]. However, when PVC eventually starts to burn, harmful HCl gases are released [16], [23]. Thus, flame-retardant fillers are used for additional flame resistance [23]. Moreover, flame retardants need to meet high performance and environmental requirements, thus the number of commercially available retardants is small [10]. The most commonly used flame retardants for PVC (to name a few) are Aluminum Trihydrate, Magnesium Hydroxide, Aluminum Hydroxide, and Antimony Oxide [13].

2.2.2 Calendared PVC Flooring

Modern calendared PVC flooring can be designed to imitate certain natural materials such as wood and minerals for more appealing offerings. Due to the positive properties of PVC and its cost-effectiveness when compared to other alternatives, it's used for domestic, commercial, and industrial applications. PVC flooring has seen extensive use in schools, hospitals, and other public and private gatherings due to its cleanability [24], durability [25], and maintainability [26]. Furthermore, the healthcare sector in Europe is dominated by PVC [27] due to its cost-effectiveness and shock absorbance capability. Also, PVC flooring doesn't attract bacterial growth and can easily be cut and repaired or replaced with hot plastic-welding [26].

Calendared PVC flooring (PVC carpet rolls) can be divided into two general types; Homogenous and Heterogenous PVC flooring. Homogeneous PVC flooring, usually one layered, offers more practical and economical use, although it can be less aesthetically appealing. Heterogeneous PVC flooring is constructed out of multiple layers, more color, and natural pattern options. The layers can even differ in material choice for more aesthetical and comfort options [25]. Furthermore, the average lifespan of PVC floors ranges from 10-17years [10], although depending on the use and maintenance, it can last even more [28].

The PVC content of plastic flooring can be as low as 20% [14]. The combined content of fillers, plasticizers, pigments, and other additives can outweigh the PVC content by six to one [13]. Typically, PVC flooring recipes consist of 28-50% PVC, 10-20% plasticizers, 25-60% fillers, and 0.5-5% other additives (pigments, stabilizers, and slip agents) [10].

2.2.3 PVC Recycling

PVC (polyvinyl chloride) is produced in large quantities due to its wide range of uses and varying uses in different industries. It is one of the most widely used polymers in the world as it has different uses and can be used in, flooring, furniture, packaging, power cables, different training applications, coated fabrics, etc. Because PVC has inherent durability properties, it is recyclable. Due to the low thermal conductivity, PVC products contribute to energy efficiency. PVC is energy efficient over several applications and has low thermal conductivity. It is also resource-efficient as it can be used to make new products.

Due to the versatility of PVC, it is possible to change the formulation parameters. This results in an improvement in the safety and eco-efficiency properties of the end product. It is very useful for enabling the recycling and production of new products. Due to the possibility of recycling PVC, production energy is economical.

The preservation of PVC quality and safety is of great importance because PVC is an important part of the individual's life because of its versatile properties that contribute to a better quality of life. PVC is considered to have a minimal environmental impact on carbon dioxide emissions compared to metal or glass products in the same application. Recovering PVC reduces emissions and can be recycled several times without significant loss of performance. It has been proven via laboratory tests on PVC pipes that PVC can be recycled up to eight times, depending on the application [29].

Phthalates

In plastic, phthalates are often used as plasticizers. In PVC, DEHP is used as a plasticizer, where it is primarily included in the manufacture of flooring, wallpaper, cable, foil, and weave plastic. Phthalates have also been used as plasticizers in paints, textiles, adhesives, etc. Because phthalate is not bound to the PVC polymer, it can be excreted throughout its lifetime. Some phthalates are classified as toxic; these are DEHP, DBP (dibutyl phthalate), and BBP (benzyl butyl phthalate). They cause reproductive capacity and birth defects, and DBP is environmentally hazardous and toxic, especially for aquatic organisms. Other phthalates classified as dangerous are "DEHP, DBP, BBP, Diisobutyl Phthalate and Di (branched C6-C8) alkyl phthalates and Di (branched and straight C7-C11) alkyl phthalates". In Sweden, DINP, DIDP, and DNOP are less dangerous, and therefore the prohibition applies that they are not used for the manufacture of children objects such as toys and other things that can be put in the mouth. PVS recycling devices should comply with European requirements for REACH regulations for a safe environment and lifestyle [19], [30], [31].

PVC recycling methods

Mechanical recovery

This method is suitably pre-subdivided and single waste stream waste from PVC. The mechanical recycling method is convenient when the waste is of a type of PVC product. The process may involve the mechanical grinding of waste products. If the product/substance is contaminated, which may depend on the type of waste material, it requires pre- or post-treatment. PVC thermoplastic properties make it possible to heat, mold, or extrude PVC many times to create new products without loss of technical performance. There are two types of mechanical recycling, conventional and non-conventional technology.

Conventional technologies: The processes involving, sorting, shredding, and separating ingredients, which are then pulverized or granulated. The intention is that the granulate or powder should later be processed to create new products.

Non-conventional technology: This process uses solvent-based processes or pretreatment. This is to access PVC from difficult or intricate waste streams.

Raw material recovery

This type of recycling is best suited for unsorted plastic mixtures and waste streams containing composite material. The process may involve thermal treatments for the recovery of hydrogen chloride. Hydrogen chloride (HCl) can be reused at a later stage in PVS manufacturing or other types of manufacturing. Hydrocarbon, a combination of hydrogen and carbon monoxide, extracted from PVC products, can be used to produce syngas or as an ingredient in chemical production.

In this recycling process, different methods can be used: gasification, pyrolysis, and dehydrochlorination.

1. Gasification
   This step in the process is based on a high-temperature reaction using a limited amount of air, oxygen, or steam. The process can convert PVC waste into carbon dioxide and be singed, which can be used in the production of chemical raw materials such as methanol, ammonia, oxo-aldehydes, or the production of fuel.

2. Pyrolysis
   This step in the process is used to convert non-halogenated plastics and involves temperature degradation, mainly without air or oxygen. It should provide a residual carbon (still considered a challenge) or heavy hydrocarbons. Due to chlorine-containing plastics, this becomes a special challenge.

3. Dehydrochlorination
   This step contains more gentle degradation processes involving the removal of chlorine and gasification or pyrolysis. For this to be possible, the process takes place under pressure in water in ionic high boiling liquids, and can also be carried out in a dry processor, such as through melting, or hydrogenation [29].

2.3 Spectroscopy

The study of how light, electromagnetic radiation, interacts with matter is called spectroscopy [32]. Although, the general term used today for the science behind the interaction of energy and matter is called spectroscopy. However, as aforementioned, electromagnetic radiation is the most widely used spectrometric method for spectroscopic analysis [33]. Electromagnetic radiation encompasses a variety of radiation, hence there are various types of spectroscopy (e.g., x-ray, ultraviolet light, visible light, and infrared spectroscopy) [32]–[34].

Spectroscopy is used (among other things) in analytical-chemistry and material analysis for the qualitative and quantitative determination of molecules [32], [33]. When performing analytical spectroscopy, electromagnetic radiation of different frequencies (X-Ray, UV, IR, etc.) is applied to materials. Then, spectral characteristics of the material are obtained by recording the interaction (i.e. absorption, emission, reflection, etc.) between the electromagnetic radiation and materials. Furthermore, the material spectra (spectral characteristics) is typically a graphical representation of the intensity (reflection, emission, and or absorption) versus the frequency (often converted to wavelengths in Nanometers). All materials differ from one another in their molecular structure and constituents; thus, each material interacts differently with different electromagnetic energies. Also, by comparing the obtained material spectra, differences can be found between a set of materials [32]–[34].

2.3.1 Infrared (IR) Spectroscopy for polymer identification

IR spectroscopy can be used as rapid, nondestructive, quantitative, and qualitative analysis of polymers. IR-spectroscopy is widely used in polymer science and by physicists and chemists for quality and classification analysis of a wide set of materials [34].

The physical foundation of IR spectroscopy is based on the interaction of electromagnetic radiation within the IR-region (ranging from 700 nm to 1000 000 nm in wavelength and from 14 000 cm^{-1} to 10 cm^{-1} in wavenumber) with mass. Wavenumber (cm^{-1}) denoted by $\underline{v}$is often used instead of wavelength, it represents the number of waves per centimeter and is given by $10^7/\lambda_{nm}$ [10], [34], [35].

Polymers are composed of small repeating molecules (repeating units) linked together in long chains and the repeating molecules are composed of atoms bonds. The bonds between the atoms and molecules are not static but in motion (or rather in vibration). Under ambient temperature, the molecules and atoms vibrate within their fundamental energy levels (vibrational states). The participating atoms (or group of atoms) in chemical bonds are being displaced with relation to their displacement to one another in a defined frequency depending on the strength of the chemical bonds and the mass of the atoms (or group of atoms). Furthermore, when external energy is transferred to the molecules via IR radiation of a given wavenumber ($\underline{v}$) and absorbed by the atoms in the molecules, the amplitude of these vibrations will increase due to the transitioning of electrons to different energy states. If the initial energy state is denoted by E1 and the final state denoted by E2, then the IR-radiation of the given wavenumber ($\underline{v}$) is absorbed only when equation 1 (provided by *Planck's Equation)* is upheld. Where *h* is Planck's constant and *c* velocity of light.

$$\underline{v} = (E1\text{-}E2)/hc \qquad (1)$$

Similarly, equation 1 defines the wavenumber (or frequency) of the emitted radiation of the reverse transition from higher to lower energy state after the atoms or rather the excited electrons return to their initial state. The vibration of the chemically bonded atoms coexisting in a molecule is referred to as bond deformations such as (to name a few) stretching, bending, wagging, and twisting. The simpler and more representable types are bond stretching and bond bending [34], [36]. The bond stretching can be of symmetrical or asymmetrical movement, see figure 7.

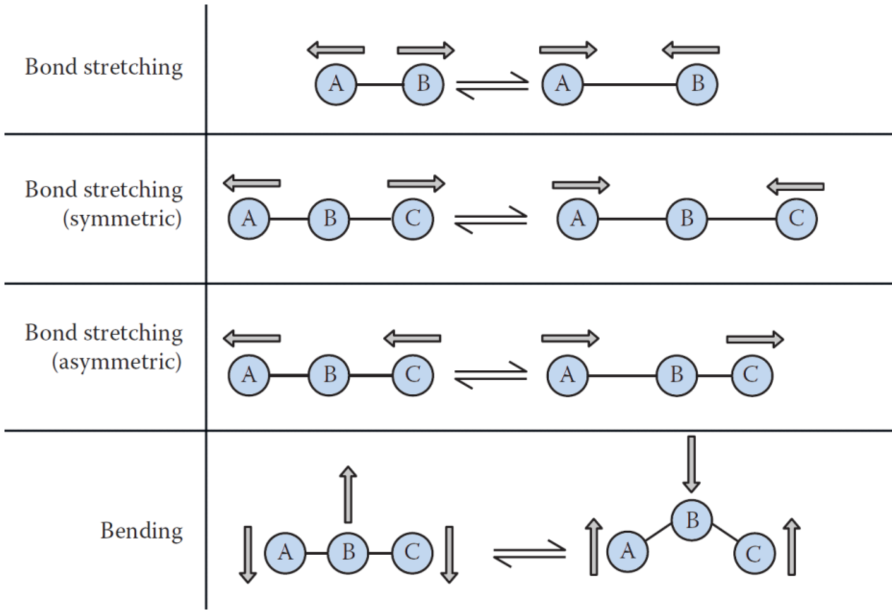


Figure 7: Illustration of the most common bond deformation (vibration). Modified from Manas Chande, 2018.

Different molecules (atom bonds) absorb IR-radiation at different frequencies (wavenumbers) and correspond to different bond vibrations (or bond deformations). Thus, a spectrum of the absorption of IR-radiation over a range of frequencies (or wavenumbers) can be obtained. Additionally, the presence of other atoms in the molecule does not heavily affect the characteristics of the specific bonds. Thereby, the wavenumber corresponding to particular bond deformations due to absorption is approximately the same for all molecules (including polymers) for that specific bond [34].

Obtaining the IR spectra of polymers may appear difficult due to the large chains of molecules. Conversely, it is relatively simple, polymers consist of repeatable units containing vibrational groups of the carbon backbone like C-C, CH, CH2, CH3, C-O, CN, C-CL, etc. [36]. Since different materials are made up of different and unique combinations of atoms, no two materials are exactly alike. Thus, different materials produce different IR spectrums, therefore, identification of organic materials (including polymers) is achievable. Although, the identification between hydrocarbon polymers (hydrocarbon materials in general) can present some problems due to similarities in the material constituents. However, polymers containing various special elements such as O, CL, N, S, C creating functional groups (such as C-CL, C-N, C=O, etc.) can be analyzed with relative ease [10], see figure 8.

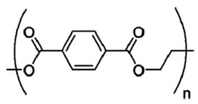
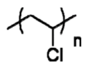
Polymer	Chemical structure	Absorption bands (cm^{-1}) used for identification	Assignment
Polyethylene terephthalate (PETE)		1713 (a) 1241 (b) 1094 (c) 720 (d)	C=O stretch C–O stretch C–O stretch Aromatic CH out-of-plane bend
Polyvinyl chloride (PVC)		1427 (a) 1331 (b) 1255 (c) 1099 (d) 966 (e) 616 (f)	CH_2 bend CH bend CH bend C–C stretch CH_2 rock C–Cl stretch

Figure 8: Comparison between PET and PVC, important vibration bonds are shown corresponding to specific wavenumbers. Modified from Melissa R. Jung et al., 2017

Near and Mid Infrared Spectroscopy

The IR range can be divided into three regions; near-infrared (NIR), mid-infrared (MIR), and the far-infrared region (FIR), see table 4. Therefore, IR-spectroscopy is also divided into three corresponding regions.

Table 4: The three regions of the IR.

Range	In Wavelength (nm)	In Wavenumbers (cm^{-1})
NIR	780 to 2500	14000 to 4000
MIR	2500 to 25000	4000 to 400
FIR	25000 to 1000 000	400 to 10

However, the interesting regions for polymer and other organic additives identification are performed in the NIR and MIR regions [35]. Starting with the NIR-region first, the theory behind near-infrared spectroscopy is the same for all IR-spectroscopy. That is, radiation of a given frequency that can supply the exact amount of energy needed for a molecule (or bonds of atoms) to transition between two vibrational levels can be absorbed and thus, produce vibrational excitation specific to that bond and energy. This means, for a given range of wavenumbers, some frequencies, those that match the energy difference (equation 1) of two vibrational states, can be absorbed by the molecules. Conversely, frequencies of wavenumbers that do not correspond to any energy differences will not be absorbed, while some are partially absorbed. Thus, by measuring the intensity of absorption versus the corresponding wavenumber and making a graphical representation (spectra), a material or substance can be determined [37].

The transition of the vibrational state from a ground state (n=0) to a final state (n=1) is called the fundamental vibration, see figure 9. The wavenumbers corresponding to the frequencies triggering the fundamental vibrations coincide mainly in the MIR (and bit in the FIR region), more precisely in the 4000 to 200 cm^{-1} region. Fundamental vibrations can't be reproduced within the NIR region. However, the overtones of the fundamental vibrations and combination bands of two or more fundamental vibrations can be obtained in the NIR region [35].

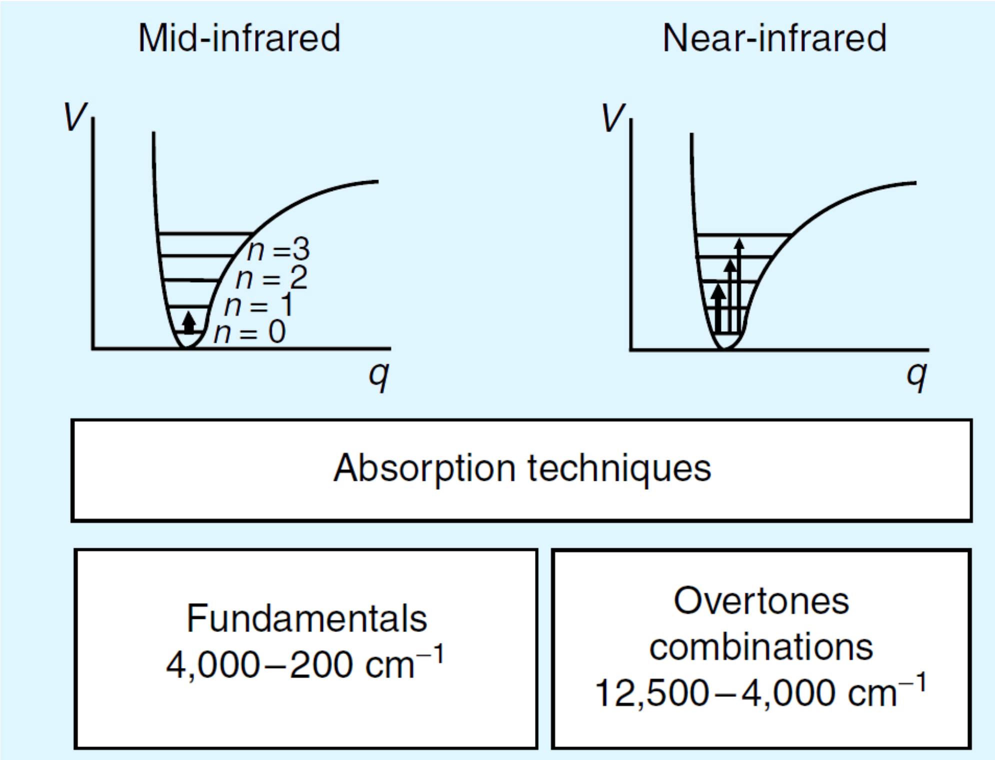


Figure 9: Illustrating the principle of MIR and NIR vibrational states. Modified from Donald A. Burns and Emil W. Ciurczak, 2008.

The first overtone is approximately double the number of frequencies or wavenumbers corresponding to a fundamental vibration, while the second overtone is three times the wavenumber corresponding to a fundamental vibration and so on. Combination bands are combined vibrations of two or multiple vibrations (e.g, a combination of stretching and bending bond deformations/vibrations from other bonds) [35].

Advantages and disadvantages:
NIR: Since the NIR-region is dominated by overtones and combination bands, some signals are weaker, less sharp, and more complex compared to their fundamentals in the MIR region. Thus, the signals can be complicated to measure and interpret. Conversely, the combination band absorption can give (under some circumstances) more information since a combination of two or more absorption bands are present instead of one. The uniqueness of combination bands is distinguishable in the NIR region while overlapping in the MIR region [35], [37], [38].

Some polymers/materials contain strong MIR absorbers (such as water), rendering the performed spectra useless. Furthermore, nonhomogeneous polymers; polymers including an array of different inorganic filler; thick samples (cm) present problems for spectroscopy measured in the MIR region. On the other hand, NIR spectroscopy requires little to no sample preparation, analyzes sample thickness up to centimeters, and can measure organic compounds in the presence of inorganic fillers and samples containing water. Additionally, NIR spectroscopy due to the fast measurement time, no sample preparation, and no interference of inorganic can be used for real-time applications and on-line systems (conveyor) at the industrial scale. NIR spectroscopy is, therefore, a very useful, fast and nondestructive tool for material (including polymer) identification [35], [38], [39]. Unlike conventional and common MIR instruments, NIR instruments are more robust and flexible and can be used in the field as portable devices for material identification. Since NIR deals with lower absorbance levels than MIR due to the weaker overtone and combination band dominated region, absorption increases linearly with concentration. Thus, bulky samples can be analyzed without the need for sample preparation [40].

NIR is not a stand-alone method and requires intensive training from reference models. NIR is heavily reliant on a good reference model and on periodically calibrating for new unknown material and contaminants. However, with modern software, dedicated algorithms, and neural network training on powerful PCs present no problems for the future of NIR devices and applications [40].

MIR: The second region of the IR-spectroscopy is referred to as the mid-infrared region which ranges from 4000 to 400 cm^{-1}. In this region, fundamental vibrations (such as bending stretching, rocking, etc) are dominating and the graphical representation of the absorption versus the wavenumbers (the spectra) is much clearer than in NIR. The absorption peaks in the MIR are strong, well-defined, and high resolution. Furthermore, the spectra obtained by measuring the intensity of the absorption versus the frequencies corresponding to bond-vibration in the MIR region can be seen as the molecular fingerprint. Thus, MIR can be used to identify the consistency and quality of materials [10], [36].

Dark or black colored polymers present a challenge for NIR measurements due to the extensive absorption (and lack of reflection). Several different plastics in different colors (including black) were tested with NIR and MIR spectroscopic devices respectively. The results showed that MIR was able to detect and identify all types of plastic regardless of color including black. While the NIR device was able to detect and identify all plastic types regardless of color excluding black [39], [41].

Instrumentation and performance

There several different design choices for implementing a NIR analysis based on different optical configurations. However, the two basic and widely used designs are based on reflectance and transmittance. Furthermore, the NIR-reflectance can be utilized in the diffuse-reflectance model or the interactance-reflectance model. In the diffuse reflectance, the light source is positioned at an angle relative to the detector and both can be stored in the same housing. While in the interactance-reflectance, the light source is placed in parallel with the detector and separated to avoid any interference. Therefore, the light and detector can't be placed in the same housing [38]. Conversely, the probability of the radiated light interacting with the sample is higher in the interactance model due to the deeper penetration [37].

When specific wavelengths are needed for dedicated applications (such as the classification of between specific polymers and quality determination) filters are used. The filter acts as wavelength selectors, only selecting relevant wavelengths and increasing scan speeds. Such an example is AOTF based NIR instruments have no moveable parts and can reach high scan speed over a wide range of NIR spectral regions. The scan speeds can reach up to 2000 selected wavelengths per second [37]. For the MIR and FIR, Fourier transform instruments are widely and almost extensively used (FTIR). These systems use an interferometer which consists of a splitter, a fixed and a moving mirror. The scanning is performed by moving the moving mirror, back and forth at a constant speed. FTIR based instruments are of high precision and accuracy and output high signal-to-noise ratios. However, they are slower than some NIR instruments (especially AOTF based instruments) and require a steady vibration-free environment and relatively clean samples. Some FTIR instruments require material separation first (i.e. extensive sample preparation that requires additional time). FTIR measurements are more sensitive to layered materials, surface contamination, and sample thickness [35]. The attenuated total reflection (ATR) sampling method is often used by the FTIR instruments. In this method, the sample is placed on top of a high refractive index crystal with force. An IR beam is then reflected through the diamond, bouncing between the sample and the diamond in a zigzag trajectory until reaching the detector, see figure 10. Furthermore, each bounce produces some absorption and when reaching the detector, the absorption is strong. Also, probing multiple points on the surface is advantageous for more uniform measurements. However, this method is effective against thin layered materials and will fail against more bulky samples [38].

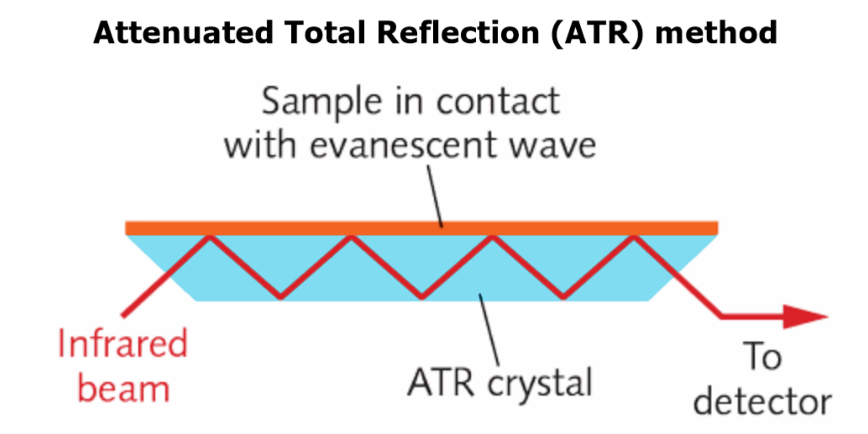


Figure 10: Illustration of the ATR FTIR method. Source: https://alliedscientificpro.com/

2.3.2 Other Spectroscopic methods for polymer identification

X-ray spectroscopy

The general term for several different spectroscopic techniques in the X-ray region of the electromagnetic radiation is called X-ray Spectroscopy. Like other spectroscopic methods, the interaction of emitted electromagnetic radiation (photon) with matter is still studied here. However, it is performed in the range of 0.005 to 10nm which corresponds to the X-ray region [42].

When higher energy X-ray photons interact with a matter, the atoms get excited. Furthermore, the high energy causes excitation of electrons thus electrons move from a low energy state to a higher energy state (shell). Upon their return, the electron releases different energies in the form of radiation (photons) at different wavelengths in the X-ray regions. The wavelength characteristics of the released radiation dependents on the chemistry of the excited element. Some matter can even be ionized when excited with high energy X-ray radiation [42], [43].

Two widely used X-ray spectroscopic techniques include X-ray Transmission (XRT) and X-ray Fluorescence (XRF). An XRF-instrument works based on illuminating a sample with X-ray radiation (incident beam) and excites individual atoms present in the sample. However, some of the radiated energy will be scattered, but some are absorbed, and depending on the atomic weight/element type(s) present in the sample, unique spectral signatures are emitted back. Since each element has a different characteristic in the X-ray spectrum, XRF can be used to identify elements [44], [45]. Additionally, modified versions of XRF techniques such as the Energy Dispersive X-ray Fluorescence (ED-XRF) also exist. ED-XRF is designed to simultaneously analyze a group of elements. ED-XRF instruments utilize special filters to separate the incoming fluorescence of a multiple-element to separate and complete spectrums [45], [46].

XRT, on the other hand, emits the same radiation as before but the detector is placed underneath the sample, thus only the transmitted radiation is measured. Moreover, some of the radiated energy is absorbed by the sample while some penetrate through the sample and into the detector. The absorption levels depend on the thickness and density of the measured sample. Additionally, modified versions of XRT such as the Dual Emission X-ray Transmission (DE-XRT) also exist. DE-XRT radiates two different energy levels at the same time i.e., two incidents beams (hence the name dual emission). By doing so, the density of various materials can be measured and differentiation according to density can be applied [44].

X-ray methods have been used in old automated recycling lines. They were used for PET and PVC separation since conventional "sink float" density separation methods struggle due to the density similarities between PVC and PET. Thus, an automated system based on X-ray spectroscopy was developed in the late 1990s. PVCs' unique structure and the approximately 57% Cl content makes it detectable and identifiable in X-ray based spectroscopic systems. Also, X-ray radiation can pass through containers and detect multiple layers, ignoring labels, and surface contaminants. X-ray sorting of PVC among other waste is still an effective method [10], [17]. Today, X-ray based instruments are used in both industrial and analytical applications for (among other) material science, forensic science, and polymer analysis [42].

Near-Infrared Hyperspectral Imaging

Hyperspectral imaging (HSI) captures and processes information across a wide range of the electromagnetic spectrum. The captured information (image) includes both spatial and spectral features. Moreover, the captured image is referred to as a *hypercube* and consists of three axes (*x*, *y, and* ***z***). The spatial information represents the two-dimensional image of the captured object, i.e., the vertical (*y*) and horizontal (***x***) pixel coordinates, while the spectral information represents the wavelength (***z***), see figure 11. Thereby, when capturing the two-dimensional spatial information across the NIR region, it is referred to as NIR-HSI. Further, when capturing the hypercube (the spatial and spectral dimensions) of a scene, a NIR spectrum is obtained for each pixel within an image. NIR-HSI deals with the same theory of other spectroscopic methods only now capturing the spectrum of each pixel within an image. Thus, NIR-HSI can also be used for material (polymer) identification with one addition, each pixel within the captured image representing a single spectrum. Meaning, if two (or more) pixels represent different constituents but present in the same image, each pixel will receive different spectrums. The added spatial dimension enables each pixel to obtain its spectral information in an image. This makes NIR-HSI a very suitable method for heterogeneous sample analysis. Furthermore, the reflected spectra for each pixel of the constituents (that absorb the NIR wavelengths) within a sample can be determined and visualized as opposed to traditional NIR spectroscopy which can only determine. This means that HSI has the potential of not only measuring the constituents but also describing their distribution within the sample [47]–[50].

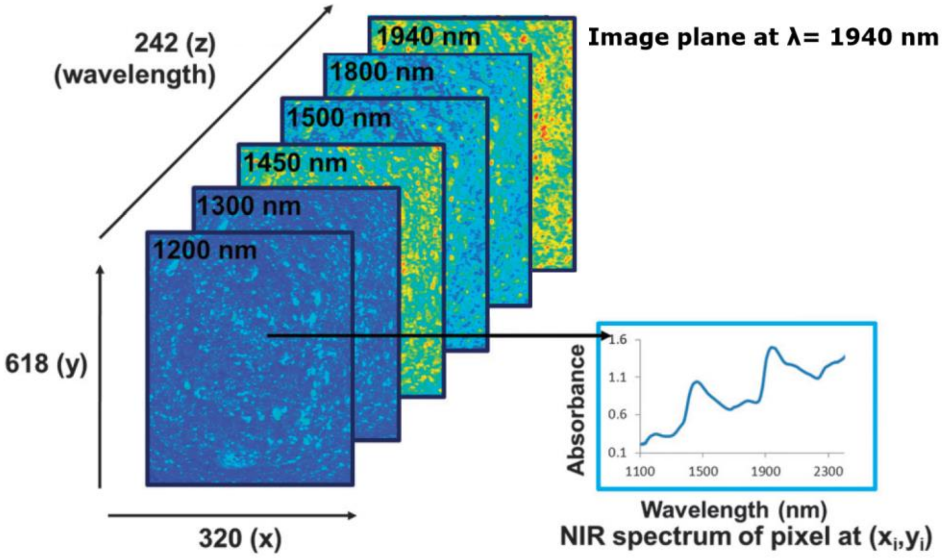


Figure 11: Illustration of NIR-HSI hypercube of a scene.

HSI is not limited to the NIR region, it can be applied in both the MIR and FIR regions. However, since HSI builds on the theory of IR spectroscopy (vibrational spectroscopy), it inherits the same advantages and disadvantages of the respective spectroscopy regions. The advantages of implementing NIR can be summed up with a rapid and non-destructive on-line application for molecular identification [47], [49], [51]. Also, the NIR region has deeper surface penetration than the MIR region which is an advantage if surface contaminated or multi-layered waste/plastics are present [52].

Hyperspectral imaging has been mainly used in agriculture and geographical remote sensing applications but in recent years, NIR-HSI cameras have seen wide adoption in the food [47], medicine and recycling industry [51], [53], [54] Furthermore, there are several different sampling and scanning techniques (configurations) and algorithms for data acquisition and processing. Some configurations require the sample to be stationary like in laboratory analysis while sampling images for each wavelength one at a time requiring an extensive amount of time. Other configurations such as *linescan* or *pushbroom* configurations can be used for scanning moving objects and acquiring the data simultaneously line by line. Allowing for a good ratio between spatial and spectral image resolution while taking only a few seconds [47].

2.3.3 Polymers and additives identification with spectroscopy

IR-spectroscopy is a widely used method (methods) for analytical chemistry and has been used for the analysis of organic molecules for a long time. Some of these methods and instruments are mainly intended for laboratory use and require extensive sample preparation. Also, some methods require the samples to be separated into core constituents, and analysis of each substance is done separately [55], [56]. ATR FTIR, on the other hand, can be used for non-destructive analysis. Also, phthalates can be screened in the mid-region with ATR FTIR based instruments [22], [34], [36], [57]. Agilent technologies USA were able to discriminate between several different phthalates using their portable ATR FTIR device [22]. Still, the samples need to be prepared and relatively thin in size for the device to get a decent reading. Also, ATR FTIR requires contact with the sample.

The IR spectrum is divided into three regions; near, mid, and far. The mid and far region is mainly used for the aforementioned applications due to their strong absorption and high-resolution readings. Near-infrared (NIR), on the other hand, is by far the most adopted region for industrial applications due to its flexibility and robustness. NIR spectrometers can be used for fast non-contact (i.e. absorption and reflection) and non-destructive measuring tools for the discrimination of plastics resin and other organic materials [39]. Also, fast response NIR InGaAs photodiodes detectors and tunable filters can be used for sub-seconds reading in real-time on-line monitoring applications [58], [59]. A variety of chemometrics and multivariate data analysis methods such as Principal component regression and partial least square regression have been used for separating plastic resin by type and from other waste in NIR spectroscopy-based systems. Neural network analysis has been proposed for the separation of PVC according to the plasticizer type. It was found that by combining near-infrared spectroscopy with neural network analysis, PVC could be differentiated according to the plasticizer type. The tested plasticizers included DINP, DOP(DEHP), DOA, TOMT [60].

Hyperspectral imaging in the NIR or MIR region can help with heterogeneous surface contamination. NIR-HSI is very well established in the food quality and product quality monitoring applications. Since NIR-HSI builds on NIR spectroscopy, the same features and properties of the NIR region are applied here with one addition. HSI takes images for which each pixel is represented by its spectrum. Making HSI a more suitable method for heterogeneity [61]–[63].

NIRs can also be used for the separation of PVC and non-PVC plastics [35], [39], [61], [63]. Thereby, NIR-HSI is also capable of sorting different plastic resins. However, other spectroscopy-based methods such as X-ray fluorescence can also be used for the separation of PVC from other plastics [10], [17], [29], [44], [64] (see section 2.4.2 and 2.6.3). X-ray based methods are particularly useful for elemental analysis. While X-ray cannot discriminate resin type, it can detect standalone elements such as Cl in the PVC or metallic and halogenic fillers used in the PVC flooring.

2.4 Pattern recognition System

Pattern recognition is a process that can assist with solutions to many problems. By estimating criteria or algorithms, patterns can be identified by different types of data as input. Pattern recognition focuses on the recognition of patterns and regularity. It is a machine learning system that has its root in artificial intelligence (AI). One of many areas of use is to define common characteristics such as fingerprints, signature names, faces, barcodes, etc. The term pattern can be defined in many ways, it can be behavior or an image, i.e. a model that can be imitated. It is an arrangement made of elements [65], [66].

In the topic of pattern recognition, algorithms have a large role. A set of algorithms is also called Neural networks (NN). It is designed to recognize patterns that are numeric, in vectors, that exist in real data, such as images, sounds, text, etc. Raw data (from the physical environment) are translated by the algorithms to be clustered (detection of similarities) or classified

Machine learning that has the abbreviation ML is part of AI, it allows algorithms to learn from input data or training data. There are three different types of learning that need to be defined. They are supervised unsupervised and semi-supervised learning. Supervised learning is learning with a set of known data input, and the algorithm is trained for some specific type of task and gives an output. Unsupervised learning is learning with unknown data input. The algorithms learn to find patterns when data inputs are given, to provide the output. Also, Semi-supervised learning is learning between supervised and unsupervised learning. When the trained data input and the requested output are given, in parallel, and that the relationship of data input to output is learned by algorithms. In this way, the algorithms learn to find patterns as well as missing relationships.

The task of image classification is to identify and categorize various elements of images, which are solved by an algorithm. ML is a Teknik created to mimic the human brain's way of processing images with the help of algorithms. ML is often met by the difficulties that arise when processing images with different conditions, such as illuminations, rotations, transformations, other objects in the image, etc. the problems arise when the images are identified, as well as in recognition and classification.

Image classification can be based on pixels or objects. For pixel-based, the attributes of each pixel are extracted to label the one belonging to a particular class. For Object-based, the segmentation is made to extract regions or objects in the selected image/picture, then the attributes are evaluated. Features or attributes must be extracted for them to be classified. The number of functions in the process determines the efficiency of the algorithm, the more functions, the more processing and storage of data is needed, which is time-consuming. The ML algorithm produces its logic based on input data, therefore it's not necessary to code for every task or problem, because algorithms learn themselves. The ML algorithms classification choice is based on the previously learned or saved pattern of data.

Deep neural networks (DNN) are inspired by artificial neural networks (ANN) and its composition is called Deep Learning (DL). Unlike neural networks that have two to three hidden layers, Deep neural networks have hundreds of hidden layers. DNN is a base term for a variety of neural network designs in the field of DL. The purpose of DL is to solve complex tasks, it selects and extracts functions from a data input automatically. Where they then classify the target set, concerning the defined trained set. DL works in such a way that node layers (also called artificial neurons), through which data must pass in a multistage pattern recognition process, process data. Each of the pixels from a captured image is fed to a neuron/node in the first layer of the neural network. It forms the input, where data comes in and at the other end is the output, where results are obtained (see Figure 12). Each neuron represents a number with the hidden layers that exist between them. The information is transmitted from one layer to another via connecting channels. In other words, the layers are linked together, where the output of the previous layer is the input for the current layer. The inputs and outputs are weighted, the weights determine the network's performance. Training or learning the network means gaining appropriate weights for the different layers.

As hundreds or more of images are fed as input and trained into the deep network, the network begins to identify features in the data that can be used in categorization. Processing takes place at each layer in the network and is fed to the next layer in sequence (as previously explained). The size and pixel depth (depending on the selected color imaging system) of the image determines the number of input values [67]. For DL to work, it requires higher processing capability, high computer speed, a large database, and proper software. An example of a deep learning network is CNN (Convolutional Neural Network). It is mainly used to classify and cluster different types of images as well as to object recognition through scanning. Different uses are, for example, identification of faces, writing characters, cancerous tumors, etc. [68]–[70].

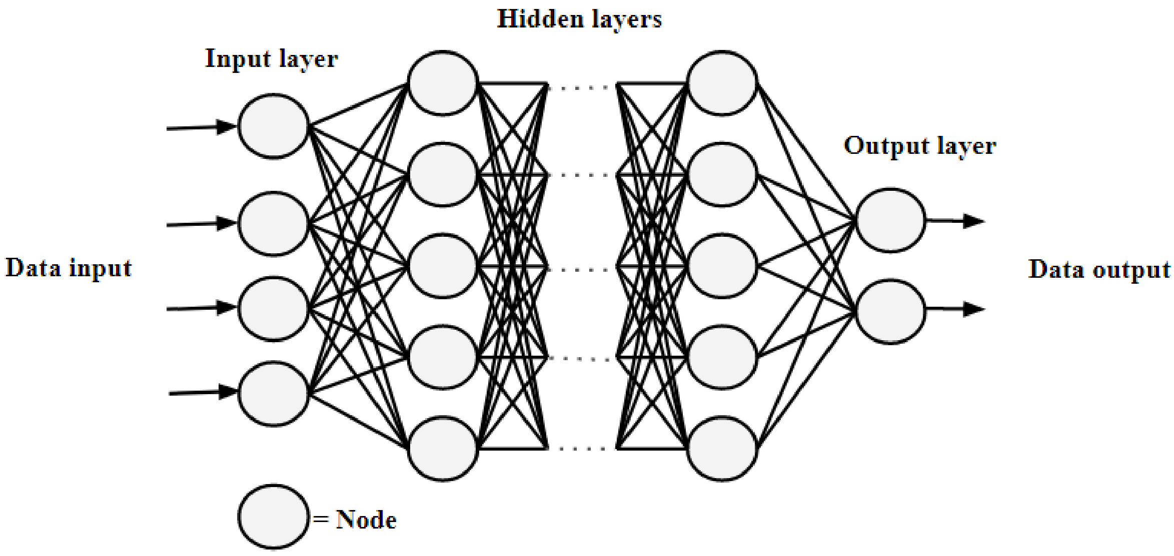


Figure 12: The Deep neural network processing structure.

2.5 Automated waste sorting for plastic separation

Plastic waste can either be recycled by mechanical recycling processes or feedstock recycling. The latter method breaks down the plastic to its constituent monomers and recycles the chemicals for other use. This method utilizes chemical treatments, gasification, and other property changing methods. Thus, feedstock recycling is more tolerant to impurities than mechanical recycling. Mechanical recycling, on the other hand, utilizes size reduction, cleaning, and separation methods before melting the polymers and adding new raw material for reuse. Thus, the quality and purity of the mechanically recycled plastic are heavily reliant on the sorting-separating process [71].

Plastic waste, and waste sorting in general, are still heavily reliant on manual sorting. While manual sorting offers a simple solution, human labor, it is less cost-effective in terms of limited throughput and labor cost. There are three key points that any sorting process strives for; high purity, high consistency, and height quantity. Manual sorting is performed by trained staff that sort according (in our case) color/pattern, resin type, and texture. Although trained staff are capable of accurately sorting plastics with high purity, humans are prone to *human error*. Furthermore, manual sorting of heavy plastics can strain the operator and cause permanent damage, besides, operators are constantly exposed to toxicity and impurities. Humans operators, on the other hand, can formulate a train of thought and act accordingly to unforeseen circumstances where computers might have failed [64].

Nevertheless, with proven methods and emerging technologies in both optical and spectroscopy-based methods, automated plastic sorting of high purity and quality can be achieved. As previously mentioned, X-ray based sorting systems have been used for automated sorting of PVC and PET for a long time. Furthermore, a combination of new and old technologies (such as electrostatics and gravity-based sorting methods) can also be utilized to achieve automated sorting [64], [71]. In 1994, a German company by the name *Bühler* combined an X-ray and IR based sorting system capable of sorting PET, HDPE, PP, PS, and PVC with a purity of up to 99.8% [17]. The throughput speed and capacity of this machine are unclear, nevertheless, newer and more reliable automated solutions are being deployed across several industries including plastic recycling. Also, based on current industry trends and the shift towards automation across different applications, it is safe to say the demand for automated plastic sorting technologies will continue to grow [72].

2.5.1 Size reduction, screening, feeding and ejection mechanism

The quality, purity, and efficiency of the automated recycling and most certainly sorting, is dependent on two steps; namely, size reduction and cleaning. Some recycling systems combine cleaning with sorting by either dry or wet clean/separating (see section 2.5.2). Size-reduction can be either applied before or after the sorting process. Furthermore, size-reduction plays an important role in both internal and external logistics and storage. Also, size reduction is performed to lower storage requirements, shipping, and transportation cost and more importantly, ease of material handling, conveyor configuration, and impurity liberation [73].

Shredding

Shredders, cutters, and granulators can be used for most of the size reduction tasks. Shredders have been used for a long time in scrap recovery applications. There are many variants available in a wide selection of dimensions and features. To a large extent, they function on the same bases of automatically pulling down materials through cutting shafts and reducing them in size. They are capable of reducing tons of materials per hour. Desired shredding size and capacity can be achieved by configuring the shaft speed, size, quantity, and arm types. The most widely used shredding variant consists of a single rotary shaft with arms/hammers and placed between two walls. Other options include multiple rotary shafts which are capable of shredding large amounts but at lowered speed. Furthermore, shredding can be performed by shearing, tearing, and breaking [64], [74].

Screening

Screening is usually performed after the initial size reduction to remove oversized, middle-sized, and undersized unwanted objects such as glass, stone, wood, paper, etc. from the targeted material. Moreover, screening can either be performed wet or dry. Typical screening sizes are; undersize (<50mm), middle-sized (50-300mm), and oversized (300mm). Screening equipment typically includes rotary drums (trommel screens), vibrating screens, and disk screens [74].

Trommel screens

Trommel screens are large cylindrical rotating drums with varying screen stages. The drums are mounted horizontally to the ground with a declining angle. Usually, the size of the screens increases with the length of the drum, i.e., smaller holes at the beginning and large holes at the end. The efficiency of the trommel screens depends heavily on the length and diameter of the drum. The waste will remain in contact with the screen for a longer time if the drum is longer; and, the greater the diameter, the more efficient waste separation. Furthermore, the rotation speed can be configured to Cascading, Cataracting, or Centrifuging waste rotation. Trommels are by far the most widely used screening equipment in waste recycling and material recovery applications. Figure 13 showcases a typical trommel screen.

Figure 13: A typical Trommel screen design. Source: https://www.alibaba.com/

Vibrating screens

Vibrating screens, as the name suggests, consist of one or multiple flat vibrating screen plates of varying pattern sizes mounted on top of each other. The larger screen is on top and followed by the smaller screens underneath so that waste is sorted according to size, see figure 14.

Figure 14: A typical vibrating screens design. Source: https://www.dynamiceq.com/

Disc screens

Disc screens are not exactly screens in a traditional sense, rather, they consist of multiple rotating shafts placed in series within an adjustable distance from each other. They operate on the principle that smaller and non-rigid-solid objects will fall through the narrow gaps between the shafts while rigid-solid and heavier objects will be transported horizontally across the shafts [75], see figure 15.

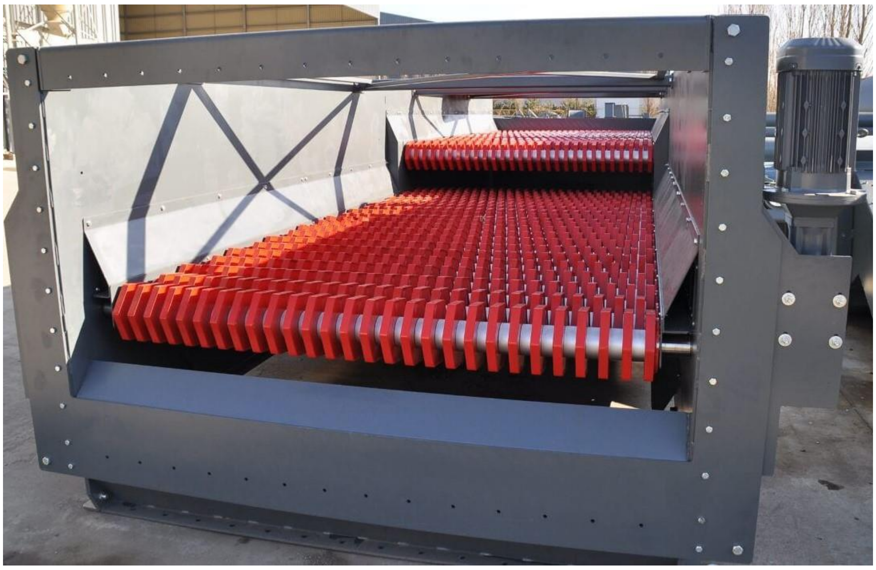


Figure 15: A disc screen machine for the recycling of municipal waste. Source: https://www.adrecyclingmachines.com/en/

Feeding systems

Vibrating feeder

Vibrating feeders are used for discharging recyclables (materials) onto conveyor belts. Incoming bulk recyclables are broken down to manageable streams for sorting equipment to process, through vibrating chutes. Vibrating feeders offer the ability to control the discharging material rate and spread onto conveyor belts. An unbalanced electric motor is used as a vibrating source for the chutes. Other advantages include continuous and adjustable flow rates and instantaneous stop-stars feeding [76].

Ejection systems

Robot arms

A robotic arm is a programmed machine built to perform specific tasks. Robot arms are fast, efficient, and accurate in their work, and can perform several different operations. The work they usually do is lifting / sorting heavy materials and repetitive procedures, over long periods. In industry, they are often used in production, manufacturing, machining, and assembly processes. They are often bench mounted or floor mounted and controlled electronically. Robot arms have different core functions that make them particularly suitable for specific roles and industrial environments. A majority of robotic arms are made up of six joints connecting seven sections, which are powered by stepper motors and computers. The most important differences among different types of robotic arms lie in how their joints are designed, the range of the movement, the work to be performed, the types of frameworks that they are disturbed by, and what they need to be installed and operated [77], [78]. They use a wide range of industries and sectors, such as manufacturing, and recycling [79].

Pneumatic system

A Pneumatic System is a compressed air technology. The system uses compressed air to perform work through compressed air. It is used in various types of applications in manual and automated machines, such as industrial manufacturing. Through a gas medium under pressure, the pressure is generated and transmitted with controlled power. For separation purposes, use this method to separate or capture materials based on material density and aerodynamic properties. The method is used to get the desired target group of materials to move in the desired direction using the principle of terminal speed. With air deficiencies, the trajectory of a falling object can be changed [80], [81].

Conveyor belts

A conveyor belt is a general tool in the material handling industry. The conveyor belt consists of two or more pulleys/drums. The conveyor belt rotates around the infinite loop with the supporting medium to transport material in the desired direction. The belt itself consists of several layers of material, in material handling in general, it consists of two layers [82]. There are various types of conveyor belts, such as Polyester conveyor belts (also called EP or PN conveyor belts), Nylon conveyor belts, and Cotton belts [83].

Conveyor belts have different designs and characteristics, depending on the need, among other things, it has been used for different sorting purposes. There are various sorting options made via conveyor belts, including, pusher sorter, linear arm sorter, and drop-down sorter (see figure 16, 17, and 18) [84], [85].

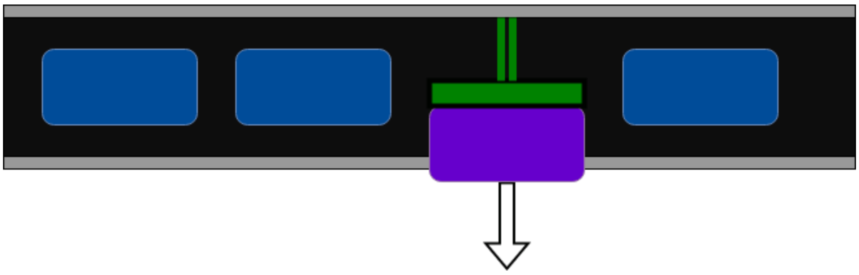


Figure 16: Push-sorter.

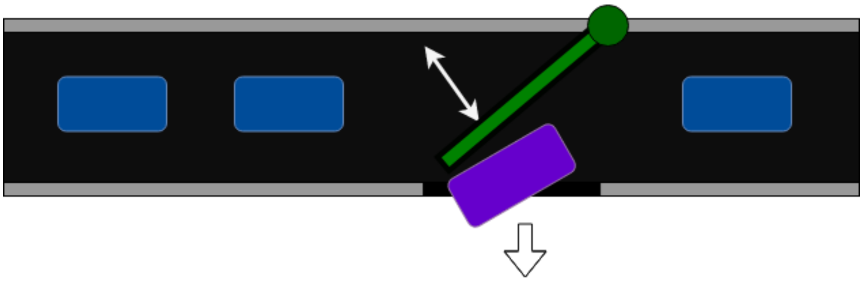


Figure 17: Linear arm sorter.

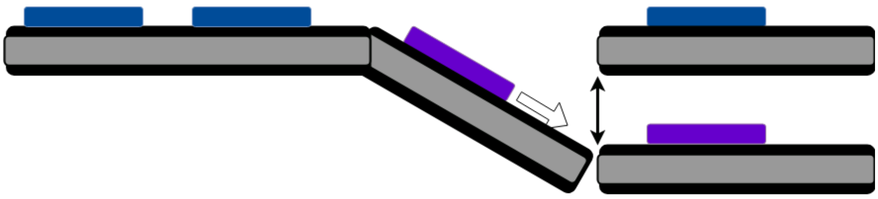


Figure 18: Dropdown sorter.

2.5.2 Direct sorting methods

Automated plastic waste sorting systems can be divided into two main groups; direct sorting and indirect sorting. Sorting systems that utilize the materials' physical properties are classified as direct techniques. Such properties include (to name a few) electrical conductivity, material density, size, shape, weight, material state (solid, rigid and flexible), etc. Also, direct methods use conventional mechanical systems and have been utilized in industries for a long time [44].

Magnetic separation methods

Magnetic based sorting is an effective method for separating non-ferrous materials (plastic, wood, and nonmagnetic metals) from ferrous materials (magnetic metals containing iron). After size-reduction, different magnetic-based designs can be implemented for the separation of ferrous metal from non-ferrous metals and plastic. These magnets can be implemented on top of conveyors, inside moving conveyors, in rotating drums, etc., see figure 19. These methods can be used multiple times at separate locations for optimal purity. However, these methods only subtract ferrous metals from the accumulated waste, other methods are needed if non-ferrous metals are to be separated from plastics. Eddy current and electromagnetic metal detectors can be used instead [44], [86].

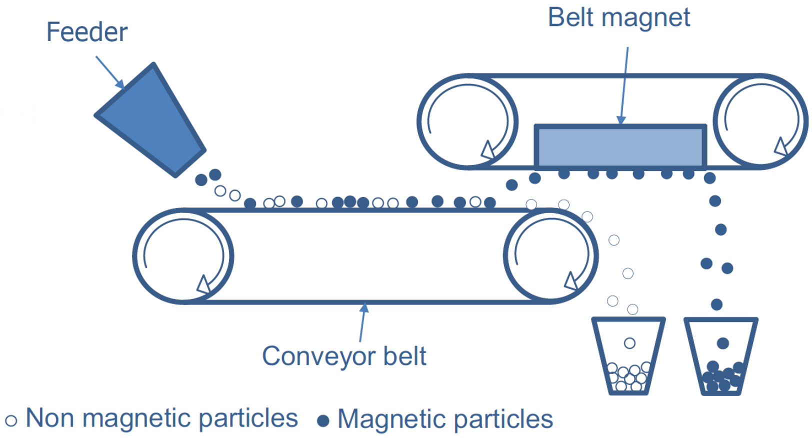


Figure 19: One of the many variants of a magnetic separator. Modified from Fernando Pacheco-Torgal et al.,2019.

Eddy current based methods

Eddy current based methods can segregate nonferrous metals from plastic with a rotary drum mounted inside a conveyor and placed at the rear (near the end). The rotating drum is in-lined with multiple alternating magnets (alternating polarity). The magnetic flux created by the rotary magnet (alternating polarity magnets) repels the nonmagnetic but electrically conductive metals [86]. Thus, plastics (non-electrically conductive materials) will receive a normal fall trajectory of the belt while the non-ferrous metals get a push and travel farther (depending on the speed of the belt, the rotating magnets, and the electrical conductivity of the metal) and can be collected separately [87], see figure 20. This method has relatively high performance and cost-effectiveness while using relatively simple mechanics [44].

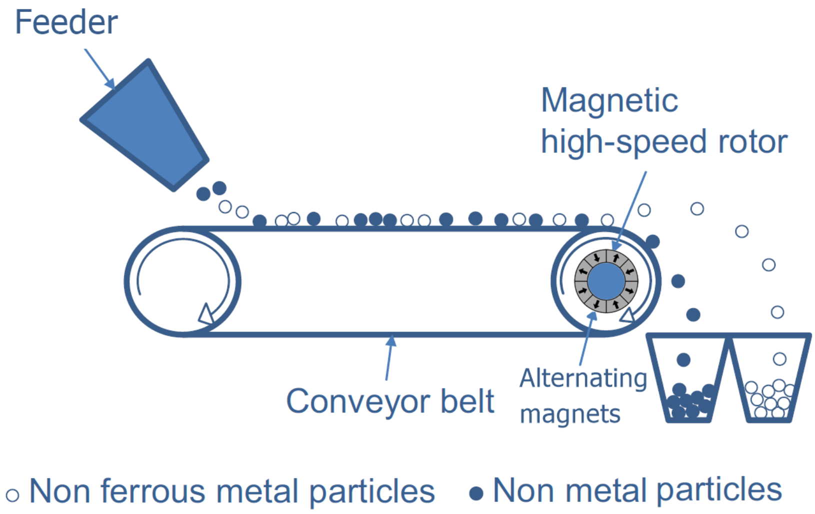


Figure 20: One of the many variants of Eddy current separator. Modified from Fernando Pacheco-Torgal et al.,2019.

Gravity based separation methods

A very common and widely used method for separation of plastic (among other waste) by resin type is called float-sink. The float-sink method is based on density separation, two (or more) plastic resins with different densities are poured into a large tank. Plastics of higher density will sink while those of lower will float thus a separation can take place. Plain water is usually used as the separating medium, but some plastic densities exceed or recede that of water and or have similar densities, see figure 21. Thus, special water solvents (such as different salts) are used to tweak the density of the separation medium [88]–[90].

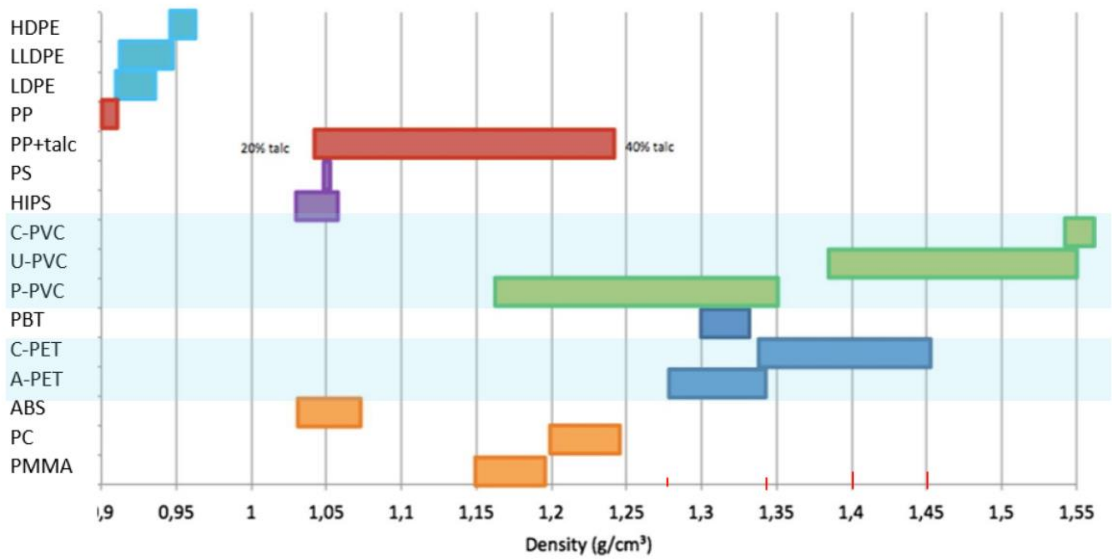


Figure 21: A polymer density diagram. PVC and PET, highlighted in light blue, have very similar densities. Modified from Laurens Delva et al., 2019.

Additionally, mechanical rotating drums with cleats, conveyor belts with cleats, and or long rotating worm-screws are used to increase the processing speed, separation, and quality. Float-sink-density separation methods are very inexpensive and effective. They can also be set to function in series for several material separations (i.e. multiple stages) [90]. However, depending on the desired capacity and speed, a large amount of water is needed to fill the tanks, and the solvent has to be replaced or recycled

[89]. Also, plastic waste has to be granulated to relatively small. Otherwise, the sinking rate may be affected [44].

There are other methods of similar principle but utilize centrifugal force to separate particles (Hydrocyclones). Hydrocyclones operate at higher speeds, accuracy and are more flexible when dealing with particle size. Also, they consume less water and solvents, but the initial price is higher. Materials of similar densities have a higher chance of separation with these methods, although these methods have a lower capacity [10], [89]. Other techniques with similar principles include froth-flotation and magnetic density separation [10], [64].

Light and a heavy fraction or rigid and nonrigid plastics (waste) can be separated with air, either by blowing or sucking light fractions out. This is particularly useful when the plastic film (bags) are to be separated from rigid and solid plastics. This can also be used to separate external waste such as paper, cardboard, fibers foam, and light debris from heavier plastics [10], [90].

Electrostatic methods

Electrostatic or Triboelectric separation methods can be used for plastic sorting. They can also be used to sort non-plastic materials such as wood, paper, and cardboard. There are several variations of these methods. Usually, waste particles (shreds or granules) are statically charged through friction (friction electrification) by either rubbing against each other or a wall. Thus, depending on the different chemistry of the plastics (or waste), they get charged with different polarities. Thereafter, the particles pass through an electric field via a conveyor belt trajectory or free-falling through. Depending on the amount of carried charge, the particles fall into respective pins (positive charge repels positive, negative attracts positive and non-charged falls in the middle, etc.) [44] [91], see figure 22. With this type of separation, nearly all plastics can be separated however the particle sizes have to be 2 to 4mm small for efficient recycling [92]. Combining the float-sink method with the electrostatic separation method can achieve higher accuracy and material purity [10].

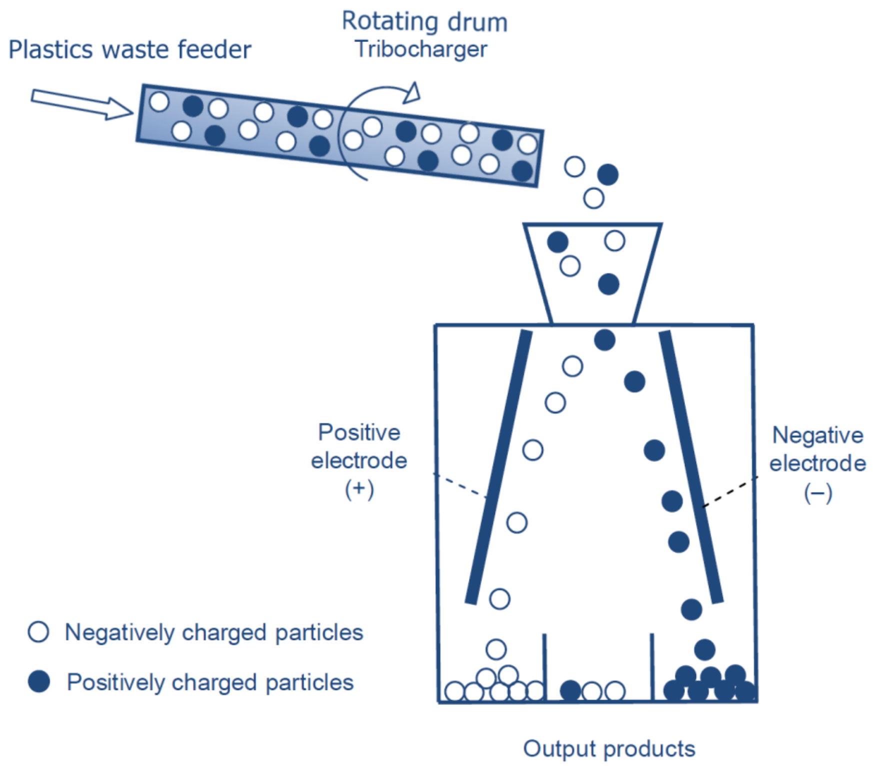


Figure 22: An illustration of a triboelectric separation method. Modified from Fernando Pacheco-Torgal et al.,2019.

2.5.3 Indirect sorting methods

Indirect sorting methods, on the other hand, utilize more modern technologies such as optical instruments, sensors, and spectroscopic systems for material identification and position tracking [44].

Eddy Current based methods

Eddy Current based metal detectors can also be used for sorting out unwanted non-ferrous metals. The metal detectors can be placed beneath the conveyor belt or over the belt forming a tunnel. Furthermore, these systems need an ejection system since they only detect and not act. Modern metal detectors utilize balanced metal coil heads, these heads create a magnetic field and there are usually two, a transmitter and a receiver coil. The magnetic field will change when an electrically conductive material (both non-ferrous and ferrous metals) passes through. Furthermore, sensors are employed to detect and measure these changes in the magnetic field. Thereby, different metals can be detected [44], [93].

Spectroscopic based methods

Spectroscopy methods are not new but new advances in this field have led to mass adoption in the waste recycling industry and analytical applications. Among these methods, Near-Infrared Spectroscopy (NIRs) and Near Infrared Hyperspectral imaging (NIR-HSI) have seen the most use in the food, agriculture, and recycling industry today. X-rays, on the other hand, are proven spectroscopic methods and have been used for (among others) to separate PVC from other plastics and contamination. Furthermore, while the direct sorting method utilizes physical material properties to perform the separation, spectroscopic methods can separate materials at an atomic and molecular level [35].

X-ray spectroscopy

X-ray methods, as previously explained (see section 2.3.2), utilize X-ray radiation to excite atoms and measure the reverse-radiation (fluorescence), or capture the transmitted X-ray beam and measure the absorption. X-ray methods are very useful tools for elemental identification (atomic identification). Polymers consist of long repeating organic (carbon-backbone) molecule chains. Thus, X-ray can't be used for plastic separation with one exception, PVC can be detected, or rather halogen Cl can be detected. X-ray based methods, on the other hand, can be used for detecting fillers such as halogenic flame retardants, heavy metal stabilizers, and other metallic fillers [45], [58], [86], [92].

Infrared spectroscopy

Infrared methods, as previously explained (see section 2.3.1), utilizes IR radiation to cause molecular vibration. Then, the absorption and or reflection intensity versus the wavelength of the emitted radiation is captured (i.e. spectra). Also, different materials have different spectrums. It is said that IR can be seen as the fingerprint region (i.e. a fingerprint analyzing tool for polymer identification). This region corresponds to the fundamental bond vibration of various organic molecules (such as polymers) which are unique to each molecular bond. The fingerprint region is located in the mid-IR to the far-IR region. Yet, the majority of IR-spectroscopy based industrial equipment are based on the NIR region [35], [39], [94] while MIR-FIR is reserved for laboratory and analytical applications. However, the fundamental bond vibrations are not shown in the NIR region, but their overtones and combination bands are still shown and thus, a wide range of materials (including polymers) can be positively identified [95]. Also, the flexibility of the NIR region enables several different measuring techniques and instrument design for rapid material identification. Filter based reflectance NIRs are capable of identifying several commodity polymers (PVC included) at a rapid rate [39], [64], [96].

This can be achieved with the NIR reflectance spectrometer, NIR illuminating lights, air nozzles (or any other ejection system), and a processing unit. The NIR spectrometers along with the illuminating lights are mounted on top of the conveyor belt and the air nozzles can be placed more freely at the end of the conveyor belt. The lights illuminate and excite the molecules of the passing waste particles. The reflection (i.e. the transmitted radiation from the excited molecules) is captured by the NIR spectrometer. Then, the processing unit analyzes the gathered data and commands the air nozzles to act and perform the separation [44], see figure 22. Different processing techniques and classification algorithms are employed for an increase in process efficiency and material purity. Also, various filters and modifications of the NIR spectrometer for specific wavelength scanning can be applied for speeding the process [39], [40].

Hyperspectral imaging

Hyperspectral imaging in the near-infrared region (NIR-HSI) is another spectroscopy-based technique. What hyperspectral imaging does differently, is gathering the spatial information of a scene and capturing a NIR (or any other region) spectrum for each pixel within an image of that scene. In other words, Hyperspectral imaging builds on the foundation of NIR spectroscopy with the advantage of capturing a NIR spectrum for every pixel instead of an average point reading [97]. In that regard, Hyperspectral imaging has the same advantages of ordinary NIR spectroscopy, i.e., rapid and non-destructive qualitative and quantitative material analysis [49]. Also, with the added spatial information, HSI is more suited for heterogeneous material analysis since each pixel can have a different spectrum [47]. Moreover, the distribution of constituents within a sample can be visually represented. This is particularly useful for the detection of non-homogeneous waste and surface contaminated waste [52].

NIR-HSI can be used for on-line quality monitoring and material identification applications. Special NIR-HSI cameras have been developed for on-line applications and can be installed above speeding conveyor belts. Also, with NIR illuminating lights, processing units, and compressed air nozzles, material spectrums can be captured by the camera, classified by the processing unit, and ejected to respective bins with the air nozzles [44], see figure 23. This can be applied for separating plastic from external waste (paper, glass, cardboard, wood, etc.) and by resin type [44], [49], [63]. With modified identification and classification algorithms, non-ferrous metals can also be detected and separated [98].

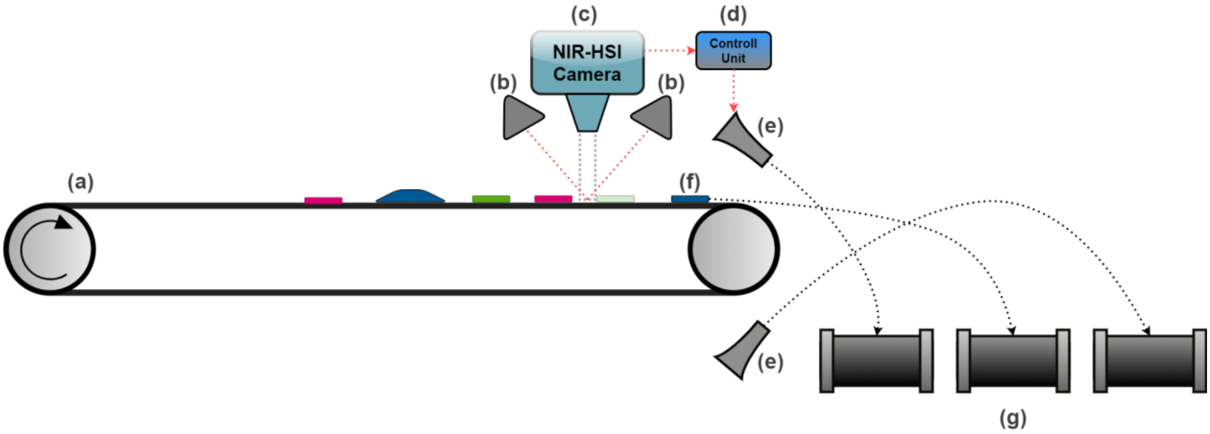


Figure 23: a) Conveyor, b) light source (NIR), c) NIR-HSI camera, d) control unit for classification analysis, e) compressed air nozzles for multiple trajectories, f) a plastic piece with a normal trajectory towards the middle conveyor/bin and (g) multiple conveyors/bins for different plastics.

Pattern recognition

The pattern recognition system is one of the branches of artificial intelligence (AI). With the help of Deep Learning (DL), the efficiency of the system in data processing can be improved and be able to process complex data [99]. The system is used for various purposes in different organizations, such as identification of plastic bottles [100], face recognition [101], specific designs in textures and colors [102], and much more. The system has varying characteristics that can be adapted for different purposes. Some uses are pattern classification, similarity detection and extraction, and representation. The system can adapt and learn from input data [103].

3. Method

The methodology used in this work is mainly based on a heavily modified product development process, see figure 24. Priority was given to the understanding of the recycling process with more focus on the sorting process. Starting with data collection of the current sorting process, performing a need-finding, and extracting requirements for an automated sorting process, investigating relevant technology, evaluating technology based on scientific literature and tests.

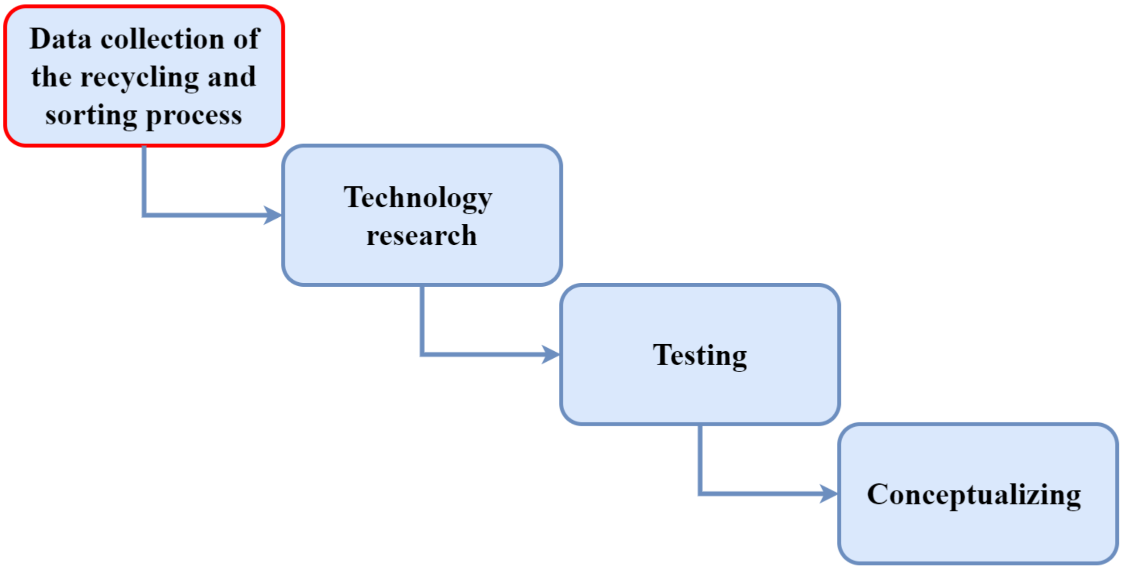


Figure 24: Approach of work.

3.1 Data collection

To conceptualize a new and improved sorting process, the functionality and limitations of the current sorting process had to be understood. Thus, data concerning the current sorting process and the project was collected through interviews and observations.

Workers, project leaders, and managers of the sorting and recycling process were interviewed. The interviews were mainly discussions and explanatory meetings with project leaders and key workers. Consequently, the interviews took an unstructured form in which the interviewee had the main floor, and questions that emerged were asked in time.

The current manual sorting process and other recycling processes were observed. The authors were invited to a typical workday and observed workers operate the sorting and recycling system. Furthermore, the workers explained and demonstrated the sorting process among other processes, and questions that emerged were asked at that time.

When the functionality and limitations of the current process were understood and the desired outcome mapped, needs were established. Thereby, the collected data from the interviews and observations were translated into needs. The needs were then listed and later converted to the requirements of the new sorting process.

3.2 Technology research

When enough information about the current sorting process was received, research of various technologies and sorting methods was conducted. At first, PVC as a polymer and PVC recycling methods were studied. Later research focused on various sorting methods and technology used in the current municipal waste recycling and plastic waste recycling industry. Tarkett was not interested in developing its sorting process completely from scratch. Thus, the research focused on finding existing technologies that can be modified and adapted for the recycling of plastic floors. This was done through a literature review.

The reviewed literature consists of books, academic journals, research papers, papers from scientific publications, dissertations, and technical reports. The articles, books, and papers have been gathered from the internet through various databases such as Google Scholar, Scopus, ResearchGate, and BTH summon. These web databases are accessible by students and thus have been used for research purposes. BTH summon and Scopus were used the most since they are freely accessible by BTH students. Relevant keywords fitting of this work were used in these databases and other keywords from the found articles have been also used.

Further information regarding specific technology and sorting methods were sought through various companies and organizations. Also, the credibility of certain technologies could be proven through company and organization offerings present on their websites.

3.3 Testing

Testing and experimentation have been limited due to the lack of available instrumentations, physical restrictions, and closing of public institutions imposed by the current pandemic COVID 19. Consequently, no self-made experiments or testing were conducted. Instead, limited collaborative testing was performed with selected companies.

After performing technology research, some technologies were considered more relevant than others. These technologies needed further exploration and confirmation of capability. Thus, testing was conducted in collaboration with two companies; *Holger Andreasen AB* and *Emsys-Visiongeek*. Near-infrared scanners were tested with *Holger Andreasen AB*, while pattern recognition systems were tested with *Emsys-Visiongeek*.

The companies were contacted with interest and request in confirmation of technology capabilities through experimentation. When the two following companies accepted the desire to carry out experiments, various samples of physical and digital plastic floors were sent.

3.3.1 Testing near-infrared scanner and building spectrum library

Holger Andreasen AB is a Nordic reseller for *Thermofisher USA*. Holger was asked to test the diffuse reflectance near-infrared handheld scanner on multiple plastic floor samples of different contents, condition, and manufacturer. *Holger* was chosen due to its offerings and geographical location. Being in Sweden meant fast shipping and easy communication. Moreover, the interaction was conducted in Swedish. Also, Holger kindly accepted this testing proposal and challenge and offered some feedback free of charge.

The reason for testing a handheld NIR device instead of a complete NIR sorting system meant faster testing. Also, the location of companies offering a complete NIR sorting system and current pandemic favored the choice of Holger and their offering. Besides, the NIR handheld device functioned similarly to that of a complete sorting system and the tests were meant as a proof of technology. Thus, labeled plastic floor samples and test instructions were sent through the mail, and the results were viewed and discussed through email.

Samples and test instructions

Sixteen different floor samples were sent to *Holger* for testing. The samples consisted of (majority) homogeneous Tarkett, heterogeneous Tarkett, and non-Tarkett floors. The homogeneous Tarkett floor samples included four different plasticizers; DINP, DEHP, DINCH, and Castor oil. Moreover, two samples were of impure condition, meaning an adhered mix of glue and concrete or wood residue was present. The sixteenth-floor sample was marked with an X since Tarkett was unsure of the exact model type. However, it was similar to two Tarkett samples and could be cross-referenced when an internal library was established. All samples and their description can be seen in table 5.

In addition to the provided samples, a PDF with clear test instructions as to which sample should be tested against each other and in what order was also given to *Holger*. Also, *Holger* was asked to scan and create an internal spectrum library of the provided samples. Hence, if normal testing proved insufficient, the spectrum library could be used as a reference model when comparing two or more spectrums. The complete test instructions can be seen in Appendix B.

Table 5: The 16 physical floor samples sent to Holger for testing.

Sample Nr	Producer name	Flooring Name	Polymer type	Plasticizers Type	Condition Type	Other characteristics
1	Tarkett	Optima & Granit Multisafe	PVC	Phthalate: DEHP	Pure	HO
2	Tarkett	Wallgard	PVC	Phthalate: DINP	Pure	HO
3	Tarkett	Natural	PVC	Castor Oil	Pure	HO, Natural plasticizers
4	Tarkett	Granit & Optima	PVC	DINCH	Pure	HO, Phthalate free
5	Forbo	-	PVC	Phthalate-free	Pure	HO, non-Tarkett
6	Forbo	-	PVC	Phthalate-free	Pure	HO, non-Tarkett
7	Gerflor	-	PVC	Phthalate-free	Pure	HO, non-Tarkett
8	Tarkett	-	PVC	Phthalate free	Pure	HE
9	Tarkett	-	PVC	Phthalate free	Pure	HE
10	Tarkett	-	PVC	Phthalate-free	Pure	HE front and HO backing
11	Tarkett	iQ-One	TPU	Phthalate free	Pure	HO and Non-PVC
12	Tarkett	-	PVC	Phthalate free	Impure: Glue & concrete	Used, and torn floor
13	Tarkett	-	PVC	Phthalate-free	Impure: Glue & wood	Used, and torn floor
14	Tarkett	Primo Premium	PVC	Phthalate free	Pure	Different filler type
15	Tarkett	Safe-T	PVC	Phthalate-free	Pure	Contains Al-Flakes
X	Tarkett	Eclipse or Natural (?)	-	-	Pure	-

3.3.2 Testing pattern recognition scanner and building pattern library

Emsys-Visiongeek was asked to test their pattern recognition systems on plastic floors with different types of surface patterns. The plastic floors were sent online, via a link. The plastic floors consist of different types of surface patterns, both random patterns (in small scales) and repeated patterns. Tarkett's heterogeneous and homogeneous plastic floors have been sent as well as seven other companies' plastic floors (see Table 6). The purpose was to test whether the pattern recognition system can distinguish between Tarkett and non-Tarkett plastic flooring, as well as homogeneous and heterogeneous plastic flooring.

A 16K line scan camera was used to scan each plastic floor. Through the learning period, pattern recognition systems learned to see the difference between the different patterns. When all plastic floors were scanned, a library of plastic floor patterns was created. Tarkett's plastic floor was when compared with the competitor's plastic floor, and homogeneous plastic floors were compared with heterogeneous plastic floors.

Table 6: Samples to Emsys-Visiongeek

Samples	
Plastic flooring manufacturers/companies	**Number of samples**
Tarkett	63 Heterogeneous and 94 Homogeneous
Altro	22 Mixed
Amtico	5 Mixed
Armstrong	5 Mixed
Falckdesign	2 Heterogeneous and 4 Homogeneous
Forbo	16 Heterogeneous, 38 Homogeneous and 3 Other
Gerflor	22 Mixed
Pergo	6 Mixed

3.4 Conceptualizing

Conceptualization for the requested sorting system began when enough knowledge was gathered from Tarkett, literature searches, and the performed tests by *Holger Andreasen AB* and *Emsys-Visiongeek*. In conceptualization, manual sorting was used as a basis/reference. Based on the sorting requirements, the technologies able to adapt to the plastic floor's attributes were selected, also, according to the data obtained, and the results of the tests done at *Halger* and *Visiongeek*. The sorting systems approach/structure was partly based on manual sorting and partly on the capabilities of the technologies. Three concepts were designed with different separation methods, which depend on the size and properties of the plastic floor.

First, a flowchart was created of each concept based on the separation requirements, to show how and when each concept performs a certain part of the sorting process. For the flowchart design, the draw.io tool was used for all three concepts. The draw.io tool was then used to design concepts 1 and 2, for a complete illustration of the system. Concept 3 was designed with CAD; Autodesk inventor was used for a clearer expansion and overall illustration of the entire sorting system. Other tools used for conceptualizing were Photoshop where images were edited, for a clearer construction of the separation.

4. Results

This section aims to answer the research questions (RQs), shown in section 1.2.1, by proposing three conceptual solutions for an automated sorting process that are based on the combined theories, conducted need-finding, and tests.

4.1 Automated sorting of plastic floors

4.1.1 Needs for automated sorting

There is a great need for an automated sorting system for the recycling line of plastic flooring. The current sorting system has no flow in the sorting process due to it being handled manually. The manual work results in an inefficient and slow sorting process and potentially harming the employees, due to the heavy lifting of plastic floors. At the beginning of this dissertation, continuous discussions with employees in the sustainability department have been made. The discussions have given more insight into how the plastic floors arrive and are handled in the manual sorting system. The search for information continued until the needs of the sorting system became clear.

There is a need for the sorting system:

- To be automated.
- To be built according to Lean production.
- To have a continuous flow.
- To be able to distinguish plastic floors from external.
- To be able to distinguish between Tarkett plastic floor and competitors. plastic floor
- To be able to distinguish homogeneous plastic floors from heterogeneous plastic floors.
- To have the ability to sort different types of homogeneous plastic flooring based on properties.
- To be able to use different techniques and tools to improve the quality of the sorting process.
- To have a safe working environment.
- To not be higher than 11 m.
- To handle at least 2 tones/h.

4.1.2 Requirements for automated sorting

When plastic floors are transported to the recycling facility, they appear with products and substances of different types of materials, in other words, garbage. The sorting system needs to handle these materials first, for the sorting system to proceed. The requirements of the sorting system were determined when the needs became clear.

Separation of accompanying materials (external waste) with the plastic floors

The sorting system shall separate:

- Metallic material
- Wooden material
- External plastics material
- Rubber material
- Glass material
- Paper/packages
- Cardboards

After separating the plastic floors from external waste, the plastic floors will go through several separating steps.

Separation of the plastic floors
The sorting system shall distinguish:

- Plastic flooring by manufacturers.
- Heterogeneous flooring with polyester backing.
- Heterogeneous flooring with polyester free backing.
- Flooring with phthalate plasticizers.
- Flooring with Castor oil plasticizers.
- Flooring with glue.
- Non-PVC flooring (IQ-One).
- PVC flooring with aluminum fillers (Safe T).

Other requirements: the sorting systems must not be built higher than 11 m, and be able to sort at least 2 tons / h. Furthermore, the sorting system should be built according to Lean philosophy and Lean regarding employee safety.

4.1.3 Mapping the automated system

The requirements for the automated separation and sorting (described in the section above) of Tarkett plastic flooring are theoretically realized within eight automated steps presented in figure 25. First, the incoming waste material is separated according to ferrous metal and nonferrous material waste. This is due to a large number of knives and metallic tools found within the retrieved floor bags and containers. After this step, only nonferrous waste is left over. Then, in the second step, plastic flooring and non-plastic waste are separated. Meaning, plastic flooring (PVC and TPU flooring) is separated from external materials such as wood, paper, cardboard, other plastics, and nonferrous metals.

After successfully separating most of the external waste from the plastic floors, the system proceeds to the third process in which Tarkett and non-Tarkett plastic flooring are separated. As for non-Tarkett flooring, there are two options; manual sorting or automated sorting done separately, more on that later. However, Tarkett flooring proceeds to the fourth step which includes two sub-processes. In the first sub-process, homogeneous Tarkett flooring (HOTF) is separated from Tarkett heterogeneous flooring (HETF). While the separated HOTF proceeds to the fifth step, HETF undergoes a final separation at the second sub-process in which polyester backing and polyester free backing are separated.

In the fifth step, HOTF are sorted according to the used plasticizer. There are three separate categories, phthalate-free, phthalate, and natural vegetation oil-based plasticizers. Phthalates have gone through extensive health impact study and received several prohibitions (see section 2.2.1 and 2.2.3). Thus, it is of huge importance to separate phthalate-free floors from phthalate containing floors. However, the journey for phthalate containing floors and natural-based plasticized plastic floors ends here. According to Tarkett, phthalates need to be processed separately due to the toxic nature of the phthalates, and vegetation-based plasticizers can’t be mixed with the phthalates-free plastics due to different contradicting properties. After extracting the phthalate-free plastic flooring, another important process takes place in the sixth step. Namely, the separation of installation spill from torn plastic floors. Torn plastic floors contain adhered impurities such as wood, glue, and concrete residue. While installation spills are the leftover pieces after the installation of new flooring. Thus, installation spills have no adhered impurities (from the get-go). The contaminated floors end their journey here since cleaning and purification are required before further processing.

Now after six steps, the arriving floors should be free of phthalate plasticizers, adhered impurities, and only contain HOTF. Therefore, the following steps are all about the separation between the homogeneous flooring types. In the seventh step, PVC and non-PVC homogeneous floors are separated. Currently, there are limited resin types used in the manufacturing of plastic flooring at Tarkett Ronneby. According to Tarkett, it is either Polyvinyl Chloride (PVC), which is the more predominant type, or Thermoplastic Polyurethane (TPU) resin used for their products. Thus, non-PVC flooring ends here. In the eighth and final step, normal homogeneous PVC floors are separated from homogeneous PVC floors featuring metallic fillers.

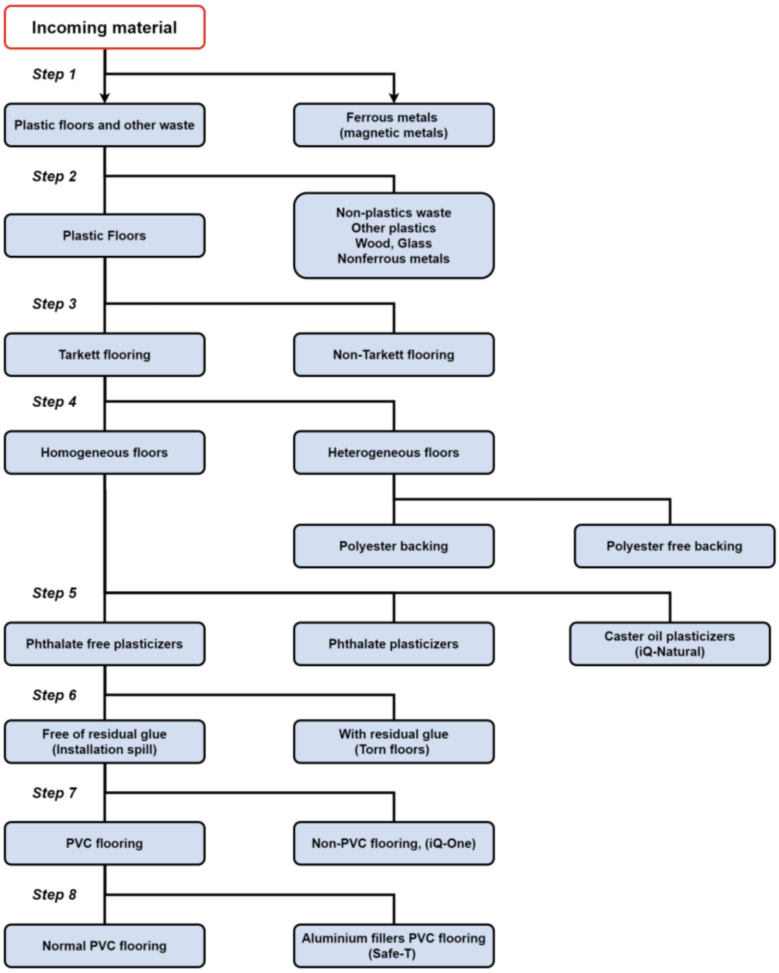


Figure 25: Mapping of the automated sorting system requirements.

4.1.4 Relevant technologies

Different types of technologies and separation methods applied in each step (see figure 25) of the sorting process, for efficient handling of the materials.

Step 1:

Through this step, magnetic metals (iron metals) are separated from all incoming materials. There are different types of tools for detecting and separating metals. Sorting of automatically magnetic metals can be divided into two main groups; direct sorting and indirect sorting. Suggestions for indirect sorting are metal detectors, Infrared, and X-ray. Suggested direct sorting is magnet-based sorting.

Step 2:
Through this step, non-magnetic metals are separated from all incoming materials, such as wood, external plastics, rubber, glass, paper/packages, and cardboards. It is divided into two main groups; direct sorting and indirect sorting. Suggestions for indirect sorting are infrared, pattern recognition, X-ray (for non-magnetic metals), and hyperspectral imaging. Suggested direct sorting is the Eddy current based method (rejects the non-magnetic but electrically conductive metals). Other possible separation methods are vibrating screens (where waste is sorted by size).

Step 3:
In this step, the competitors' plastic floor is separated from Tarkett's plastic floor. Suggestions for indirect sorting is infrared, pattern recognition, and hyperspectral imaging. Suggested direct sorting is the gravity-based separation method.

Step 4:
During these steps, Tarkett's heterogeneous is separated from homogeneous floors. Heterogeneous plastic floors with polyester backing are not mixed with the heterogeneous without polyester backing. The previous indirect and direct sorting in step 3 can also be used for this step.

Step 5:
IR spectroscopy is a proven method for qualitative and quantitative analysis of organic and some cases inorganic substances. While there are several IR spectroscopic methods, NIRs are by far the most widely used in the plastic recycling industry. Several studies have shown that NIRs are capable of detecting various phthalates in PVC when using neural network analysis and other “learning” algorithms, see section 2.3.1-2.3.3. MIR-FTIRs, on the other hand, are proven phthalate screening methods. However, not widely adopted in industrial applications, rather mostly used for slower and more controllable environments such as in laboratory use. Thus, NIRs techniques are suitable for this step.

Step 6:
Surface contamination, irregularities, material heterogeneity, and aging can be detected with Near-infrared Hyperspectral imaging (NIR-HSI) to an extent. NIR-HSI builds on the capabilities of NIRs with the addition of capturing 2D images of the scene in which each pixel gets a spectrum, see section 2.3.2-2.3.3 and 2.5.3. Torn plastic floors contain adhered impurities such as wood, glue, and concrete residue which correspond to different NIR spectrums. Thus, NIR-HSI techniques can be used for the separation of contaminated and non-contaminated plastics.

Step 7:
Polyvinyl Chloride, as the name states, includes halogen elements in the repeating molecules. Halogens, metals, heavy metals, and other inorganic elements are detectable with X-ray based spectroscopic techniques. Thus, X-ray fluorescence (see 2.3.2 and 2.5.3) techniques can be used for the separation of PVC plastics from non-PVC plastics. NIR based methods can also be used for the separation of several plastic resins including PVC.

Other methods for sorting and separating PVC plastic from non-PVC include electrostatic, gravity-density, and eddy current based separation methods (see section 2.5.2).

Step 8:
The spectroscopy-based methods (X-ray and NIR) can also be utilized for this step. Since all metallic elements are detectable with X-ray spectroscopy, Al-containing plastics can be separated from Al free plastics. NIRs, on the other hand, can't directly detect nonferrous metals. Instead, NIR-HSI can be used together with special classification algorithms for nonferrous metal detection.

Other methods for separation of nonferrous metals from plastics include Eddy current and Eddy current based metal detectors. These methods can also be used for separating ferrous metals from plastics. NIRs, as well as NIR-HSI methods, can be utilized for the separation of PVC foam from PVC free foam backing. Alt the spectroscopy-based methods, as well as pattern recognition and metal detector methods, need an ejection/extraction system since they can't mechanically separate objects and only detect.

4.2 Lean production and safety

It is of great importance that Lean can be implemented in the future sorting system and made as secure as possible. With Lean, waste (Muda, see Table 3) can be minimized, as well as satisfying the future customer through an efficient sorting of plastic floors. The security of the system supports a safe work environment for employees and ensure that the work goes as planned.

4.2.1 Lean production

For the concepts to be applied after Lean, it must have a continuous process flow. The automatic sorting makes it easy to handle and move the plastic floor. Also, it makes the work process easier to handle by employees. When the plastic floor sorting process is constantly active, the inventory of plastic flooring will be minimized. Since the sorting is sensor-based, information can be conveyed quickly between the different sub-processes, as well as giving workers enough data for better control over the sorting. Through the data from the sorting system, employees can quickly fix problems that arise. Support systems can be built into the sorting system to detect problems, as well as alert personnel if a machine or process needs to be addressed. Problems can be solved quickly if the system can transmit data. Visual support systems are also a good choice for monitoring and controlling the sorting/separation flow. Furthermore, knowledge of each sub-process in the sorting, as well as employees participate in the work, should be gathered for further streamlining of the system and working methods. Also, the team that will work with the sorting system, should be trained in how to handle it, to work towards a common goal. A trained team contributes to quality and productivity in the work.

4.2.2 Safety

To maintain safety, technology must first be tested. Once the technology proves to support the employees and assist the sorting of plastic floors, it can be implemented. A visual system is effective for monitoring and can quickly show where the problem lies, for it to be corrected. All automated parts/installations in the sorting system should have built-in emergency stops and breaks. The purpose is to stop or brake, parts, or the whole sorting system before the system or employees are harmed. The sorting system should be equipped with manual or automatic brakes, which can brake/stop the parts or the whole sorting system.

Security stops and machine shields are suitable to have in areas with a high risk of injury. If any person enters a hazard area, such as getting too close to an active machine, the facility should be able to stop parts or the entire sorting system by the security stop or shields. Appropriate safety stops can be implemented by, for example, light rays that stop the machine (or trigger an alarm) automatically, if a person crosses through it. A security stop and machine shield/protection can be a good option for the fast and automated sorting processes, such as the robotic arms and the shredders. Machine protection makes machine risk areas inaccessible for people to enter without a key (Lean and safety; see section 2.1).

It's known that X-rays can cause DNA mutations, thus leading to cancer later in life. The World Health Organization (WHO) classifies X-rays as carcinogenic and should, therefore, be handled with caution. When using X-rays, it should be already encapsulated with some layer/barrier as protection.

4.3 Results of testing technology capability

4.3.1 Near-infrared

Holger could not detect the exact substances present in each sample thereby measuring and specifying the exact plasticizers used in each sample was not plausible. For that reason, Holger did not follow the exact test instructions. However, Holger was asked to create a spectrum library of all samples. Thus, Holger scanned each sample five times across multiple places and created an internal spectrum library of all the samples. Then, the library was used as a reference model for sample identification.

All samples could be differentiated from each other when correlated to the newly created internal spectrum library, i.e., each sample has a different spectrum, unique to the type and amount of materials used. With the use of the internal spectrum library, all four homogeneous samples with different plasticizers could be reliably differentiated from each other, i.e., homogeneous Tarkett floors with DEHP, DINP, DINCH, and Castor oil were reliably identified. The identification accuracy was 95% and could increase if more samples were scanned, see figure 26. Furthermore, different types of samples could be differentiated; homogeneous from heterogeneous, Tarkett from non-Tarkett, PVC from non-PVC, normal PVC floors from PVC floors with AL-filler, and pure from impure sample surfaces.

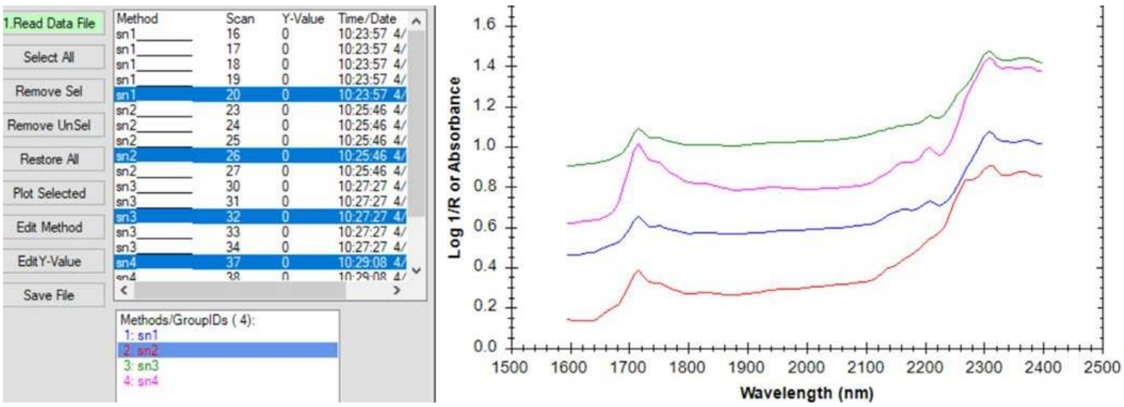


Figure 26: The NIR spectrum of the four different plasticizers. Green: Castor oil, Pink: DINCH, Blue: DEHP and Red: DINP.

The X marked sample was speculated to be either Tarkett *Natural* or Tarkett *Primo Premium*. After establishing the internal spectrum library, sample X was cross-referenced against all scanned samples and correlated the most with Tarkett *Primo Premium*. Thus, sample X was confirmed, see figure 27.

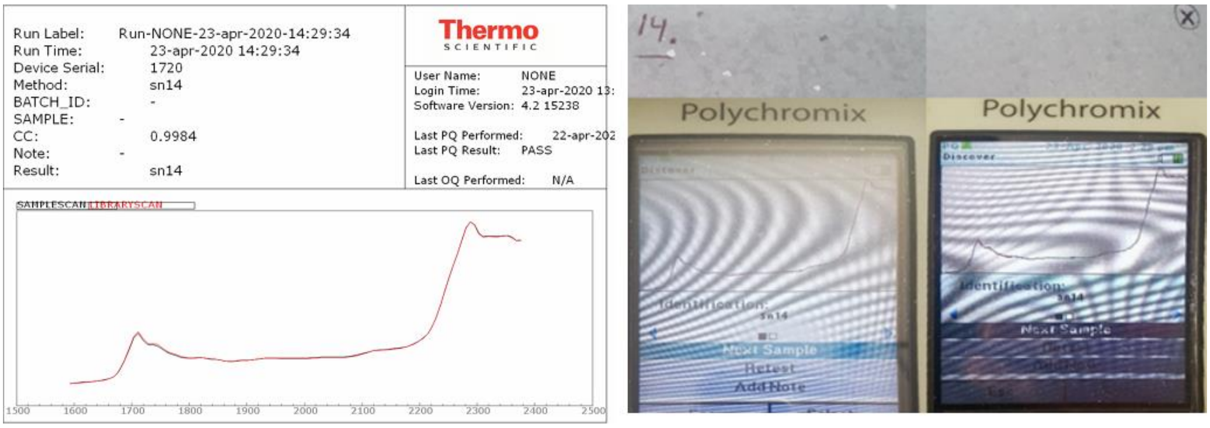


Figure 27: The NIR spectrum of sample X and sample 14, the Correlation Coefficient (CC) was 0.9984.

Sample 15, Safe - T, was provided in two colors, light gray and dark gray with black shades, see figure 28. The NIR device had problems detecting the darker sample but with more readings (scans), a positive correlation coefficient of the relationship was given.

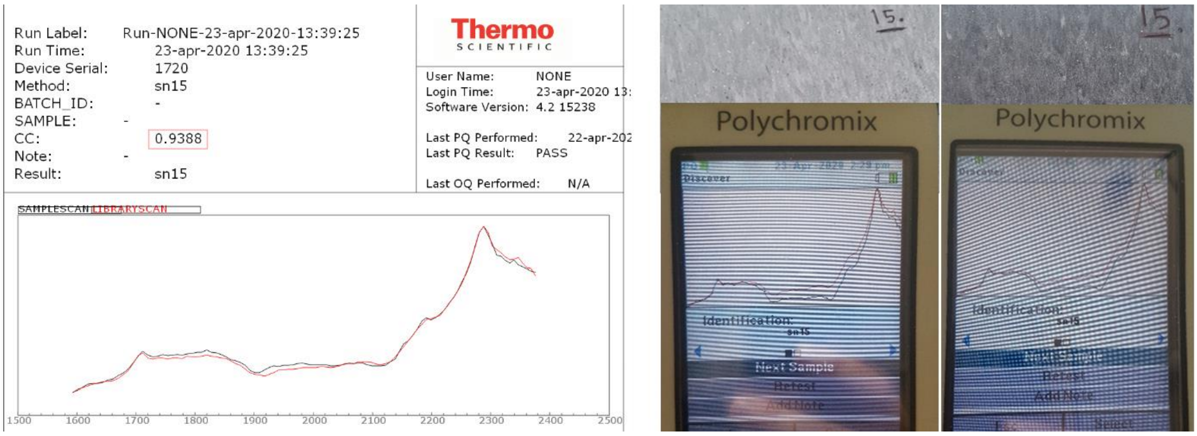


Figure 28: The NIR spectrum of samples 15, the Correlation Coefficient (CC) was 0.9388.

4.3.2. Pattern recognition

When the plastic floors were used for *Emsys-Visiongeek*, a library of all plastic floors was made of all plastic floors. Of all the samples, only four plastic floors were not recognizable by the pattern recognition system (see figure 29). The samples that were not recognized are a Tarkett's plastic floor compared to a competitor's plastic floor (line a), and homogeneous plastic floors compared with a heterogeneous plastic floor (line b).

Figure 29: The four not recognizable plastic flooring.

4.4 Concepts

4.4.1 Concept 1: The waste eradicator

Concept 1 utilizes pattern-recognition, near-infrared hyperspectral imaging, and X-ray fluorescence (i.e., indirect methods) for the separation and sorting of the plastics floors according to the described process map. However, magnetic and air separation methods are also used, see figure 30. A complete overview of Concept 1 can be seen in Appendix C.

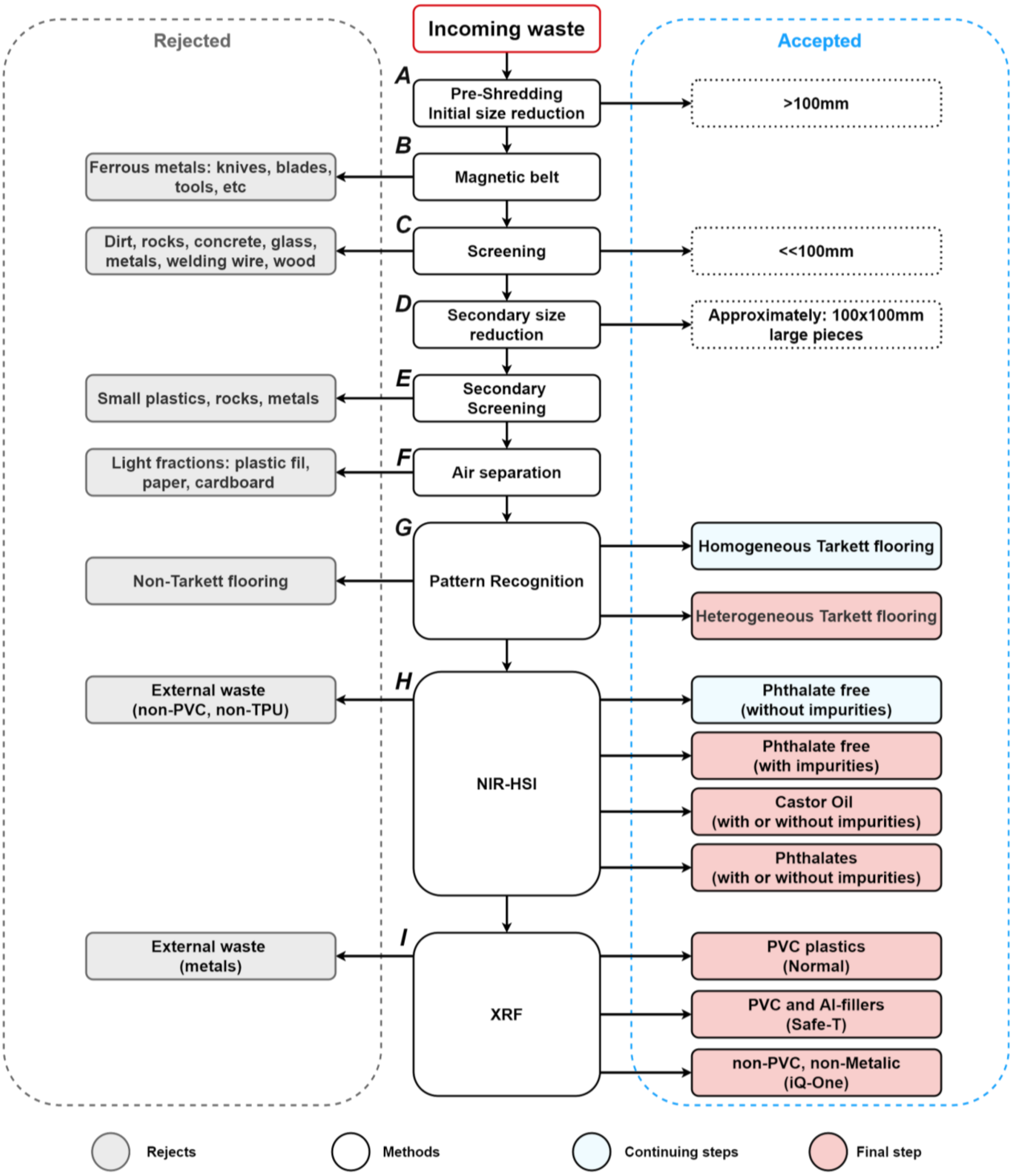


Figure 30: A flow chart representing the sorting and separation process in Concept 1.

A: In concept one, the system starts with reducing the size of the incoming waste. The incoming plastic floors are of two types, large plastic rolls in containers and smaller cut off pieces in bags when undergoing the initial size reduction, the size of the two streams should be in the same range. Also, any hidden objects within the rolls or garbage bags and loosely adhered impurities will be exposed when the waste is reduced in size. The size reduction can be performed with heavy equipment shredders capable of shedding small amounts of metals, concrete, wood, and large 2m long plastic floor rolls.

B: After shredding the waste into smaller pieces and exposing any hidden objects with the waste streams, a magnetic conveyor belt is applied to remove any unwanted ferrous metals. As reported in section 1, knives, blades, nails, and other metallic tools are often found within the waste streams, see appendix A. The magnetic conveyor belt can be applied directly above the initial conveyor transporting the shredded waste stream or embedded in the transporting belt, see figure 19, or inside the conveyor, see figure 31.

C: After the removal of ferrous metals, material filtering or screening is performed for the separation of unwanted materials based on their size and form. Loosely adhered concrete, crushed drywalls, crushed glass, plastic welding wires, and other small objects are separated from larger plastic flooring pieces. The shredded waste stream from step ***B*** is transported via the same initial conveyor belt to the screening equipment. There are several types of screens (see section 2.5.1), however, the unwanted materials will fall through the screens while the appropriately sized and more rigid materials will be transported to the next stage.

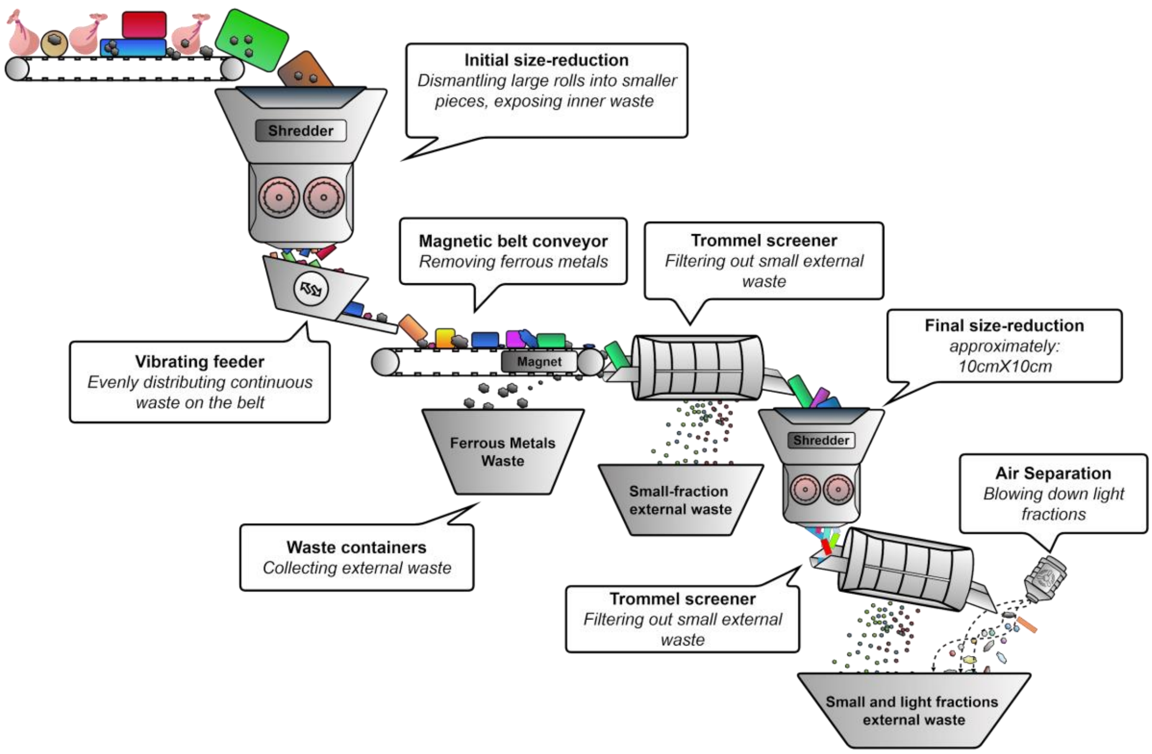


Figure 31: A 2D illustration of Concept 1 from step A to F, i.e the size reduction and waste removal stage.

D, E, and F: Step A and C are repeated in stages D and E for a final size reduction and higher material purity. The waste streams transported from section C are reduced to a final size of approximately 10x10cm and then filtered through smaller screens, removing further unwanted external waste while the approximately 10x10cm plastic flooring pieces are transported to the next stage, in which air separation is performed.

In case light materials like thin plastic films, plastic bags, paper, and cardboard accompany the 10x10cm plastic flooring pieces, air separation is used by either blowing or sucking out lighter materials from heavier plastics, see figure 32.

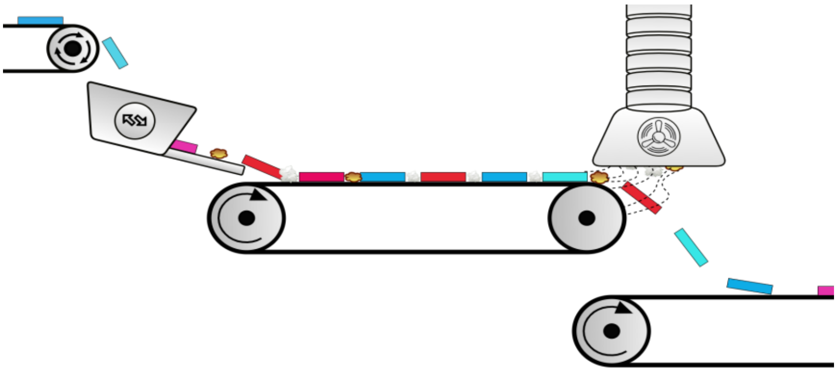


Figure 32: An illustration of the method of air separation, in this case, air suction is used to separate light fractions from heavy plastic floor pieces. Light fractions are sucked with air while the heavy fractions fall to the next conveyor.

G: Now that the incoming plastic pieces are to a large extent free of external waste, classification scanning can take place. Pattern recognition is used first for the separation of homogeneous Tarkett, heterogeneous Tarkett, and non-Tarkett flooring. Additionally, the heterogeneous Tarkett floors are separated into polyester and polyester free backing. The rejected non-Tarkett flooring and classified heterogeneous flooring will not travel any further, only the homogeneous Tarkett flooring is permitted to proceed to the next stage via a conveyor system. The following four groups are separated here:

1. Homogeneous Tarkett flooring
2. Heterogeneous Tarkett flooring with polyester backing
3. Heterogeneous Tarkett flooring without polyester backing
4. non-Tarkett flooring (Heterogeneous or Homogeneous)

A line-scan or multiple area-scan cameras can be installed above a transporting conveyor (first orientation), the scanned data is then analyzed, and coordinate data is given to the pneumatic system for separation. In the second orientation, line-scan cameras are installed underneath the upper conveyor belts thus scanning the bottom of the plastic flooring through gaps/splits in the belt. In the third orientation, the first and the second orientation are combined, allowing for upper and lower scans. Heterogeneous flooring implies a design difference between the upper and lower layer (i.e. face and bottom) and therefore if one orientation does not provide sufficient information for classification, a combination (third orientation) can be used, see figure 33.

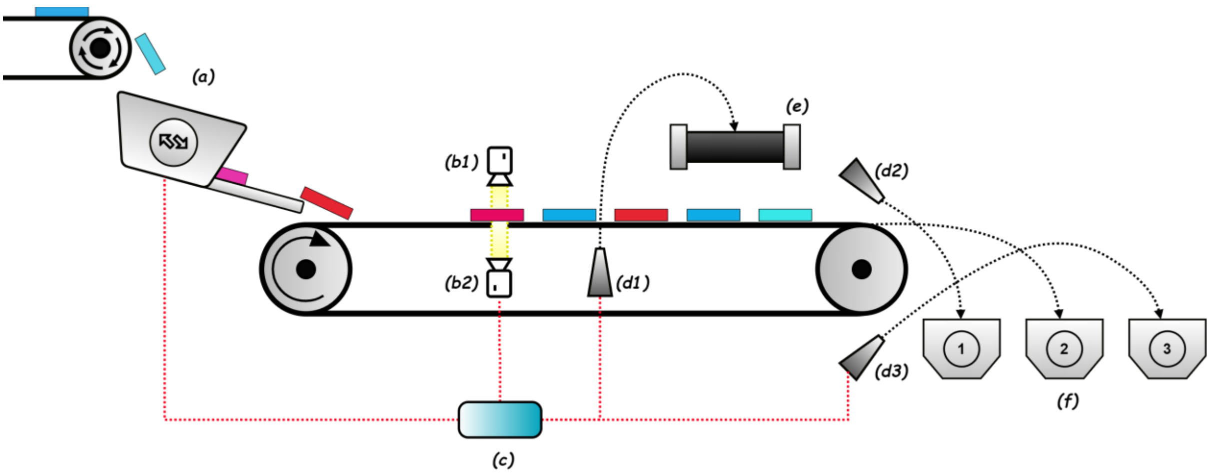


Figure 33: A demonstration of the pattern recognition system (G) of concept 1.

Figure 28 demonstrates the different camera placements and the pneumatic air nozzle ejectors of the pattern recognition section of concept 1. a) A conveyor is supplying a vibrating feeder which in turn discharges the plastic pieces onto the conveyor at a controllable rate. b) Line-scan RGB-cameras mounted above (b1) or below the belt (b2) or both, depending on the task, scan the incoming plastic floor pieces. c) A control unit analyzes the captured 2d image and sends separation action coordinates to the pneumatic systems. d) Three air nozzles systems placed at different sections of the conveyor belt for flexible separation of multiple options. An air nozzle system is placed within the conveyor belt (d1) for the separation of group 1 (Homogeneous Tarkett flooring), and two are placed near the end of the conveyor (d2 and d3) corresponding to bin 1 and 3. e) A smaller transport conveyor belt mounted above the main transporting conveyor and corresponds to the ejected plastics by air nozzles system (d1), i.e., capturing and transporting the homogeneous Tarkett floors to the next step. f) Three collecting bins (1, 2, and 3). Bin number 1 corresponds to ejected polyester free heterogeneous Tarkett floors. Bin number 2 corresponds to non-Tarkett floors, no ejecting is needed, only a normal trajectory. Finally, bin number 3 corresponds to the heterogeneous floors with polyester backing.

H: Now that the incoming plastic pieces consist of a large extent of homogeneous Tarkett flooring, classification according to substance and condition can take place. Near-infrared Hyperspectral imaging is used for the separation of floors according to plasticizer type and condition. Four different groups are derived from these two conditions:

1. Free of phthalates and without adhered impurities
2. Free of phthalates and with adhered impurities
3. Containing phthalates and with or without adhered impurities
4. Containing castor oil and with or without adhered impurities

Only the first group, i.e., only plastic floors free of phthalates and adhered impurities proceed to the next stage. Still, the four groups have to be separated into respective lanes or bins. This is done with a line-scan NIR-HSI camera, lighting source, control unit, vibrating feeder, a meshed conveyor belt, and multiple pneumatic air nozzles.

First, a controllable amount of plastic flooring pieces is spread on to a striped conveyor belt with a vibrating feeder. Then, a NIR-HSI line-scan (or area-scan) camera is installed above the conveyor belt, scans the plastic pieces, a control unit analyses the scanned data, and sends coordinates to the pneumatic air nozzles for separation action. However, this time a series of four pneumatic systems are evenly spaced inside the conveyor. Each pneumatic system corresponds to one of the described groups above. When the NIR-HSI camera scans a plastic piece of a group, coordinates are given to the corresponding pneumatic system for separation action, see figure 34. Thus, multiple groups can be separated at once.

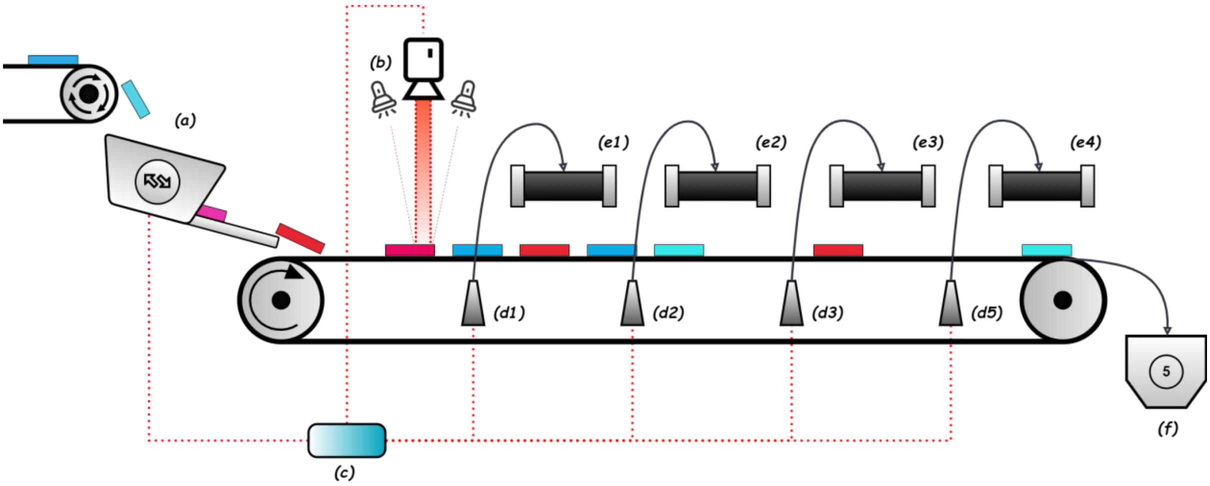


Figure 34: A demonstration of the Near-infrared Hyperspectral imaging sorting system of concept 1.

Figure 34 describes the NIR-HSI sorting system in concept 1. (a) A feeder evenly discharges the shredded plastic flooring pieces onto the conveyor belt. (b) A NIR-HSI line-scan camera and light source. The light source emits a NIR radiation and the NIR-HSI camera captures an image and a spectrum for each pixel with the image. c) The scanned hypercube is analyzed and separation orders (coordinates) are given to the pneumatic systems. d) Four air nozzle ejector systems (d1-d4) are installed inside the conveyor, each corresponds to a specified transporting conveyor belt above (e1-e4). f) A bin for unclassifiable floors and external waste. Furthermore, only group one is transported to the next stage, i.e., all but conveyor belt *e1* stop here.

I: For the final stage, X-ray fluorescence (XRF) is used for the separation of:

1. PVC flooring without any metallic fillers
2. non-PVC flooring
3. metal-containing flooring
4. External metal waste

This is done with an X-ray light source, X-ray detector, control unit, and air nozzles. The light source emits x-ray radiation, an X-ray detector captures emission of the absorbed radiation, a control unit analyzes the data and pneumatic air nozzles separate the described group to respective lanes/bins. Both the light source and detector are installed above the conveyor while the pneumatic nozzles are either installed within the conveyor or at the end.

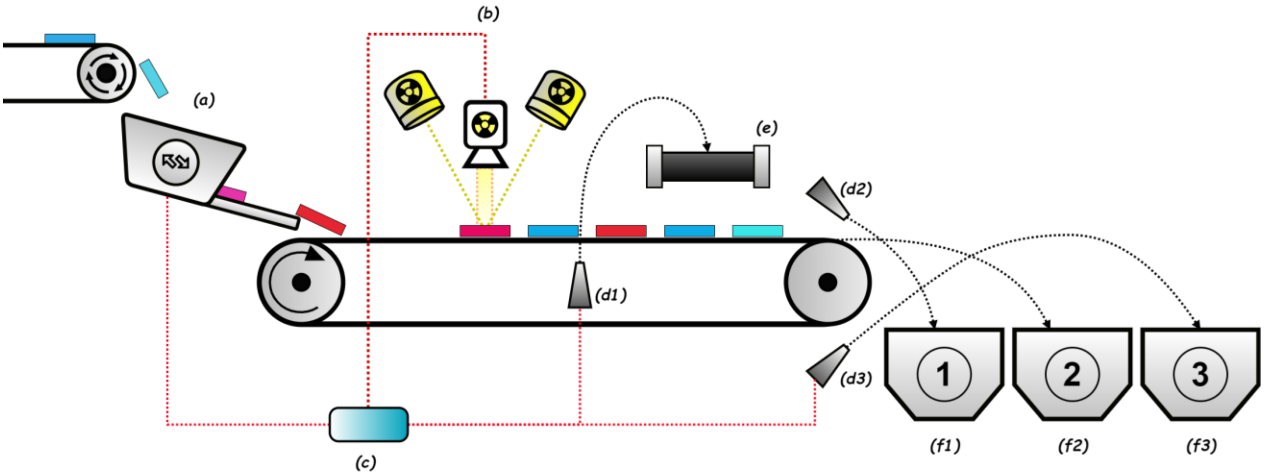


Figure 35: A demonstration of the X-ray fluorescence sorting system of concept 1.

Figure 35 describes the XRF sorting system in concept 1. A feeder evenly discharges the shredded plastic flooring pieces onto the conveyor belt (a). (b) An XRF detector and light source. The light source emits X-ray radiation and the XRF detector captures the fluorescence. (c) The captured data is analyzed and separation orders (coordinates) are given to the pneumatic systems. One air nozzles ejector system (d1) is installed inside the conveyor and launches objects to the transporting conveyor above (e). There are two more air ejectors at the end of the conveyor (d2 and d3). The upper air nozzles (d2) push objects towards the first bin (f1). The lower air nozzles push objects up towards the third bin (f3). While objects traveling in a normal trajectory fall in the second bin (f2). Thus, the four groups can be separated according to demand and preference.

4.4.2 Concept 2: The picking and pushing sorting system

The concept is based on the sorting technologies pattern recognition, X-ray Fluorescence (XRF), and Infrared (IR). The sorting process can be seen in the flow chart, Figure 36 (see below). The methods used are represented in the middle (marked with white). Under the title "Rejected", is the material that is not accepted by the sorting system (marked with gray). The materials that have been allowed to proceed in the process (marked with blue) or sorted (marked with pink), are found under the title "Accepted". A complete overview of Concept 2 can be seen in Appendix D

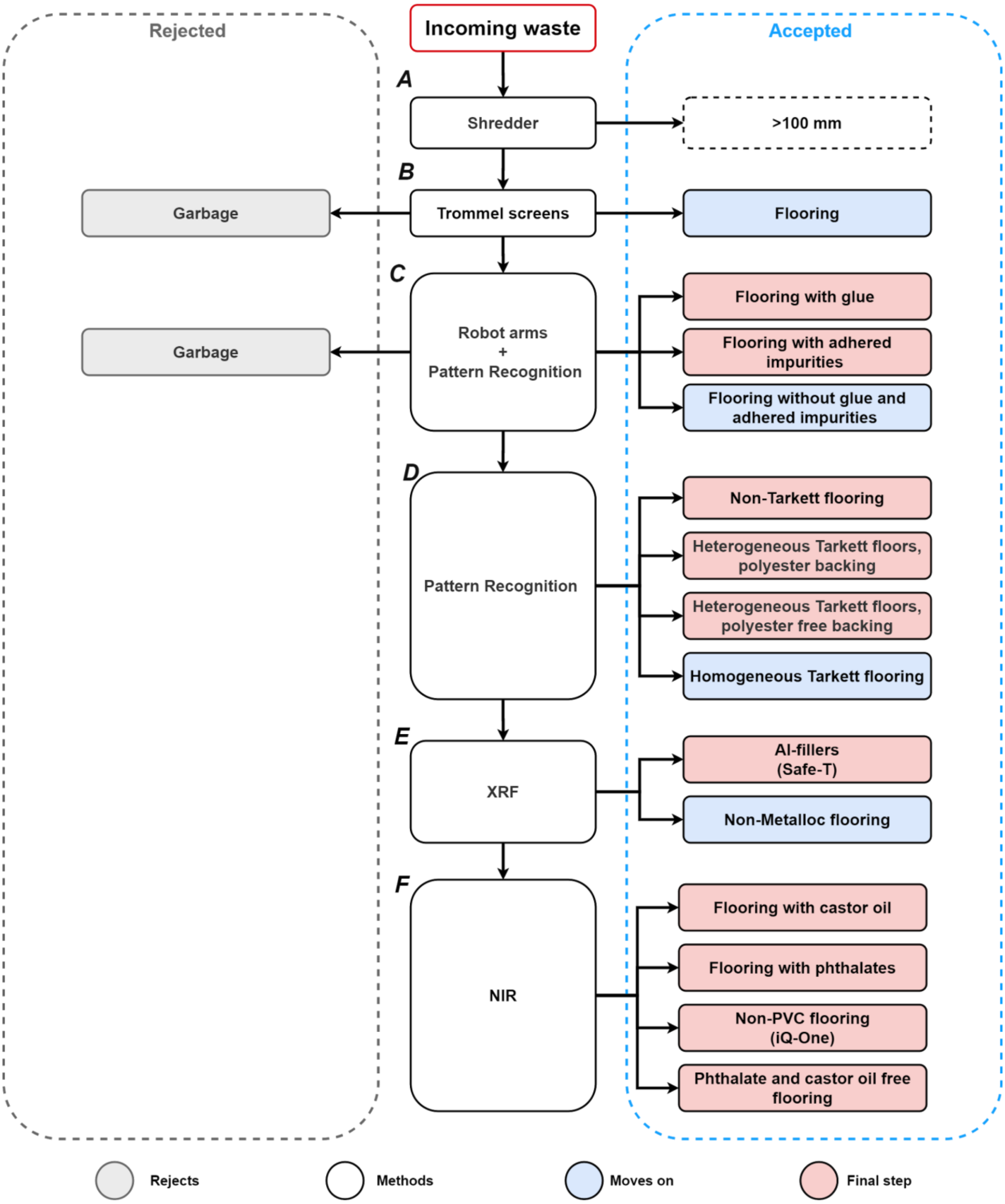


Figure 36: A flow chart representing the sorting and separation process in Concept 2.

A: The sorting system starts by reducing the size of the incoming waste. There are two different types of incoming plastic floors, large plastic rolls in containers, and smaller cut pieces in bags. When the rollers or waste bags undergo a size reduction, any hidden objects, and loosely adhered contaminants will be exposed as the waste is reduced in size (Shredding; see section 2.5.1).

B: After the waste is shredded, material filtration or screening is carried out to separate undesirable materials based on their size and shape. Materials that are intended to be filtered from larger plastic floor parts are scalpels, wooden utensils, loose adhered concrete, broken glass, plastic welding wires, and other small objects. The screen that is intended to be used for this process is drum screens. Through the rotating movement, even the hidden debris can fall out of the plastic floor. The unwanted material will fall through the screens while suitable sizes and stiffer materials are transported to the next step (Trommel screening; see section 2.5.1).

C: Through a pattern recognition vision system, the plastic floors are identified. The system sends a command to two robot arms. The robot arms pick each plastic floor and inspect it through the pattern recognition vision system for adhesives and adhered impurities. The plastic floor with adhesive and adhered impurities is placed in each container while the plastic floor, without adhesives and adhered impurities, is placed on a conveyor belt (Robot arm; see section 2.5.1 and Pattern recognition; see section 2.4 and 2.5.3).

D: Now that the incoming plastic pieces are free of external waste, a classification search can take place. Pattern recognition is used for separating the following separation groups:

- Non-Tarkett plastic flooring (heterogeneous or homogeneous)
- Heterogeneous Tarkett flooring with polyester backing
- Heterogeneous Tarkett floors without polyester backing
- Homogeneous Tarkett floor

A pattern scanning system allows the pattern recognition system to inspect the plastic floor. A scanning camera needs to be placed on top of the conveyor belt and below for the best results. Using a split conveyor belt, approximately 5 mm apart, a scanning camera can be placed. In this way, the underside of the plastic floor can be inspected (see figure 37). For the scanning camera to be able to read the pattern on the plastic floor, the floor needs to have a mostly flat surface. An embedded / built-in platform around the scanner camera can be used to smooth the surface of the plastic floor. By lowering the platform, the plastic floor can be pressed down, before scanning. Tarkett homogeneous plastic flooring proceeds in the process to the next step through the transport system, while competitors' plastic flooring and heterogeneous plastic flooring (Tarkett and non-Tarkett flooring) don't proceed. Tarkett heterogeneous floors are also separated into polyester- and polyester-free substrates (Pattern recognition; see section 2.5 and 2.5.3).

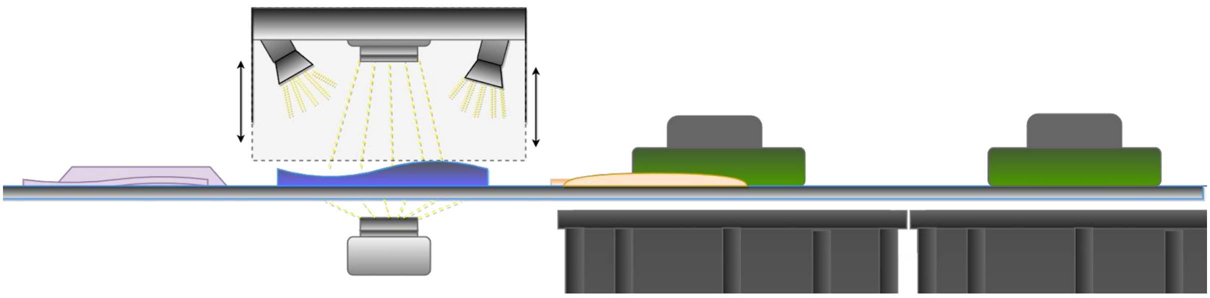


Figure 37: Pattern scanning system.

E: For the next step, X-ray fluorescence (XRF) is used to separate:

- Metal-containing floor (safe T)
- Non-metal containing flooring

Based on spectroscopic techniques, elements in materials can be identified. The purpose is to identify metal-containing floors as the Safe T-plastic floor. The light source and detector are installed above the conveyor, where the light source emits X-rays, an X-ray detector captures emissions of the absorbed radiation, where a controller then analyzes the data (see figure 38). Thus, the system finds the Safe T-plastic floor. Other non-metal-containing plastic floors are allowed to pass through the transporter (XRF; see section 2.3.2).

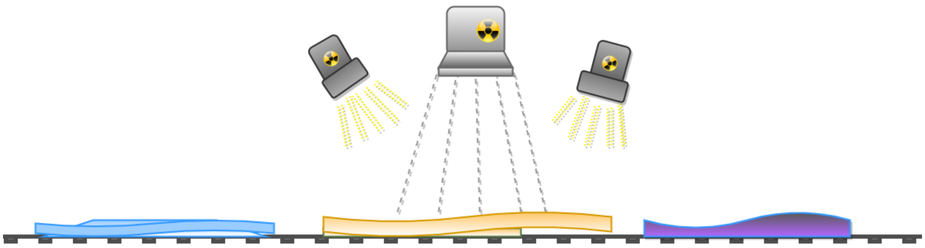


Figure 38: Separation by X-ray fluorescence (XRF).

F: The last inspection method is performed by Infrared (NIR) (see figure 39). The floors to be separated are:

- Flooring with castor oil
- Flooring with phthalates
- Non-PVC flooring (iQ-One)
- Phthalate and castor oil-free flooring

Because different materials have different spectrums, the differences in the content of the plastic floor can be identified by NIR. The purpose is to locate plastic floors with phthalate softener, plastic floor with castor oil (plasticizer), and non-PVC floor (iQ-One), and sort them separately. Remaining plastic floors, which are homogeneous phthalate and castor oil-free plastic floors, can either be moved to a container or proceed in the process and sorted based on other content differences (NIR; see sections 2.3.1 and 2.5.3).

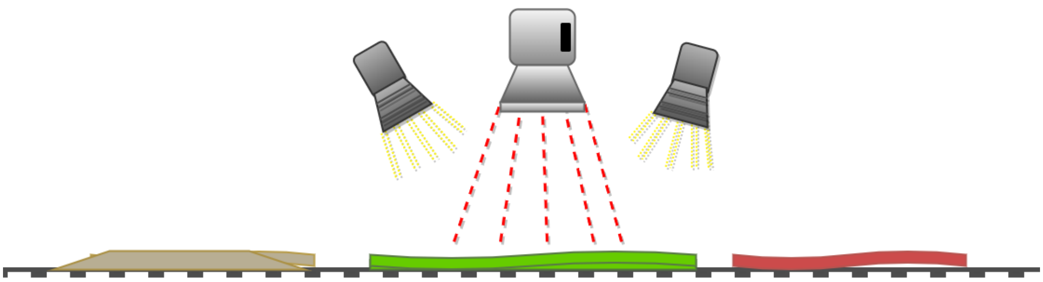


Figure 39: Separation by NIR.

This concept is based on the robot arms placing each plastic floor on the conveyor belt one by one. As a result, the plastic floor does not overlap with other types of floors, and the separation is simplified. The conveyor belt needs to be between 1.2 and 1.5 m in width, to handle the floor size variation. The conveyor separates the floors via a built-in sorting system, via a push sorting method (see Figure 40). The sorting system sorts plastic floors after they have been identified by the pattern recognition system, XRF, and IR, between process steps, D to F. The plastic floor is pushed into a container by a pusher sorter after the identification. Linear arm sorting and roller sorting can also be used (Conveyor belt; see section 2.5.1).

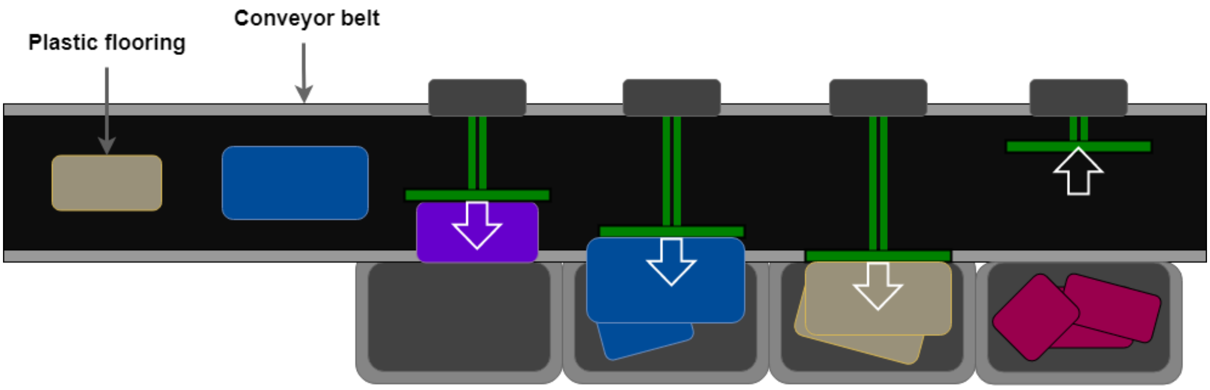


Figure 40: Sorting by pushing each type of plastic floor in its container (the push-slide is green).

4.4.3 Concept 3: The streamlined hyper-sorter

Concept 3 utilizes near-infrared hyperspectral imaging and X-ray fluorescence for the separation and sorting of the plastic floors according to the described process map, see figure 41. Furthermore, Concept 3 consists of three stages. The first stage sees the size-reduction and waste removal, and the initial near-infrared hyperspectral imaging. X-ray fluorescence is used in the second stage and near-infrared hyperspectral imaging is used again in the third and final stage of the sorting process, see figure 48.

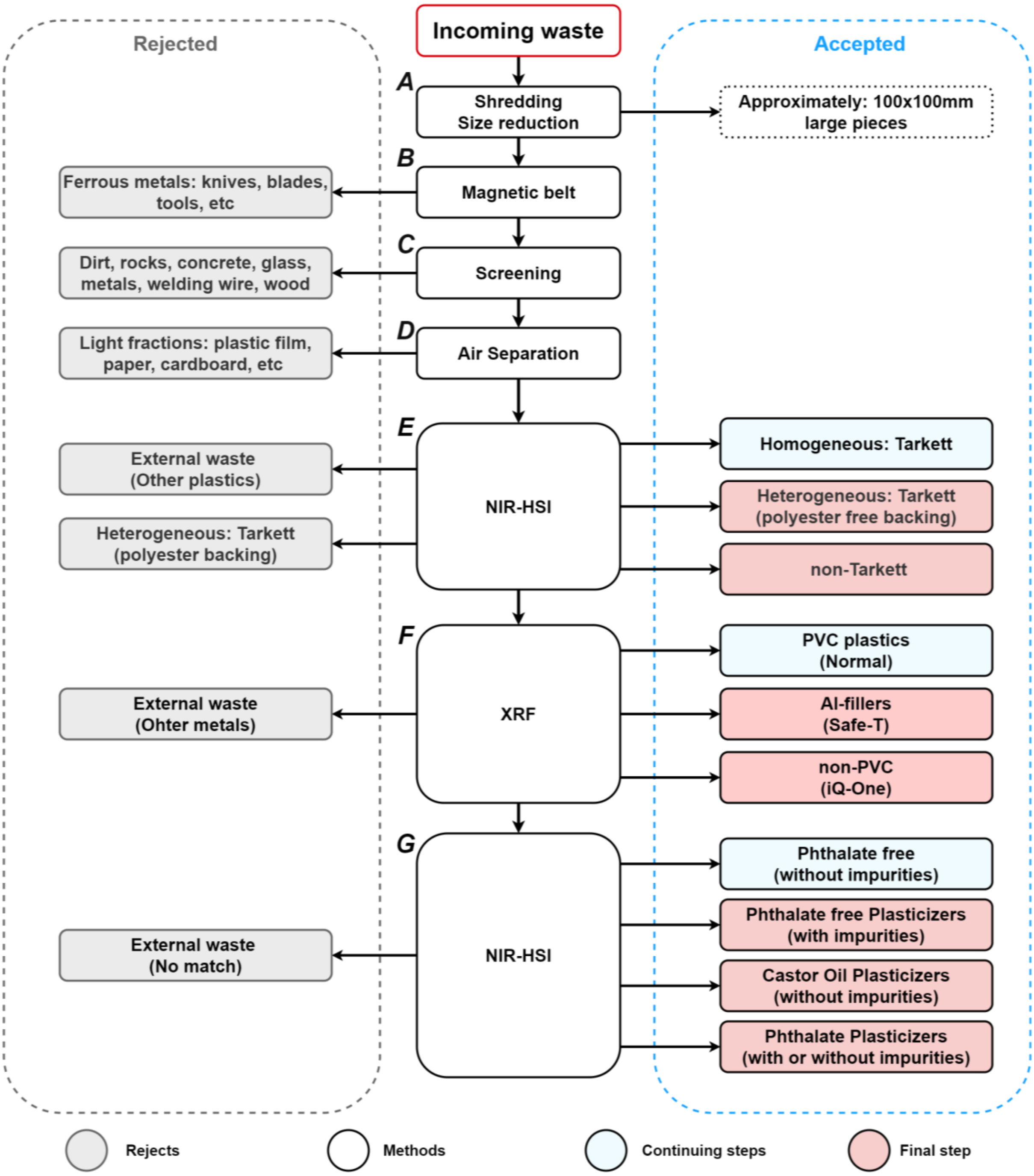


Figure 41: A flow chart representing the sorting and separation process in Concept 3.

A: Like Concept 1, Concept 3 performs size reduction and waste removal at the very early stages of the process. Conversely, Concept 3 only performs one size reduction and waste screening. The incoming waste is shredded to a final size of approximately 10cm x10cm exposing any hidden objects within the floor rolls or garbage bags. Besides, loosely adhered particles will fall off the floors when reduced in size.

B: A magnetic conveyor belt is applied to remove any unwanted ferrous metals such as knives, blades, nails, tools, and other magnetic objects that are often found within the plastic floors. The magnetic conveyor belt can be applied directly above the initial conveyor transporting the shredded waste stream or embedded in the transporting conveyor.

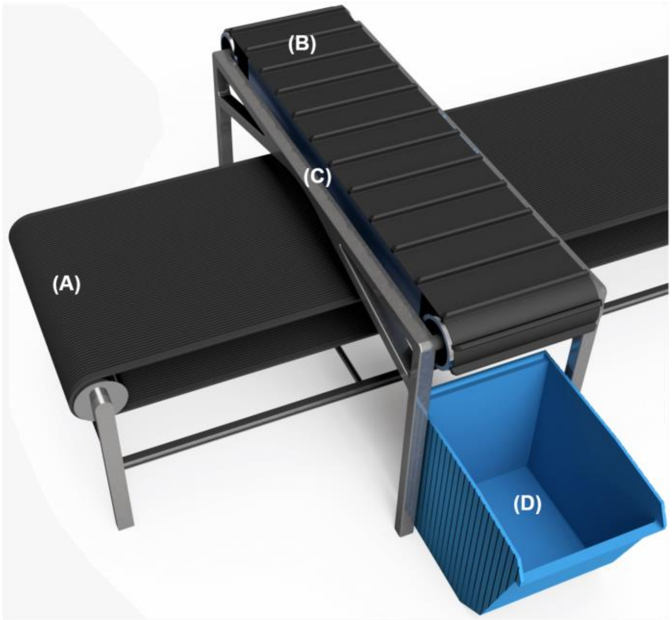


Figure 42: A CAD model illustrating the magnetic conveyor separation process.

Figure 42 shows a magnetic conveyor (B) installed above the main transporting conveyor (A). The magnetic waste is captured by a magnet mounted inside the belt (C), the belt transports the captured waste to the collecting container (D).

C: Loosely adhered concrete, crushed drywalls, crushed glass, plastic welding wires, and other small objects are separated from larger plastic flooring pieces with a screening machine. There are several types of screens, however, the unwanted materials will fall through the screens while the appropriately sized and more rigid materials will be transported to the next stage. The screening machine can be implemented as a vibration feeder.

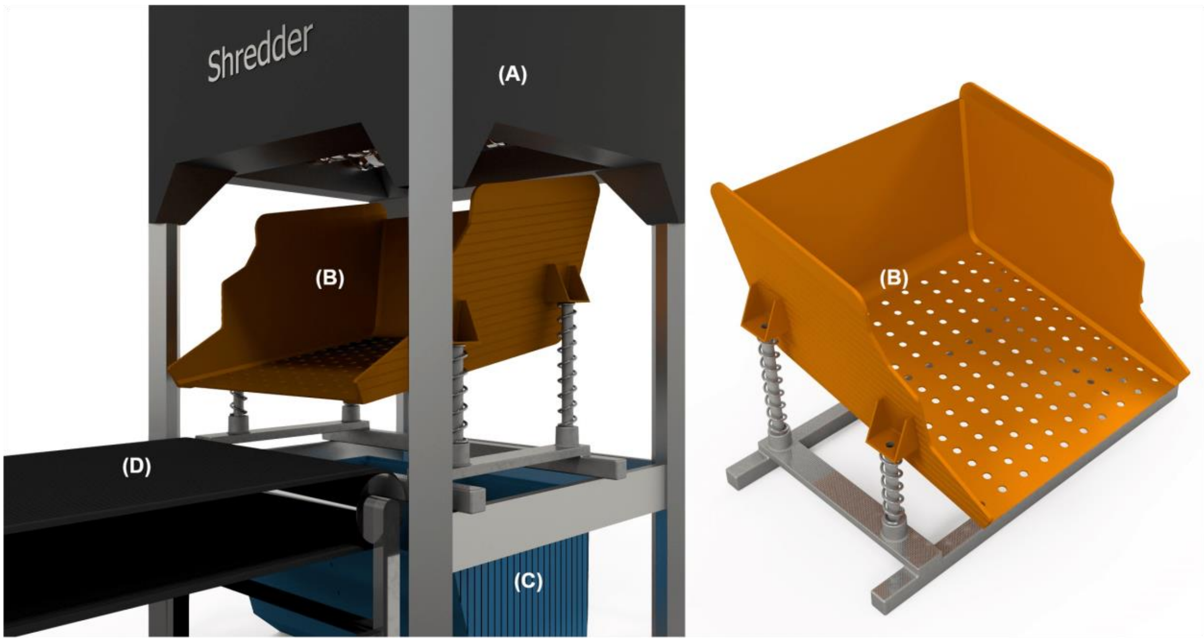


Figure 43: A CAD model of the vibrating screen, conveyor belt, shredder, and waste containers. The vibrating screen doubles as the initial vibrating feeder.

Figure 43 shows one layered vibrating screener that doubles as a vibrating feeder (B). The screen is mounted underneath the shredder (A). Small fractions fall through the one layered screen and collected in the waste container (C) while larger shredded floor pieces land on the conveyor belt (D).

D: Light fraction waste such as thin plastic films, plastic bags, paper, and cardboard are separated from the shredded and heavier plastic floor pieces with air. This is done by streaming and sucking air through a strip-belt. The lighter fractions are lifted from the conveyor belt and travel with the airflow while the heavier plastic floor pieces remain on the conveyor belt.

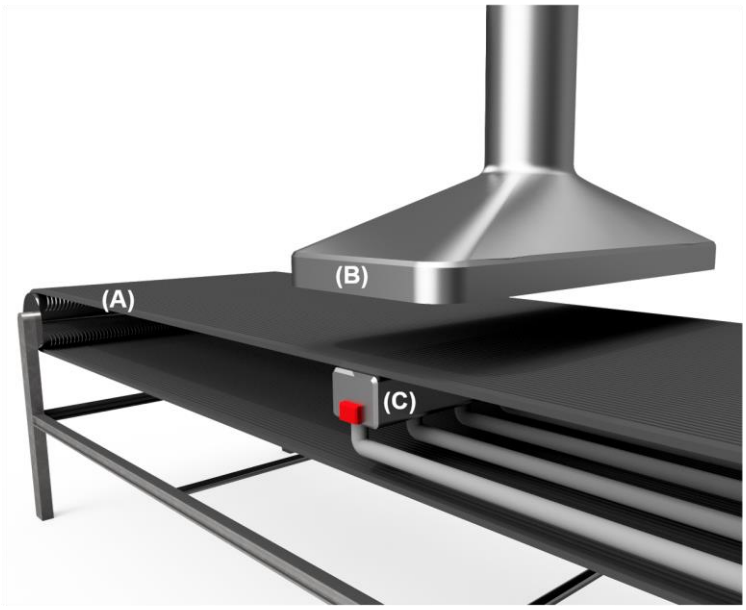


Figure 44: A CAD model illustrating the air separation process in Concept 3.

Figure 44 describes such a system. The air blower (C) pumps airflow through the split-belt (A) and is sucked by a suction system mounted above the belt (B). In this way, the light fractions follow the airflow while the heavier fractions remain on the conveyor belt.

E: The first Near-infrared hyperspectral imaging scanner/camera sorting process is used for the separation of homogeneous Tarkett floors, from heterogeneous Tarkett and non-Tarkett floors. The following four groups are separated here:

- External waste and unidentified floors, Tarkett heterogeneous (polyester backing)
- non-Tarkett floors (both HO & HE)
- Heterogeneous floors: Tarkett (polyester free backing)
- Homogeneous floors: Tarkett

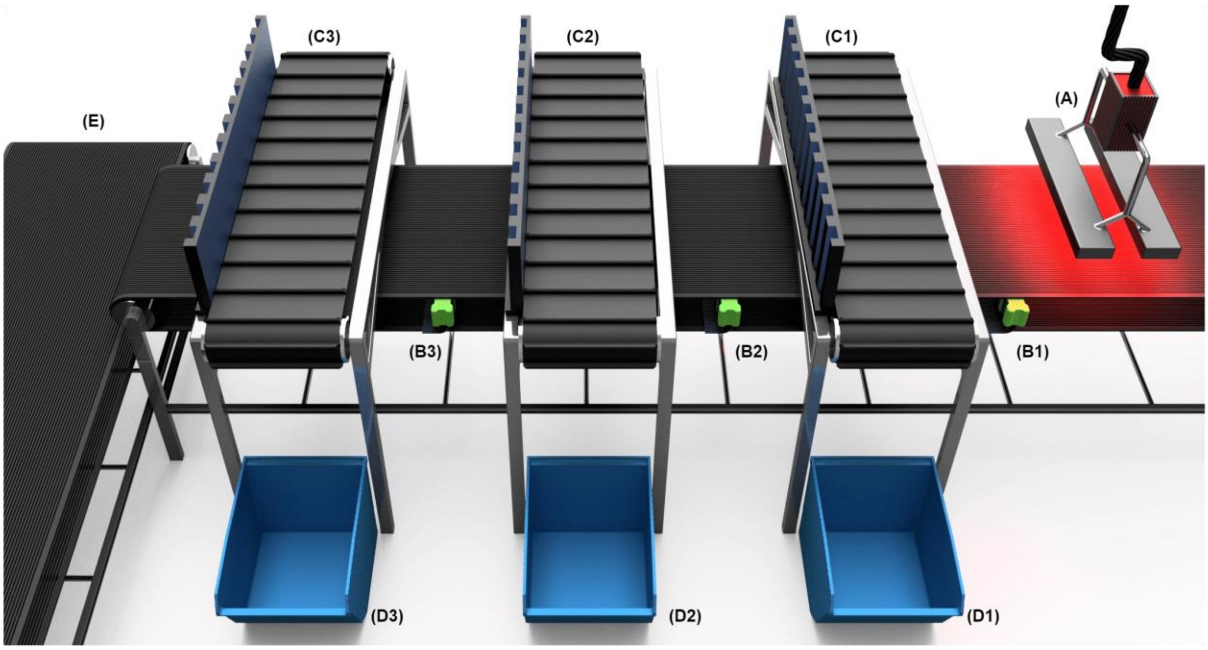


Figure 45: A CAD model illustrating the first NIR-HSI separation process in Concept 3.

Figure 45 describes how the four groups, above, are sorted with the pneumatic and hyperspectral imaging camera. A near-infrared light source illuminates the recyclables on the conveyor belt and the reflected light is captured with a hyperspectral imaging camera (A). The data is then analyzed in a PC or a microcontroller, and separation orders are given to the separation mechanism. Pneumatic ejectors are used as the separation mechanism in Concept 1 and Concept 3. Furthermore, the pneumatic ejectors are mounted within the main transporting conveyor. The sorting process works as follows:

- First, external waste, unidentified objects, and HE Tarkett with polyester backing are separated by the first pneumatic ejector (B1) and land on the first conveyor (C1) which transports the waste to the first collecting container (D1).
- Then, non-Tarkett floors (both HE and HO) are separated by pneumatic ejector B2 and land on conveyor C2 which transports the floors to collecting container D2.
- Heterogeneous Tarkett floors are then separated by ejector B3, transported by conveyor C3 and collected in container D3.
- Lastly, homogeneous Tarkett floors remain on the main transporting belt until free-falling onto the next conveyor (E) for the second stage of the sorting process.

F: X-ray fluorescence is used for the separation of PVC plastic floors from PVC floors with Aluminum-fillers and non-PVC floors. The following four groups are separated here:

- External waste and unidentified floors
- Non-PVC floors
- PVC floors with Aluminum fillers
- PVC floors

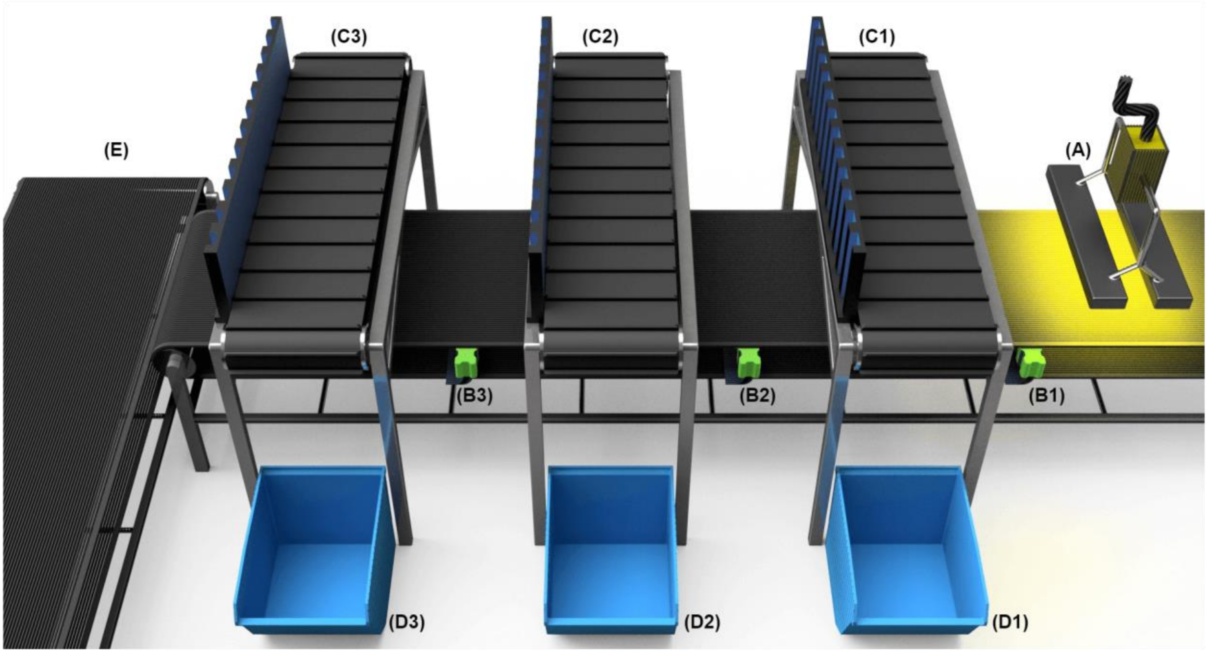


Figure 46: A CAD model illustrating the XRF separation process in Concept 3.

Figure 46 describes how the four groups, above, are sorted with the pneumatic ejector and XRF detector. An X-ray light source illuminates the recyclables on the conveyor belt and the fluorescence is captured with an X-ray detector. Pneumatic ejectors are used for the separation action. The pneumatic system is mounted within the conveyor and receives orders from a microcontroller. The sorting process works as follows:

- First, external waste and or unidentified objects are separated by the first pneumatic ejector (B1) and land on the first conveyor (C1) which transports the waste to the first collecting container (D1).
- Then, non-PVC floors are separated by pneumatic ejector B2 and land on conveyor C2 which transports the floors to collecting container D2.
- PVC floors with Al-fillers are then separated by ejector B3, transported by conveyor C3 and collected in container D3.
- Lastly, PVC floors remain on the main transporting belt until free-falling onto the next conveyor (E) for the third stage of the sorting process.

G: Near-infrared hyperspectral imaging camera is used again for the separation of PVC floors according to included plasticizers and the presence of adhered glue impurities. The following four groups are separated here:

- External waste and unidentified floors
- PVC floors with phthalate (with or without adhered glue)
- Phthalate-free PVC butt with adhered glue
- PVC floors with natural-based plasticizers (Castor oil), with or without adhered glue
- Phthalate-free and glue-free PVC floors

The NIR-HIS in third stage functions in the same way as the NIR-HIS in stage 1. However, this stage requires one additional separation slot, see figure 47.

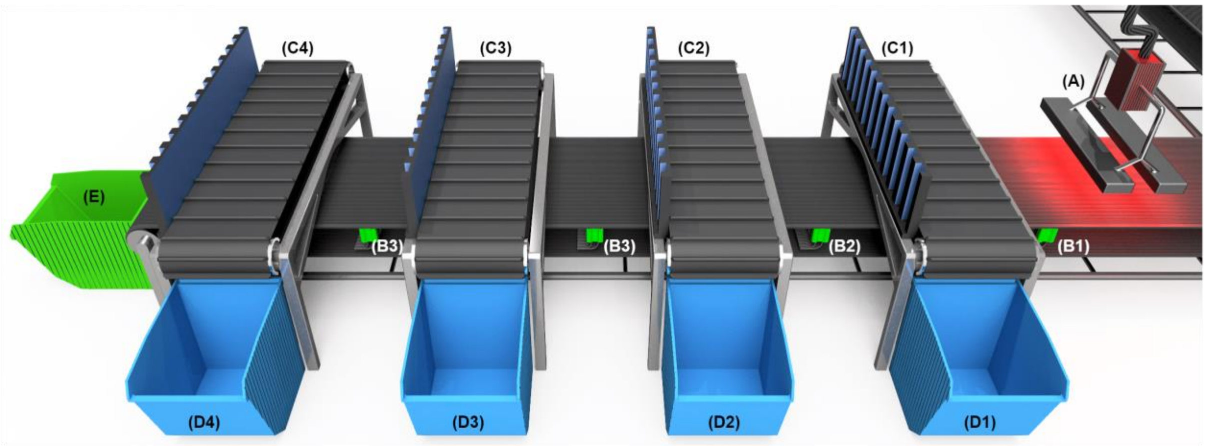


Figure 47: A CAD model illustrating the second NIR-HSI separation process in Concept 3.

The sorting process works as follows:

- First, external waste and or unidentified objects are separated by ejector B1 and land on conveyor C1 which transports the waste to container D1.
- PVC floors with phthalates (both with and without adhered glue) are separated by pneumatic ejector B2 and land on conveyor C2 which transports the phthalate floors to collecting container D2.
- Phthalate-free (including natural plasticizers) floors but with adhered glue are separated by ejector B3, transported by conveyor C3 and collected in container D3.
- Floors with natural plasticizers (without adhered glue) are separated by ejector B4, transported by conveyor C4 and collected in container D4.
- Lastly, phthalate and glue-free PVC floors remain on the main transporting belt until free-falling into collecting container E and marks the end of the complete sorting process.

The complete sorting process with all subprocesses can be seen in figure 48. The subprocesses are linked with vibrating feeders. The first stage is elevated above the second stage and the second stage is elevated above the third stage. The last container (the green container) collects PVC floors free of phthalates and adhered glue.

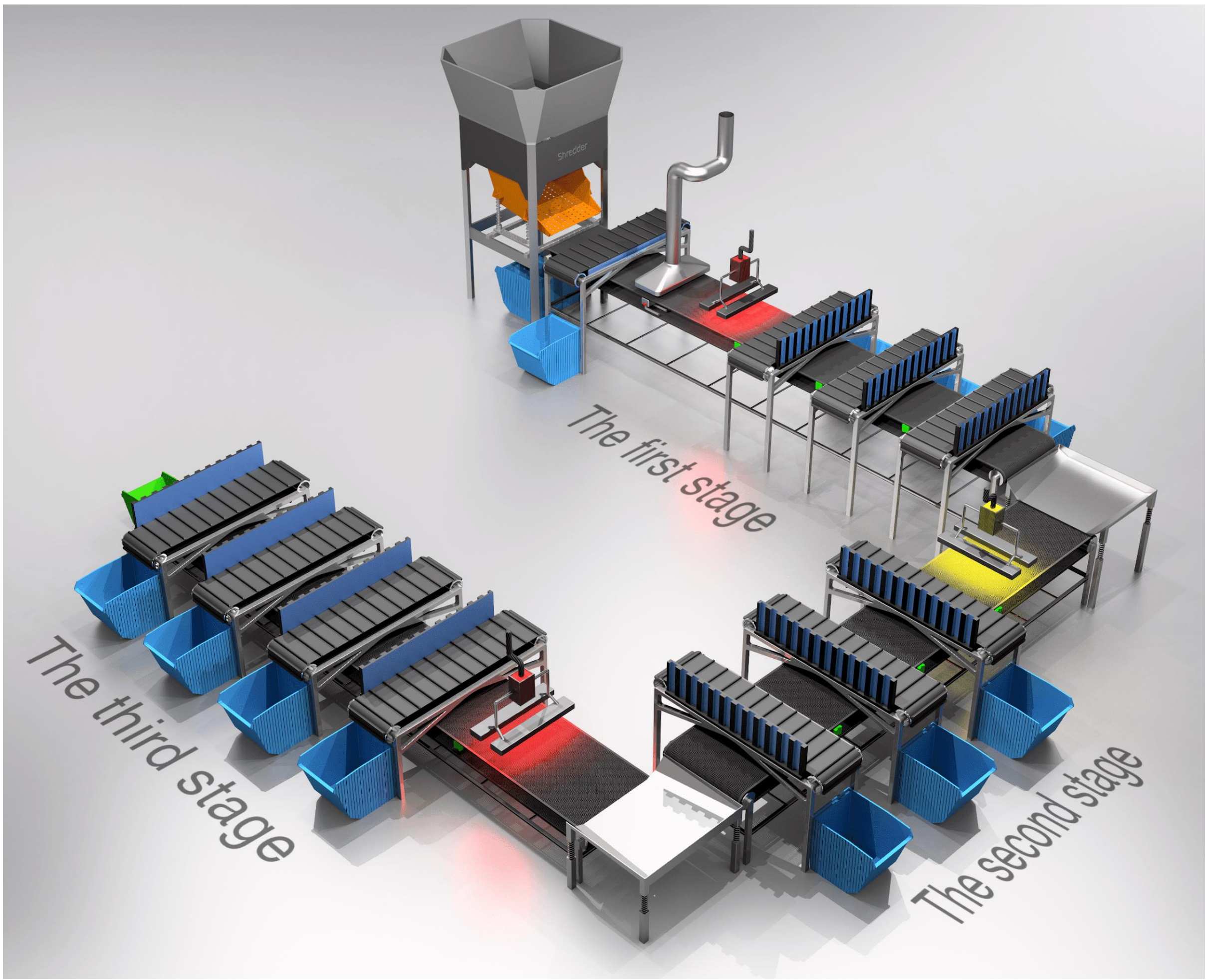


Figure 48: A CAD-Assembly model of the complete sorting process in Concept 3.

5. Discussion

In this section, the research questions, testing results, and the proposed concepts will be discussed.

5.1 Automated sorting of plastic floors

A chart flow diagram of the desired sorting process, shown in figure 49, was compiled and based on the needs and requirements extracted from multiple interviews and observation sessions with both Tarkett personnel and project supervisors. The desired sorting process was redrawn to a more structured mapping of the automated sorting process in which each subprocess was thoroughly explained and highlighted with a number. This was done so that each subprocess could be given fitting technology and an explanation as to why said technology is fitting.

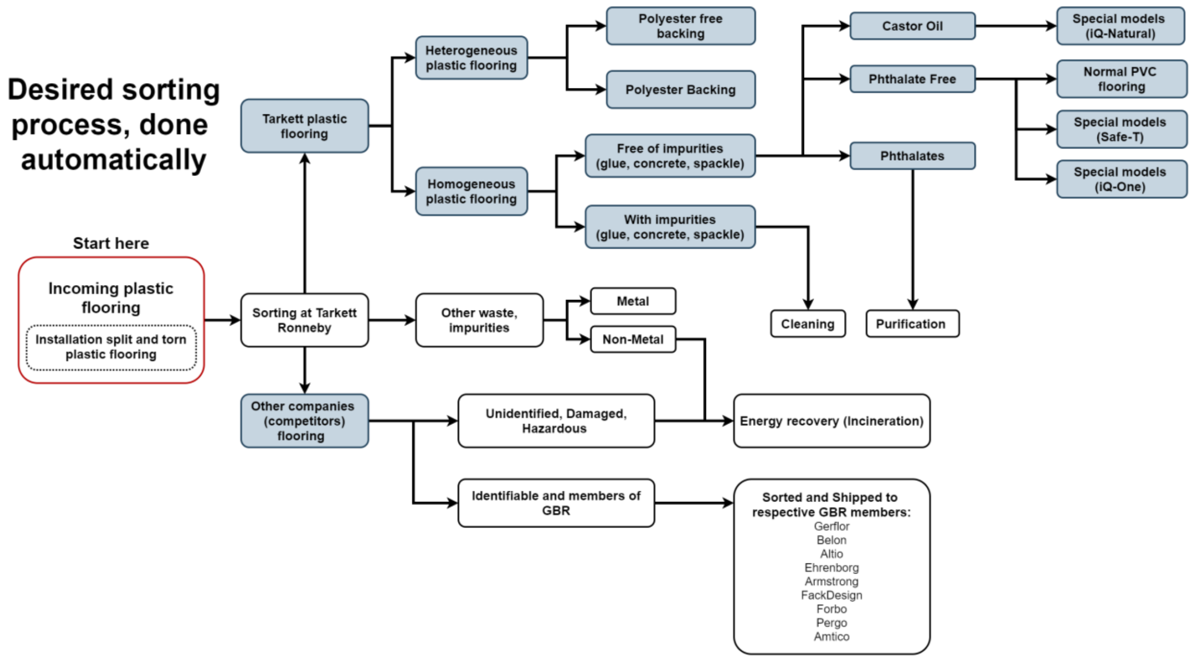


Figure 49: A Flow chart diagram of the desired sorting process, conducted through interviews with Tarkett officials.

5.1.1 Relevant technology and their implementation

Indirect methods are more relevant than direct methods when dealing with recyclables of similar physical properties and similar polymers. Direct methods, on the other hand, are more suited for the removal and recycling of plastics from external waste. Thus, as an answer to RQ1, "*How can plastic flooring be distinguished by manufacturers and from external contaminants…?*", a combination of direct and indirect method seems most suitable for this task. Conversely, as an answer to RQ2 and RQ3, "*How can Homogeneous plastic flooring be distinguished from Heterogeneous flooring…?*" and "*How can Homogeneous plastic flooring be distinguished by type and surface contamination…?*", since we are dealing with similar polymers, a combination of indirect methods seems most suitable for this task.

Theoretically, the presented technologies, shown in section 2.3-2.5 and 4.1.4, can be adapted to the properties of the plastic floors (as well as external waste) for customized separation. Also, these technologies have different abilities and can be applied differently so that when combined, more effective separation is achieved. Therefore, a tailor-made solution seems most fitting for this task.

5.1.2 Analysis of performance and dimension

Cost, dimension, and performance estimations of the proposed concepts are very difficult to calculate at this early stage. Performance and dimension parameters depend on the width of the conveyor belt, speed of the belt, size of the plastic floor pieces, and technology used. Thus, without testing at an industrial scale and with real systems, it is impossible to give a correct and reliable number. However, the average throughput capacity and size of NIR and XRF sorting systems can be discussed.

Performance

One of the requirements of the proposed solutions was a sorting capacity of 2 ton/h, this is very achievable with existing NIR and XRF sorters. The throughput capacity of NIR sorting systems depends heavily on the size of the sortable fractions. However, NIR systems used in the PET recycling, and the municipal waste recycling industry can reach capacities ranging from 1 ton/h up to 8 ton/h [104] [72], with accuracy levels reaching 98% [72]. The throughput capacity of XRF sorting systems is also size-dependent. XRF systems used in scrap metal recycling and mining applications can reach capacities ranging from 1ton/h up to 30 t/h [105] with accuracy levels reaching 98-99% [72]. Sortable fractions ranging from 15 mm to 120 mm can be recycled at 28-30 ton/h on conveyor width ranging from 450 to 1370 mm [106].

Cameras used for Pattern and color recognition, been around for a long time and have seen huge improvements in terms of image quality and capture speeds. It is often the classification algorithm that needs to keep up with the camera ranter than the other way around.

Dimensions

Sensor-based sorting systems usually work in conjunction with a conveying system. The sensors/detectors are either installed within or above the conveyor, usually, directly before the separation mechanism. The working width is heavily influenced by the capability of the installed sensors/detector system. Additionally, the sorting capacity, conveyor speed, and sensors-scan capability all influence the width of the sorting system (i.e. the width of the conveyor belt). Typical working width for NIR (and NIR-HSI) sorting systems ranges from 400-2800 mm [54], 1000-2800 mm [53], and 1200-2800 mm [104]. The height and length of the sorting system are subjective to manufactures' designs and customer constraints. However, one of the requirements was, the height of the proposed concept should not surpass 11 m, which is absurd for sensor-based sorting systems. The typical height for and NIR and XRF system is in the range of 2 m to 3 m [105]. Length, on the other hand, can range from 7 m [53] to 10 m [105]. Also, the more sorting segmentation, the longer the system will be. To conclude, the size of the sorting system itself is not subject to significant change, but the conveying system, ejector system, and predefined layout constraints are the heavy influencers.

As for pattern recognition, color cameras have been around for a long time and have seen huge improvements in terms of image quality and capture speeds. Normal cameras are also a lot smaller in size and would not affect the overall dimensions of the sorting system. As previously mentioned, the number of sorting stages and conveying systems will affect the overall size.

5.2 Lean Production and safety

5.2.1 Lean Production

Lean is a way of thinking, a management philosophy that focuses on the constant pursuit of customer satisfaction and improvements, as well as improvements in the working environment and teamwork. For the design of a new sorting system, lean processes should be built with quality, in an organized and disciplined workplace, in continuous development. Implementing lean requires practical changes to the current sorting system. Lean is a state in a value-creating organization, with constant development work that never ends. Long-term perspective, disciplined planning, and patience are required to implement lean in a new sorting system, to change towards the better. A willingness to change their way of working and thinking is also required from the employees for a successful implementation. By allowing employees to contribute their ideas and share their experiences, they are involved in the development work. Knowledge of automated tools is required for the efficient development of the new sorting system. The requirements for support functions such as logistics, production technology, quality, and maintenance should increase as the sorting becomes more automatic. The design of the sorting system should be carried out systematically and with small steps when introducing a continuous flow. Backup processes are needed for sensitive process steps as the sorting system builds up. Backup processes prevent the flow of material processing from being stopped in the sorting process [7] (Lean production; see section 2.1).

5.2.2 Security and safety

To maintain a safe workplace, it is required that experienced personnel work with, or monitor a given process during sorting. Risks can then be reduced, and system errors can be detected early. It would also be appropriate if the employees were given a to-do list, for a more organized and suitable position in the work. The fact that the employees have an overview of their tasks reduces mistakes in the work process. The 5S-methodology for safety-focused lean includes standardized procedures and workflows to detect and prevent security risks. 5S-methodology is one of the most common ways of maintaining a safe workplace. One of the things that cause disorder in the workplace is the large storage of plastic flooring. A large stock increases the risk of disarray and damage during management and transport. Therefore, the plastic floors should be sorted as quickly as possible.

There is a wide range of approaches and tools available to maintain the security of the sorting process. Furthermore, well-proven technology should be used to detect and avoid security risks. Appropriate barriers need to be established around sub-processes that may pose security risks. One of the risky sorting processes is the X-Ray classification method if the employees are exposed to radiation [107]. It is also risky to be close to the robot arms (concept 2), because of their large movement moments. In brief, precautions should be taken, when working near or with fast automated processes, performed by machines. Rapidly automated processes are difficult to stop and therefore should be ensured with primarily a fixed barrier around them. Also, alarms can be used if a person came too close to the machines [108].

5.3 Testing of technology capability

Due to difficult circumstances and lack of tools, no self-experiments have been conducted. Instead, relevant companies/manufacturers, *Holger Andreasen AB* (reseller for *Thermofisher* USA) and *Emsys-*

Visiongeek have been contacted with the request for testing of their tools/programs on plastic floors. The technologies tested are near-infrared scanners on plastic flooring of different contents, and a pattern recognition system on plastic floors with different types of surface patterns.

5.3.1 Near-infrared - Classification through sample library

As previously mentioned, whether these concepts are applicable in real life depends on a variety of key factors, one of which is the quality and consistency of an internal spectrum library of Tarkett floors. For that reason (among other reasons), Holger AB was approached, and 16 different flooring samples were sent. Holger AB used a NIR diffuse reflectance handheld scanner (made by Thermofisher), capable of differentiating several commodity polymers through the internal spectrum library. Thus, a new spectrum library of the provided samples had to be scanned and stored in the device. This was plausible, which Holger demonstrated by scanning each sample 5 times.

Since phthalates are dangerous and largely prohibited across the world, differentiation of the four samples of different plasticizers was heavily emphasized. Fortunately, Holger confirmed that through an internal spectrum library of the provided samples, all four samples could be differentiated from each other. The accuracy of which the four samples were differentiated was 95%. However, Holger argued that with more samples and higher quality scans, the value could reach 98%. This proves the necessity of creating a high-quality reference library for each Tarkett and non-Tarkett floors if needed. Also, with more samples scanned, it is possible to increase the accuracy even further. The downside of scanning all floors, Tarkett and non-Tarkett, is large files and more powerful processing equipment are needed, especially when using Hyperspectral imaging in the near-infrared region.

5.3.2 Pattern Recognition - Classification through sample library

After the test, it has been found that the pattern recognition system found it difficult to discern the differences in four samples, patterns between Tarkett's plastic floor and the competitor's plastic floor, as well as homogeneous and heterogeneous plastic floors. The result obtained may be due to many sources of error, for example, that the images sent varied in quality. The quality is very important for the perception of the pixels in the patterns, the quality may have caused the pixels not to be received in the right way/ratio. Another source of error is that the pattern recognition system has not learned enough plastic floor patterns. There may be more unknown sources of error. In theory, the pattern recognition system can be used to classify patterns and colors. Furthermore, it can be possible to increase the accuracy with more samples scanned (Pattern recognition system; see section 2.4 and 2.5.3).

5.4 Concepts

In this section, the challenges, benefits, and disadvantages of all concepts will be discussed, then a more complete understanding of the concept's structure can be obtained.

5.4.1 Concept 1

Concept 1 focuses on eliminating any external waste and metallic fraction at a very early stage to ensure high purity and consistency. Therefore, all incoming materials are shredded to a smaller initial size, exposing all hidden objects within the collecting bags and rolls. After the first size reduction, the plastic floors are reduced to a final size of approximately 0.1x0.1m to increase scan speed and ejection possibilities. Also, size reduction enables the use of pneumatic ejection systems. Pneumatic ejectors like air nozzles have no contact with the recyclables, enabling higher speeds and increased sorting capacity [109].

One other key feature of concept 1 is the striped (split) conveyor belt which consists of multiple smaller belts positioned so that there is a 5mm space between each strip. This enables pattern recognition line-scan cameras to be mounted within the conveyor and scanning the underside of the plastic floors. This is particularly useful for the separation of homogeneous, heterogeneous, and non-Tarkett flooring. Some models have similarly patterned and or colored front layers while their back (bottom) layers are quite different. Also, a striped (split) conveyor enables the pneumatic system to be mounted inside of the conveyor. Which in turn, enables separation of three or more groups at once with one scanning system as opposed to the pneumatic system located at the end of the conveyor which can for the most part only separate three groups, see figure 34 and figure 23.

The majority of the produced and recycled plastic floors at Tarkett AB Ronneby is made of PVC [110] and since PVC is highly detectable with X-ray based methods, XRF was used as the final reassuring stage.

Challenges

There are several notable challenges with the proposed concept considering the pattern recognition system. Pattern recognition line-scan cameras and classification algorithms are capable of extreme speeds and reliable results. However, the problem lies with the plastic floors, some models are quite similar in color and pattern, especially random patterned models. Also, some heterogeneous and homogeneous Tarkett flooring has the same unspecific designs. Therefore, a two-way scanning system was proposed for more exact measurement (see figure 33).

Whether this concept is applicable in real life depends on a variety of factors, one of which is a high-quality internal flooring library consisting of both spectral and spatial scans of all Tarkett floors. Both pattern and spectroscopy methods rely on cross-referencing. While it is true, X-ray can detect elements and IR-spectroscopy can detect specific molecular vibrations. However, when dealing with the classification of modified PVC from another modified PVC, internal cross-referencing, and special algorithms such as neural networks are needed for NIR spectroscopy [60]. Unsupervised methods that rely on relationship possibilities between different samples require at least hundreds of high-quality scans of the same sample [47].

Advantages and disadvantages

There are many advantages of reducing the incoming materials waste to a smaller initial size, one of which is easier material flow, conveying, and storage [64]. Then there's the advantage of higher throughput with the usual plastic size for sensor-based sorting which is around 50-300mm [111]. Also, 0.1x0.1m large floor pieces are relatively light (approximately 0.03kg) and easier to handle with a pneumatic ejector system. Moreover, the pneumatic ejectors are far simpler and faster than robot arms, and with striped split belts, they can be mounted inside the conveyor for further separation capabilities. Furthermore, with the striped split belt conveyor, cameras can also be installed in the conveyor, enabling two-way scanning.

Another advantage of concept 1, is the use of hyperspectral imaging cameras in the near-infrared region that can capture plane images as well as the NIR spectrum for each pixel within the captured scene. This is particularly useful for detecting surface heterogeneity and contamination which may be present in torn plastic floors. Furthermore, NIR based spectroscopy methods are rapid, nondestructive, and non-contacting methods that complement the non-contacting pneumatic ejectors.

If the incoming waste is shredded, manual sorting sections become harder for the employees. Also, small plastic flooring pieces can present a problem for the pattern recognition system since it requires flat 2D images. Furthermore, the split-belt design may increase dirt and other waste collection which in turn, can tamper with the pneumatic systems located inside the conveyor.

5.4.2 Concept 2

The concept has been designed to handle plastic floors in the size between 1m and 0.1m. The aim is to maintain the size throughout the sorting process. When using pattern recognition, part D, the floors must be so large that the characteristic properties of the surface can be read. The plastic floors have different types of designs that vary in size and shape, both random and structured design patterns occur in the recycling department. The size of the plastic floor affects the reading of the pattern recognition system. The recognition of the pattern depends on the type and size of the pattern, as well as the size of the plastic floor being read. When classifying via NIR and X-ray, the size does not matter.

The robot arms have been chosen specifically to identify and place the plastic floor on the conveyor belt, one after the other. When the robot arms place the plastic floors with spaces between each other, the identification of the plastic floor is simplified. Also, the plastic floor can later be easily and quickly separated via the push mechanism on the conveyor belt. The push system is a great way to quickly sort the plastic floors in each container when they are large. It is also possible to use other sorting options on the conveyor belt (see section 2.5.1).

Challenges

In concept 2, one of the challenges of placing the plastic floors one after another, for scanning. The robot arms must be trained to identify and pick the plastic floor. Also, learning how to find glue and adhesive materials or objects on the plastic floor. Another challenge is getting the plastic floor in a position that facilitates pattern recognition, part D of the sorting. The surface area of the plastic floor pattern must be large enough for the pattern to be classified. The plastic floor must not be too wrinkled or folded. Furthermore, the plastic floor must have a certain distance between each other, on the conveyor belt. The distance is needed for the plastic floor to be able to sort through the push sorting mechanism/system on the conveyor belt.

Advantages and disadvantages

The advantages of concept are that it performs the sorting/separation in a systematic way, where the plastic floors of different sizes can be examined and sorted (size between 0.1m and 1m). Because the plastic floor retains its size after the shredding process, there is no great propagation of particles and dust. If the sorting system is to stand still, because of some error, experienced personnel/operators can handle the sorting process. This is the advantage of not granulating the plastic floor. Other advantages are that the concept has a simple sorting system through the conveyor belt, the push system. Furthermore, because the plastic floors remain in their varied sizes, at the end of the sorting, the plastic floors can be further sorted under other sorting groups or used for other purposes.

The disadvantage of the concept is that the plastic floors must have spaces between each other on the conveyor belt. The distance between the plastic floors is necessary when sorting the plastic floors. Also, the pattern recognition system requires that the plastic floor is large enough to be recognized, if the size is too small for the pattern, the system will not recognize the pattern. Therefore, the position of the plastic floor is affected by the classification. Furthermore, the plastic floor should not be wrinkled or folded during the scanning of the pattern, and the pattern is calcified by the pattern recognition system.

5.4.3 Concept 3

Like Concept 1, Concept 3 features an extensive size reduction stage, strip-belt conveyor system, and pneumatic ejector system. However, unlike Concept 1 and 2, Concept 3 only uses X-ray and NIR-HSI sorting systems, i.e., the pattern recognition system is excluded and replaced with another NIR-HSI system. The decision to not use a pattern recognition system in Concept 3 can be credited to the result of the testing done by Holger in which the NIR scanner could differentiate between all sent samples. Concept 3 can be divided into three stages. Size reduction, waste removal, and initial sorting according to type (homogeneous or heterogeneous) and manufacturer are performed in the first stage. In the second stage, XRF is used to separate PVC from non-PVC and metallic PVC floors. Then in the final stage, the PVC floors are separated according to used plasticizers and the condition of the floors.

The initial NIR-HSI system in the first stage separates Tarkett HO from Tarkett HE and non-Tarkett floors. There is a possibility to identify and reuse other homogeneous floors of competing brands. However, a larger spectrum library of Tarkett and non-Tarkett floors have to be created, and more sorting stages are also needed. Alternatively, using a spectrum library featuring only Tarkett floors will reject non-Tarkett floors by default. Thus, saving space and cost but losing the number of possible recyclables.

According to Tarkett, at least in their offerings, only PVC floors use different plasticizers including phthalates. Thus, in the second stage, XRF is used for the separation of PVC from non-PVC floors so that only the PVC floors undergo the third stage. Also, PVC floors with metallic fillers are recycled separately to that of the non-metallic PVC floors. Thereby, XRF is used again (in the same operation) for the separation of the floors.

NIR-HSI is used again in the final stage for the separation of HO Tarkett floors according to plasticizers and surface condition of the floors. Floors with phthalates are of the highest priority and should be collected to gather regardless of surface condition. Furthermore, floors with adhered impurities (glue) and non-phthalic are of the second-highest priority. Floors with natural plasticizers and glue-free can be mixed with phthalate-free and glue-free floors. However, natural-based plasticizers, according to Tarkett, are of higher value and should be separated if possible.

Challenges

Glue contaminants can present problems if the glued area is not correctly presented to the scanners. Besides, the concentration and appearance of the glue contaminated floors vary. Therefore, a hyperspectral spectral imaging camera operating in the NIR region was proposed instead of a typical NIR detector. However, the presentation, i.e., if the glue is face down or faces up when scanned can still play a huge role. A best practice case would be a decontamination of all floors (i.e. cleaning) before sorting. Alternatively, installing a two-way scanning system, above and beneath, can be used for more accurate and advanced scanning. Still, more testing is required before an exact solution is acquired.

If for some reason, Tarkett decides to recycle competing floors, large spectrum libraries are needed. The libraries will be in constant need to update and include new or older unregistered models which can be problematic if outdated floors lack content information. However, this problem is not specific to the automated sorting process, as it affects the manual as well as the automated sorting process.

Keeping track of the plastic pieces on a long conveyor can be a challenge. However, with modern position tracking cameras and fast computing algorithms, this challenge can be overcome.

Advantages and disadvantages

Since Concept 3 shares a lot of similarities with Concept 1, it features similar advantages and disadvantages. Small shred size, strip-belt conveyor, and pneumatic ejector enable possibilities for higher throughput than robotic arms and or sliding mechanisms. Modularity, pneumatic ejectors are far smaller and can be installed inside the transporting conveyor. Pneumatics ejectors require far less use of advanced sensors and operating software. Unique advantages include the lack of a pattern recognition system, i.e., one less technology to deal with, a more compact and streamlined sorting process.

6. Conclusion

The purpose of this thesis is to conceptualize an automated sorting system for recycling plastic floors using existing technology. Furthermore, the task is to determine what existing technologies can separate plastic flooring through manufacturers, homogeneous from heterogeneous plastic flooring, and to distinguish homogeneous plastic flooring by type and surface contamination. With data on existing technologies and the test results made by *Holger* and *VisionGeek*, it has been found that Near-infrared Spectroscopy, X-ray Spectroscopy, Hyperspectral imaging, and Pattern Recognition are suitable classification options. The classification is based on the surface pattern and content of the plastic floor, according to requirements. Three concepts have been designed based on the technologies, according to Tarkett's needs and requirements. Furthermore, a high-quality pattern and spectrum library should be created for optimal and reliable reference models of plastic flooring. Also, more tests are needed for efficient sorting, on an industrial scale.

6.1 Future work

This work is mainly conceptual and further work involves more testing, concept development, calculations, simulation, and modeling.

The concepts in section 4.4 can be further developed by extending the research and testing to ensure fitting technology. A more sophisticated NIR, NIR-HSI spectrum and pattern library needs to be created and tested at a more industrial level, i.e., tested on a conveyor belt. After ensuring working technology and calculating performance capabilities, simulation of the proposed concepts can be implemented for output capacity estimation and concept benchmarking. Furthermore, more advanced CAD models and layouts can be modeled, and demission estimations calculated. Thereafter, cost estimations should be calculated.

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8. Appendix

Appendix A: Waste of plastic floor

Appendix B: Test instructions

Test instructions and sample description for portable NIR device

Tarkett Ronneby & Holgen AB

Device: microPHAZIR PC Analyzer for Plastic/Polymer Identification

Plasticizers identification testing: (Samples involved: 1, 2, 3 & 4)
(Sample Number = SN)
(SN1-4, Homogeneous Tarkett plastic flooring)

SN1 is made from PVC and uses Phthalate (DEHP) plasticizer
SN2 is made from PVC and uses Phthalate (DINP) plasticizer
SN3 is made from PVC and uses Phthalate Free and Natural substitute, "Ricin oil" plasticizer
SN4 is made from PVC and uses Phthalate Free plasticizer, DINCH. SN4 is currently the standard and most used type, thus, it will be the sample to test against for the upcoming tests.

In General: Is it possible to detect differences in the "fingerprint region" of the spectra with the NIR (diffuse reflectance) portable device, especially of those samples containing phthalate viruses those without or other concrete differences that can be used for identification purposes?

1. **Test:** SN1, SN2, against SN4 — **Purpose:** detecting and differentiating flooring samples with phthalate
2. **Test:** SN3 against SN4 — **Purpose:** detecting and differentiating flooring samples with natural plasticizers
3. **Test:** SN1 against SN2 — **Purpose:** differentiating between different phthalate plasticizers
4. **Test:** SN1, SN2 against SN3 — **Purpose:** differentiating between phthalate and natural plasticizers

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Non-PVC flooring test: (Samples involved: 4 and 11)
(SN4&11, Homogeneous Tarkett plastic flooring)

SN4 is made from PVC
SN11 is made from TPU
(SN1-4 & 14-15, all use PVC as the main polymer)

5. **Test:** SN11 against SN4 — **Purpose:** detecting and differentiating Non-PVC from PVC Flooring
6. **Test:** SN11 against SN1-4, 14&15 — **Purpose:** other Tarkett PVC samples for additional testing if the first test is not proving any result

PVC with AL-Flakes flooring test: (Samples involved: 4 and 15)

(SN4&15, Homogeneous Tarkett plastic flooring)

SN4 is made from PVC and does not include any metallic fillers
SN15 is made from PVC and contain AL-flakes for increased friction additional. Also, there are two samples, one dark, and the other light.

7. **Test:** SN15 against SN4	**Purpose:** detecting and differentiating Normal-PVC from Metallic filler PVC Flooring
8. **Test:** SN15 (Dark) against SN4	**Purpose:** NIR struggles with darker samples due to the light absorption

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Tarkett PVC flooring and competing PVC Flooring test: (Samples involved: 1-4, 5-7, and 14-15)

(SN1-4&14-15are Homogeneous Tarkett plastic flooring, while 5-7 are of competing brands)

SN5, 6, 7: Forbo, Forbo, Gerflor PVC flooring
SN1-4 & 14-15, all use PVC as the main polymer (although other fillers and additives may differ)

9. **Test:** SN5, SN6, SN7 against SN4	**Purpose:** The main test, detecting and differentiating Tarkett-PVC flooring from other competing brands
10. **Test:** SN5-7 against SN1-4, 14&15	**Purpose:** Detecting and differentiating other Tarkett PVC samples from competing brands

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Homogenous and Heterogeneous Tarkett PVC flooring test: (Samples involved: 1-4, 8-10 and 14-15)

(SN1-4&14-15, Homogeneous, while 8-10 are heterogeneous, both Tarkett)

SN8,9 Heterogenous, PVC
S10 Heterogenous front and Homogeneous back, PVC. Since some of these samples are heterogeneous, a reading of the back may be required as well as from the front.

11. **Test:** SN1-4 against SN8-10	**Purpose:** detecting and differentiating between Homogeneous and Heterogenous PVC Flooring
12. **Test:** SN14-15 against SN8-10	**Purpose:** additional samples, same purpose as above
13. **Test:** SN5-7 against SN8-10	**Purpose:** detecting and differentiating competitors Homogeneous flooring from heterogenous Tarkett PVC flooring

Used and torn plastic flooring identification testing: (Samples involved: 1-4, 8-10, 13-13 and 14-15)
(All samples Tarkett plastic flooring)

SN1-4, 14-15, are pure homogeneous PVC flooring
SN12 impure homogeneous PV flooring, glue, and concrete
SN13 impure homogeneous PV flooring, glue, and wood

This seems to be a long shot, however, some of these samples have impurities, a reading of the back may be required as well as from the front.

14. **Test:** SN12 against SN4 — **Purpose:** detecting and differentiating impure (glue-concrete) flooring from pure sample.
15. **Test:** SN13 against SN4 — **Purpose:** detecting and differentiating impure (glue-wood) flooring from pure sample.
16. **Test:** SN12-13 against SN1-4&14-15 — **Purpose:** additional samples, same purpose as the two above
17. **Test:** SN12 against SN13 — **Purpose:** differentiating between impurities, glue-concrete against glue-wood

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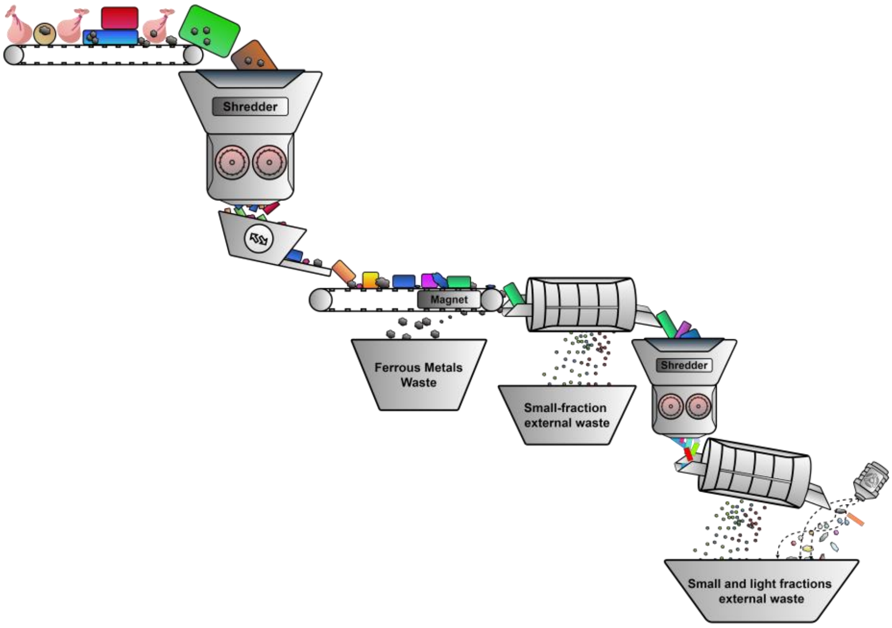
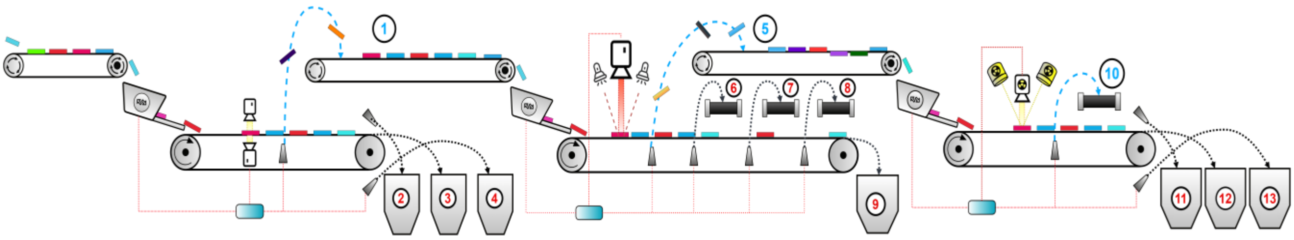
Additional testing: (Samples involved: all samples)
(All samples Tarkett plastic flooring)

SNX The unknown Tarkett sample

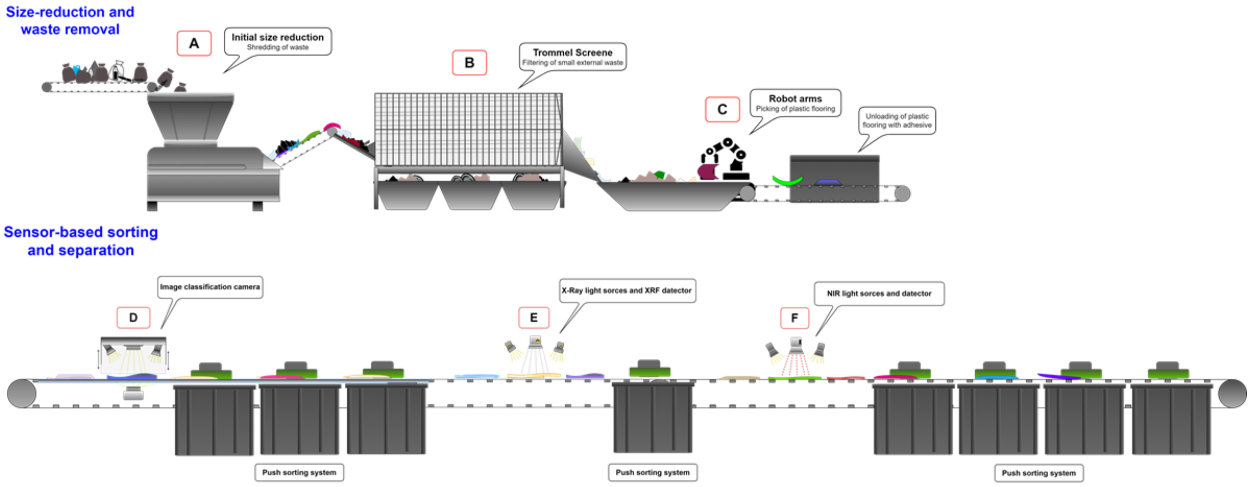
18. **Test:** SN11 against SN15 — **Purpose:** Non-PVC against PVC with AL-flakes
19. **Test:** SN8-10 against SN12-13 — **Purpose:** Heterogenous against impure PVC flooring
20. **Test:** SNX against all samples — **Purpose:** Unknown Tarkett sample against all samples for finding the closest match

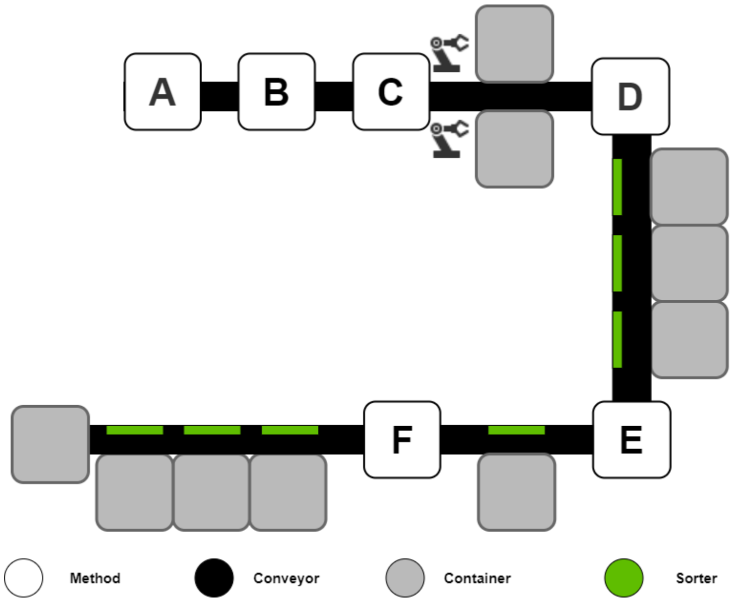
Appendix C: Illustrations of Concept 1





Appendix D: Illustrations of Concept 2





Appendix E: Illustrations of Concept 3