MSc Thesis Report

REC-HERO

Material and design optimization of injection-molded reinforcement spacers using plastic residues of WEEE recycling

BERK ADSAN

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ABSTRACT

The thesis explores how plastic residues from Waste Electrical and Electronic Equipment (WEEE) recycling, which are typically being sent to energy recovery by incineration or destined for landfills, can be transformed into injection-molded building components. By focusing on reinforcement spacers which are located at the internal shearing layer of concrete introduces a viable application scenario for low-grade, contaminated polymers within the built environment. The research employs a dual-track methodology: a bottom-up material experimentation track and a top-down product development track with their respective evaluation parameters that sustain a feedback loop within both tracks throughout the thesis. The material experimentation track reproduces the key mechanical recycling steps at lab scale to develop a processable polymer recipe and a heating/cooling cycle for injection molding. The lab-scale mechanical recycling steps including density separation, colour sorting, FT-IR and DSC analyses which are replicated to achieve an injection moldable polymer recipe of carbon black Polypropylene/Polyethylene (PP/PE), Polypropylene, and Polystyrene. Meanwhile, the product development track iterates material source-specific designs, which are graded by the parameters in a design optimization tool. The custom multi-criteria evaluation model guides the selection of the optimal design for the contaminated waste input. The application scenario confirms the thesis' structural compatibility and production feasibility. The thesis proves the processability of rejected plastic fractions into non-exposed recycled heroes of construction through complex and multi-iterative techniques.

REC-HERO

MSc Thesis - Berk Adsan

ACKNOWLEDGEMENTS

First and foremost, this thesis made me realize what I want to pursue in life after education. Even just for that, I'm incredibly grateful to anyone who influenced my work—even in the slightest—or helped me in any way. I lived a master's experience to its fullest, experienced so many joyful moments that I wished for and made unforgettable memories that I will carry with me.

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1. RESEARCH FRAMEWORK

1.1 Context

The plastic industry has been a significant part of everyday life since its inception in the early 20th century. Even though the early innovations were limited to Bakelite, Polyvinyl Chloride (PVC), and Polyethylene (PE), today, the large variety of available plastic types has allowed the material to be used in every sector, including packaging, building and construction, automotive, electrical and electronics, healthcare, etc. According to recent data, around 460 megatons of plastics were used, with a 40% majority of polyethylene and polypropylene (Wang, n.d.). It is expected that plastics will remain important while always choosing to produce new materials will result in a doubled amount of energy consumption and greenhouse gas emissions (Wijngaard et al., 2020).

1.2 Scientific Gap

The reliance on plastics generates large quantities of waste that need handling. Worldwide, the amount of plastic ending up in landfills is almost half of its production amount, with a 150 Mt annual landfill rate (Ragaert et al., 2017). Additionally, respective organisations predict the waste quantity to triple by 2060 if circular policies and sustainability goals are not implemented (Wang, n.d.). Based on the standardised methodologies, replacing virgin plastic polymers with recycled ones with the technique makes plastic recycling a valid approach to tackling waste. However, about %10 of global production is recycled, whereas %25 is incinerated, and %60 ends up in landfills. From the 10 percent of recycling implementations, half of the waste material is still lost during the recycling process. In an optimistic scenario where 90% of plastic is collected, and 80% is sorted, the overall efficiency of recycling still stands at 50% (Lange, 2021). Therefore, the material that is still unrecycled during the recycling stages shows great potential for further study.

There are multiple reasons plastic waste is identified as unrecycled. The composing polymers and their respective ratios might be unknown. The plastic waste **a. is not mono plastic but mixed plastics, b. is contaminated with organic or inorganic fractions, c. has small fractions of other polymers, d. cannot be identified with sorting techniques**. This creates challenges for recycling that waste to produce secondary plastics. When recycled, the plastic **a. generally presents lower mechanical and thermal performance, b. may still contain foreign materials (additives, retardants etc.), c. may not have good purity results, and d. might have degradation**.

The data collected in 2018 in the Netherlands shows that the total amount of plastic produced and discarded in the country is 990 tons. This includes 856 tons of fossil-based plastic, 124 tons of high-quality recycled, and 10 tons of bio-based plastic (Wijngaard et al., 2020). The Netherlands' laws do not allow the wastes that can be incinerated for energy to be landfilled. Even though incineration is a better alternative to landfills, the CO2 data indicates that the emissions from incineration are three times the total mass of plastic waste worldwide. Therefore, plastic waste embodies potential CO2 emissions equal to 2% of current global emissions (Vollmer et al., 2020). TNO agrees that incineration is not the preferred route for plastic waste in terms of resource efficiency, except for medical waste. TNO identifies hidden costs based on plastics manufacturing and extra costs that alternative solutions can avoid. Based on this definition, an economic estimation can be made from the data by Carbon Tracker, which arrives at 350 BEUR per year (Wijngaard et al., 2020). These environmental and economic data showcase the need to evaluate existing plastic recycling steps to improve the end-of-life potential of plastic waste.

1.3 Research Objective

The growing accumulation of plastic waste presents significant environmental and economic challenges. Recycling is the last step that could be taken before incineration or landfill. The thesis takes its boundary of the recycling of plastics and tries to close the loop for that implementation. Mechanical recycling is the simplest and most common technology for recycling composite plastic waste (Ragaert et al., 2017). This process involves collecting, sorting, washing, and grinding the material. Based on the recycling facility, this order and the number of times one step is taken varies. The interviews have proven that a majority of plastic material is also lost during recycling (A. Neiva, personal communication, 2024). Typically, depending on the collection and sorting technologies, contaminated, blended or even unsorted plastics also end up not being recycled, which counts as a material loss.

The building and construction sector has the second-highest demand for plastic (Ragaert et al., 2017). Both micro- and macro-level plastic products are used in a building's external or internal shearing layer. Therefore, it is evident that there is a need for recycled plastics in the construction sector. However, there is limited information on transforming contaminated, unrecycled plastic waste into an architectural component. The project aims to transform the contaminated and mixed plastic waste into a functional, non-exposed component that has high demand in the construction industry. The building component of reinforcement spacers in reinforced concrete construction is selected for the function of the product. The project adopts a dual-track methodology, combining bottom-up material experimentation that aims to find an optimal recipe, and a top-down product development that finds an injection-moldable design. The set parameters for both tracks conclude with a workable polymer selection, injection cycle, optimized final design and final application scenario that takes its material source from the unrecycled waste electrical and electronic stream.

1.4 Research Question

As a high percentage of material is lost during the sorting and characterisation stages of plastic recycling of WEEE plastics, the thesis focuses on the potential of converting the contaminated and mixed plastic into valuable resources for the reinforced concrete construction industry through open-loop mechanical recycling and injection molding. From material experimentation and product development tracks, a final recipe with contaminated polymers and an original design of a reinforcement spacer is aimed to be obtained based on the assigned parameters and feedback loop.

The aim is to create a workable product from a contaminated mixed blend based on the defined parameters.

"How can plastic residues from WEEE recycling be processed into an optimized injection-moldable building component? "

The sub-questions are formulated to assist the road map of the thesis and to define checkpoints for the crucial areas where further consideration is needed. The sub-questions are as follows:

- What is the state of the art of plastic manufacturing and plastic recycling?
- What are the primary challenges of recycling plastics from one waste stream?
- What are the material characteristics of WEEE plastic waste?
- What are the technical requirements and limitations of injection molding for plastics?
- How does the presence of contamination and unknown polymer composition affect the injection molding behaviour of WEEE plastic waste?
- What architectural applications are suitable for contaminated and mixed plastic?
- What parameters influence the structural performance, moldability and concrete compatibility of reinforcement spacers?

1.5 Methodology

The thesis consists of three main phases that branch out to necessary subbranches inside one phase. This aids in the structure and flow of laboratory and computer work.

Phase 1 – Literature Review

The first phase of the thesis is reserved mainly for identifying the state of the art of plastic recycling and its current technologies. Firstly, the plastic waste rates of the EU and worldwide data are compared. This makes the starting point for the situation in the Netherlands more defined. Secondly, the waste streams and their respective polymer ratios are analysed. A special focus on the waste electrical and electronic equipment (WEEE) stream is analysed, and the possibilities are defined.

To determine which polymers are suitable for structural applications, their most common structural and thermal properties must be evaluated. A comparison between mechanical and chemical recycling, and between open- and closed-loop recycling, is crucial to define the optimal technology selected for the thesis. This includes the potentials and limitations of dealing with mixed and contaminated plastics in a new service life. Furthermore, the characterisation and sorting of polymers in mechanical recycling is further analysed and assessed based

on their respective efficiencies. The main focus is given to density sorting, colour sorting, and metal separation.

The review of the building components that are suitable for the use of contaminated and mixed plastic, based on being exposed and not exposed, is reviewed to state boundary conditions for the final design of the thesis. The state-of-the-art injection molding of plastics is reviewed to determine the processing method and how it functions. The review also explored relevant simulation tools to predict and validate the injection molding process and moldability, as well as its mechanical strength.

Current studies, research, and prototypes are valuable tools for determining the limitations and possibilities of plastic recycling with injection molding. As creating a compatible blend is prioritised for prototyping, finding current blending techniques and seeing polymer blend morphologies are crucial in the next phases. In addition, existing regulations and performance benchmarks related to concrete construction and reinforcement spacers are studied to frame the structural quality expected from the final product. After emphasising the plastic demand in architecture, the available prototypes that blend recycled, virgin, and mixed polymers to develop a product are documented. Here, the respective designers' evaluation criteria that have been set during the phase are also analysed. This shows the possible design paths the thesis can follow and how advanced an outcome the researcher can expect.

Finally, a significant focus on the end-of-life potentials and waste treatment technologies is evaluated. This outlines the recovery steps that the thesis can impact while determining methods that will be suitable for the recycled product at the end of the predicted service life. The existing regulations that have been set for WEEE plastic recycling are also analysed to assess the limitations of recycling the waste stream.

Another crucial part of the first phase is the interviews and sample collection. As the thesis focuses on the unrecycled plastic waste from the recycling process, the data from the recycling companies is significant. A questionnaire is prepared for each selected plastic recycling company regarding their facilities and which mechanical recycling stage a high percentage of waste stays unrecycled. Companies' primary challenges regarding focusing on specific waste streams are further analysed. The efficiency of sorting technologies and the issue of contamination are further discussed. The end of each meeting concludes with a sample request from the company's unrecycled fraction of plastic waste and a share of available polymer data sheets. This aids both phases two and three during polymer selection.

Phase 2 – Material Experimentation & Product Development (Dual-track Methodology)

The second phase of the thesis follows a dual-track methodology that consists of an interconnected material experimentation track and a product development track that are set to be in a continuous feedback loop. Each track has its respective evaluation parameters that create checkpoints throughout the thesis for validation and assessment.

In the material experimentation track, the aim is to develop an injection-moldable material recipe from unrecycled WEEE plastic waste by firstly evaluating the sorting and characterisation steps of mechanical recycling, and mimicking it in a low-tech manner. Firstly, the plastic waste samples are collected from various recycling companies, and the focus is given to Coolrec's fridge and small domestic appliances lines from WEEE stream. Firstly, the physical and chemical characterisation of the manually selected polymers are assessed by Differential Scanning Calorimetry (DSC), Fourier-Transform Infrared (FT-IR) spectroscopy and a microscope. The aim is to develop an understanding of the reason why the polymers are being sent to incineration. Alongside, the key mechanical recycling steps of washing, density sorting, colour sorting, and infrared sorting are mimicked to put the waste polymers into another recycling line to obtain workable polymers. Polymer batches are created after each sorting and characterisation step to be tested in experimental setups for injection molding.

The experiment setups include rapid testing with a manual press, manual plunger-type injection molding, and pneumatic plunger-type injection molding. These three setups enabled the conversion from the most low-tech method to a more industry-scale method that mimics injection molding. Different waste lines are selected from four different waste types, which are from the fridge and small domestic appliances. The polymer selection for the testing includes: colour-sorted polymers, density-separated polymers, FT-IR identified polymers/blends and recylcled Polyproplyene. After the sampling process is done on the experiment setups and polymer selection,

the results are assessed by the evaluation parameters of mixing, morphology, degradation , stability, and smell results. The track concludes with the selection of a recipe and an injection cycle suitable for molding for the final design.

In parallel, the product development track aims to design and optimize a reinforcement spacer for concrete construction by evaluating performance-based design parameters and aligning them with the material behaviour outcomes of the other track. The track begins with the review of existing reinforcement spacers and their structural necessities. Based on the collected data, a set of parameters are defined which will be used to evaluate firstly the suitable application of the spacers and the design options. The parameters include contact area, flexibility for rebars, plastic use per product, injection flow analysis, compressive test and Charpy impact analysis. Two mediums are designed to evaluate the design options: simulation results, physical testing. Some parameters are tested physically, whereas others are tested on simulation software. Spacer designs are continuously iterated with simulation conditions adapted based on real-time feedback from the material experimentation track. A design optimization tool is crafted to evaluate score for each design with weight percentiles on each parameter that conclude a final score from auto scores and manual scores.

A checkpoint is assigned to test the workability of the resin printed single-cavity mould and the complexity of the spacer design. The resin printed mould is adapted to based on the durability in high temperatures and surface quality until the final injection molding. Meanwhile, the design with the best score is refined and mofidied for final application. The most viable design is processed for the final proof of concept and application whilst final cavity mould being manufactured alongside for the final recipe.

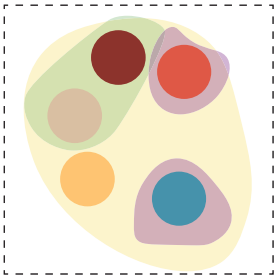
FRIDGE 1
Reject fraction of water seperation tables

FRIDGE 2
Sink fraction of density sorting

SDA 1
Reject fraction of near infra-red sorting after SDA 2

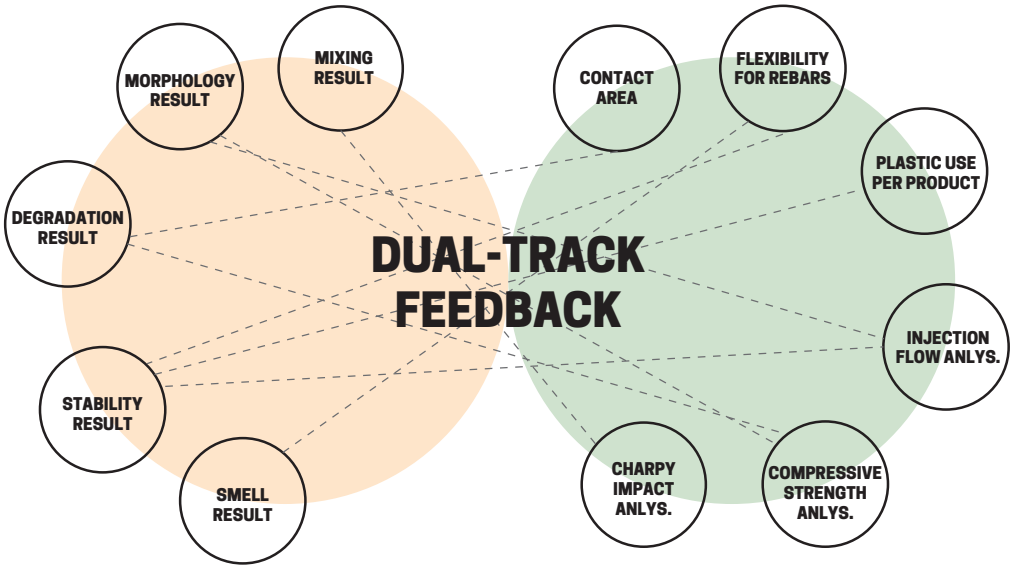
SDA 2
Sink fraction of density sorting

PHASE 2: DUAL-TRACK METHODOLOGY
MATERIAL EXPERIMENTATION & PRODUCT DEVELOPMENT



TRACK I.
MATERIAL EXPERIMENTATION

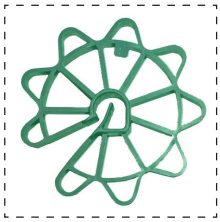
TRACK II.
PRODUCT DEVELOPMENT



FINAL POLYMER SELECTION
FINAL INJECTION CYCLE

FINAL DESIGN
FINAL APPLICATION

rec-HERO



PHASE 3: APPLICATION

Phase 3 - Application

The final phase of the thesis focuses on the applicability and validation of the proposed dual-track development with a full-scale proof of concept. 1:1 mockups with varying aggregate sizes of concrete were tested with the designed reinforcement spacer and a generic commercial-use spacer for the proof of workability. The selected recipe and the design is used for the final prototyping using a custom resin mold inside an aluminium cavity mould, which was tested concurrently under a defined injection cycle. The parameters for each track was evaluated, and the limitations/possibilities are defined.

A comparative assessment was done for the use of different aggregate options to test and validate the real life scneario beased on the results on spacer's rebar retention mechanism, concrete mix penetration in-between the spacer and exposed spacer surface at the concrete finish. Lastly, the thesis offers alternative methods and future recommendations for adapting the methodology for other waste streams. Possible technologies to enhance the efficiencies of the current mechanical recycling techniques are also shared.

1.6 Societal Relevance

It is evident that a high percentage of industrial processes, their by-products, and their wastes are closely linked to environmental pollution and public health issues because they use non-renewable energy sources. The scarcity of raw sources and increased critical raw materials threaten the current flows' extinction. Therefore, EU-based business models like the Green Deal set a goal by 2050 to become climate-neutral while cutting pollution and restoring biodiversity. As an efficient recycling process minimises energy consumption and waste production over the product's life cycle, focusing on recycling as an alternative to typical end-of-life scenarios for the thesis will benefit the future society (Lange, 2021).

Regarding the societal relevance of plastics, TNO's hidden cost analysis can indicate the analysis. The costs taxpayers pay to clean up, burn, or dump waste or clean the water and land can be the first indicator of plastic waste's effect on society. Secondly, health issues are caused by microplastics found in water, air, water, and food. Finally, the loss of biodiversity and GHG emissions can be an indicator of why there is a need to think of the existing recycling process and prevent material loss (Wijngaard et al., 2020). A typical customer's action consists of four steps: decision, purchase, usage, and disposal. Current governmental actions, like the ban on plastic bags in the Netherlands, are already focusing on changing the customer's approach to a product. The thesis aims to prevent plastic material loss during recycling and give it another service life in an open loop.

The OECD 2022 report showcases the environmental and health impacts of seven common plastics if no new policies are implemented by 2060. The analysis shows that the production of plastics will be responsible for more than %85 of ozone formation, acidification, and land use. The mismanaged waste and incineration cause terrestrial and marine ecotoxicity. As most environmental and health impacts tend to double by 2060 projections mostly because of production rates (see Fig.1), the shift towards secondary plastics by mechanical recycling will present a lower societal impact than primary plastics.

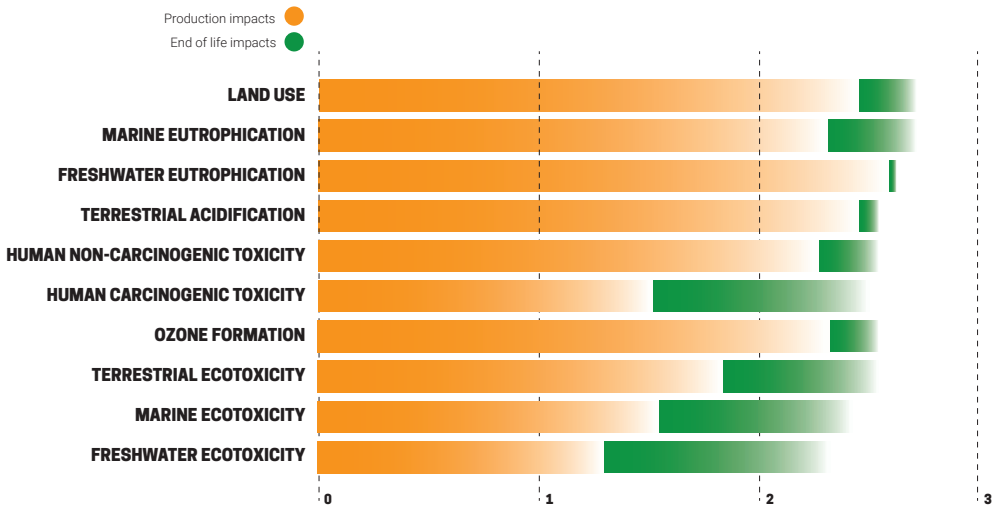
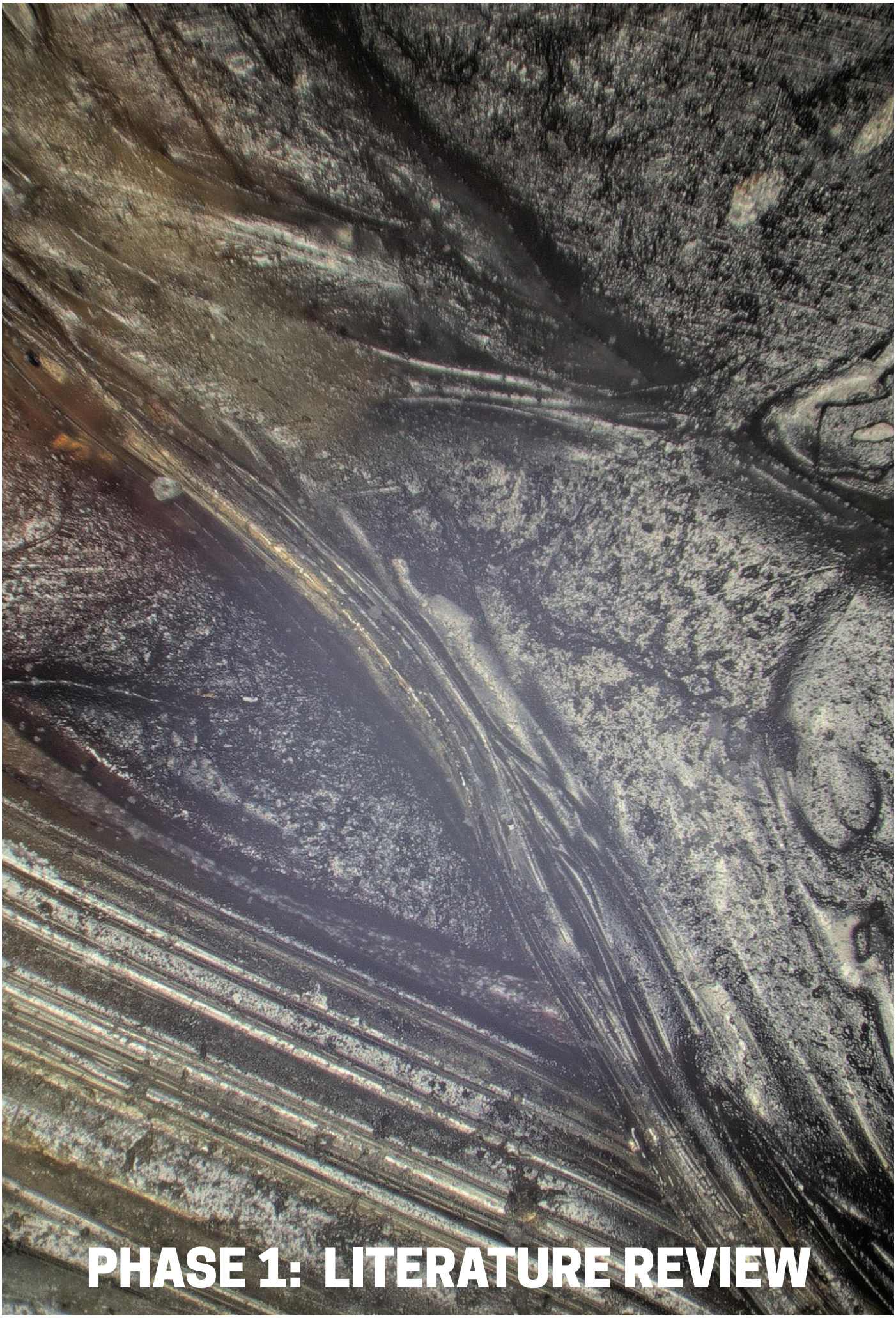


Figure 1: Evolution of environmental LCA impacts in 2060 compared to 2019 (Adapted from: OECD, 2022)



PHASE 1: LITERATURE REVIEW

2. LITERATURE REVIEW

PE	Polyethylene
PP	Polypropylene
PET	Polyethylene Terephthalate
PVC	Polyvinyl Chloride
PS	Polystyrene
PP/PE	Polyethylene - Polypropylene Blend
PA6/PA66	Polyamide 6 - Polyamide 66 Blend
HDPE	High-Density Polyethylene
LDPE	Low-Density Polyethylene
PLA	Polylactic Acid
PC	Polycarbonate
PA	Polyamide (Nylon)
ABS	Acrylonitrile Butadiene Styrene
PMMA	Polymethyl Methacrylate
PET-G	Polyethyleentereftalaatglycol
SAN	Styrene Acrylonitrile
POP	Polyolefin Plastomer
POE	Polyolefin Elastomer
WEEE	Waste Electrical and Electronic Equipment
MSW	Municipal Solid Waste
SDA	Small Domestic Appliances
ELV	End-of-Life Vehicles
C&D	Construction and Demolition Waste

Figure 2: List of acronyms for plastic (Source: Author)

2.1 Material: Plastic

With the introduction of synthetic polymers in industrial-scale production in the 1940s, plastic has become an integral part of everyday life. First, plastic innovation was promoted through consumer products in households (McGuirk & Idenburg, 2019). Thereafter, there were three historical phases in using plastics as products—the first designs aimed to mimic an existing product and make an alternative feasible copy. The second phase introduced cold injection moulding, which enabled the mass production of low-quality plastic products. The last phase allowed a new perspective on plastic products that gave the material its own right, which made the development of composites with durable structural materials possible.

The properties of plastic products have increased tremendously due to their high resistance to corrosion, highly flexible processing, and low manufacturing cost. These versatile properties made the usage of plastic grow from 1.5 million to 299 million in sixty year period (Awasthi et al., 2017). It has been estimated that the use of plastic will continue to grow and expand in other sectors of the world. The typical production of plastic relies mostly on natural materials like oil, coal, and natural gas, with crude oil as a critical raw material. It is expected that the crude oil production will be halved by 2030 (Peters, 2011). The scarcity of these natural materials poses a threat to the conventional ways of manufacturing plastics.

2.1.1 The chemistry of plastic

A simplified plastics production line involves a cracking/refining stage with an energy input to the fossil fuel products, and right after polymerisation, with an input of heat, chemicals, pressure, etc., a plastic end product is produced. The joining of monomers to form a polymer molecule differs with various plastic polymers. The five selected common polymers will be analysed based on their process chains and usage.

PE requires two-step processing sourced from petroleum, and it is widely used in packaging film and bottle sectors. It is chemically the simplest polymer, and it consists of thousands of ethylene units that create the PE compound. Similar to PE, PP is also sourced from petroleum in two steps, with a wide range of uses, including automotive, packaging, and small domestic appliances. One of the most common polymers is polyvinyl chloride (PVC), made in three steps: petroleum, chlorine, and air. This makes PVC one of the strongest polymers, with 50% of the material used in the construction sector. PVC has replaced traditional materials like

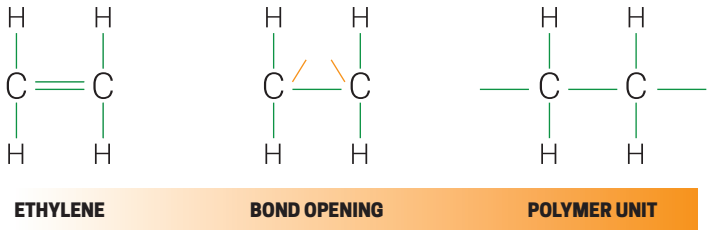


Figure 3: Schematic diagram of formation of PE (Adapted from: Sorensen, n.d.)

wood, concrete, and clay as it is cheap and easily installed. At the end of its lifetime, the incineration process emits dioxin and heavy metals and landfilling leaches toxic additives. There are currently three different types of PVC manufactured based on their usage. Therefore, the material covers a wide range of applications, from piping to coatings. Polycarbonate (PC) is another common material widely used in construction. It is produced by reacting phosgene with bisphenol-A. It has high impact strength, low moisture absorption and thermal stability. The typical uses include packaging, medical devices, glazing, etc. Polystyrene (PS) is a versatile polymer commonly used in packaging, electric, and electronic equipment. Firstly, a styrene monomer is produced and polymerised to PE by opening the double bonds in the monomer (Sorensen, n.d.). These thermoplastic examples are advantageous because of their availability to be mouldable and reusable multiple times. Based on one of the most used thermoplastics, PE, PP, PVC, PC, and PS, an overview of the process chain for production (see Fig. 4) can be made.

2.2 Waste: Plastic

Global plastic use is projected to increase even though crude oil will grow scarce in the upcoming decades. In the Baseline scenario, plastic use is expected to grow faster than most other materials. The projected increase of plastics by three times in 2060 is dependent on four main indicators: population growth, economic growth, structural change and technology change (OECD, 2022). The estimations assume that plastic use will grow at the same rate as population growth and GDP. Plastics are categorised into primary and secondary plastics. Primary plastics include fossil-based and biobased plastics; secondary plastics are the end-product of plastic recycling. In the Baseline scenario, secondary plastics production grows higher than primary as its projection estimates doubled rate from %6 to %12 from 2019 to 2060 (OECD, 2022). The scenario also expects a large increase in plastic in the construction sector. The lifespan of plastics in construction exceeds the average of 13 years, nearly 35 years. As the current plastic lifecycle is only 8% circular, plastic waste management needs to be tackled.

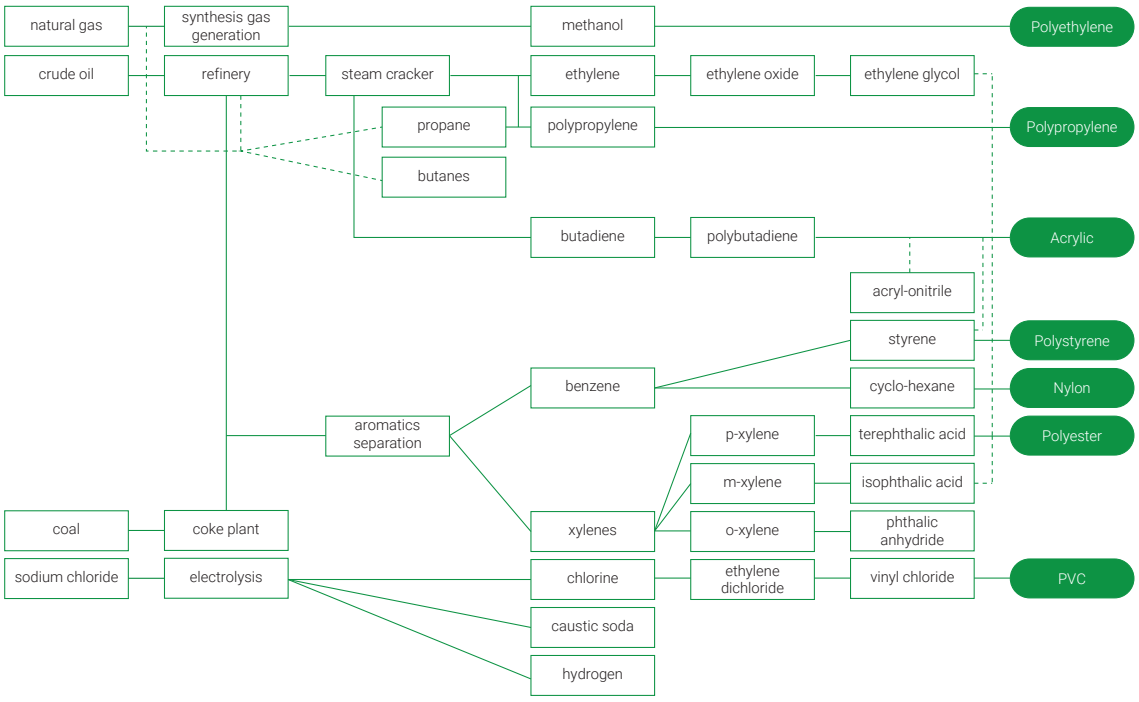


Figure 4: The process-chains for production of various plastics (Adapted from: Sorensen, n.d.)

There are two types of plastic waste: pre-consumer and post-consumer. Pre-consumer waste arises from plastic production and conversion processes. Post-consumer waste refers to plastic products from various streams that the final user discards. The thesis focuses on post-consumer waste and its projections for the future.

2.2.1 Numbers on plastic waste

The data collected in 2020 shows that 29.5 million tonnes of post-consumer plastic waste were collected, one percent of them being organic waste (Plastics Europe, 2022). The waste includes 61% packaging, 6% construction, and 6% electrical and electronic waste. The Organization for Economic Cooperation and Development (OECD) models four end-of-life scenarios: recycling, incineration, landfilling, and mismanagement. According to projections for 2060, plastic use will triple from 460 Mt to 1231 Mt, with 88% still being primary plastics and 12% being secondary plastics. Even though there is an apparent increase in the projected use of secondary plastics, the 2019 data shows that 15% of plastic waste collected for recycling only 9% was recycled. Another data report for OECD shows that recycling will outgrow all other waste management techniques in 2060. Another crucial issue is mismanaged plastic waste, which refers to improper waste disposal. Mismanagement rates of plastic waste are also projected to grow in percentage, but in OECD countries, in which the Netherlands is involved, this rate will decrease by %1. (OECD, 2022).

Plastic leakage currently and will be a problem for the environment as the plastic build-up rates are expected to increase. Littering is the main reason for the leakage (OECD, 2022). Microplastics refer to plastic particles smaller than five millimetres, whereas macroplastics are typically over five millimetres. There is an apparent difference between the plastic leakage schemes of the OECD countries and the rest of the world. High-income countries will not face high volumes of microplastic leakage, but low-income countries will. Therefore, there is a need for better waste management. Optimising waste management, especially recycling, is essential for resource efficiency and lowering the 2060 projections. Separate collection is the key to pre-sorting the waste while ensuring that other types of waste are not limiting the process. Plastic Europe's report states that the plastic waste recycling rates are thirteen times higher if the waste is collected separately, as opposed to mixed collection schemes. (Plastics Europe, 2022).

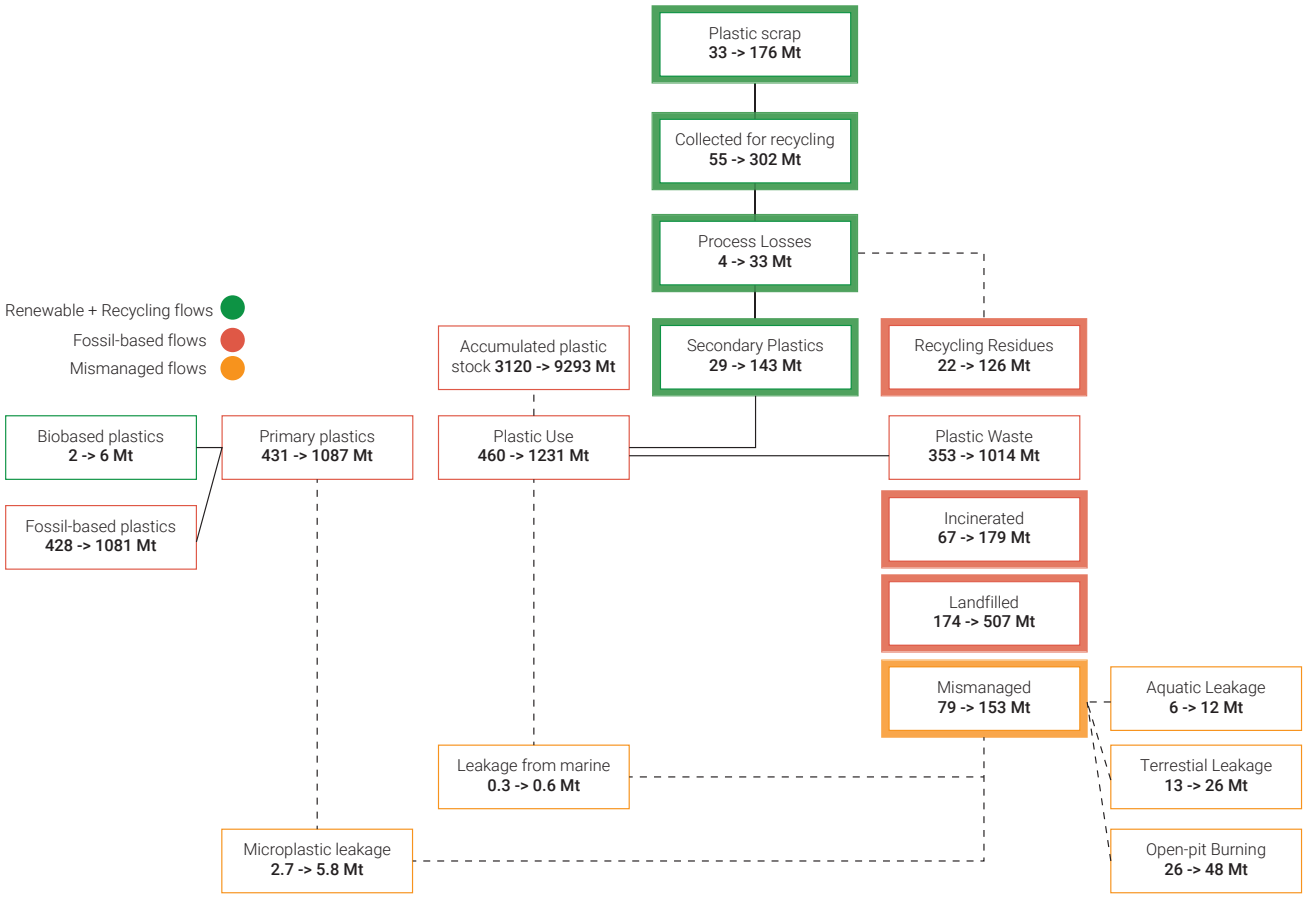


Figure 5: The lifecycle of plastics without new policies in 2060 (Adapted from: OECD, 2022)

According to the OECD global reports, another plastic waste issue is the exports. The increase in secondary plastics is calculated even without stronger policies in mind (OECD, 2022). Accordingly, the current decreasing direction of EU plastic waste exports shows the potential of how stronger policies regarding important bans positively affect investment in mechanical/chemical recycling in the EU. As the use of plastic is expected to grow second to timber in the Baseline scenario, the economy will rely on it more. Therefore, contextualised research is also necessary to understand the current problems in a country.

The Netherlands is one of the EU countries that has made a legislative effort to eliminate the make-take-dispose economy model for its plastic waste schemes. The 2018 data by TNO suggests that 990 kilotons of plastic are produced and discarded in the Netherlands. This consists of 856 kilotons of fossil-based primary plastics, 124 kilotons of secondary plastics, and 10 kilotons of bio-based plastics. The figure below shows that a high percentage of Dutch plastic waste is recovered, mostly at incineration facilities, where it is burnt for energy. The mechanical recycling comes in second with 285 kilotons before chemical recycling and pyrolysis. Plastic leakage and landfills are not a major issue for the Netherlands, while landfills of waste that can be reused or burnt for energy have been forbidden since 2019 (Wijngaard et al., 2020).

The end-of-life data is not distressing because the Netherlands has been producing four times as many plastics as its own consumption needs, which counts as greenhouse gas emission savings (Wijngaard et al., 2020). In addition, Plastics Europe stated that the Netherlands performs the best in the EU for the post-consumer plastic waste that is sent to recycling. TNO proposed a circular economy model for 2050 in which the use of plastic waste grows by 50% up to 2050. TNO concluded that their model proves that the transition into a circular plastics economy is technologically feasible. Their model predicted that incineration would be limited only to some polymers and the recycling's material loss would be halved.

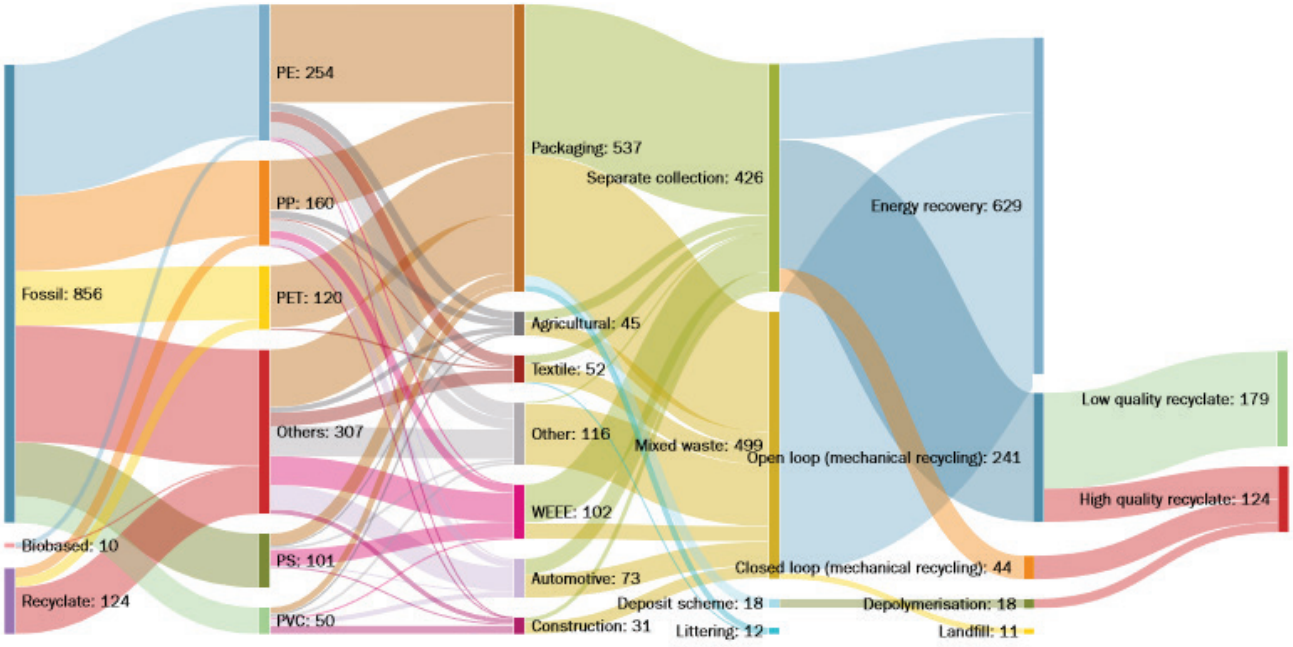


Figure 6: Lifecycle of plastic waste in the Netherlands in 2018 TNO (Source: Wijngaard et al., 2020)

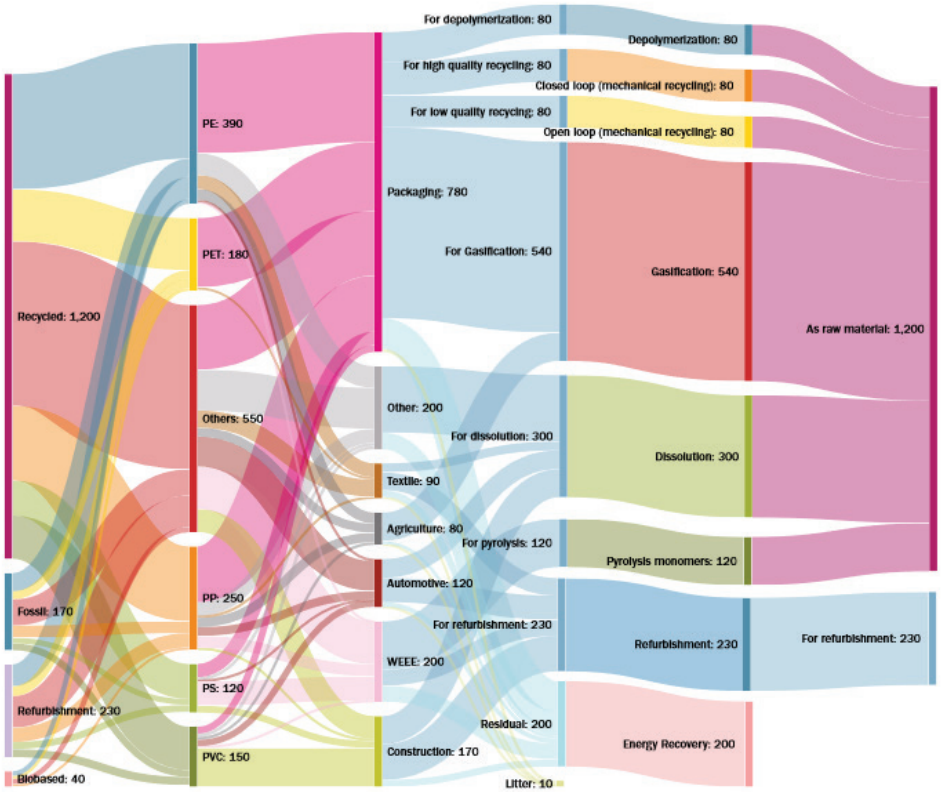


Figure 7: Lifecycle of plastic waste in the Netherlands in 2050 proposed by TNO (Source: Wijngaard et al., 2020)

2.2.2 The possibilities

Secondary plastics production is growing faster than primary. With the Baseline scenario's plastic use expectations, three of the four drivers – economic growth, structural change, and technological change- the secondary plastic sector inevitably grow in the following decade. Even though the post-consumer waste collected for recycling is accelerating, economic limitations do not allow the technically recyclable plastic waste to be recycled. The recyclable plastic wastes end up at as recycling residues because of non-feasible sorting techniques or difficult-to-sort mixes of polymers. As one of the major developments will be the high increase in plastic use for the construction sector, consideration of the current secondary plastic production schemes will benefit the scenarios by OECD and TNO for plastic circularity.

2.3 Plastic Waste Streams

The quality of recycling is always dependent on the waste streams. In the Netherlands, post-consumer plastic waste streams can be collected via source separation (SS) and commingled collection (CC). A typical step of the SS scheme consists of consumer waste separation, plastic sorting and reprocessing procedures. The difference between the two schemes (see Fig.8) lies within the steps needed to achieve a sorted plastic waste fraction. The CC scheme requires more steps to also differentiate between plastic, metal and organic waste before transporting the waste into sorting facilities (Luijsterburg & Goossens, 2014). After sorting the plastic waste streams, the facility yields plastic polymers for further processing. The potential and efficiency of mechanical recycling hinge on the purity of the waste stream, which results in a higher purity of the secondary plastic end-product. The most common waste streams include packaging, end-of-life vehicles (ELV), waste electrical and electronic equipment (WEEE), construction and demolition waste (C&D), and industrial plastics. These waste streams have their own limitations for mechanical recycling into a secondary plastic. Packaging waste is the largest contributor to plastic waste and requires extensive sorting and cleaning processes because of contamination from organic waste. C&D waste is more recyclable than packaging due to its durable and high-quality primary plastic content. Although each waste stream has its own adversity, Dutch governmental regulations aim to maximise recovery of expensive and scarce materials while prioritising waste reduction, reuse and recycling. To stimulate material recovery and decrease global emissions, the Netherlands necessitates high-standard recycling (Golsteijn & Valencia Martinez, 2017).

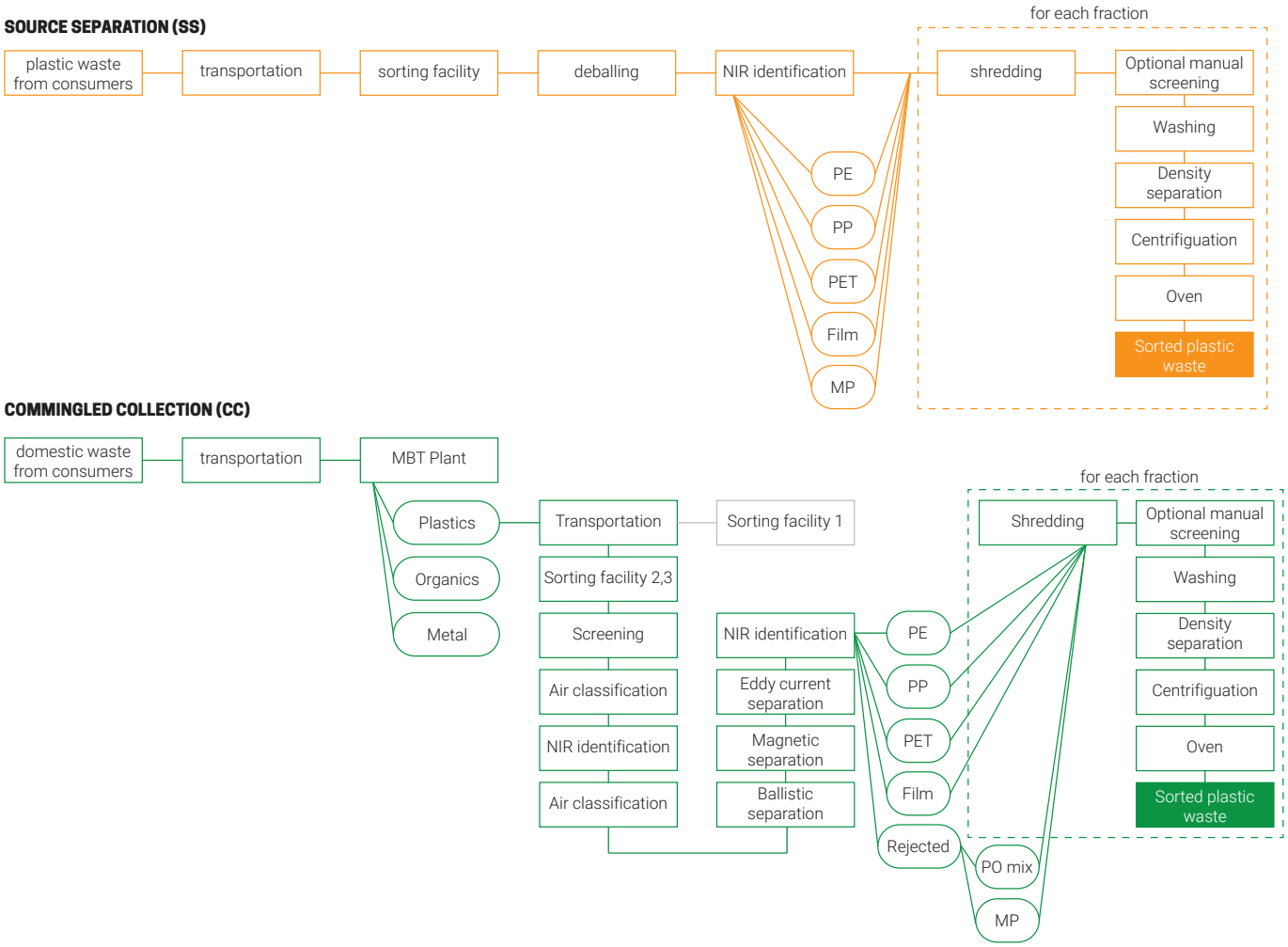


Figure 8: The flow diagram of SS and CC schemes of plastic in the Netherlands (Adapted from: Luijsterburg & Goossens, 2014)

2.3.1 Waste Electrical and Electronic Equipment (WEEE)

The projected increase in economic growth and technological change based on the OECD 2060 scenario will lead to more electrical and electronic equipment advancements. Therefore, e-waste has a global growth rate of %3-5 a year (Jadhao et al., 2022). Recent studies suggest that e-waste will increase to 74.7 MMt by 2030, compared to 2019's data of 53.6 MMt. E-waste consists of hazardous and non-hazardous categories with more than a hundred types of substances. An average composition includes 15% non-flame and 5% flame-retardant plastics (Arya et al., 2023). These plastics in e-waste are mostly treated by recycling and incineration. The applicable e-waste plastics for recycling are thermoplastics, which are apparent in common electronic appliances such as laptops, fridges, and mobile phones. Due to its additive content, e-waste needs careful characterisation of the thermoplastics, which must be removed for high-quality secondary plastic production. Several additives like pigments and flame retardants make the landfill and incineration options for e-waste plastics hazardous for both human health and the environment. Even though this makes recycling a vital option for e-waste plastics, available data in 2019 shows that out of 53.6 MMt of generated e-waste, only %17.4 have been recycled (Jadhao et al., 2022).

The second largest contributor to e-waste, plastics is a good source of material to be used in the construction industry (Goh et al., 2022). Based on the %20 of plastic in a WEEE stream, polyethylene (PE), polypropylene (PP), polystyrene (PS), polyesters and polycarbonate (PC) are few of the most common 15 polymers existing in the stream. The types of polymers highly depend on the type of e-waste. The reasons for focusing on WEEE are plastic's characteristics, such as lightweight, durability, freedom of design, energy efficiency, insulating effect, and, most importantly, recyclability. European Directive reports that based on their six categories -large household appliances, small household appliances, IT and telecommunications equipment, consumer equipment, lighting equipment and electrical and electronic tools- an average of %80 of plastic e-waste must be recovered, and %70 must be recycled based on its respective categories (Jia et al., 2022). The major contribution to e-waste plastics is from small and large household appliances. The nonprofit organisation

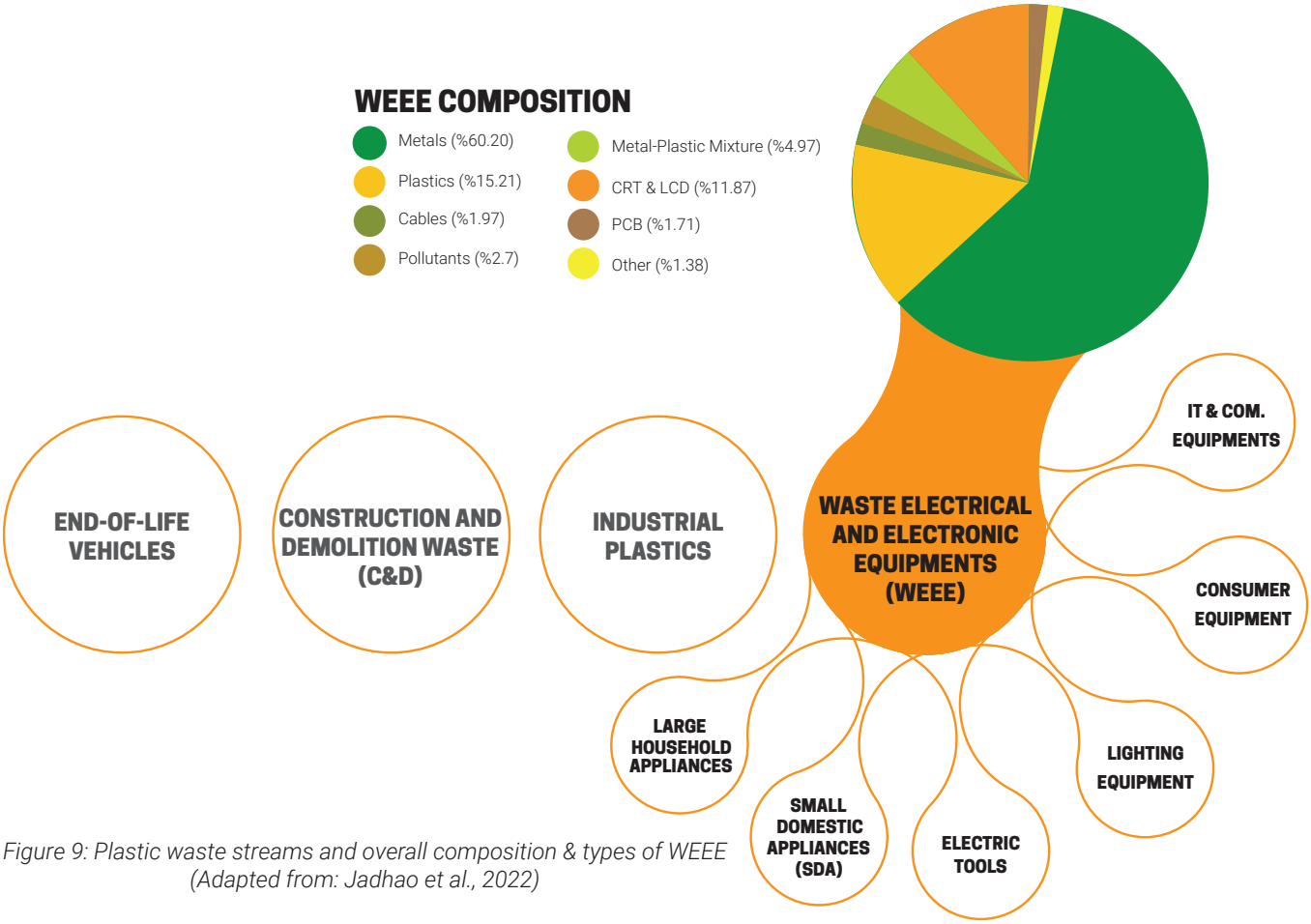


Figure 9: Plastic waste streams and overall composition & types of WEEE (Adapted from: Jadhao et al., 2022)

Wecycle organises the collection and recycling of e-waste on behalf of producers and importers, so their data was considered. Their data in 2016 indicates that 80% of the discarded e-waste in the Netherlands was recycled. Regardless of the available recycling facilities, an additional %30 e-waste was found in the Dutch municipal waste (Golsteijn & Valencia Martinez, 2017).

2.3.2 The possibilities

Developing efficient, environmentally and economically sustainable recycling from the plastic waste streams is adviced by documentation of Plastics Europe and OECD. Recycling plastic polymers from WEEE can save up to %80 energy compared to virgin material production (Jia et al., 2022). In addition, the increase in the efficiency of handling plastic waste from e-waste will also prevent micro-plastic formation. The poor enforcement in legislation lack of infrastructure for e-waste recycling are some of the few challenges of the current handling of WEEE recycling (Jadhao et al., 2022). As plastic is the second major component in WEEE, there is great potential for investigating the WEEE recycling facilities in the Netherlands and identifying the challenges related to secondary plastic production. Creating a recycled building component from WEEE for the construction sector will lower the construction industry's environmental strain while designing an effective e-waste recycling method and guideline.

2.4 Recycling of Plastics

OECD report defines four end-of-life potentials of plastics: recycling, incinerating, landfilling, and mismanaging. Recycling typically involves collecting, sorting, cleaning, shredding and reprocessing, thereby reducing the need for virgin materials. Even though there are noticeable differences between waste management globally, The 2060 scenario for OECD countries evaluating the waste flows for the waste collected for recycling showcases other end-of-life scenarios being involved because of recycling limitations (OECD, 2022).

More than 10 million tonnes of post-consumer plastics waste were sent to recycling in 2020, according to the data of Plastics Europe. %90 of the plastics input was treated into 5.5 million tonnes of recycled plastics (Plastics Europe, 2022). Various recycling technologies are available to produce secondary plastics as waste

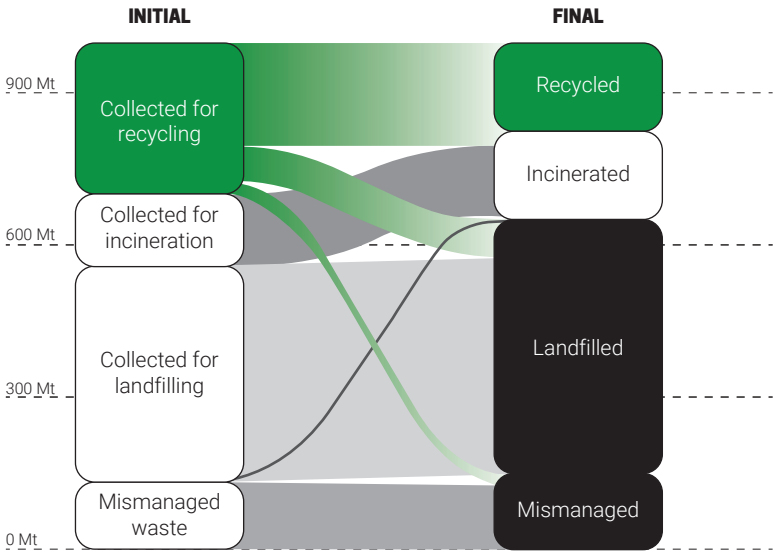


Figure 10: Plastic waste treatment in 2060 by OECD (Adapted from: OECD, 2022)

treatment. Recycled plastics can be produced by mechanical recycling, recycling by dissolution and chemical recycling technologies. There are expected to be further investments by European plastics manufacturers in recycling technologies by 2030 that will support the Circular Plastics Alliance's (CPA) plan to produce 10 million tonnes of recycled plastic products by 2025.

2.4.1 Mechanical Recycling

After the waste collection and sorting based on SS/CC schemes, the post-consumer waste streams end up with complementary recycling processes. There are two types of recycling for secondary raw materials: closed-

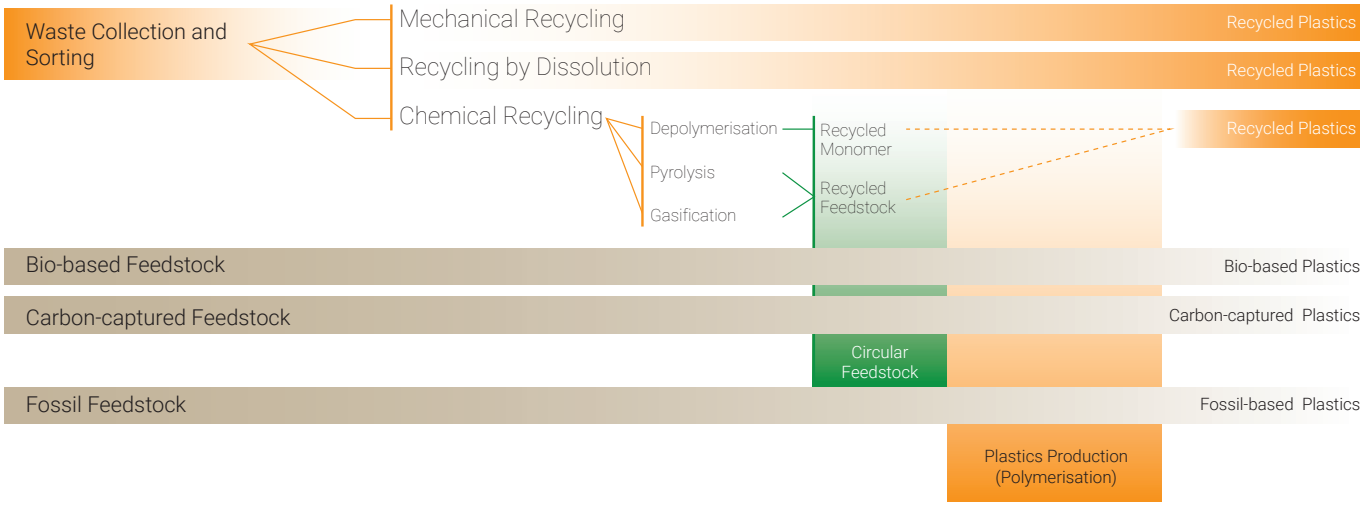


Figure 11: Main recycling processes for plastics (Adapted from: Plastics Europe, 2022)

loop recycling and open-loop recycling. Closed-loop recycling refers to the use of secondary plastics for their original use. The new product can be made fully from recycled polymers. or also with its virgin counterparts. Open-loop recycling is when the recycled plastics are used for different products than the ones they were originally recovered from (Ragaert et al., 2017). Based on Plastics Europe's three defined recycling technologies, a comparative mechanical and chemical recycling analysis will be made.

Mechanical recycling is currently producing the highest quantity of recycled secondary plastics. The simplest and most common technology consists of collection, separation and sorting, washing, grinding and compounding, and pelletising. The initial collection phase includes gathering plastic waste based on SS/CC schemes with curbside collection, drop-off centres, or public collection points. The data on post-consumer plastic shows that

the waste is commonly heterogeneous, with plastic polymers and foreign materials like and contaminants. The next step is separation and sorting, where the plastic waste is sorted based on shape, density, size, colour and chemical composition. Based on the recycling facility, the waste can be sorted through multiple phases, either manually or by sieves. These phases include eliminating foreign materials, sorting plastic polymers, and sizing and granulation into plastic recyclate. The foreign materials can be removed by gravity, water from a sink-float system, or air from an air classifier. If the foreign material content is mostly ferrous metal, then magnetic attraction can also be used. The sorting of the plastic polymers is mostly done with conveyor belts using infrared, near or short-wave infrared detectors and capturing the desired polymers with an actuator or air jet. New advanced sorting technologies have surfaced like MADSCAN by Veridis -discussed in the Field Study section-, tracer-based sorting, which uses fluorescent pigments incorporated into the plastic substrate, making the system visible only in UV lights (Lange, 2021). Nevertheless, the most common and efficient technology is

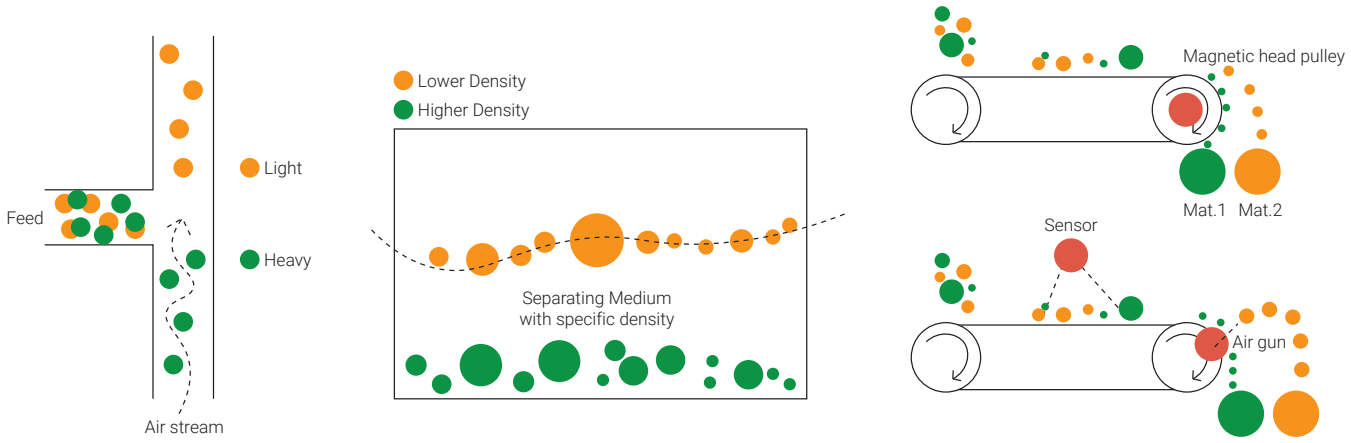


Figure 12: Sorting technologies (left to right): air classifier, density sorting, magnetic and sensor-based sorting (Adapted from: Lange, 2021)

density-based sorting which relies on the floating and sinking fractions of the polymers that are inside a liquid medium (Van Den Eynde et al., 2024).

Belgium is implementing a collection and sorting scheme called PMD (Plastics, Metalen en Drinkkarton) that sorts HDPE, blue PET, green PET, and clear PET for transport off-site. PMD is implementing a progressive rotating sieve first to sort the waste by size. Then, a wind sifter separates medium (40-120 mm) and large (120-220 mm) fractions to ensure that plastic bags are thrown out of the waste. Thirdly, a ballistic separator

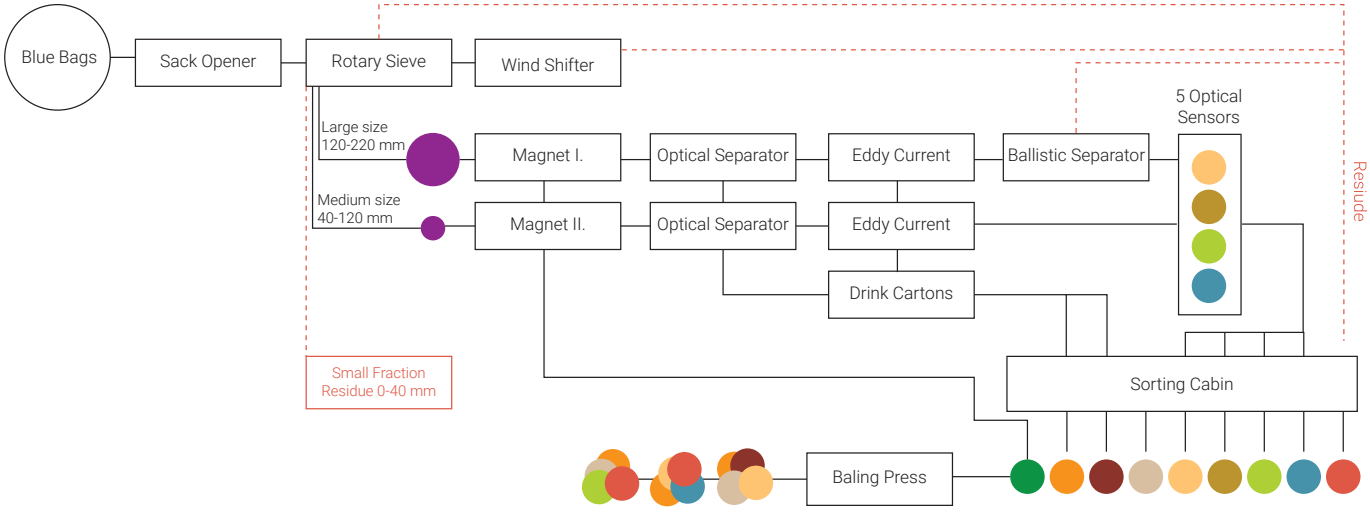


Figure 13: Flow diagram showing the sorting of Plastic-Metal-Drink (PMD) cartons (Adapted from: Ragaert et al., 2017)

removes all soft plastics from hard plastics. This showcases how the majority of the reject fractions of the sorting technologies still include plastic polymers. A difference in the sorting mechanisms of plastic-metal-drink cartons (PMD) offers compared to conventional systems is optical colour recognition after near-infrared sorting between HDPE and PET, which classifies each PET polymer into its colours (Ragaert et al., 2017).

A common view on manual sorting states that the upcoming advanced sorting technologies recover more plastic and are more feasible and efficient, especially referred to as pre-sorting in the household. The transportation of pre-sorted household waste streams is viewed as not as efficient as central post-sorting all at once (Lange, 2021). The PMD scheme can exemplify the view of manual sorting at the facility. The trained operator is believed to be more efficient in sorting based on products coherent with the plastic polymer the product is made of. However, the time efficiency and feasibility of manual sorting with a trained operator are costly (Ragaert et al., 2017).

The washing phase of mechanical recycling is mostly done to remove contaminants and foreign materials suitable for reprocessing. Because of feasibility, cleaning is mostly integrated into the sorting phase. The last steps are grinding and compounding. The selected size of the plastic fraction goes into granulators that reduce the size of plastics into granules. If necessary, a final regranulation can be done with melt filtration to increase the bulk density of the final secondary plastics. This aids in removing non-melting contaminations from the melt. Mechanical recycling concludes with processing the pellets by selecting from various technologies: extrusion, hot pressing, injection moulding, compression moulding, 3D printing, etc.

2.4.2 Chemical Recycling

Mechanical recycling is limited to a fraction of plastic waste as a major part of the process involves carefully sorting and separating the mixed waste into a mono-stream for the purest secondary plastic results. According to Plastics Europe, the complementary method of chemical recycling will reach higher recycled plastic quantity with a quality that is the same as its original polymer (Plastics Europe, 2022). There are three subbranches of chemical recycling: depolymerisation, pyrolysis, and gasification. These processes create recycled feedstock or monomers for polymerisation into recycled plastics. The principle of chemical recycling solely depends on chemical bond breaking, such as C-C, C-O, and C-H, for recycling into high-value recyclates. Depolymerisation refers to the process of breaking down polymers into monomers or oligomers. In the case of depolymerisation of PET, the end-products can be terephthalic acid (TPA), dimethyl terephthalate (DMT), or partly depolymerised into its oligomers (Ragaert et al., 2017). Pyrolysis refers to breaking down polymers into smaller molecules of gas, liquid or solid residue by heating up the plastic waste without oxygen. The process takes place at moderate to high temperatures, around 500°C, which breaks down the macrostructure of the polymer. The main challenge of pyrolysis is similar to the challenge of mechanical recycling, in which the waste stream's contamination level and purities make the end product lose part of its original value due to the polymer mix. Even though pyrolysis is a simpler chemical recycling technology, it is feasible only with large volumes of waste input, and the conversion is only possible for the most common polymers -PP, PP, PS, PVC- because of the complexity of the separation of the mixture is complex (Ragaert et al., 2017).

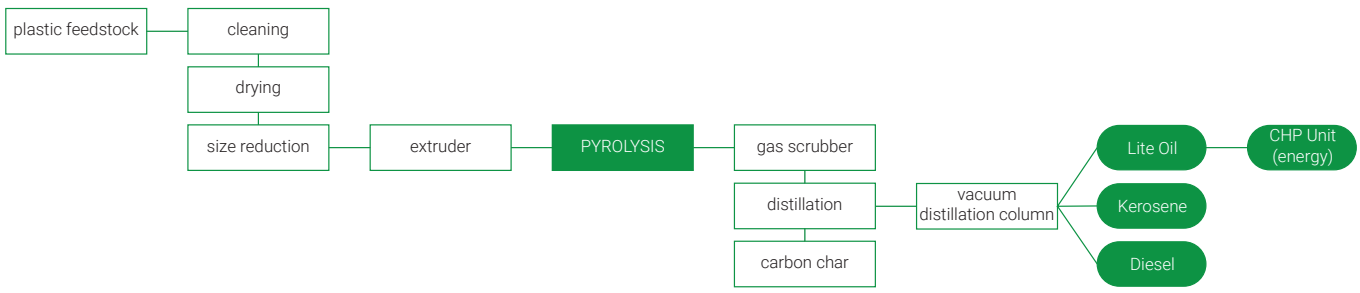


Figure 14: Process-flow diagram of a typical pyrolysis with novel vortex reactor technology (Adapted from: Ragaert et al., 2017)

Gasification converts plastic waste into syngas by using an oxidation agent like oxygen and steam at high temperatures. The end product of syngas consists of hydrogen and carbon monoxide, which are commonly used for electricity and fuels. The main advantage of gasification is the ability to convert any non-treated waste containing organic material into a gaseous mixture and light hydrocarbons. The operating temperature varies between 1200 and 1500°C. The process also involves cleaning to get clean and dry end-product gas.

Operational cost is a big indicator of the use of gasification, while a higher gas flow rate of the oxidation agent results in lower separation rates. Overall, chemical recycling introduces a complementary technology to mechanical recycling to address a solution for mixed plastic streams that could only be recycled into low-quality products.

2.4.3 The limitations and possibilities

The current state of the art for recycling plastic waste streams is mechanical and chemical recycling. Mechanical recycling of post-consumer plastic waste is a widely adopted method that reduces the volume of plastic waste destined for landfills and incineration. Several limitations of mechanical recycling of thermoplastics affect the quality of secondary plastics production. Firstly, mechanically recycled plastic presents lower performance compared to virgin polymers. This is caused by the grading of the plastic waste input, which may not meet the high-end requirements. Secondly, secondary plastics may contain additives like fillers, flame retardants and plasticisers. Thirdly, the purity of the secondary plastics may not be the same as that of virgin ones. This is caused by the immiscibility of different polymers that would create weak spots in the recycled material because of minor fractions with foreign polymers. The fourth reason mostly relates to the processing in which the repeated hot temperature might cause polymer chain degradation (Lange, 2021). The other major limitation regarding mechanical recycling is the sorting techniques. The FT-NIR near-infrared technique necessitates that the plastics be dry and pre-treated before being sorted. Additionally, black-coloured plastics are undetectable in the near-infrared. Another limitation of most advanced sorting techniques is their cost-effectiveness; for example, in magnetic density separation, the smaller the waste input, the less feasible the process becomes economically. The current efficiency of the sorting techniques is evident in a pilot program in the UK, where they were able to sort %67 and %62 for reprocessing while leaving the reject fraction as mixed plastics.

European plastic manufacturers' plans for higher investment values suggest the potential of chemical recycling. However, there is still a need for better collaboration between the stakeholders along the value chain and better investment strategies. The pilot plants for the three subbranches of chemical recycling state that there is a lack of suitable waste streams and the price difference between crude oil and pyrolysis oil hinders commercial viability (Vollmer et al., 2020). Generally, the chemical recycling process requires high volumes of waste input to be considered cost-effective, but it is limited to condensation polymers. There is a general lack of technical information, and further research that is required for advanced chemical recycling technologies. In the case of pyrolysis, even though it is the most common technology, there is a need for suitable reactor technology, and it has a low tolerance for PVC. Due to the imperfect separation of polymers, there is always a remaining small fraction of PVC in the stream during pyrolysis. This requires special removal processes that prevent the end product from being used as fuel because of the remaining halogens. Lastly, chemical recycling is highly energy-demanding when operating in high solvent/polymer ratios.

Mechanical and chemical recycling complement each other in creating a circular approach to plastic waste management. However, for an optimistic scenario, where %90 efficiency is given to mechanical recycling and %80 efficiency is given to chemical recycling, the overall efficiency for the end product is still at %50. Leaving nearly %50 of the input material to be lost in the reject fraction (Lange, 2021). This concludes that both recycling technologies need improvement to meet the projections of 2060. The comparative figures showcase the difference between the total CO2 emissions and the polymer range differences for both recycling technologies. The thesis requires a cost-effective and low-tech technology that is effective for a wide range of plastic waste streams. While mechanical and chemical recycling have their respective advantages, mechanical recycling stands out for the thesis study. As the reject fraction of the recycling facilities implements mechanical recycling, repetitive mechanical recycling would be optimal to showcase the possibility of using the reject fraction as secondary plastics to close the loop. The well-established infrastructure, reduced complexity, and immediate applicability would speed up the phase two experimentation of my thesis tremendously.

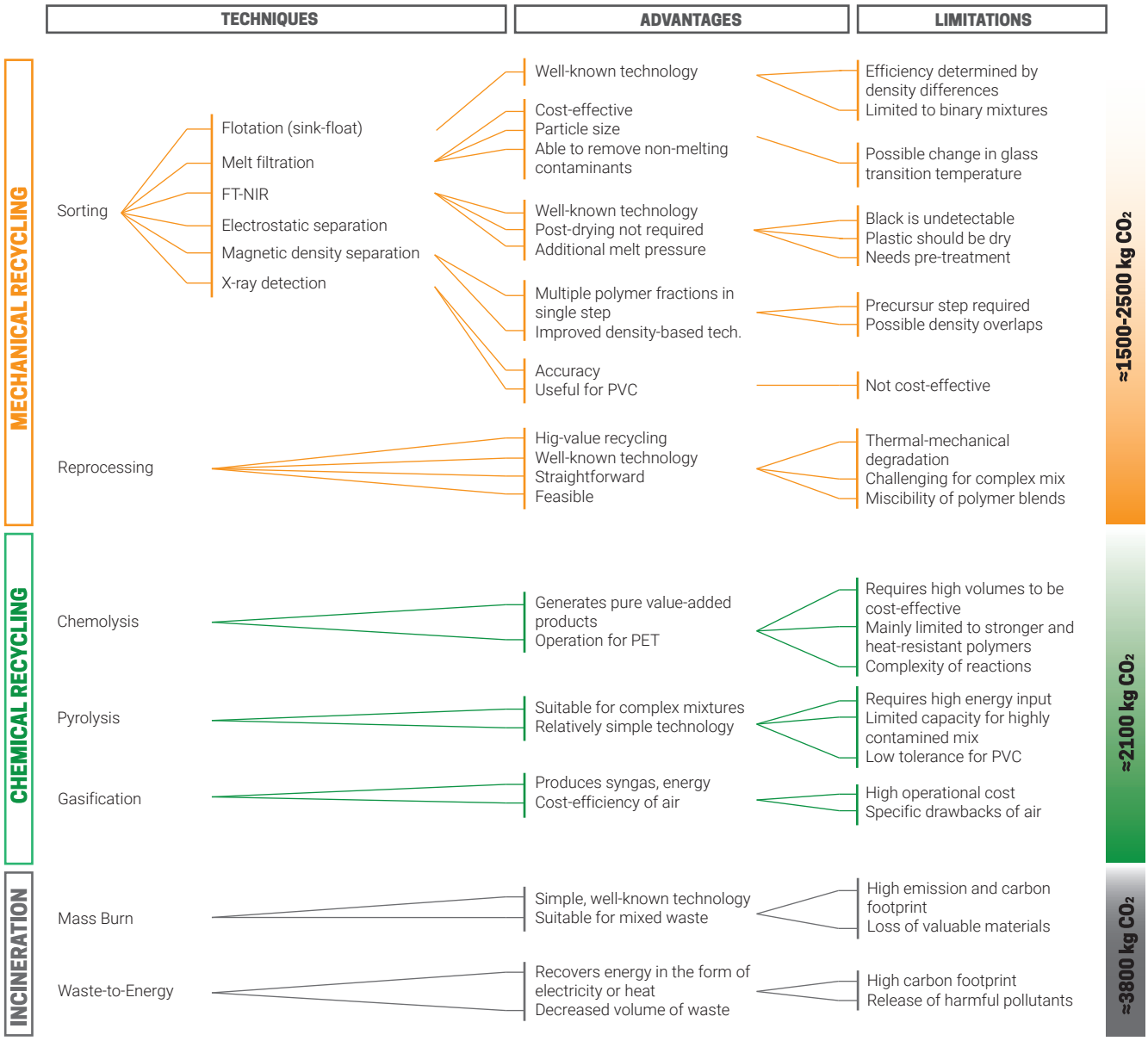


Figure 15: A comparison of advantages, limitations, and CO_2 emissions (emission values are based on polyolefins) of mechanical, chemical reycling and incineration (Adapted from: Ragaert et al., 2017 & Lange, 2021)

2.5 Properties of Polymers

Due to chemical stability, lightness, cost-effectiveness and versatility, plastic polymers have been used widely in the large scope of applications. As humanity needs to co-exist with more plastics in the future because of the growing need, the reliance on secondary plastics compared to primary has increased. The global transition to circular plastic economy, creates a high demand for high quality recycled plastics (Pelto et al., 2023). The current life cycle assessments done by the University of Trento show that there is clear evidence that the replacement of virgin polymers with recycled polymers could be beneficial both environmentally and economically (Dorigato, 2021).

2.5.1 Virgin and recycled polymers

The mechanically recycled architectural component for the thesis necessitates a thorough understanding of the difference between virgin and recycled polymers. Virgin polymers refer to unused material that has not been previously used or processed. They are produced directly from fossil-based feedstocks, which cause uniform molecular structure and higher molecular weight. As mechanical recycling causes polymer degradation during the process, recycled polymers might present reduced mechanical performance and altered molecular characteristics. The degradation is stated to be mostly because of the recycled polymers' weak notched impact strength, which causes the polymer to behave brittlely. This is determined by the Charpy impact test, in which the material's resistance is tested for impact loading for structural applications. The application of recycled

polymers with fluctuating origin, composition and properties has a negative impact on the morphology and the impact properties (Pelto et al., 2023).

The recent studies on specific polymer types can deduce the difference between virgin and recycled polymers. Research on polymers of high-density polyethylene (HDPE) and low-density polyethylene (LDPE) comparing the performance of virgin and recycled types conclude that there is a significant decrease in performance of rec-HDPE and rec-LDPE as the polymer chains degrade during mechanical recycling. In addition to impact loading, which Charpy impact tests can test, dynamic loading is crucial for the structural application of recycled polymers. The cyclic loading on the polymer and its resistance before failing is measured by fatigue resistance. Both rec-HDPE and rec-LDPE presented lower fatigue resistance than virgin alternatives (Zhang et al., 2022).

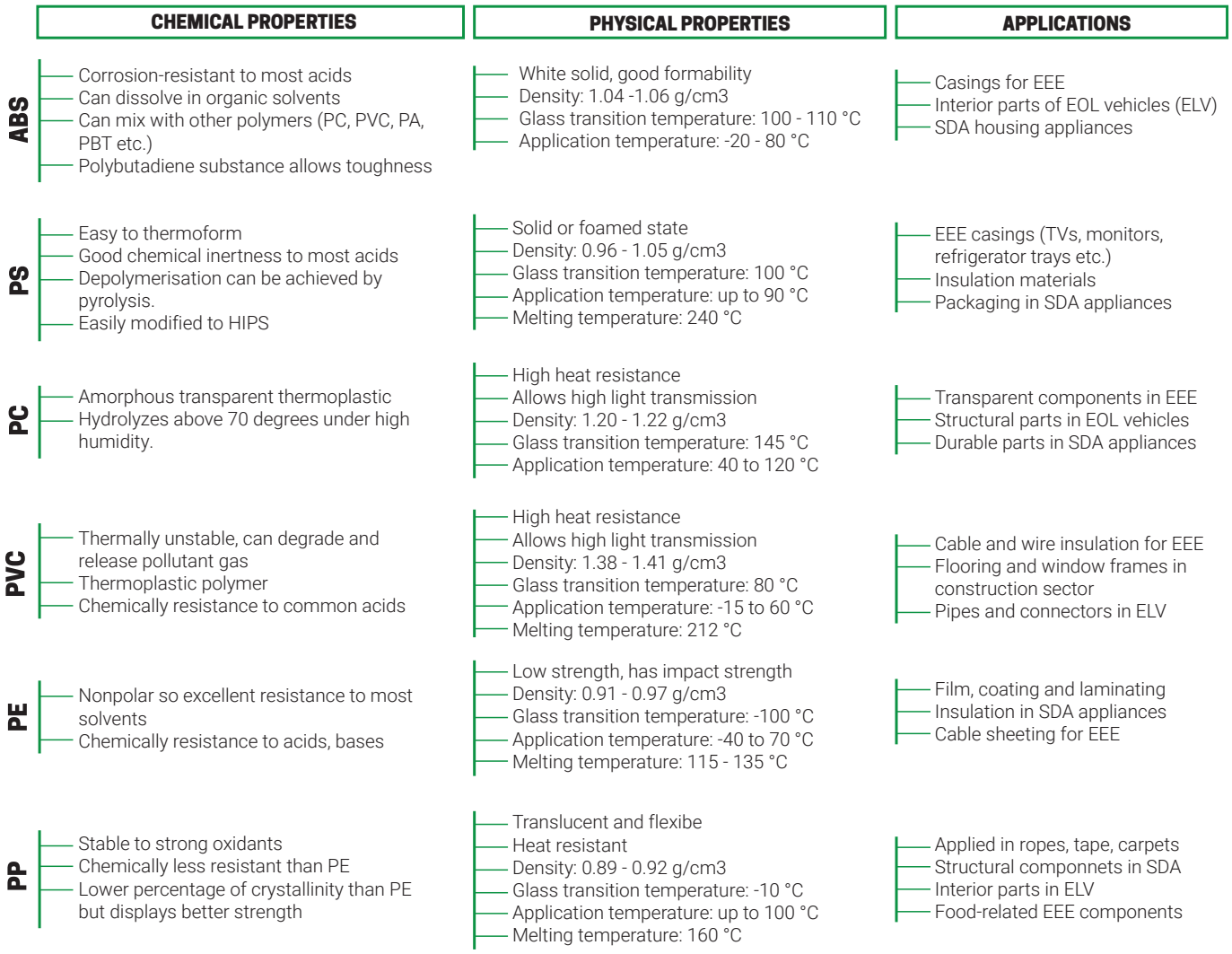


Figure 16: Chemical properties, physical properties and applications of six common plastic polymers (Adapted from: Jia et al., 2022)

In addition to structural performance, the thermal performance of recycled polymers compared to virgin polymers is significant for its application in the construction industry. The polymer must be thermally stable to be used as a product. The service temperature refers to the range between the glass transition and melting temperature where the polymer functions effectively. If it is thermally unstable, it will result in thermal ageing, while the majority of the polymers are less resistant to UV radiation (Singh et al., 2023). The glass transition temperature is a main indicator of the thermal performance, which shows the polymer's stiffness, flexibility, and thermal stability. The temperature indicates the phase separation of the molecules from a brittle state to a softer state. A single glass transition temperature results in good miscibility and compatibility if more than one polymer is used. Another research done on acrylonitrile butadiene styrene (ABS) between virgin and recycled variants concludes that even though there is an apparent decrease in mechanical performance, the glass transition temperature remained relatively stable across multiple mechanical recycling cycles (M. I. Mohammed et al., 2019). The possible breakdown of polymer chains and contaminants results in altered thermal properties of recycled polymers.

Research on rec-PE found it to have lower thermal stability due to impurities and reduced molecular weight. The presence of foreign polymers can change melting temperature and thermal performance, necessitating the analysis of polymer blends.

2.5.2 Compatibility of polymer blends

Polymer blending has become a prominent area of development in which the current blending technologies involve the modification of the physical, mechanical and chemical properties of polymers that generate durable and thermally stable materials (Singh et al., 2023). The thesis aims to provide adequate knowledge of polymer blends while focusing on the unsorted polymer fraction of recycling. The unsorted fraction addresses various polymer types that might differ based on the waste stream. The typical composition in the waste streams differs from the common polymers that are being used in application.

Advances in blending trials, such as incorporating virgin polymer, recycled polymers, compatibilizers, etc., can enhance the applicability of the thesis's end product. Industrial and scientific communities are trending towards producing high-performance materials by polymer blending (Singh et al., 2023). This can potentially become a useful solution for meeting the high standards of secondary plastic manufacturing. The common polymers that have been used for blending are ABS, PP, PE and PET. The decisive factor for whether a polymer blend becomes workable depends on its compatibility. The term compatibility is based on the end morphologies' melt viscosity and mutual solubility. As incompatible heterogenous blends present poor mechanical properties, a compatible blend is desired for construction. Another indicator of a workable polymer blend is its miscibility. The polymer concentration and the molecular mixing determine it. To evaluate the compatibility, various polymer blend trials are analysed to determine the limitations and possibilities for the thesis.

Singh et al. state that ABS is the most favourable polymer for blending. Currently, ABS and its blends are used to manufacture bumpers, seats, and electrical components. ABS presents great toughness but lower tensile strength and elongation. Therefore, PP with high tensile strength was chosen for the polymer blend. Coupling ABS and PP enhances the final product's physical and thermal properties only if the blend is miscible. Therefore, an additional compatibiliser is used. Compatibiliser refers to the component that is used to create of physical or chemical bonds between the blend phases. There are several techniques to introduce compatibiliser into the mix in which mixing it while the blend melted is the preferred option for mechanical recycling (Dorigato, 2021). However, Singh et al. implemented a graft polymer method where the carbon black was placed in situ during melt blending. The final recipes with and without a compatibiliser proved that a compatibiliser has a negative effect on the tensile strength and a positive effect on the impact strength. The morphology of the blends was tested with SEM and TEM images to see the conversion of the polymer chains. The results concluded that the polymer with a higher wt% in the blend is the decisive component for the glass transition and melting temperature of the blend. Singh et al.'s 80/20 wt% PP/ABS blend shows that even though the melting temperature of the blend is higher than ABS's melting temperature, it is still lower than PP's.

Ragaert et al. mixed waste case study for the unsorted fraction represents 20 wt% of the total input waste from a recycling facility in the Netherlands. The first limitation of the study was the PVC removal because of its poor thermal stability, which causes degradation within 250-320˚C. During degradation, HCL is released, which causes high corrosiveness and toxicity. A polymer blend of a complex mix of remaining polymers with decreased PVC fraction (PET, PP, PVC, PS, other) and a compatibiliser is created. The addition of compatibility significantly improves the properties of impact strength, ductility, toughness, and strain-at-break. A stiffness/impact graph is created to showcase the effect of compatibiliser compared to remaining polymers. This concludes that polymers with lower Young's modulus tend to exhibit higher toughness as they can deform more easily. Therefore, polymers with higher Young's modulus will be prone to being brittle because of lower Charpy impact strength. The analysis done by Granta Edupack concluded that the general trend of higher modulus polymers also exhibits higher tensile strength. The main reason is the stiffness that makes the polymers resist the deformation better, like PC. The suitable application of the polymer can be deduced from the relation. Polymers with high modulus and tensile strength are suitable for structural elements, whereas polymers with low Young's modulus and moderate tensile strength perform better in flexible applications.

Another polymer blend trial for PP/PE compares the blend performance of virgin polymer blend and recycled polymer blend. The study confirms that the same polymer type obtained from different waste streams can also be considered a polymer blend if it is mixed. The study confirmed that PE shows brittle behaviour when

it's blended with small amounts of PP. A stable and continuous morphology was achieved with 30-40 wt% PE/PP ratio. It is deducted that the small size crystals appearing at the blend's morphology could increase the resulting blend's stiffness and durability (Dorigato, 2021).

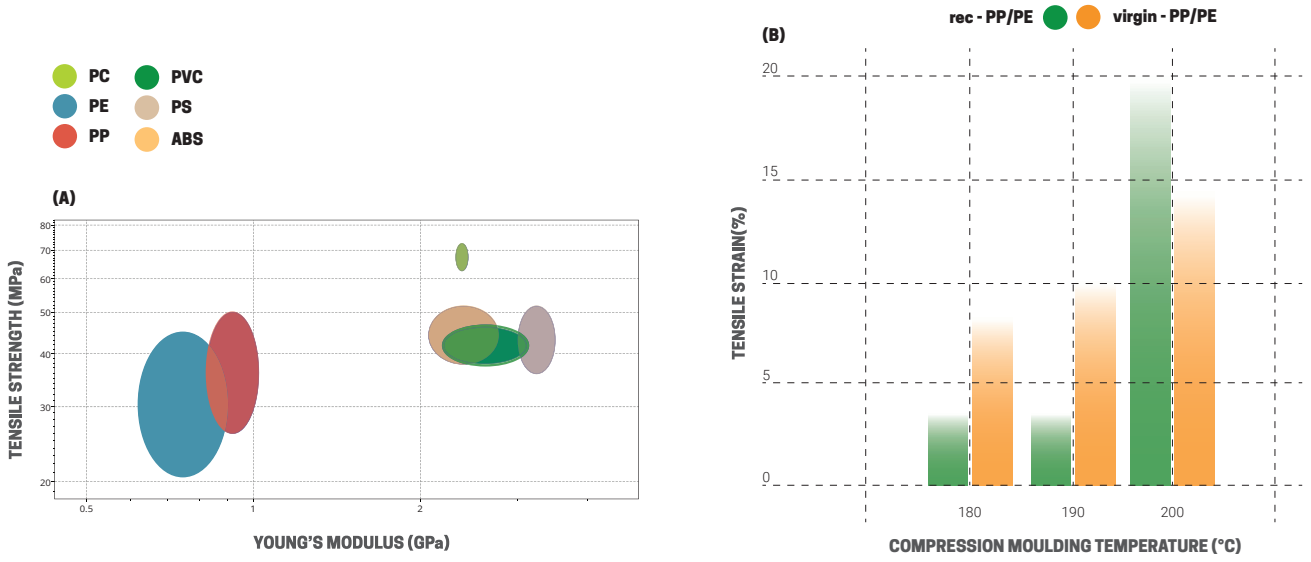


Figure 17: (A) Relation between Young's Modulus and Tensile Strength for six polymers (Source: Author, Edupack). (B) Relation between compression moulding tempoerature and tensile strain for the PP/PE polymer blend (Adapted from: Dorigato, 2021)

The difference between the morphology results of polymer blends by available technologies like SEM concludes whether the blend is compatible or not. The evolution of the morphology of PLA/polybutylene adipate terephthalate (PBAT) with different weight ratios showcased the possible crystal formations at the morphology. Compatible blends exhibit a smooth transition between one polymer to another or have co-continuous phases, whereas incompatible blends show clear phase separation. Evenly dispersed morphology also hints at compatibility if the phases are uniformly distributed. However, in order to conclude whether a polymer blend is compatible or not, thermal and mechanical testing is also necessary.

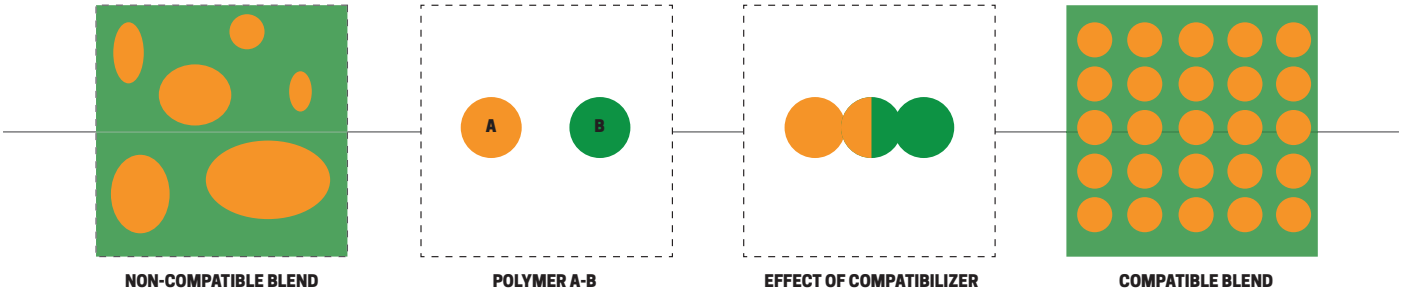


Figure 18: The role of compatibiliser in a polymer blend (Source: Author)

Based on the evaluation of the polymer blend trials, polymer blending provides a good alternative to state-of-the-art recycling techniques. The possibility of reprocessing unsorted polymers with the addition of compatibiliser, if necessary, for homogenisation proves feasibility and flexibility. The second phase of the thesis -experimentation- will evaluate polymer compatibility using data from existing trials, while the detailed chemistry of the polymers falls outside the scope of the thesis.

2.5.3 Contamination

The contamination in the plastic waste stream poses significant challenges for recycling. Apart from polymers, foreign materials exist in the mixed waste. These materials include incompatible polymers that act as mechanically weak points or cavities, additives, flame retardants, catalytic metal compounds that would increase the possibility of polymer degradation during recycling (Pelto et al., 2023). To fulfil the requirements of new products for waste streams like WEEE, additives are added to the virgin polymers before their conversion into plastic products (Jia et al., 2022). The additives contain heavy or toxic metals with halogenated substances,

which will affect the recycling process after their service life. The flame retardants have high rates of addition into plastic polymers, up to 15% (Jia et al., 2022). The function of flame retardant is to stop the fire process by possible methods like disrupting the combustion stage. Different types of flame retardants are used for various waste streams. The most common use in EEE appliances is brominated flame retardants (BFRs). Secondly,

2.6 Injection Molding of Plastics

Injection molding is a predominant manufacturing process for plastic production, enabling for the production of complex shapes with high precision. The low maintenance of the processing equipment, high production rate, short cycle times and low percentage of waste make injection molding an advantageous processing technique to be used in the plastic sector (Zhong & Li, 2005). In the context of recycling, particularly with the contaminated and mixed plastic waste, the material's physical and chemical properties influence the morphology and phasing of the polymers considerably. To be able to use the waste stream efficiently, injection molding was found to be a promising method as it operates in high shear rates, which aids the blending of immiscible polymers. Recent studies suggest that the high shear facilitates compatible morphologies and improved mechanical properties (Hirai et al., 2019; Yin et al., 2023). The flexibility of the injection cycle adjustment is another advantage for dealing with polymers with unknown composition or contamination. The process parameters can easily be adjusted if no result is observed during fabrication (Luna et al., 2022).

There are different types of injection molding machines with different operating mechanisms suited for specific applications of plastics. The machine types include plunger, screw and twin-screw machines which all follow a similar mechanism where the molten plastic is injected with pressure into a mold. The plunger injection molding machine is beneficial for systems that are suitable for materials necessitating moderate temperature and small prototypes (Török & Kovács, 2018). Screw plunger machines include a screw-based extruder allowing for better melt flow and consistency. The twin screw machines are mainly used to process higher viscosity materials, blends or composites. All these options have a mixer variant, which creates efficient blending of materials to improve compatibility before injection. The plunger injection molding consists of manual and automated alternatives. The manual one has the advantages of being flexible and a preferable option for low-volume production. The main difference between the conventional, automated machine is the achievable pressure and efficiency (Török & Kovács, 2018).

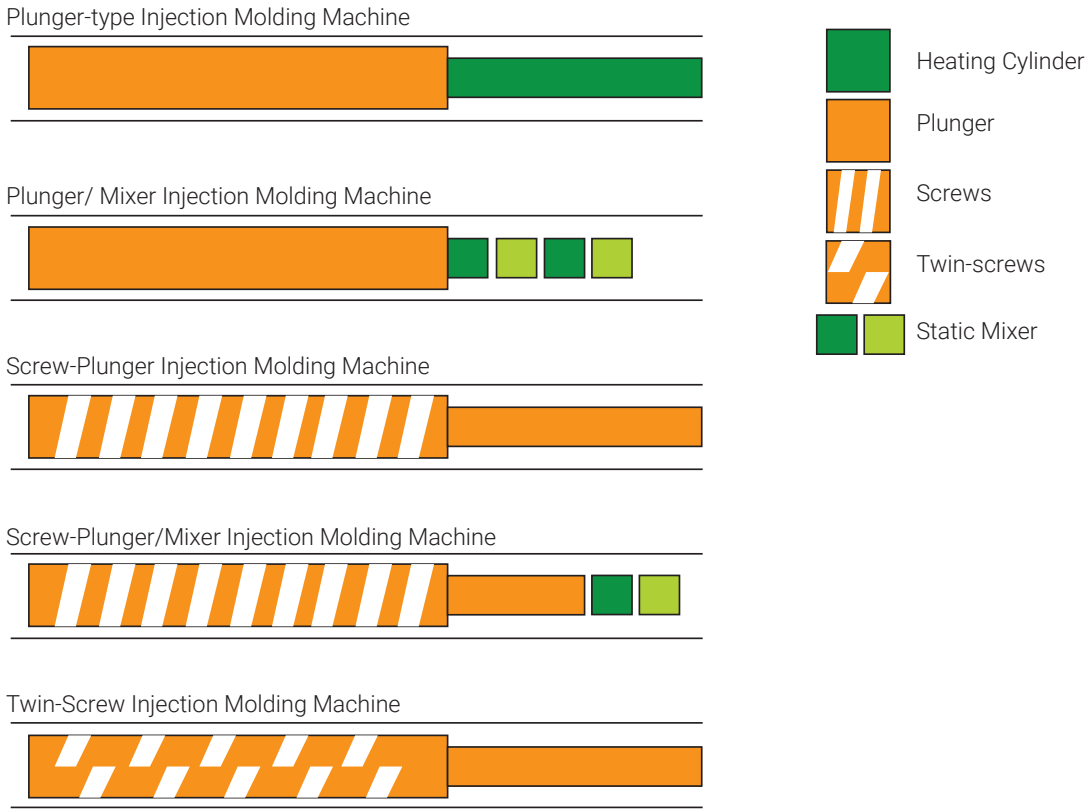


Figure 19: Schematic of different types of injection molding machines (Adapted from: Han et al., 1977)

The injection molding cycle consists of three main stages: filling, cooling and packing. As plastic flows into the mold wall, the first layer in contact with the mold forms the frozen layer. The upcoming plastic flow occurs inside the envelope created by the frozen layer. Then, the streamlines of melted plastic fluid filling the mold are called the fountain flow. The fountain flow allows the plastic to expand and flow inside the mold, which causes solidification. During the process, the plastic deforms into a U-shaped cross section. The solidification time refers to the duration during which average melt temperature drops below the glass transition temperature. The velocity profile from the melted plastic is linear because its viscosity is highest when the shear rate is the lowest (Fellahi et al., 1995).

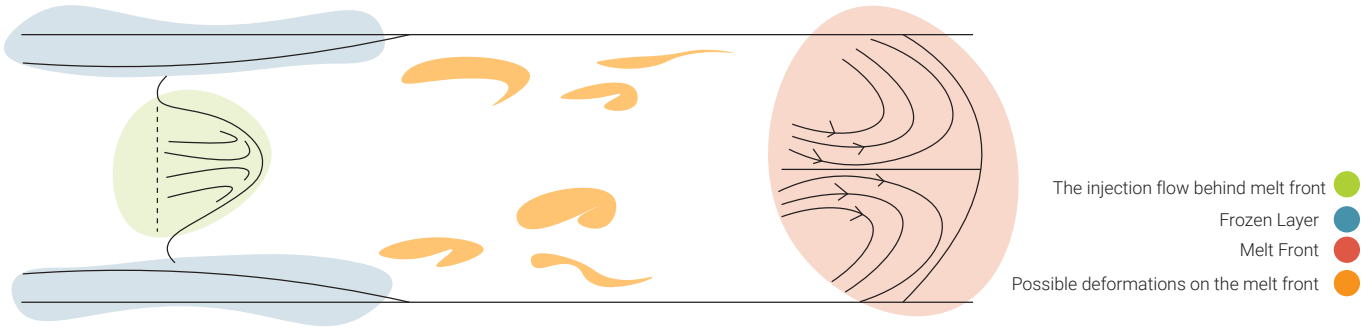


Figure 20: Schematic showing the formation of the frozen layer and the velocity profile in the core (Adapted from: Fellahi et al., 1995)

The parabolic behaviour of the plastic with the U-shaped cross section causes the formation of a thin region around the periphery of the frozen layer, which is called the subskin. The core of the melting plastic is the last region to solidify, which forms evenly during cooling (Zhong & Li, 2005). During polymer blending, the structure from skin to core of the melted plastic can result in phase separation because of the incompatible blends. Generally, the deformed particles are seen on the skin layer and the spherical droplets at the core. The fast crystallizing polymers generally present a multi-layered morphology, which causes an increase in the size of the spherical droplets due to the crystallization time and stress history. This leaves the skin layer with small crystals and a shear zone between the skin and core layers. The shear zone is proven to be thinner for the thinner products due to higher shear forces. Based on the recent studies, flow rate, mold temperature and melt temperature turn out to be decisive factors to influence the injection cycle of polymer blends (Zhong & Li, 2005).

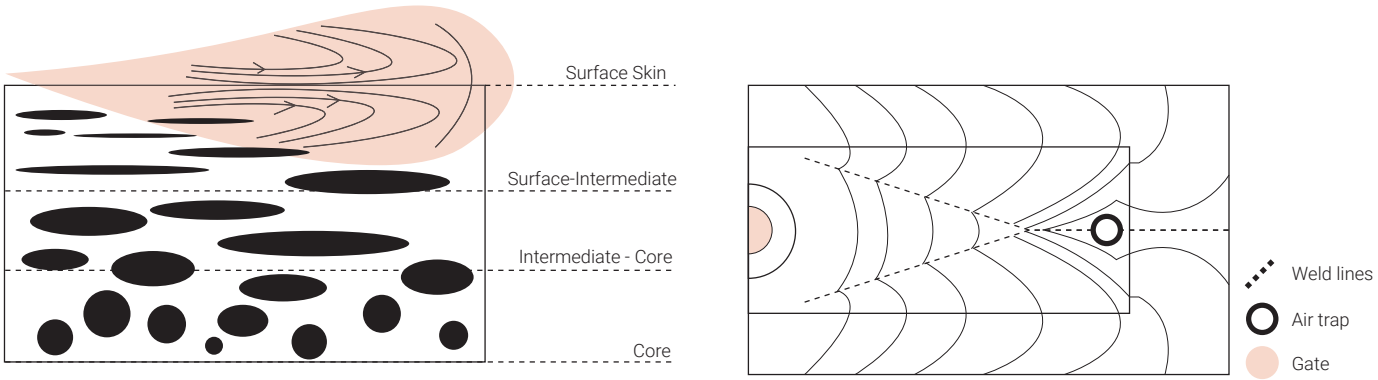


Figure 21: Schematic of the (1) morpholgoy of the phase differences on various layers (2) formation of air traps at the moulds (Adapted from: Zhong & Li, 2005)

2.6.1 Morphology Defects and Weld lines

Weld lines are regarded as the most undesirable phenomena during injection molding because of the poor physical appearance and potential source of weakness in molded parts (Zhong & Li, 2005). In theory, weld lines are formed as two separate melt streams join in multiage molds or result of a flow around obstacles. The two melt streams forming a contact form weld lines (Fellahi et al., 1995). The formation of weld lines can be divided into two categories: melt fronts that are flowing in opposite directions or a multi-cavity mold. As there is only one ejector location available on the single cavity mold, the first category is taken into consideration. The width of the weld line region is approximately twice the thickness of the skin layer (Zhong & Li, 2005).

Research has been done on the elimination of weld lines during molding, which states a weld line vanishing angle of 140-150 degrees. This angle causes a change in the melt-front angle to completely change the morphology of the molded plastic (Fellahi et al., 1995). The effect of weld lines on the structural performance is mainly tested with dog bone specimens with double ejector locations. For the impact testing, research has been done for the styrene-based plastics PS, SAN, and ABS, which showcase the reduction of impact strength when a weld line occurs. However, for the semi-crystalline polymers like PP, the formation of a weld line does not influence the behaviour of the chain mobility of the melt fronts as the mold temperature is above the glass transition of the polymer. PP generally presents four stages during melting: mold filling, filling-packing transition, packing, and end of molding. During the filling-packing transition and packing, crystallization occurs differently based on the pressure difference on the stages. The increased pressure leaves behind a sub-layer of low crystallinity, as the front of the melt carries the majority of crystallisation to the core. It results in a more complex morphology of the weldlines in semicrystalline materials compared to amorphous (Fellahi et al., 1995).

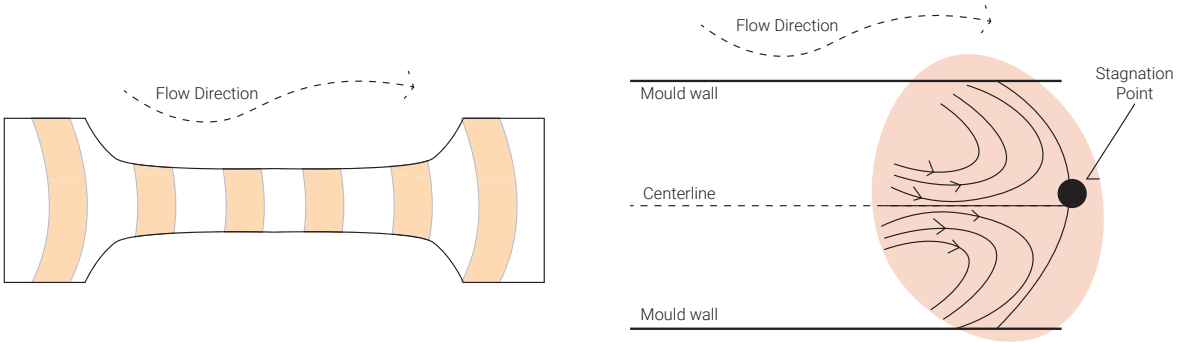


Figure 22: Schematic of the formation of flow marks with assymetric path lines of melt front (Adapted from: Zhong & Li, 2005)

The processing conditions affect the morphology of the weld line as well. The higher injection flow rate, with lower injection temperature, the force on the dispersed phase became larger, which causes particles to become more deformed, which makes them easier to break. Adding a compatibilizer reduces the dispersed phase size which narrows down the weld line region.

Another morphology defect is flow marks apparent on the injection-molded polymer blends. A visual appearance of tiger stripes perpendicular to the flow direction forms as glossy and dull bands. The dull band region is referred to as flow marks (Zhong & Li, 2005). It is generally caused by a flow transition from a stable symmetric fountain flow to an unstable oscillating asymmetric flow. The spacing of the flow marks was proven not to be because of the processing conditions but the thickness of the parts. However, the formation of the flow marks are caused by the low cylinder temperatures and high injection speeds.

2.6.2 Existing Polymer Blends

There has been a growing interest in injection molding with polymer blends, mainly because of the feasibility aspect. The final morphology and the mixing results of injection with polymer blend is highly dependent on the physical and chemical characteristics of each polymer. As there is no additional step during injection cycle to mix plastics, the polymers' thermal and mechanical properties profoundly affect the moldability fo the resulting blend as well (Han et al., 1977). The blending trials containing PP and PE polymers are prioritized.

As the complete separation of PP from PE from post-consumer waste is fairly difficult, there is a fair number of blending trials that have been done to test the behaviour and compatibility (Tai et al., 2000). The sorting techniques used to separate PP and PE with methods like flotation are unfeasible due to the need for solutions while their densities are similar to one another. Tai et. al investigated the two types of PP/PE blend with HDPE and LDPE with 20 wt.% PE content for both blends. The tests have been done on dog bone specimens with a single-screw extruder. The impact behaviour is tested with a pendulum impact tester compatible with Charpy impact principles. The results showcased the highest result for the impact strength on virgin HDPE and the lowest on both PP/PE blends. The increase of HDPE will lower the impact strength, meanwhile, the addition of LDPE will marginally increase the impact strength. Radial cracks were observed in all specimens that caused fracturing. The temperature for the impact test altered the behaviour as well, which caused the PP/LDPE blend to perform the best at both 0°C and 20°C. Another study on the effect of thermal aging and blend composition on PP/LDPE blend showcased how polymer blends meet the performance requirements (Mourad, 2010).

The influence of morphology on the physical properties of immiscibility of polymer blends is crucial, which makes the phase separation a crucial issue. In polymer blends, morphology can be assessed by three distinct layers of skin, subskin and the core. The miscible and compatible blends refer to homogenous blend morphology, whereas the dispersed phase of the blend refers to heterogeneous blend. The methods affecting the morphology of the blend include blend preparation, mixing, and intensity. A study done for PP and EPDM showcased the differences of how each polymer behaves. It is observed that PP molecules are highly oriented in the flow direction as the dispersed phase separation (Fellahi et al., 1995). It is proven that compatibilizers create more stable morphology with lower elongation on the subskin layer.

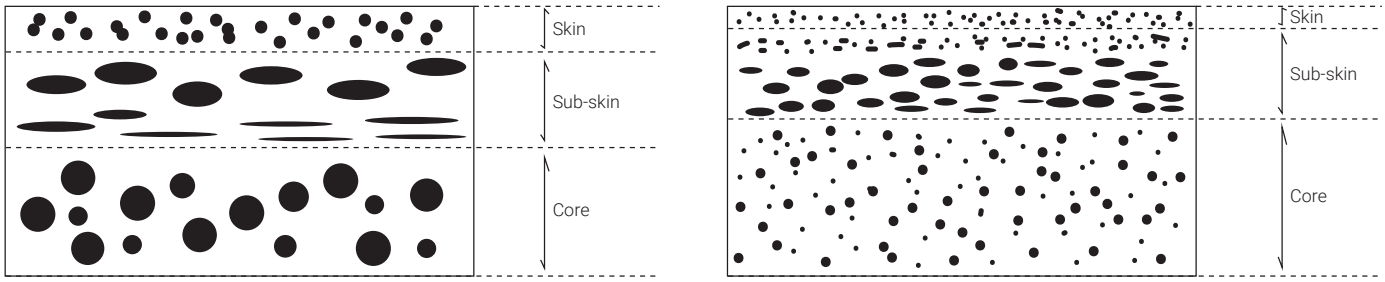


Figure 23: Schematic of the skin/core layers of injection molded blends (a) without compatibilizer (b) with compatibilizer (Adapted from: Fellahi et al., 1995)

Therefore, evaluating the miscibility of polymer blends is crucial to assess compatibility. A study has been done on the PP/PS blends with a plunger injection molding machine on ten specimens to determine physical and morphological properties. To create a blend for the injection molding, the polymers were first extruded with a single-screw extruder and chopped into flakes. The morphology of the blends with different blend ratios, including 60 wt.% PS and 40 wt.% PP, 75 wt.% and 25 wt.% PP, and three mixing devices, including a single-screw plunger, a single-screw plunger with a static mixer and a twin-screw plunger, were tested. The use of a single-screw plunger with a static mixer gave a smoother transition from PP to PS behavior. The elongation at break and shrinkage results did not affect the morphology results on different blends and mixing techniques. A recent study by Tai et al. also suggests the inevitable phase separation and incompatibility of PP/PE blends, therefore, Strapasson et al. evaluated the tensile and impact properties of PE/LDPE with 100/0, 75/25, 50/50, 25/75, and 0/100. The injection moldig results showed that the optimal processing temperatures of PP dominate the blend behavior in terms of compatibility, which is within the range of 170-180°C. The impact behavior tends to be lowered as the PP content increases. The appropriate temperature range for the injection cycle to prevent polymer degradation of PP is also found to be between 170-180°C.

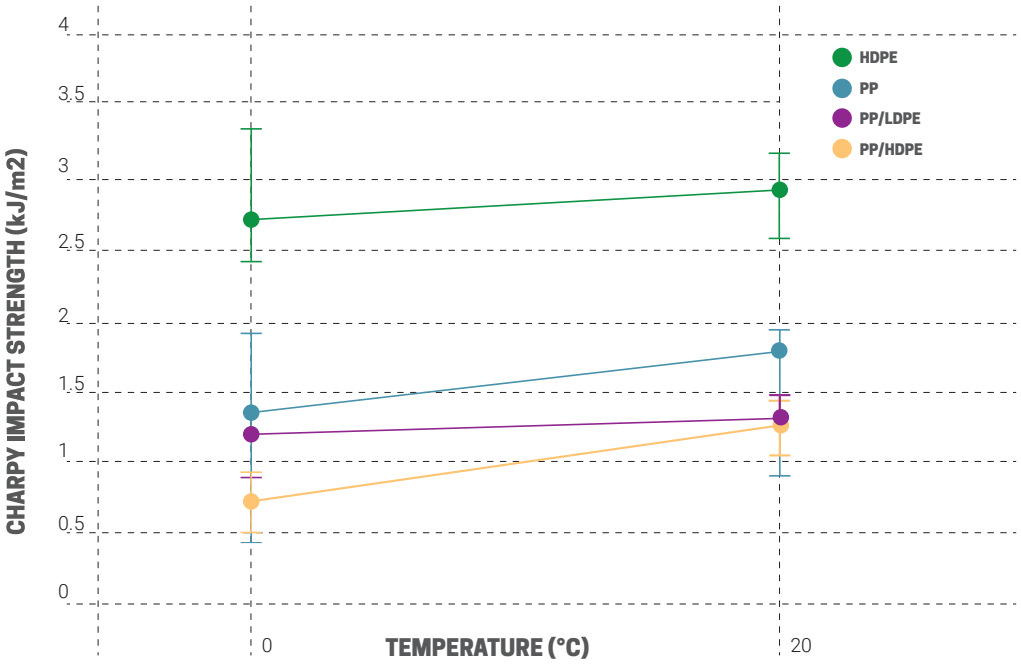


Figure 24: Charpy impact strength comparison of PP/PE blends (Adapted from: Tai et al., 2000)

colourants may decrease the recycling efficiency with dyes that are not detectable during the sorting process of mechanical recycling. The soluble or insoluble coloured dyes bond strongly to the polymer molecules during its application. A majority of plastic products contain plasticisers, which are softening agents used to decrease plasticity or reduce the material's viscosity. Plasticisers are commonly used in PVCs to increase the material's flexibility (Jia et al., 2022). As contaminations reduce the mechanical properties of recycled plastics, strategies like polymer blending with virgin materials enhance the mechanical performance and processability of the end product. This strategy also allows recycled plastic to be used in high-value applications despite its contamination (Vidakis et al., 2021).

2.7 Plastic in the Construction Industry

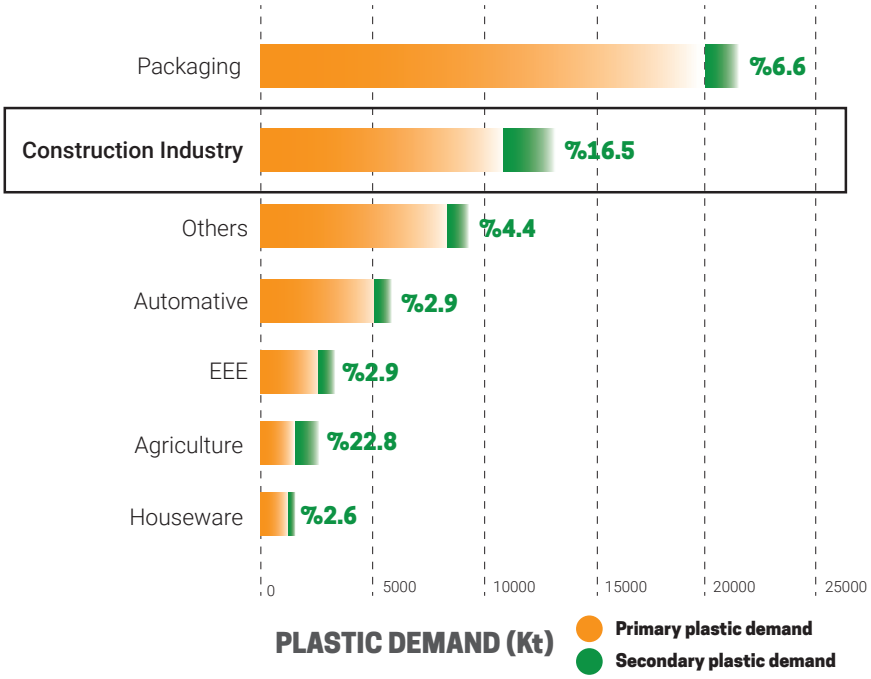


Figure 25: The primary and secondary plastic demand in new products per sector (Adapted from: Plastics Europe, 2022)

Plastic products and parts have become an integral part of daily lives to meet both functional and aesthetic demands. The wide range of its applications includes packaging, building and construction, automotive, electrical and electronic products, agriculture, medical fields and household (Plastics Europe, 2022). Plastic use poses a different life span based on its field of application. Some products tend to be exported for a second life service; therefore, they are not becoming waste. The lifespan of plastics in construction can be up to 35 years (OECD, 2022). In the Baseline scenario from the OECD report, plastic is expected to increase significantly in the construction industry.

The most used plastics in the construction industry are PVC, PE, PS, and PC. These materials provide resistance to corrosion, ease of fabrication, and their lightweight structure enables flexibility of application (Sadeghi et al., 2021). The growing economies invest in infrastructure and construction for durable plastics with long spans. The recent advancements in polymer technology have enabled the development of high-performance plastics that can withstand extreme conditions suitable for the construction industry (Sadeghi et al., 2021). The exploration of recycled plastics in the construction industry is also gaining traction. In 2020, converted plastic parts and products had a post-consumer recycled plastic content of 8.5% (Plastics Europe, 2022). The higher share of recycled plastics is apparent from the increase rate from 2018 to 2020. The construction industry has the second-highest recycled content rate in its products (see Fig.25). The reuse of solid plastic waste is commonly used to substitute virgin construction materials in mortars and concrete (Ragaert et al., 2017). Otherwise, it is recycled mechanically or chemically in an open/closed loop.

2.7.1 Existing prototypes

Integrating mechanically recycled plastics into the design sector has gained momentum as a sustainable alternative to traditional plastic products. Many prototypes include modular construction elements, consumer

goods, and packaging solutions. This section will evaluate the state-of-the-art existing trials of recycling plastics while mentioning the limitations and possibilities. By learning from the existing designs, the thesis can be optimised according to the existing integration of recycled materials into mainstream production.

The advancements in printer technology, like direct granule extrusion, allow for the reuse of plastic granules instead of filaments. Mechanically recycled plastic granules for 3D printing, such as PET, PLA, and ABS, can serve as distributed recycling for the additive manufacturing (DRAM) approach. M. Mohammed et al. argue that the DRAM approach can potentially increase recycling rates to reach circularity for plastics while it is feasible. DRAM's approach is centred on open-source plastic waste extruders known as recycle-bots, which upcycle post-consumer plastic waste into 3D printing filaments while decreasing the material cost of additive manufacturing. M. Mohammed et al. investigated the possibility of using ABS post-consumer EEE waste to fabricate 3D printing for tensile and compression samples. The virgin ABS filament and recycled ABS filament was comparatively analysed. The WEEE input consisted of black ABS components from computer equipment. The standard 3D setting for ABS with a print temperature of 235°C and a line thickness of 0.4 mm was used. The results showed that the optimal print temperature for e-waste ABS is within the range of 195-205 °C. The mechanical testing aided in the evaluation of material degradation of the recycled polymers. The results concluded that e-waste ABS printed material performed better under compression as opposed to virgin ABS printed material. The study showcased the potential of the DRAM approach replacing conventional 3D printing as there was over 500 times reduction in cost (M. Mohammed et al., 2022). Secondly, The Upcycle Lab project has implemented large-scale 3D printing from recycled PET from single-use plastic bottles. The study focuses on the applicability of additive manufacturing with recycled polymers for full-scale architectural applications (Yuan et al., 2023). The research setup included two extruders, a robotic arm and a 1.00 x 0.60 m heated build plate. The project concluded with a satisfactory implementation that proved the necessity to reduce issues of the extrusion of plastic flakes (Yuan et al., 2023). In addition to the Upcycle Lab Project, Ror et al. investigated the use of virgin, waste and recycled PET flakes' possibility to manufacture 3D filament. PET samples included water bottles, soda bottles, commercial bottles, recycled bottles, and virgin bottles in varying colours. A thermogravimetric analysis (TGA) demonstrated the thermal characteristics of the filament. Mass loss is the main indicator that can be used to conclude the thermal behaviour of each material. The initial thermal degradation of the filament samples started from the temperature range of 400 °C, in which recycled PET filaments showed the minimum mass loss compared to other samples. Other analyses, such as tensile property and morphology, showcased the possibility of using mechanically recycled PET as 3D filament rather than virgin PET polymer (Ror et al., 2023).

Integrating mechanically recycled plastic into the construction industry has gained momentum due to the growing demand for sustainable building material alternatives. Several prototypes integrate recycled plastics from various waste streams into a building material. EEE plastic waste is treated mainly by incineration, which releases secondary pollutants and harmful gases. Plastic is the second major component in WEEE streams and a good source to be used in the construction industry (Goh et al., 2022) (Arya et al., 2023). Researchers have been studying the capability of WEEE plastic to be substituted as aggregate in concrete. Arya et al. proposed replacing natural fine aggregates with obsolete WEEE keyboard plastic polymers to reduce WEEE's environmental impact. The experiment included creating several brick cubes with varying ratios of materials, including plastics, eggshells, fly ash, sand, and cement. A combination of brick cube specimens with different material ratios, as concluded by thermal, mechanical, and water absorption tests, shows that the correct ratio of WEEE plastic polymer in the concrete would showcase a workable, sustainable alternative to the traditional concrete block. Goh et al. performed a life cycle analysis on the recycled WEEE plastic use in concrete, aiming to prove the replacement of natural fine aggregates with recycled plastic polymers will reduce the carbon footprint. The several drawbacks of the analysis were the complexity and cost of the WEEE stream to recycle, lower compressive strength compared to natural aggregate use, and the hydrophobicity of plastic that causes weak bond development (Goh et al., 2022). Overall, the study regarded the maximum allowable replacement of WEEE plastic as aggregate by 20 wt%. Considering that CO2 is the highest contributor to environmental damage, the use of WEEE plastics for aggregates of concrete blocks shows a significant reduction in carbon footprint.

In addition to implementing recycled polymers into concrete blocks, Debele investigated the replacement of cement with recycled polymers for floor tile applications. The recycled plastic-sand composite material comprises LDPE, HDPE and PET waste plastic inputs. The shredded plastic polymers were mixed with heat and sand until a homogeneous blend was achieved. Water absorption and structural tests point out the

applicability of the tile specimen with recycled polymer content (Soni & Das, 2022). Another prototype done in the construction industry is a comparative study between recycled plastics roofing tiles and three traditional roofing solutions: ceramic roofing tiles, concrete roofing tiles, and zinc sheets (Gaggino et al., 2018). The used waste stream for the recycled prototype includes crushed rubber from end-of-life tyres and LDPE from an industrial waste stream. Mechanical tests such as impact resistance, thermal conductivity, and permeability to air and water were done to test the applicability of the prototype. The recycled roof tile had lower thermal conductivity than the traditional tiles, which indicates that without the use of additional insulation material on the roof, the prototype performed the best. Other mechanical tests proved the compliance of all roofing tiles with standards with satisfactory results. Additionally, an economic feasibility study showed that the price per m2 of recycled roofing tile is lower than ceramic roofing tile, which proves its' feasibility (Gaggino et al., 2018). Finally, Thomas et al. investigated using recycled plastic polymers in brick construction. Shredded HDPE waste polymers and clay with a 1:4 weight proportion are moulded into 225 x 125 x 75 mm bricks. Compared to normal clay bricks, the compressive strength, tensile strength, and water absorption tests were acceptable (Thomas et al., 2023).

Some prototypes showcase the use of recycled polymers in application on a product scale. Çetin and Türkan tested the applicability of blending 30 wt% recycled and 70wt% virgin ABS polymers for switch and socket frames. After obtaining the mechanically recycled ABS recyclates, grinding mill and oven-drying facilities were used before blending them with the virgin ABS polymers. Various mechanical performance tests, such as impact and yield strength, were conducted to ensure safe and effective implementation for EEE appliances. The results of the study based on the comparison between virgin ABS products and recycled polymer blend products conclude that even though there was a slight decrease in tensile and impact strength, the prototype maintains applicable mechanical performance like its reference grade (Çetin & Türkan, 2024). Secondly, another product-scale prototype of mechanical recycling is the Greentile slanted green roof elements. The study aims to apply a material-driven design to inject the mould of a product from the sink fraction of the post-consumer waste sourced from the Netherlands (Ragaert et al., 2020). The sink fraction is mainly implemented to remove non-ferrous metals and PVC and obtain PET and PP. As the mould is an original design, a FEM simulation has been done for various load scenarios to conclude the mould development. The product optimising tool, FEM simulation, enhances the applicability of the product by providing insights into material behaviour and performance evaluation. A life cycle assessment was conducted on different scenarios containing incineration, use of virgin polymers, etc., resulting in the product's open-loop mechanical recycling to be the best alternative.

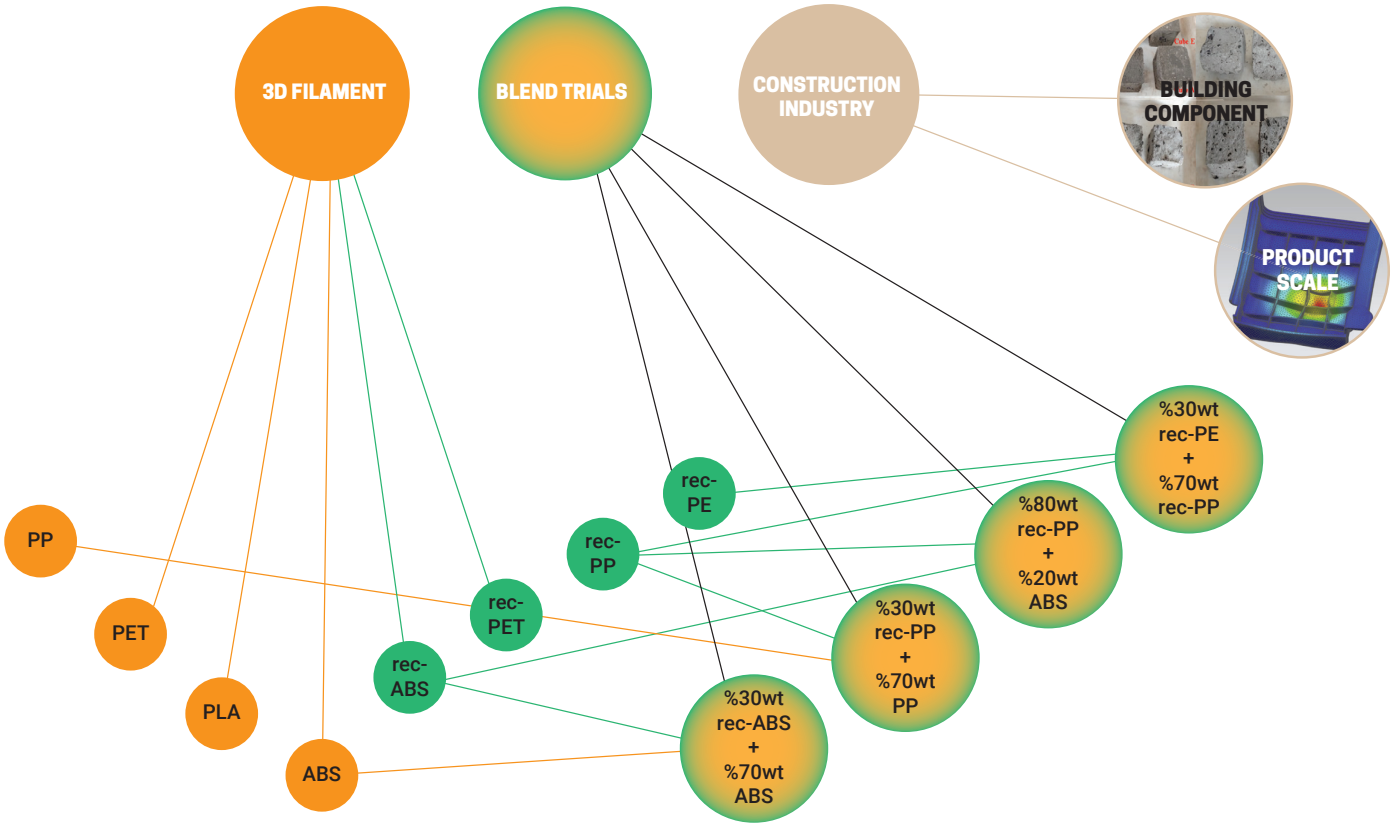


Figure 26: Diagram summarizing existing prototypes under their respective categories (Source: Author)

After the physical implementation of the Greentile on a roof system, it has been proven that the recycled plastic design is a good alternative to conventional designs (Ragaert et al., 2020). Finally, Gabriel and Tiana proposed recycled pellets from various virgin and recycled PP blend ratios to see the applicability in packaging. The study included mechanical testing such as modulus of elasticity and tensile strength of the blends compared to %100 virgin PP. Based on the mechanical properties of the specimens, the density difference was negligible. However, the tensile strength and modulus of elasticity tend to increase as the virgin plastic content in the blend increases. Another major contributor to the best-performing blend selection was the elongation at break, in which blending recycled PP made the specimen less brittle. Overall, the best-performing specimen was the blend with 30 wt% recycled content.

2.7.2 Existing Methodology and Criteria

Sustainable design approaches consider a product's social, environmental, and economic performance over its lifecycle. This includes implementing closed loops and reverse logistics, where recovered materials are used to reduce raw material extraction while returning the material to manufacturing after the end of service life. Therefore, Design for Recycling has gained momentum from the industries to enhance resource efficiency and minimise waste. A survey done by the University of Warwick on 150 manufacturing companies shows that companies' most used sustainable design strategies include design for reduced resource use and design for recycling (Dornfeld & Linke, 2012). End-of-life process flows are critical to determining the effectiveness of the recycling technologies. The EOL process flow model (see Fig. 27) represents a product's processes until the final treatment. Mizuno et al. proposed an EOL process flow model for WEEE LCD TVs that showcases the individual flows of each component (Dornfeld & Linke, 2012). The existing flow diagram has the potential to be compared with future scenarios to identify resource efficiency.

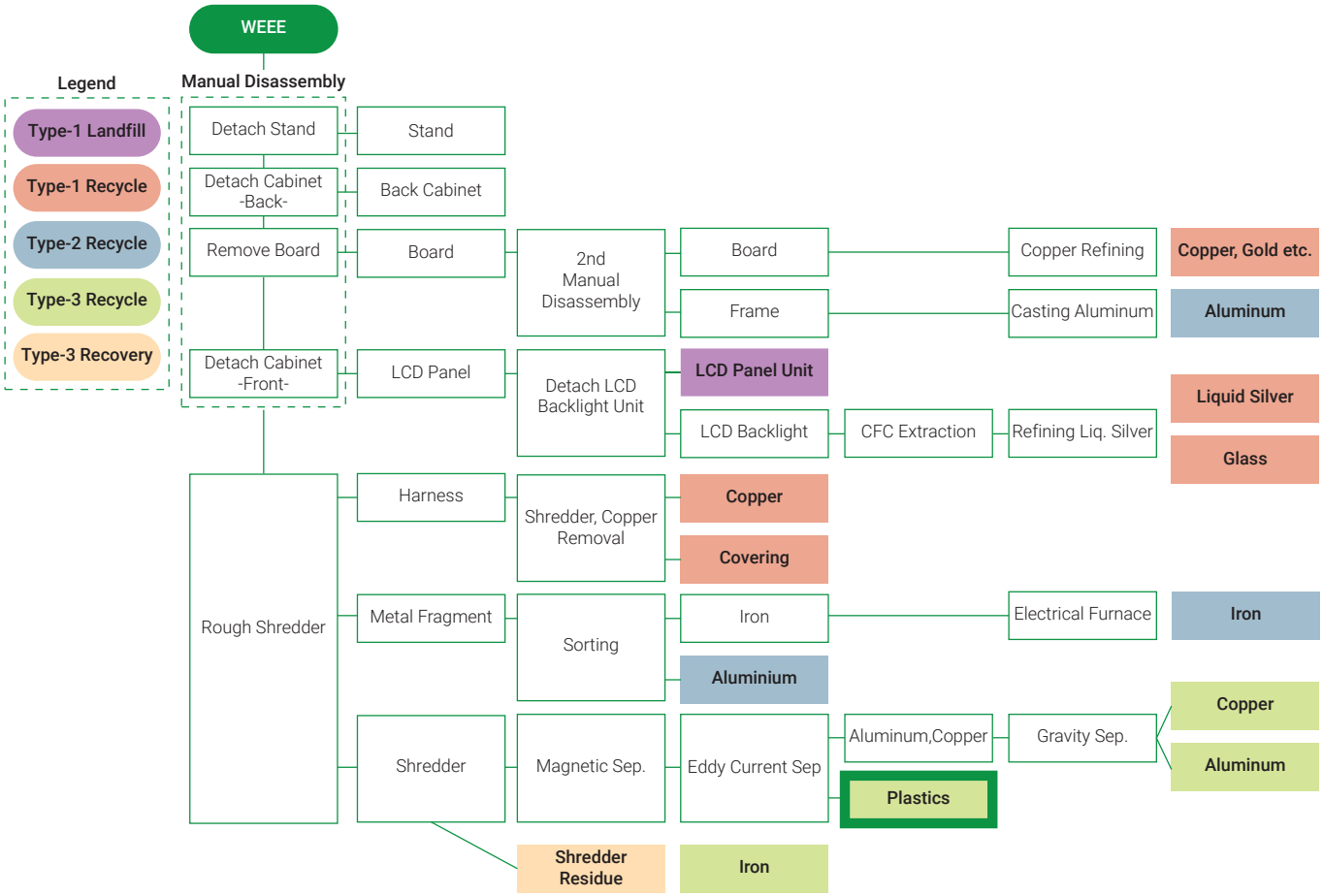


Figure 27: EOL process flow model in Europe scenario (Adapted from: Dornfeld & Linke, 2012)

Kawecki et al. propose a similar flow model (see Fig.28) for no specific waste stream component but for seven polymers (LDPE, HDPE, PP, PS, EPS, PVC, PET), showing the plastic flows from production to waste management. The flow model consists of five stages: production, manufacturing, consumption, waste collection and waste treatment. The model differentiates the polymers based on primary and secondary production. The

intermediatory import and export flows identify the product sectors of packaging, construction, automotive, electrical and electronic equipment, agriculture, clothing, etc. A separate flow diagram for the individual polymers in Europe, which enables visual comparison between other polymers, concludes that production is the dominating input for all modelled polymers (Kawecki et al., 2018). Kawecki et al. state the usability of flow models in identifying priorities to reach recycling targets. The first European Circular Economy Action Plan (CEAP) adopted the Plastics in Circular Economy strategy that aims to transform how plastic products are designed and produced in the future (Berwald et al., 2021).

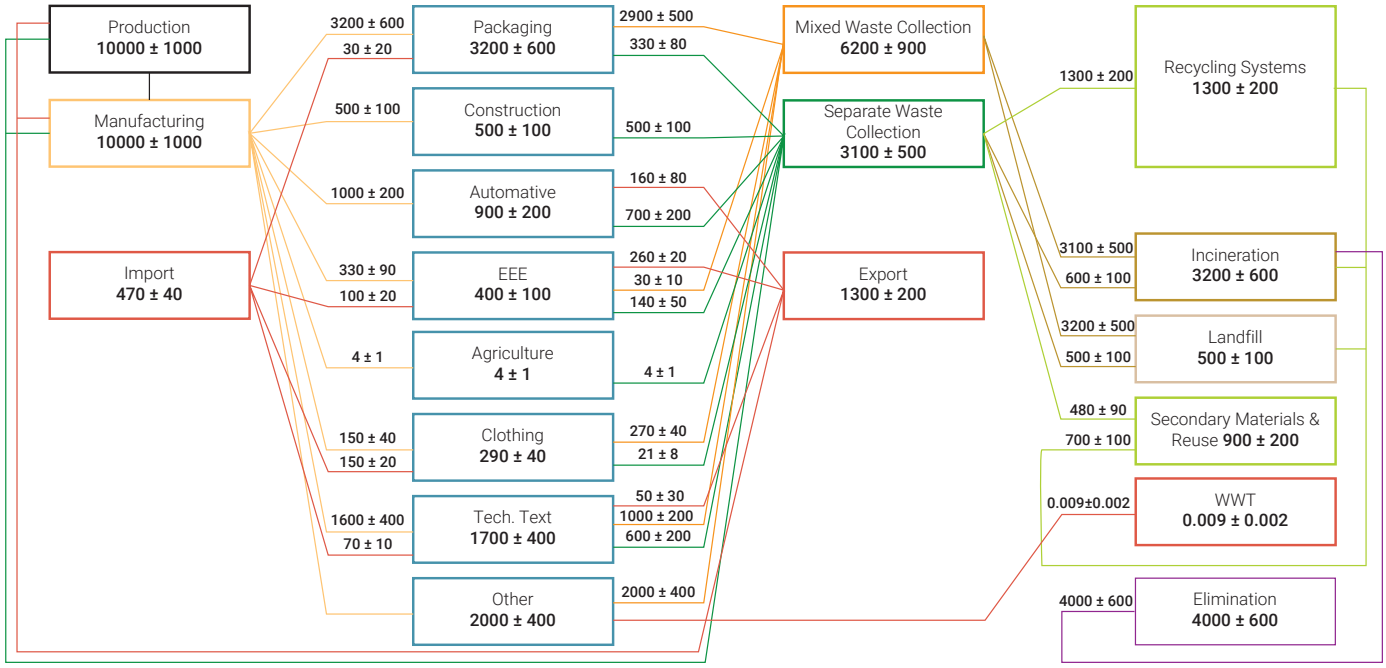


Figure 28: Material-flow model for PP polymer with the width of the arrows indicating the volume of mass flow and white bars indicating large mass accumulation (Adapted from: Kawecki et al., 2018)

The second CEAP restates the strategy and the importance of more resource-efficient and better plastic recycling. Despite the advancements in the methodologies for the DfR approaches, several challenges remain during the product design phase. Therefore, developing effective methodologies and criteria for prototyping with waste streams is important. An analysis of the existing guidelines and frameworks for DfR is made. Peters et al. developed a performance indicator for the design for recyclability parameters from the design for excellence method (DFX). The proposed design support tool that evaluates recycling performance has been proven satisfactory with tested trials (Dornfeld & Linke, 2012). The lowest value from the indicator concludes the product to be the best fit for energy recovery, whereas a high value proves the product's recyclability. The application of the support tool includes the user setting a recyclability performance objective and selecting the strategies to achieve that objective. Then, a prototype is created that complies with the strategies, and finally, the product's recyclability is assessed.

Berward et al. proposed a guideline specifically for the WEEE plastic stream, divided into two levels: the product level, which encompasses the start-to-concept stage, and the part level, which encompasses the concept-to-production stage. The guidelines mainly include avoiding hazardous substances, removing polluting parts, using recyclable materials that WEEE recyclers will recycle, eligible material combinations, and using recycled materials. The design guidelines proved to be serving the Circular Plastic Alliance's objective of boosting the EU market for 10 million tonnes of recycled plastics by 2025 (Berwald et al., 2021). Additionally, recycling/recovery rates is another matrix used to evaluate the efficiency of the recycled products. LCA assessment is one of the methods that can be used to compare the primary and secondary production of the material (Stallkamp et al., 2022). Two mathematical assessments, including material substitution rate (MSR) and circularity potential (CP), are calculated to assess both physical and quality losses. Eventually, the three assigned quality groups (low, medium, and high) are identified. If the material is identified as low-quality, the assessment suggests the application of the construction sector or automotive for the recycled product (Stallkamp et al., 2022). The assessment method was tested for lightweight packaging waste cases in Germany, and its applicability for assessing secondary plastic material quality was proved.

2.7.3 Plastics in Concrete Construction - Reinforcement Spacers

The construction industry accounts for 20% of total European plastic consumption, making it the second-highest field of plastic application (Plastics Europe, 2022). A variety of applications, including insulation, piping, reinforcement, and formwork accessories, utilize plastic components. They are being used mainly in reinforced concrete structures to enhance durability and functionality (Yang et al., 2020). There has been recent studies that incorporate plastic into the construction elements. As mentioned earlier, Arya et al. proposed a recipe in which WEEE plastic polymers are used as aggregates in concrete. Other studies include incorporating plastic fibers into concrete to enhance tensile strength while reducing cracking (Neamat & Shamsborhan, 2020). The industry reports indicate the need for plastic materials used for reinforcement, particularly on infrastructure, high-rise buildings and reinforcement (Zezulová et al., 2023). The growing need for innovation in the construction sector to reduce resource consumption is apparent in recent studies.

A growing percentage of the plastic applications in concrete construction contain critical injection molded pieces like reinforcement spacers that are used to maintain the required concrete cover over steel reinforcement, guarding the steel from corrosion. The corrosion of concrete reinforcement occurs in a pH range of less than 9. For the context, a newly made Portland concrete has a pH value between 12 and 13 (Zezulová et al., 2023). In general, reinforcement spacers are made from fine-grained concrete, plastic or metals. Spacers are an indispensable apparatus in reinforced concrete construction (Neamat & Shamsborhan, 2020). The main purpose of a reinforcement spacer is to protect the steel rebar and hold it in a precise location inside a formwork. As the size of the spacer governs the size of the concrete cover, the spacer protects the enclosed steel strengthening from the outside atmosphere. It is proven that if the spacer attains the as-built state after casting, it proves its predictable design purpose in terms of toughness, firefighting and serviceability. The regulations and building codes necessitate a spacer to be placed for every meter or less span to guarantee workability (Neamat & Shamsborhan, 2020). Although the concrete covers the spacers during casting and the spacers hide under the concrete matrix, spacers play a vital role, as an improper placement can lead to serious structural weaknesses (Maran et al., 2022). The type of spacers can be categorized into six main types: plastic spacers with a clip-on/off action, plastic tower spacers, plastic wheel spacers, cementitious block spacers for heavily reinforced sections, continuous line spacers, and steel wire chairs.

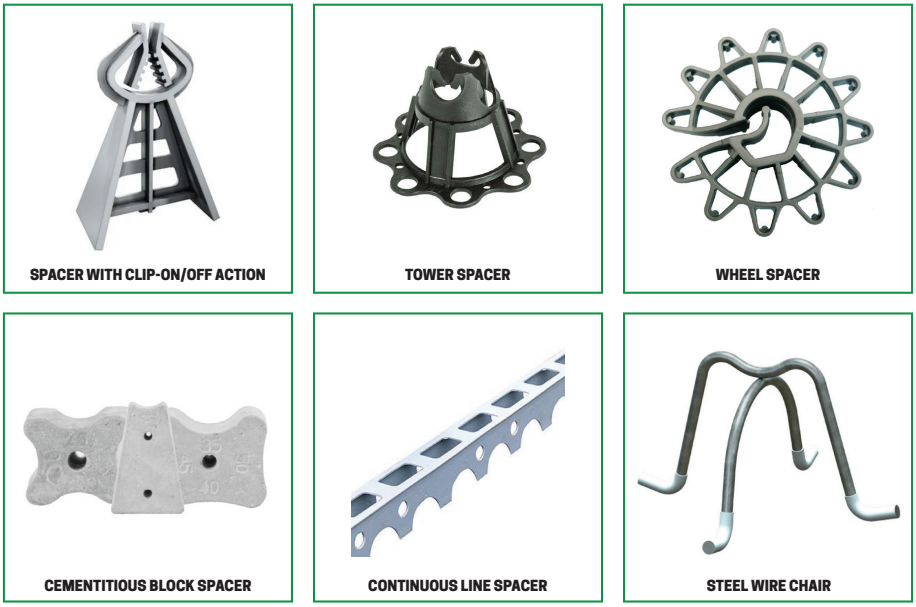


Figure 29: The six types of reinforcement spacers (Adapted from Alzyoud et al., 2016)

Different types and materials of reinforcement spacers create a distinctive difference in the behavior. The use of fine-grained concrete is the most advantageous as there is no significant weakening of the structure after the structure is concreted. However, the concrete options are more expensive, so the plastic reinforcement spacers is the most commonly used components for reinforced concrete constructions (Zezulová et al., 2023). The plastic spacers present a linear and systemic weakening of the structure and the design allows the concrete to flow in between while casting. The plastic spacers are the most common because of cost effectiveness and not being labor-intensive (Alzyoud et al., 2016). Therefore, the thesis considers the plastic type reinforcement spacers as the focal product.

2.7.4 The limitations and possibilities

As there is limited research available on the effect of plastic reinforcement spacers on concrete microstructure and long-term effect during the lifespan of concrete, Neamat & Shamsborhan investigated the ground reinforcement spacers' advantages and disadvantages based on five main factors: size, assembly step, clamp, weight and manufacturing. The structural necessities based on the European and British standards are used to come up with benchmarks.

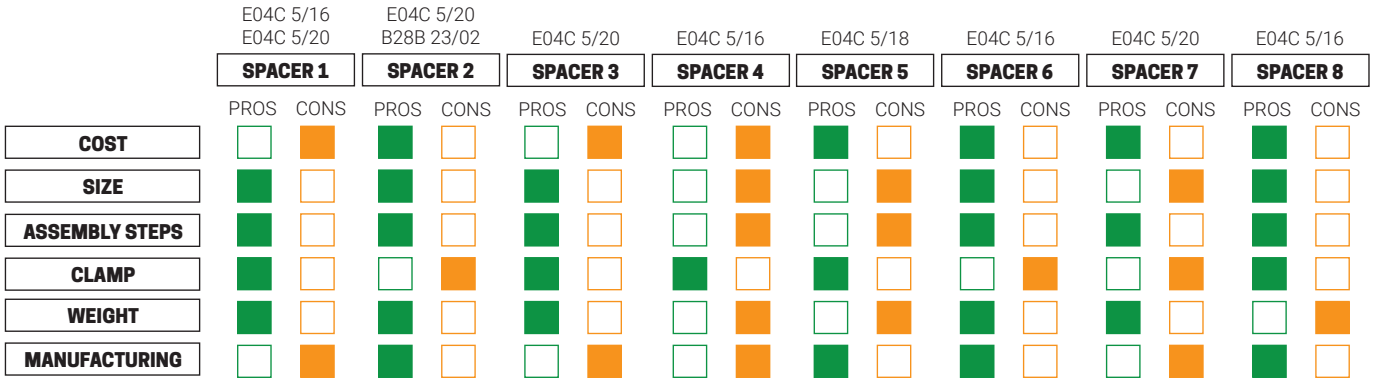


Figure 30: Evaluation on various papers written for reinforcement spacers based on five factors (Adapted from: Neamat & Shamsborhan, 2020)

For the identification of the plastic reinforcement spacers, two possible fixing locations (straight, upside down) are defined to be able to fix the strengthening bars in place. Structural behavior of a reinforcement spacer is not included in the design calculations based on the European parliament regulations. This removes the requirement to showcase any of its characteristics structurally (Zezulová et al., 2023). Neamat & Shamsborhan suggested that a spacer still needs to be able to carry the movement of the steel bar under 5 N loading. To locate that movement, a clip-on/off function can be designed in the spacer or a fixity piece, such as wires, can be used to tie them together. The author highlights the importance of stability and resisting deformation, which showcases possible failed scenarios of spacers before casting. The loading scenario for the least assessed weight defined for a generic spacer based on the labor, concreting, is found to be 3.0 kN. For the submission of the strengthening steel, an extra 0.15 kN is estimated for placement.

The available variations of plastic reinforcement spacers, including wheel spacers, cage spacers, detachment spacers, and adjustable spacers, are analyzed. Some characteristic advantages are found to be controllable height and position aspect assigned to the user, which prevents deformation of a vertical and horizontal rebar. Additionally, the ability to execute bar arrangement for rebars in different directions excludes the necessity to use another component for a coupler to connect to rebars. However, Neamat & Shamsborhan did not find any of the available variations compatible with all five factors that were used to evaluate. Another limitation is the chance of a spacer facilitating agents like chloride, water, and oxygen through the spacer. This would cause the spacers to accelerate deterioration (Alzyoud et al., 2016). Another observation by Alzyoud et al. states that there is a high chance of local corrosion occurring at the locations where spacers are. Even though there is no fundamental research being done on this topic, the spacer being highly porous, having poor compaction, and the issue of debonding are taken into consideration. Alzyoud et al. carried out an experiment on the effect of reinforcement spacers from all plastic, cementitious and steel materials on the effect on the microstructure of concrete. Various aggregate sizes, cover depth, curing age, and cement mix were tried to prove the effect on the penetration of the concrete matrix into external media. It is proven that the spacer-concrete interface has higher porosity, lower cement content and higher water/binder ratio. Therefore, debonding and microcracking occurred in that interface. The weak bond of plastic and concrete resulted in the highest porosity results out of all spacer types. These results showing the defects spacers have on the microstructure are tested for all the horizontal reinforcement, including beams and slabs (Muslim et al., 2020).

Muslim et al. conducted another experiment on the plastic and cementitious reinforcement spacers on vertical application to determine whether the presence of spacers would affect the microstructure of the concrete columns and walls. The tested 50 mm cover plastic reinforcement spacer is made from PVC and falls into the category of clip-on/off action. After casting thirty-six columns with a fabricated timber framework, the author

concluded the study with concrete columns showing higher porosity, conductivity and increased transport of matrix for the ones with reinforcement spacers.

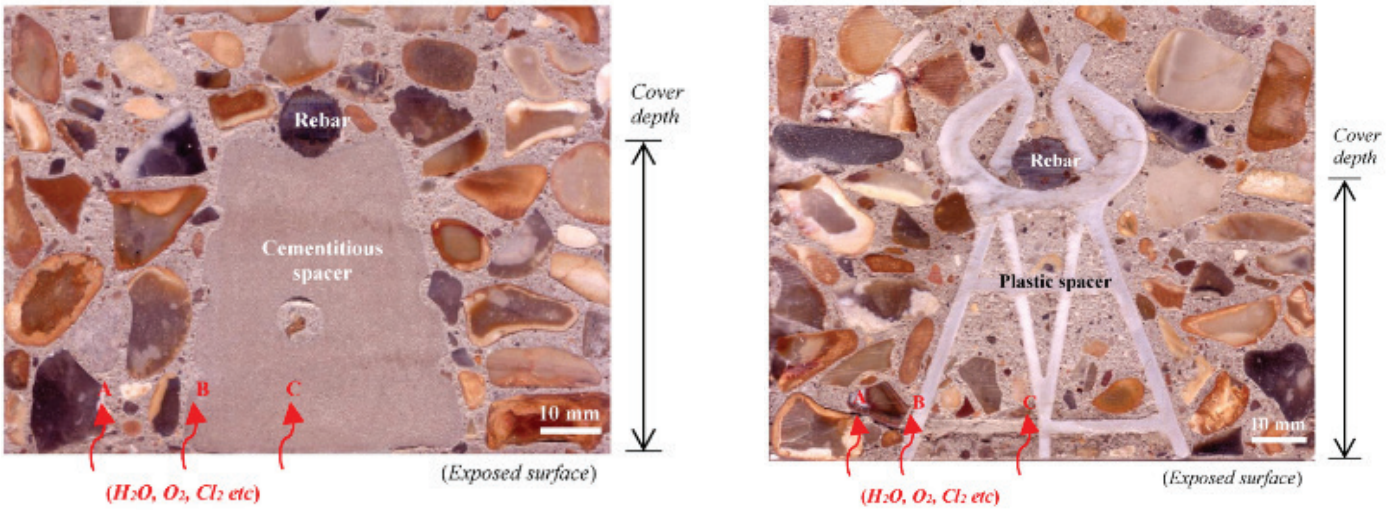


Figure 31: Cross-section of reinforced concrete with cementitious block spacer and clip-on/off spacer (Source: Alzyoud et al., 2016)

As spacers need to be placed in a span of one meter or less, it is evident that the combined effect of thousands of spacers in a structure is significant. This suggests a high quantity of reinforcement spacer use; a reinforced concrete construction site requires implementation. One of the significant advantages is how the spacers are hidden inside the concrete matrix for the whole life span after the concreting process. Not being exposed to environmental factors which normally cause degradation of performance suggests the applicability of using contaminated or low-quality blends (Barreto et al., 2016). By ensuring the correct positioning of the reinforcement spacer, the issues related to chloride ion penetration and other aggressive agents can be mitigated (Zezulová et al., 2023).

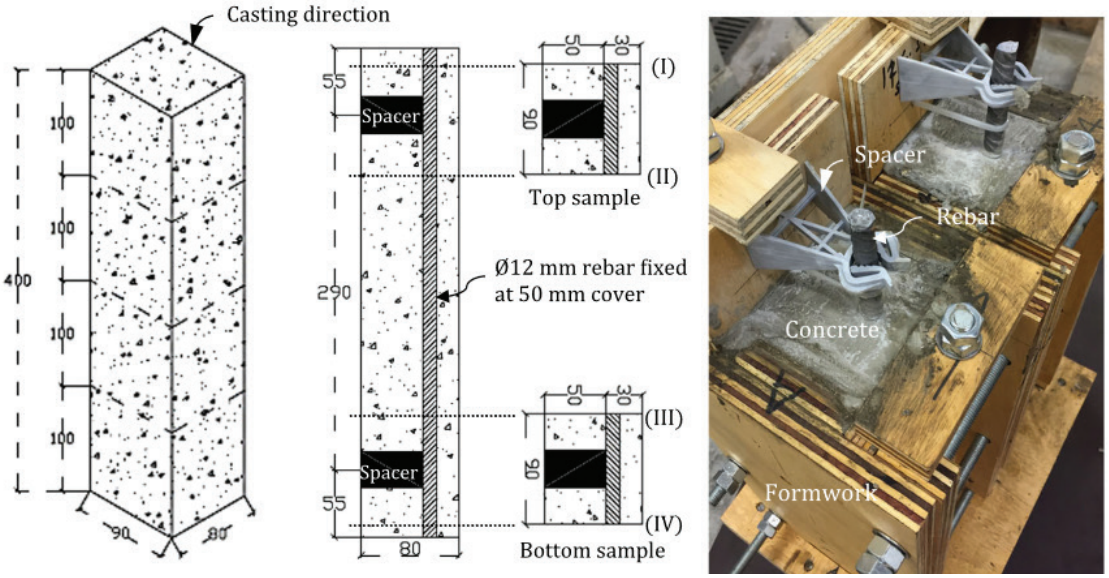


Figure 32: The experiment setup with cross section and top view of the formwork during casting (Source: Muslim et al., 2020)

2.8 Sustainability Analysis

Based on the Handbook for Technical Product Design, there are multiple methods of disposing of plastic waste: product recycling, material recycling, energy recycling, and landfilling. The handbook links product, material, and energy as recycling methods and landfilling as final disposal method (Peters, 2011). The lifecycle of a plastic polymer after becoming post-consumer waste involves either recycling or choosing between incineration and landfill. Based on the OECD report's data, the global annual plastic leakage is projected to double by 2060. Therefore, the current treatment of plastic waste is necessary to establish the starting point of the thesis.

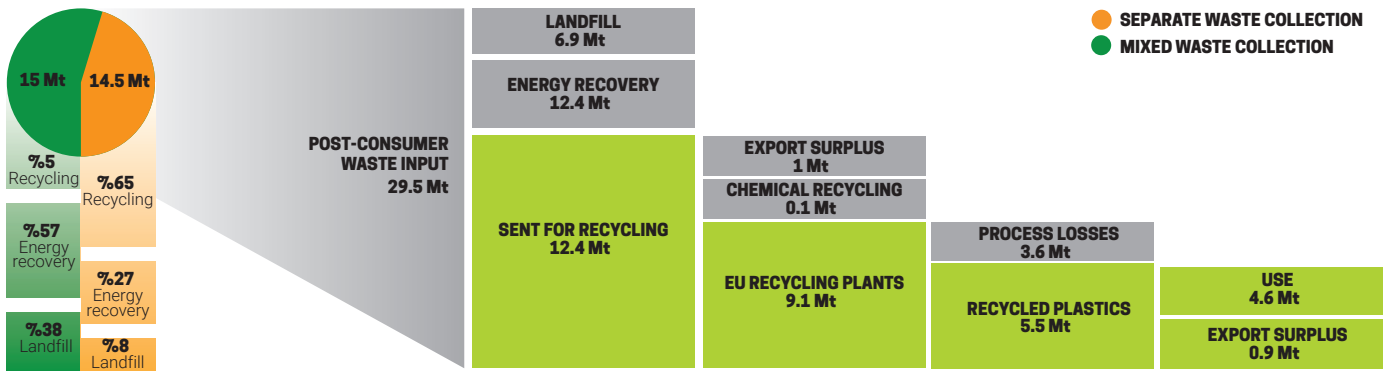


Figure 33: Post-consumer plastic waste flow in 2019 (Adapted from: Plastics Europe, 2022)

2.8.1 Global/NL plastic Waste Treatment

The waste treatment and resource efficiency depend on firstly how the waste is collected and then how it is treated. Plastics Europe 2019 data on the waste management of post-consumer plastics showcases the current limitations of the plastic value chain (see Fig.33).

Landfilling is a common practice for post-consumer plastic waste. It accounts for 40-60% of waste disposal, depending on the country's income level. There is a tendency of a decrease in the rate for European countries (Lange, 2021). However, landfill rates are still uneven across Europe based on the implementation of landfill bans. Western European countries like the Netherlands, Belgium, and Denmark have less than 10% of landfilled plastic waste. The rate goes up to 50% in countries like Greece and Spain (Ragaert et al., 2017). This amounts to 150 Mt worldwide, half of the plastics produced. This worldwide landfill amount indicates the high potential of the energy recycling method of incineration. Although incineration has the advantage of generating energy, releasing greenhouse gasses and pollutants is an inevitable part of the process. Overall, the total GHG/CO2 emissions of plastics is a result of half due to the production, the other half due to incineration.Therefore, recycling has become the preferred method for disposing of plastic waste. The worldwide data shows that based on carbon footprint and energy requirements, mechanical recycling performs the best (Lange, 2021).

Based on TNO's comprehensive analysis, the Netherlands' transition from a linear to a circular plastic economy is discussed. This contributes to strengthening the competitive advantage of Dutch companies. The 2018 data in the Netherlands shows that most Netherlands-origin plastic waste is incinerated, followed by mechanical recycling, chemical recycling, and landfill. This indicates that even before the landfill ban in 2019, the Netherlands was performing quite well in terms of landfill rates. Currently, incineration provides 2.4% of the electricity production in the Netherlands. Nevertheless, TNO states that incinerating is not optimal for resource efficiency. The 2050 projection of TNO does not include landfills as an end-of-life scenario and expects a big fall in incineration. 87% of plastic waste is expected to be recirculated as new products, and the recycling sorting will be optimal with minimum material loss. The aim of the thesis perfectly aligns with the projection set for 2050. Therefore, TNO's eight must-have solutions set for realising the 2050 goal and their step-change innovation plan are taken into consideration for further analysis.

2.8.2 Global Warming Potentials

Emissions from producing polymers and processing them into end products amount to 90% of the emissions of fossil-based plastics (OECD, 2022). The increase in emissions is mostly caused by fibres used for textiles, PP, and LDPE. The remaining 10% is caused mainly through incineration. Recycling and secondary plastics production reduces GHG emissions by limiting increased land use and eutrophication. The increase in GHG emissions in the 2060 projection concludes the need to mitigate plastic use and waste by increasing secondary plastics' availability and decarbonising production and waste treatment processes. In the Baseline scenario of OECD, total GHG emissions from plastics' production and end-of-life scenarios will increase tremendously with a slight increase in recycling. The expected increase in GHG emissions is mainly from the production and conversion of fossil-based plastics. Therefore, decrease in global plastic use, and availability of secondary plastics are suggested as mitigation options (OECD, 2022).

The Sustainable Systems Engineering Group of Ghent University's implemented an environmental impact study on seven commonly used polymers (PP, HDPE, LDPE, PVC, PS, PE, PET, PUR) that make up for 65% of total plastic use (OECD, 2022). It estimates the environmental effects of manufacturing and use of products. It considers two life stages for the seven polymers: production, where the polymer could be produced from primary or secondary material and end-of-life, where the polymer can be mechanically recycled, incinerated, landfilled, dumped or burned. Based on the study, mechanically recycled secondary plastics score the best for all polymers. PET and PS present the lowest impact, but the polymers make up a maximum of 5% of the plastics used in 2060. The production is responsible for more than 85% of the impacts on ozone formation, acidification and land use. The mismanaged waste and incineration follow-up contributed to more than 40% of the environmental impact. Therefore, an efficient transition is necessary from fossil-based feedstock to secondary plastics production.

2.8.3 Existing Policy Scenarios

Several policies and tools are currently available to change the make-take-dispose business plan for fossil-fuel-based plastics. Firstly, regional and global action policies will be discussed, focusing on OECD countries, including the Netherlands. The Regional Action policy focuses on stimulating the secondary plastic market, where the share of mechanical recycling is expected to increase tremendously through 2060. Both micro and microplastic leakage are projected to decrease by 62% in 2060. The regional policy involves a gradual approach that will boost the increase in the circular use of plastics. The policy follows three routes: restraining the demand for plastic, enhancing recycling and closing leakage pathways. This is expected to result in plastic waste facing an increase of 40% in recycling rates.

The Global Ambition scenario predicts the plastic leakage to be near zero by 2060, with an annual leakage of aquatic environment pollution to fall by 98% compared to the Baseline scenario. The projections regarding enhanced recycling techniques are similar to regional policy, where priority is given to restraining demand, enhancing recycling, and closing leakage pathways. The two policies can be compared based on the expected use of plastic in different sectors, including construction (see Fig.19). Even though the use of plastics is still high in the construction sector, it is expected that in non-OECD countries, motor vehicles will take second place in the most used sectors. However, overall, the construction sector still has the second highest plastic use demand, indicating the need for secondary plastics.

The inadequacy of global policies addressing the challenges associated with WEEE poses a public health and environmental sustainability. According to the UN's E-waste Monitor in 2020, the world generated a 21% increase in e-waste in five years (Borthakur, 2022). The European Union focused more on e-waste legislations with its WEEE Directive in 2003. The directive includes approaches like extended producer responsibility (EPR), which requires manufacturers the bear the cost of recycling their products after their life cycle. This approach is widely adopted to encourage manufacturers to design their components with recycling in mind (Bhaskar & Turaga, 2017).

In addition to WEEE Directive, other regulations like REACH also contribute to the reduction of environmental and health risks of WEEE. The regulation on the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) applies to nearly all chemical substances by defining rules that force manufacturers dealing with both the virgin and recycled polymers to comply. The legislation mainly targets the safe treatment of waste and the processes of waste to materials. REACH is designed as a linear approach for dealing with both virgin and recycled polymers, which is tricky while dealing with impurities, as they are regarded as the internal part of the substance. There is a regulation specifically meant to prevent hazardous waste from ending up in the recycling process and turning into a recyclate (De Römph & Van Calster, 2018). There are several limitations that the recyclers face under this legislation: identification of composition and registration. Gathering information for the composition of the plastic waste is possible either from available information from the industry suppliers or by conducting in-house laboratory analysis of the polymers. The registration of the polymers poses difficulties for the WEEE streams because the waste polymers can only have 20% impurities, while the other 80% needs to be the same already registered polymer before becoming waste (De Römph & Van Calster, 2018). This concludes the fact that REACH provides more obstacles to recyclers of plastic waste than primary manufacturers related to registration, restriction and compliance steps. On the other hand, the current possibility offered for the recyclers is the volume-based or time-limited exemptions offered for the research-oriented companies, which narrows down the restrictions.

The European Food Safety Authority (EFSA) is another policy focusing on the safety standards for the recycled materials used in food contact applications. The migration of the hazardous substances is evaluated based on this policy while recycling. Furthermore, standards like EN 71-3 also focus on the application of hazardous substances, mainly for the safety of toys. The standard focuses on the detection of heavy metals like lead, cadmium, and mercury that exist in high quantities in WEEE streams (L. Wang et al., 2019).

2.8.4 The Possibilities

It is apparent that the extended producer responsibility (EPR), according to the OECD, introduces a shift towards reducing environmental impacts from the production to the end-of-life of plastics. The existing mechanical recycling technologies are subjected to strict specifications of the input streams, and a limited range of output specifications showcase the gap for improvement in the current system. Therefore, TNO's alternative step-change innovation approach, as opposed to the state-of-the-art approaches, is required. Its focus on the plastic waste stream's collection, sorting, and logistics is crucial for real-life applications. Additionally, following the eight must-have solutions will meet the demand for reconsidering the current recycling technologies.

2.9 Field Study

The field study covered an essential part of the thesis, focusing on transforming the unrecycled plastic fraction from recycling processes into an architectural component. Contacting Netherlands-based companies was a priority to understand the approach and precautions taken in the Netherlands. Selected companies focus on various polymers and mechanical recycling steps, making it easy to gain practical and detailed insights into specific parts of the process. The approach taken was conducting interviews with the representatives and/or receiving samples from their unsorted plastic waste fraction. A summary of the interviews will be discussed in relation to the possibilities for the thesis. The companies included in this study are Veridis, Coolrec, Van Werven, Horizonteer, MEWA Polymers and Mirec Recycling.

2.9.1 Veridis – interview

Most plastic recycling companies do not use advanced technologies to characterise and sort plastic waste. Therefore, their sorting efficiencies are not high for mixed plastic waste. The Netherlands-based company Veridis provides a solution for the problems: different polymer types that do not mix well, complex analytical techniques, no uniform quality standards and missing accuracy of current sorting technologies. The mainstream use of optical scanning has limitations for black plastics, multi-layer plastics and compounds. In addition, current thermal analysis techniques have limitations for sample preparation and sample scale. Therefore, the company developed MADSCAN technology, which uses advanced thermal analysis to accurately identify different polymer types based on their melting and crystallisation.

Their technology can analyse larger sample sizes and measure flakes, granules and powder. The output of their scanning technologies is a polymer type-weight fraction table based on a temperature signal graph for polymers and power signals. The MADSCAN offers a patented sensor-based technology that enables unique thermal measurement principles and spatial identification systems. A sample chamber holds the polymer mix with sensor arrays located at each side of the plates, which presses the sample as it heats up and cools down. Based on the automated ML peak fitting data from each sensor located on the plate, it gives the polymer fraction map of that sensor area that outputs exact fractions. There are currently two available types of MADSCAN systems, and a new system is expected to function in mid-2025. The available MADSCAN T-30 system consists of 64 sensors with a sample limit of 30 grams and six hours of working time. The upcoming MADSCAN T-50 system has more than 250 sensors with 50-gram sample limit and 1-2 hours of working time. The precision of the T-50 system will increase while the polymer types it can detect also expand compared to the T-30 system. Based on the waste stream that the thesis will focus on, T-30 might not be feasible because it can detect only polyolefins, PET and PA6 polymers. Meanwhile, T-50 is expected to have a broader range of polymer detection, including ABS.

It is concluded that MADSCAN technology would be an optimal way to determine the weight fraction of the plastic waste sample more accurately and precisely. However, the scheduling of Veridis's upcoming system and phase two—experimentation—of the thesis will not align. Therefore, advanced sorting technology will not be used in this thesis.

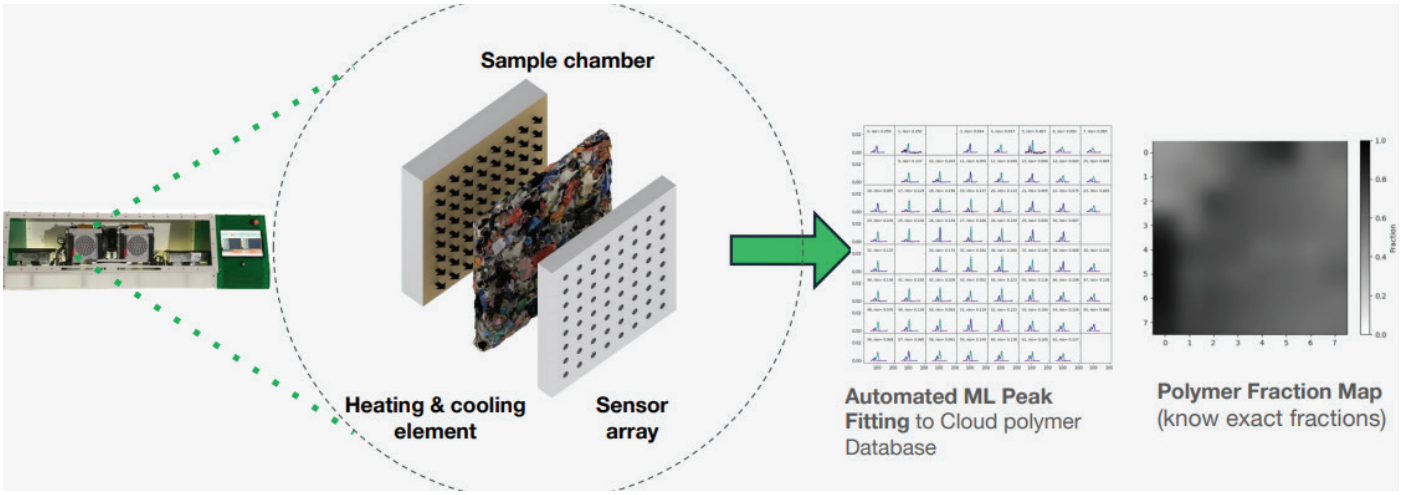


Figure 34: MADSCAN T-30 technology breakdown (Source: Veridis)

2.9.2 Coolrec – interview and sample

Coolrec is a subsidiary of Renewi, a leading waste-to-product company in the Benelux. Coolrec specializes in processing one of the dominant waste streams: waste electrical and electronic equipment (WEEE) into reusable raw materials. This includes cooling and refrigeration equipment, small domestic appliances (SDA), information and communication technology (ICT), heating equipment, and large white goods. Coolrec has three locations in the Netherlands: Coolrec Nederland, Coolrec Plastics, and Coolrec headquarters. The representative mentioned mainly Coolrec Plastics and gave insight into their facilities. Coolrec specializes in PS and ABS polymer types from the WEEE waste stream. They recycle 1,5 million fridges and produce over 30,000 tonnes of high-quality plastics annually. Their mechanical recycling process consists of four main steps: manual sorting of waste, removal of oil and refrigerants, shredding and separation of materials, and lastly, the treatment of refrigerants and blowing agents. These steps are taken partly in the Dordrecht facility and Waalwijk facility.

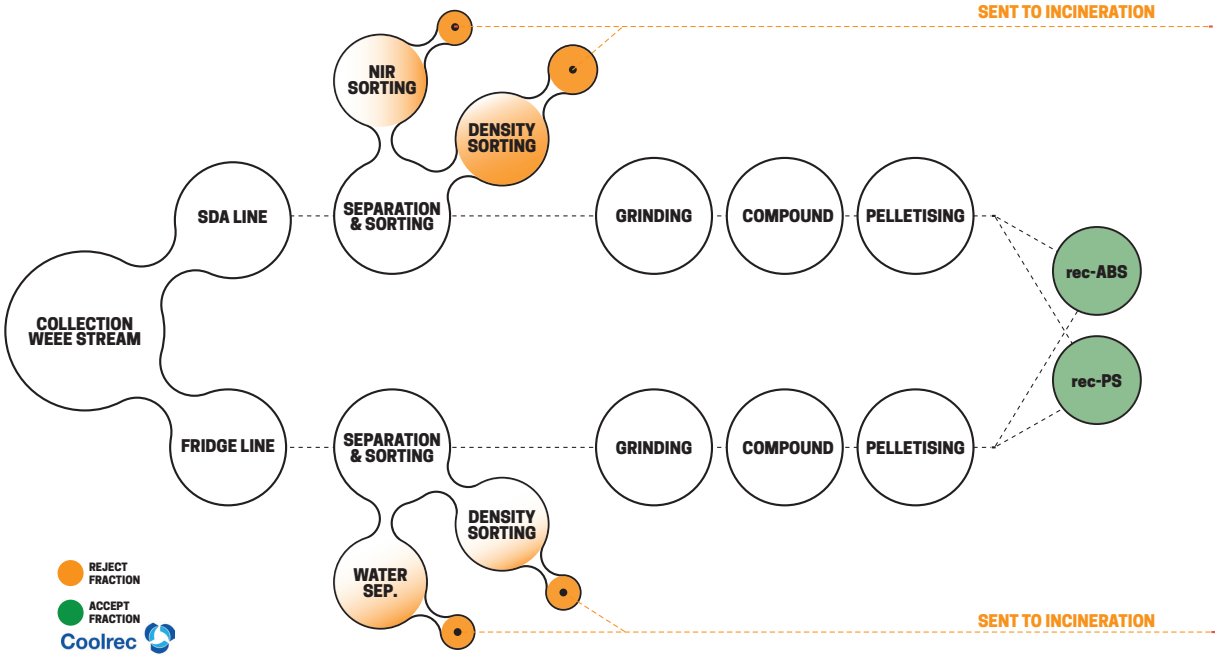


Figure 35: Schematic showing the mechanical recycling steps where reject fractions are collected from (Source: Author)

Coolrec receives two main types of mixed plastic waste input from the WEEE stream to their mechanical recycling facility: fridges and small domestic appliances. The sorting techniques are important for the thesis, while economic reasons usually limit the recycling company from recycling each polymer during the sorting stage. A common approach is to select specific polymer types and send other polymers to recovery, which is incineration in the case of the Netherlands. A detailed overview of Coolrec's sorting process is analysed to see the boundaries and possibilities of the EEE plastic waste (see Fig.35). After the company receives two types of inputs, the recycling process is maintained in two separate lines. The difference in the contamination, like

food contact and flame retardants, allows the separation to aid in having a higher yield of plastic products. The first step of the sorting process is metal separation, which sends metals to different facilities for recovery. The next step is density baths with water and salt to acquire heavy plastics -ABS, PS, and ABS/PC polymers- from the complex mix. There is an evident material loss during this stage. This reject fraction includes a high mix of materials like undetected metal, aluminium, wood, cable, foams etc. Additionally, a portion of the reject fraction is water, dust and foam. The representative mentioned possible reasons a polymer might end up at the reject fraction, such as the dust sticking to the plastic or not satisfying the %0,5-1 humidity level because of its water content. The third step is a granulator to reduce the size, which leads to suction, where existing foam and dust are removed. Then, the second density bath separates polyolefins and styrenics from the mix. The sixth step is electrostatic sorting, which outputs a purity level of over %95. The last step before compounding is colour sorting, in which the fed materials are detected by NIR and colour technology and separated by compressed air. Finally, after compounding technology, the output polymer granules achieve a purity level of 99%.

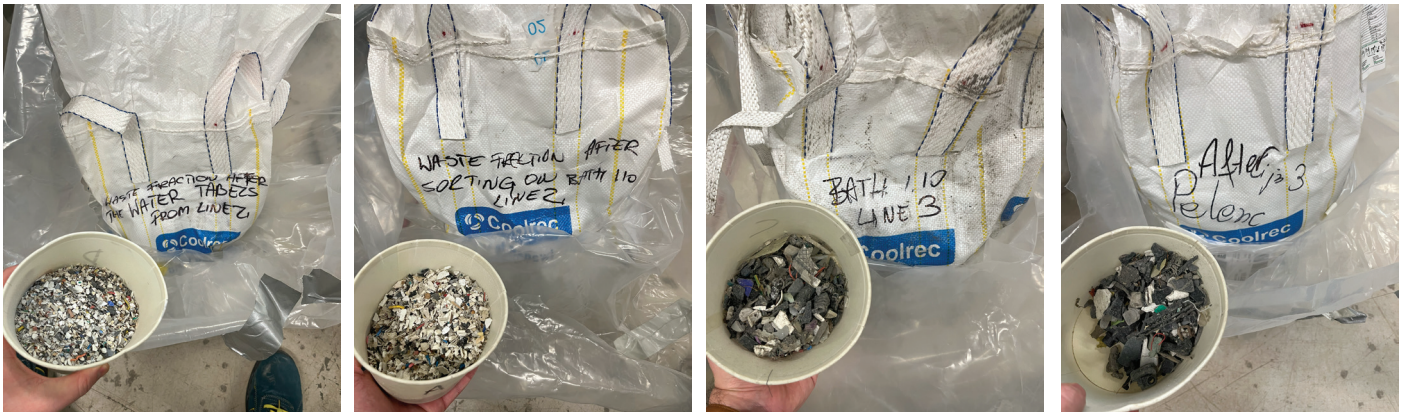


Figure 36: The waste input from Coolrec (1)Fridge-1 (2) Fridge-2, (3) SDA-1, (4) SDA-2 (Source: Author)

The limitations and possibilities of the current sorting technology were discussed. The first limitation is purely based on the plastic waste input and content. The current technology is not adequate for sorting the complex plastic waste perfectly. For instance, as high-end markets want unicolour plastic products for electrical and electronic products, colour sorting becomes unreliable. There is a density overlap with various materials during the two density baths that have been done. The representative mentioned that the first-density bath sorting is more difficult because of the high and mixed waste content. In addition, the incompatibility and immiscibility of the polymer blends pose a challenge during the sorting process. The second limitation is a general problem because of mechanical recycling. Unlike chemical recycling, mechanical recycling causes the polymer waste to degrade throughout the process. The repeated heating cycles cause the polymers to degrade during the process, and because of their shorter chains, the end-polymers represent lower mechanical properties. The third limitation relates to the regulations. A compliant plastic product is a major indicator of whether a waste is workable. Therefore, Coolrec limits its WEEE component input to a specific year of manufacture while the information on waste composition is already lacking. The fourth limitation discussed relates to the future of recycled plastic. It is the common approach of original equipment manufacturers (OEMs) to not adapt their products to be manufactured with recycled plastic, which limits the growth of recycled plastic industry.

Figure 37: Micrographs showing common traits of plastic samples from (1) Fridge-1, (2) Fridge-2 (3) SDA-1, (4) SDA-2 (Source: Author)

Based on Coolrec's two separate lines for fridges and small domestic appliances, the possibilities that the representative mentioned highly focused on the SDA line. However, there were general recommendations for both lines concerning the use of middle-ray scanning rather than infrared to see the colour black and to generally have a larger yield at the end. The representative mentioned that the challenge in Coolrec's sorting mechanisms is mainly related to the SDA line. The representative mentioned that the reject fraction from the first density bath of the SDA line is rich in plastic, requiring further investigation. After a fruitful interview, a sample from the reject fraction was sent for the thesis's second phase -experimentation.

2.9.3 Van Werven – interview and sample

Van Werven is a Netherlands-based recycling company that specialises in the processing and recycling of plastic waste into valuable secondary raw materials. Its implementations are similar to Coolrec's, where mechanical recycling of mixed plastic waste takes place to produce high-quality polymer granules for new products. During the interview, questions were asked regarding their recycling stages and the polymer types from their input/output waste line. The plastic waste streams mainly involve infrastructure and municipal waste. They create PVC, ABS, PS, and PE regrinds and sell them to the companies. Therefore, no moulding processes are being performed at their facilities. A detailed overview of the sorting and characterization process of their mechanical recycling concluded that there is %30-35 plastic content in their reject fraction, currently being sent to incineration. A major difference between Coolrec and Van Werven is that Van Werven relies on manual sorting rather than density baths. %5 is identified as metal by X-ray systems during the process and sent to metal recycling companies. After the desired polymers are removed, necessary colour-sorting steps are implemented to ensure the purity of their granules.

Figure 38: The reject fraction of Van Werven recycling facilities (Source: Author)

Seeing the potential also for the reject fraction of manual sorting techniques, the representative shared a sample and a polymer-type data sheet for further investigation.

2.9.4 Horizonteer – interview

Horizonteer is an innovation-based agency involved in various sustainable projects, such as creating circular innovation systems. It collaborates with KRAS, an international waste management company that collects post-industrial and post-consumer plastics and transforms them into reusable granules. Another collaboration Horizonteer has is with Circular Plastic Academy, which aims to transition businesses from a linear to a circular economy. An interview was conducted with two representatives from Circular Plastic Academy about the possibilities and facilities they could provide for the thesis. Their specialities involve defining the cost efficiency of the study and providing connections to various facilities. A connection for the moulding process of the thesis for phases two and three – experimentation and application- and a recycling company like KRAS's reject fraction were asked for.

2.9.5 MEWA Polymer – sample

MEWA Kunstoffen Recycling is based in the Netherlands and specializes in the complete recycling process of specific plastics through recycling and upcycling. Their facilities include plastic recycling, injection moulding, compounding, and transport. Their expertise lies in the waste stream of the CD and DVD industry, which involves PC, PS, PP, and LDPE polymers. Waste line samples of polycarbonate (PC) from the sorting processes of the water well, grinding mill, and washing line were sent, as well as the reject fraction of the colour sorting process right after the washing line was also sent.

Figure 39: The reject fractions from various sorting steps of MEWA recycling facilities (Source: Author)

The samples allowed clear inspection of the particle sizes and the complexity of each reject fraction. Even though the reject fractions of the grinding mill, water well and final washing line were mono-coloured, the reject fraction of colour sorting included multi-colour and multi-polymer content based on visual inspection. The waste line samples from each sorting process aided in understanding the real-life products and their possibilities.

2.9.6 Mirec Recycling - interview

Mirec Recycling is a Netherlands-based company that specializes in WEEE recycling. They are focusing on recovering steel, aluminium, plastics and metals. The extensive infrastructure of Mirec encompasses both resource recovery and environmental awareness. The interview is conducted after the WEEE stream is selected as the material source for the thesis. The mechanical recycling steps and the regulations affecting WEEE recycling were discussed. Their mechanical recycling steps consist of battery removal after the waste input before shredding. The shredded wate goes into metal separation to N-IR sorting. Then, density sorting is implemented, targeting two polymer types for regranulation. The second part of the interview focused on the contamination and policies that affect the recycling of WEEE. Based on REACH regulation, heavy plastics containing brominated flame retardants (BRFs) and persistent organic pollutants affect the recycling of WEEE extremely. The EU regulation 2019/1021 focuses on the management of POPs, which are commonly found in plastic applications like casings for older electronic devices.

The conducted interview ended with a discussion on the impact of contamination in plastics for the environment and recyclability, and the requirement for further research.

2.10 Conclusion

The literature review outlines the critical limitations and possibilities within the realm of plastic recycling, particularly concerning unrecycled and unsorted fractions and their potential for reintroduction as an architectural component in the construction industry. The global reliance on plastics and poor waste management and recovery techniques highlight the urgent need for innovative approaches.
Substantial material losses during mechanical recycling processes, especially at the sorting stages, needed further investigation. Therefore, open-loop mechanical recycling is selected as the primary approach due to its cost- and energy-efficient properties. Existing studies on polymer blending and virgin and recycled polymer comparison aided in understanding the study's limitations. This provided insights for the second phase of the thesis, where appropriate polymers will be selected for blending.

The construction industry has a high demand for plastics, as the second largest consumer of plastics and there is a lack of data on recycling mixed, contaminated, and unsorted waste streams into an architectural component. Therefore, various prototypes for recycled plastic applications, ranging from product-scale to construction applications, are investigated. This provided the necessary information regarding the expectations for the material behaviour of recycled and virgin polymers, which was helpful in selecting the function of the architectural component. Reinforcement spacers located at the internal shearing layer of concrete without any exposure to UV or mechanical strength emerges as a promising candidate for the low-grade secondary plastics. Additionally, the injection molding technique and its industrial parameters showed the expected behaviour of processed plastics and the characteristics of it.

The literature review adequately highlighted the possible boundary conditions and implementations for the upcoming phases of the thesis. It points out a significant opportunity for targeting low-risk hidden building components as the application scenario to upstream secondary plastics and low-grade residues of the plastic waste streams.

PHASE 2 MATERIAL EXPERIMENTATION & PRODUCT DEVELOPMENT

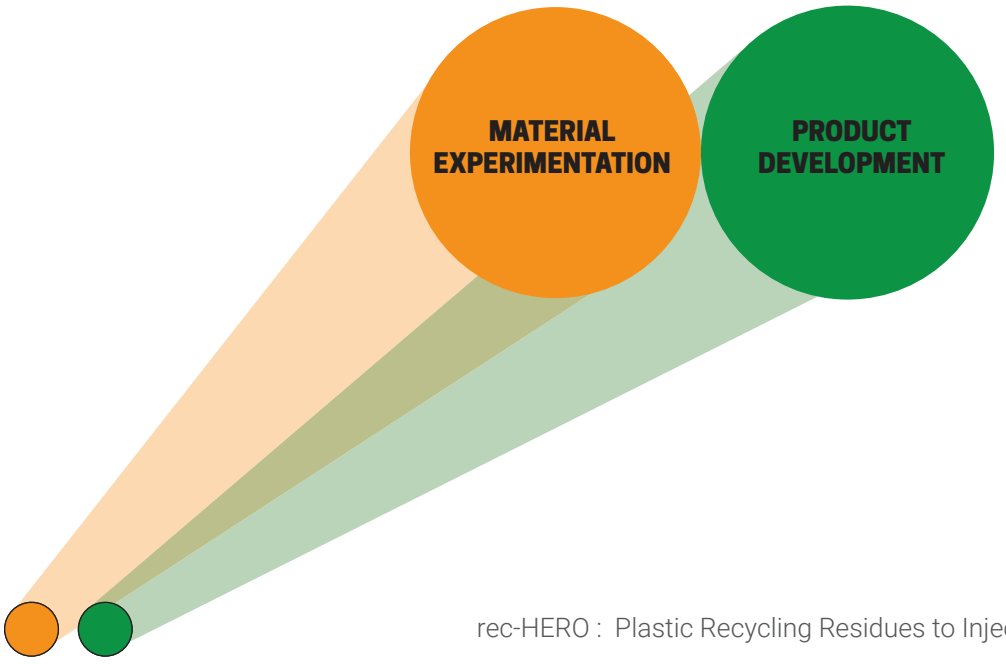
3 Material Experimentation & Product Development

Phase two of the thesis consists of two tracks of material experimentation and product development occurring simultaneously in a feedback loop to be able to optimize an injection-moldable reinforcement spacer for concrete construction by coming up with a recipe and a design. The dual-track methodology enables assessing the current limitations of plastic waste while enabling the possibility of application concurrently. Therefore, the individual parameters that are defined for both tracks provide continuous feedback to one another to shape the direction of the tracks. This was possible by identifying some parameters for both tracks with dependency and independence. As the waste source is selected to be the WEEE plastic obtained from Coolrec which consists of four different waste bags, including fridge waste and small domestic appliances (SDA) waste; the decision parameters for the product development track are solely dependent on the material experimentations. Another checkpoint is defined in addition to continuous feedback of the phase. The checkpoint is defined as a proof of concept both for processing technique and the complexity of the product development for analysing possibilities and limitations at a specified point during the timeline.

The objective of the material experimentation track is to formulate an injection-moldable recipe using the four waste bags of reject fractions from various plastic recycling steps. The unknown content of the polymer types and the undefined contamination/impurities of the waste source **necessitate a bottom-up approach**. The track adapts this approach starting from physical and thermal analysis of the waste samples, and proceeding through lab-scale mechanical recycling steps for polymer identification. Each recipe is evaluated based on the parameters with three defined setups, respectively. As a result, a workable recipe for the selected processing technique will be achieved.

In parallel, the product development track will formulate an original design for the selected reinforcement spacer based on the defined parameters and performance requirements. After specifying the component selection suitable for the waste source and known requirements, the track will **follow a top-down approach**. From the application in a non-exposed environment in the construction industry, a wheel spacer type of reinforcement spacer was selected as the target product. The selection is solely based on research and inductive reasoning based on the waste input and health requirements. Multiple spacer configurations are designed based on the parameters and structural functionality in reinforced concrete construction. The design variants are assessed both with physical setups and by injection and mechanical simulations along the way. The simulation conditions are continuously adapted based on the data gathered from the material experimentation track. This constant feedback loop allowed a co-evolving design process, as material constraints shape design iterations and product performances' impact on polymer selection.

The **dual-track feedback loop** is indicated within the template by assigning colours at the respective pages where there is a feedback between material experimentation track and product development track. This aids the explanation of the continuous data transfer between the tracks and how it affects the process until the third phase: application.



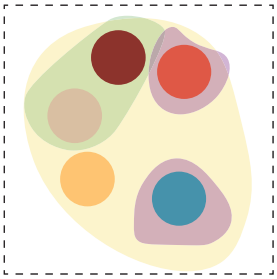
FRIDGE 1
Reject fraction of water seperation tables

FRIDGE 2
Sink fraction of density sorting

SDA 1
Reject fraction of near infra-red sorting after SDA 2

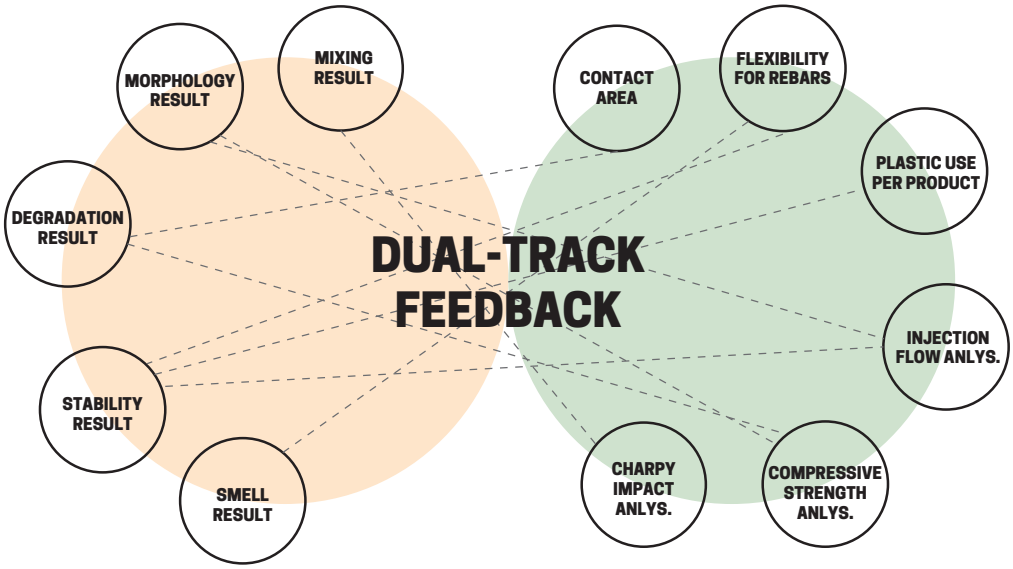
SDA 2
Sink fraction of density sorting

PHASE 2: DUAL-TRACK METHODOLOGY
MATERIAL EXPERIMENTATION & PRODUCT DEVELOPMENT



TRACK I.
MATERIAL EXPERIMENTATION

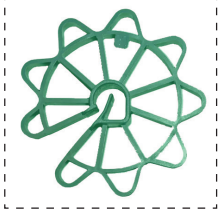
TRACK II.
PRODUCT DEVELOPMENT



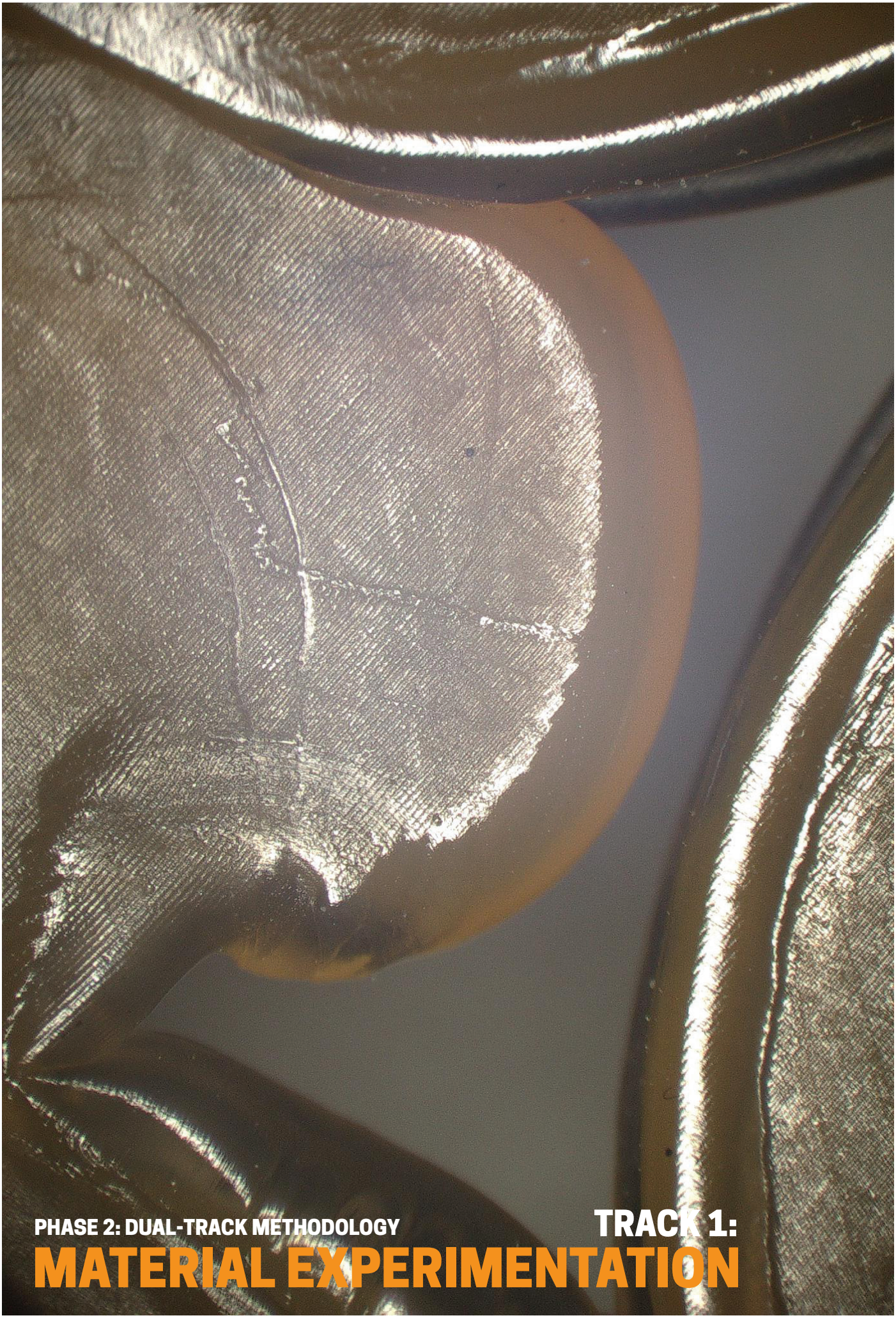
FINAL POLYMER SELECTION
FINAL INJECTION CYCLE

FINAL DESIGN
FINAL APPLICATION

rec-HERO



PHASE 3: APPLICATION



PHASE 2: DUAL-TRACK METHODOLOGY

TRACK 1: MATERIAL EXPERIMENTATION

3.1 DUAL TRACK METHODOLOGY:

MATERIAL EXPERIMENTATION

POLYMER SORTING

- Washing
- Density Separation
- Colour Sorting
- MIR Sorting
- Shredding

POLYMER CHARACTERIZATION

- DSC Analysis
- FT-IR Analysis
- Microscope Analysis
- XRF Analysis

PARAMETERS

- Mixing Result
- Morphology Result
- Degradation Result
- Stability Result
- Smell Result

FRIDGE 1
Reject fraction of water seperation tables

FRIDGE 2
Sink fraction of density sorting

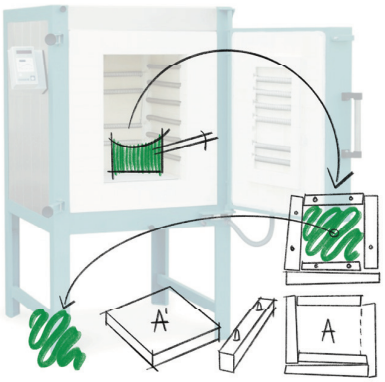
SDA 1
Reject fraction of near infra-red sorting after SDA 2

SDA 1
Reject fraction of near infra-red sorting after SDA 2

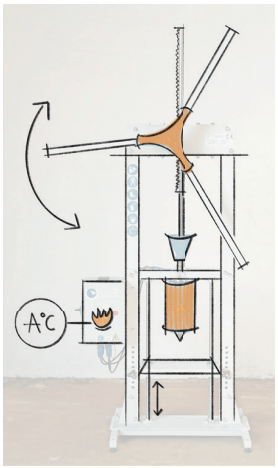
SDA 2
Sink fraction of density sorting

FRIDGE 1
Reject fraction of water seperation tables

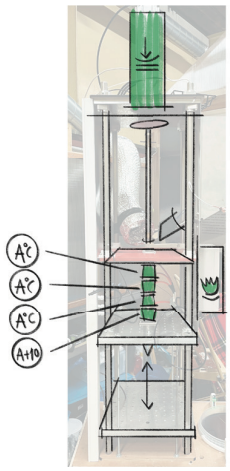
rec-PP
Anonymous Source



MANUAL PRESS



MANUAL PLUNGER-TYPE INJECTION MOLDING



PNEUMATIC PLUNGER-TYPE INJECTION MOLDING

POLYMER SELECTION

Colour-sorted Polymers	Colour-sorted Polymers	**Colour-sorted Polymers**
Density-separated Polymers	Density-separated Polymers	Density-separated Polymers
FT-IR Identified Polymers/Blends	**FT-IR Identified Polymers/Blends**	FT-IR Identified Polymers/Blends
Recycled Polypropylene	Recycled Polypropylene	**Recycled Polypropylene**

FINAL POLYMER SELECTION
FINAL INJECTION CYCLE

3.2.1 Definiton of Material Performance Parameters

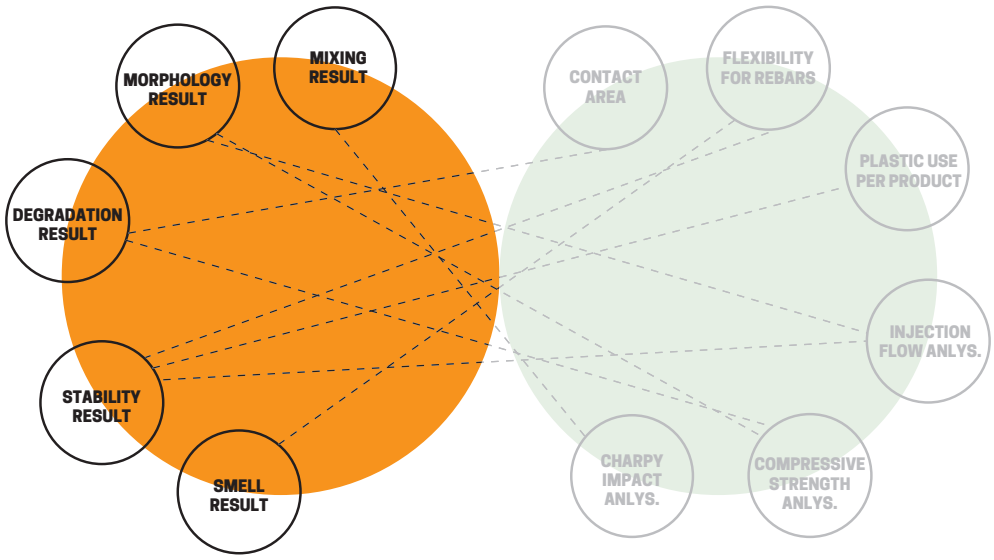


Figure 40: The indication of material performance parameters (Source: Author)

The **bottom-up approach** helps to determine how pre-processing strategies and polymer blending techniques influence the process of defining an injection-moldable recipe. Due to impurities and contamination existing in WEEE plastic, a special focus is given to the aspects that would influence the processability, mechanical performance and result after injection moulding. The parameters help in the decision-making process and allow a suitable transition from one setup to another. As the complexity of the setups increases from manual pressing to pneumatic injection moulding, the polymer selection and the timeline of the setups are crucial.

Mixing result: This parameter evaluates the compatibility and miscibility of the final blend after processing. The comparison of homogenous/heterogeneous blending aids the decision-making for the polymer selection of the new trial. The mixing result is mainly determined by visual inspection based on the sample taken from the processing medium and the pressed sample.

Morphology result: The morphology of the sample is determined both by visual inspection and microscopic analysis of the pressed sample's skin layer. The possible porosity as well as the surface finish are evaluated visually based on the comparison of the polymers before and after processing. The phase separation is assessed by micrographs to observe the domains created by various polymer blends.

Degradation result: This parameter assesses thermal degradation, discolouration that occurs during the processing steps. The effects that are observed mainly include discolouration, charring, and bubbling by comparing the samples both before and after the removing from the processing medium. Additional thermal analysis is done with DSC for the samples from the pneumatic injection molding to estimate polymer breakdown.

Stability result: The stability of the samples are estimated purely on the mechanical integrity of the samples before and after pressing. A manual bending and compression are performed for all samples to detect excessive brittleness of the polymer blend.

Smell result: This parameter is added during the experimentation phase, as the majority of the samples had a strong smell after processing. This parameter is qualitative as it serves a record of the presence of burnt, acidic or chemical odours, which points out possible degradation.

3.2.2 Polymer Characterization and Contamination Check

To ensure the reliability of the material experimentation track, prior polymer characterisation and contamination checks is conducted to develop a functioning experiment setup at further steps. As the focused waste stream, WEEE is known to be highly contaminated and has a wide range of polymers, a preliminary stage was essential to identify which polymers are in high quantity and to detect any visual impurity or contamination without significant risk of failure during processing.

The process consists of identifying specimens from each four waste bag from fridge and small domestic appliances lines of recycling process. The fridge line waste bags consist of reject fractions of water separation tables and sink fractions of density sorting. The SDA line waste bags consist of reject fractions of near-infrared sorting and density sorting. These waste bags are planned to be incinerated for energy recovery. Determining the possibility of working with reject fraction polymers was necessary. Polymer specimens from each waste bag is selected based on observable characteristics such as colour, elasticity, texture and visible contamination. The selected specimens showcased the wide range of existing polymers and their complex characteristics. The selected specimens are washed and scrubbed with detergent and water to reduce external influences on the data collection. To prevent existing concentration of water in the polymers, an extra step of drying is performed. The data collection consists mainly of polymer identification using Fourier-transform infrared spectroscopy (FT-IR), Differential scanning calorimetry (DSC) and micrograph analysis. The polymer characterisation results gave insight into the vague composition of the polymers of each waste bag which aided the decision-making on which polymers to focus for the first trials of density separation. The results helped the formation of the timeline for each injection moulding setup and to the given priority between them.

The prior visual contamination and impurity check on the polymer status before washing the specimens with detergent enabled an outcome also for the expected contamination from different mechanical recycling steps. There was a direct correlation between a sorting stage performing earlier and the contamination level of that reject fraction. The assumptions for the contamination level for each sorting stage are made based on experimental results rather than data collected from the recycling institution, as there was no possibility.

The polymer characterisation and contamination checking step of phase two is essential for defining a foundation point for the specimen selection and defining experiment setups. As there was no data available on the composition of the reject fractions of mechanical recycling steps, the prior characterisation allowed a foundational understanding of the material inputs.

FRIDGE 1

Reject fraction of water seperation tables

FRIDGE 2

Sink fraction of density sorting

SDA 1

Reject fraction of near infra-red sorting after SDA 2

SDA 2

Sink fraction of density sorting

3.2.2.1 DSC, FT-IR, Microscope Analysis

To evaluate the identity, thermal behaviour and morphology of the waste input, three instruments for characterisation are used: an FT-IR machine, a DSC instrument and an industrial microscope.

Fourier-transform infrared spectroscopy (FT-IR) was used as the primary method for identifying the polymer types and contaminations of the selected specimens. FT-IR is a method used defining the chemical structure of the polymers by monitoring the vibrational modes of molecular bonds. The technique's fast and non-destructive nature helps checking if the polymers meet the requirements for further processing (Cao et al., 2014). The fingerprint taken from the machine allows for a direct comparison with the reference spectra which enables confirmation of polymer identity and detection of contaminants.

A Nicolet iS50 FT-IR Spectrometer with a spectral range between 15 to 27,000 cm-1, located at the Stevin II Laboratory at the Faculty of Civil Engineering, TU Delft was used. The all-in-one material analysis system was chosen to be the main setup that would be used for polymer identification for the further steps of the experimentation phase.

As contaminated specimens were used for FT-IR, multiple measurements were conducted for a single specimen for reliability and accuracy of the spectral data. This approach helped eliminating data with random noise or the drift in the spectrometer. The physical characteristics of the plastic specimens which were often warped or partially deformed, sometimes gave weak signal peaks. Therefore, the repetitive data collection enhanced confidence in results while comparing to the reference libraries.

Each specimen was placed on a flat diamond surface, and the pressure arm was used to press the sample firmly until the contact was secured. The emitted near-infrared light through the crystal was absorbed as specific wavelengths by the specimen, which at the end converted into a molecular fingerprint.

Experiment Setup: Each measurement was conducted with 24 scans per one location of the specimen. The number of scans found optimal in terms of estimated time for data collection and also for getting results with cleaner and more stable spectra. To detect contamination or impurities, the number of scans enabled seeing peaks and vibrations which would have been lost in noise. For the efficiency of data collection, the resolution was kept in cm^{-1}, which provided sufficient detail on the overlapping peaks. The wavenumber range was kept between 500 cm^{-1} to 3600 cm^{-1}, which covered the mid-infrared region of relevant organic polymer vibrations. The search libraries used for the data collection are widely used in polymer and material science applications that cover a broad range of polymers and blended materials. The chosen libraries were HR Aldrich Organometallics Library, HR Nicolet Sampler Library, and Hummel Polymer Sampler Library. Based on these specifications, a methodology for the repetitive data collection is formed.

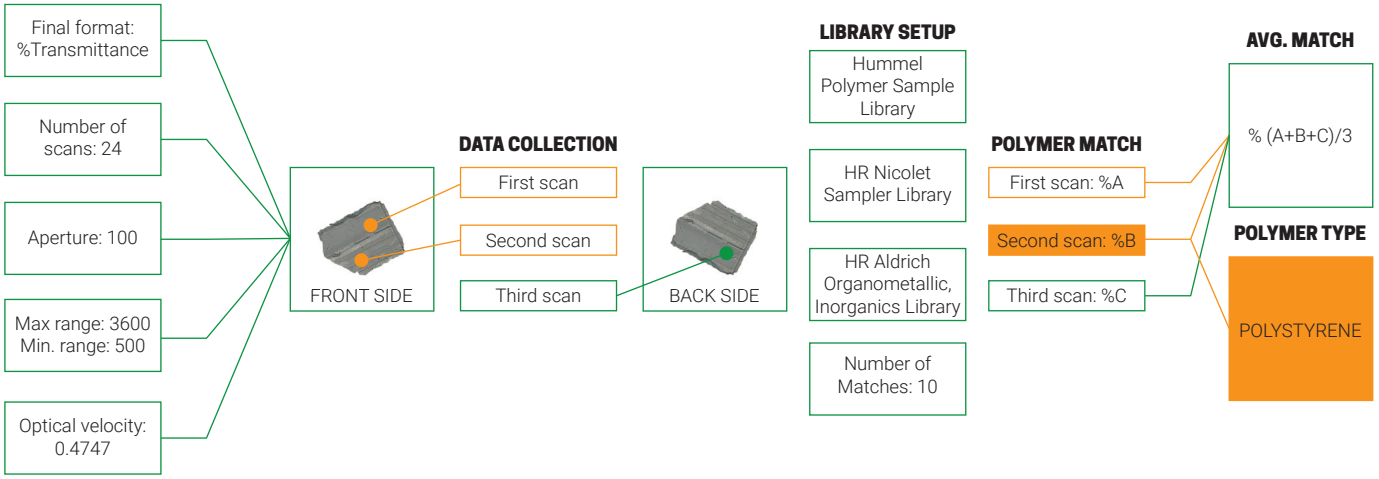


Figure 41: Workflow diagram showing the experiment setups of FT-IR analysis (Source: Author)

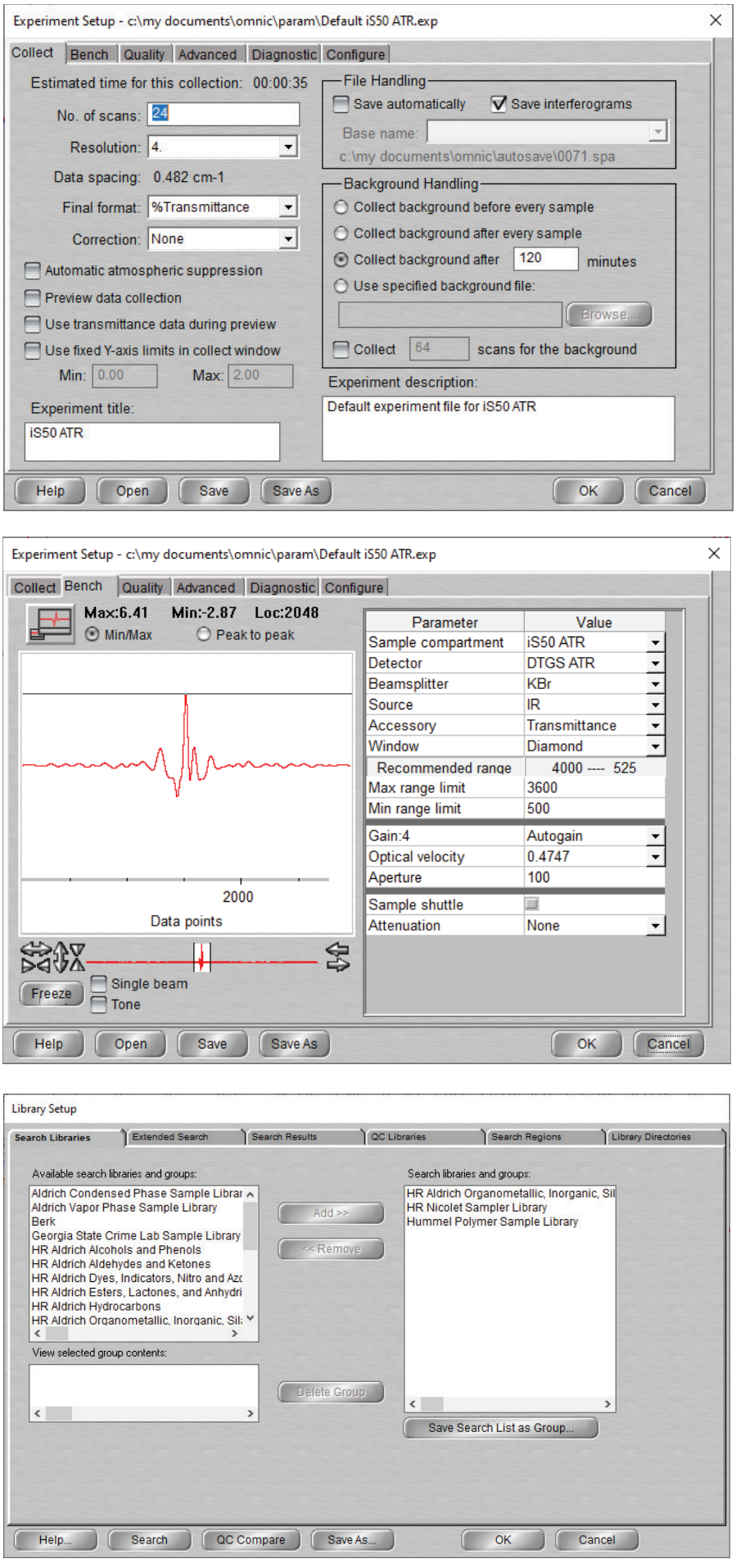
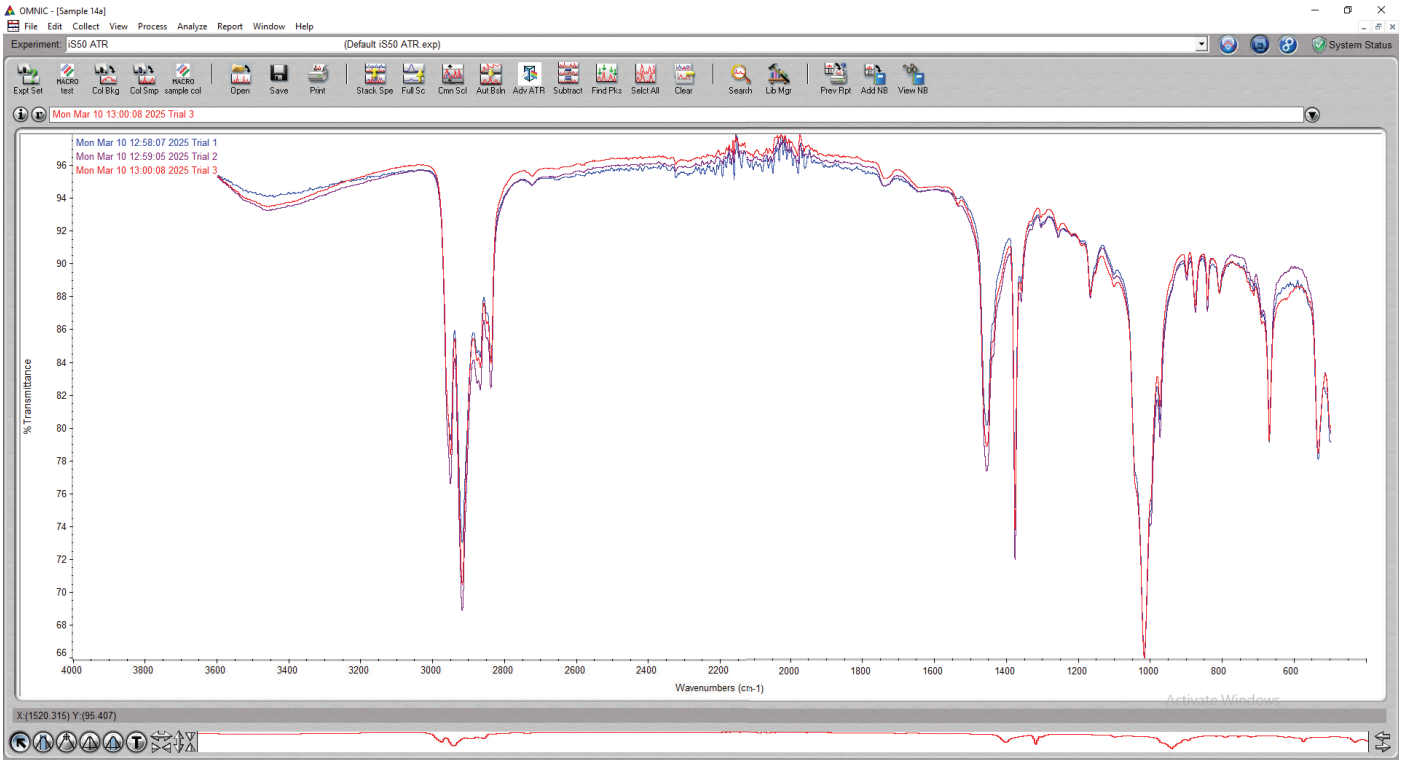
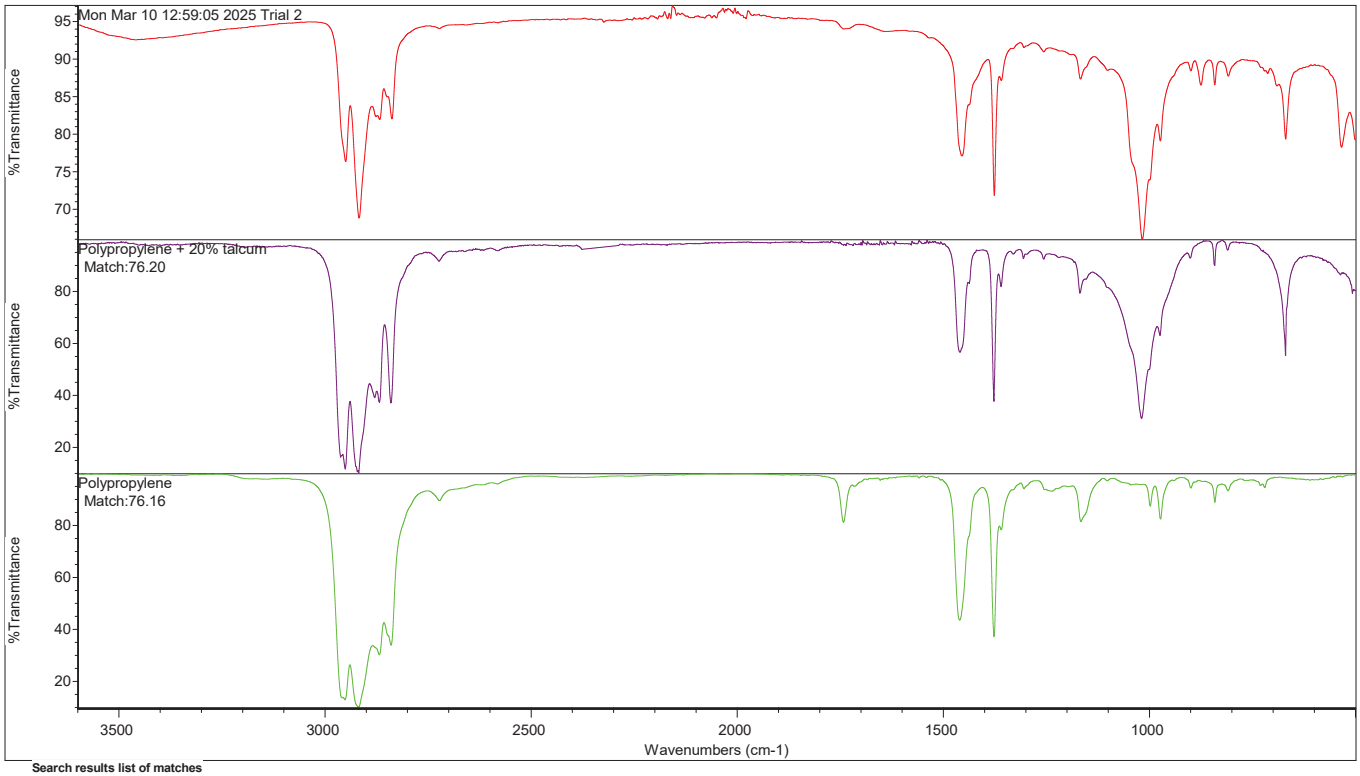


Figure 42: The FT-IR experiment setup and Library setup (Source: Nicolet iS50 FT-IR Spectrometer)



Graph 1: Exemplary FT-IR result showing three-scans done on one sample (Source: Nicolet iS50 FT-IR Spectrometer)

Search results for: Mon Mar 10 12:59:05 2025 Trial 2
Date: Mon Mar 10 13:02:27 2025 (GMT+01:00)
Search algorithm: Correlation
Regions searched: 3949.50-455.13



Search results list of matches

	Index	Match	Compound Name	Library Name
1	603	76.20	Polypropylene + 20% talcum	HR Nicolet Sampler Library
2	737	76.16	Polypropylene	HR Nicolet Sampler Library
3	624	75.71	Polypropylene+poly(ethylene:propylene)	HR Nicolet Sampler Library
4	41	72.98	POLY(PROPYLENE), ATACTIC	Hummel Polymer Sample Library
5	596	69.11	Polypropylene, atactic	HR Nicolet Sampler Library
6	38	68.63	POLY(PROPYLENE), SYNDIOTACTIC	Hummel Polymer Sample Library
7	602	63.40	Polypropylene+poly(ethylene:propylene)	HR Nicolet Sampler Library
8	39	59.26	POLY(ETHYLENE:PROPYLENE)	Hummel Polymer Sample Library
9	1521	53.92	TALC, POWDER, <10 MICRON	HR Aldrich Organometallic, Inorganic, Silanes, Boranes, and
10	490	50.86	Poly(ethylene:propylene) 54mol% ethylene	HR Nicolet Sampler Library

Graph 2: Exemplary Library search results showing the match percentages and the spectra (Source: Nicolet iS50 FT-IR Spectrometer)

As apparent at the methodology, after setting up the experiment with the specifications, the first two data is collected form the front side of the specimen at different flat locations. Then, the third scan is collected at the back side of the specimen. Based on the search form, the libraries, the first 10 matches are recorded and the match with the highest percentage is taken as the final. The repetitive three scans enabled a more trustworthy percentage match of the polymer. The collected data with the highest percentage is taken to decide on the polymer type of the specimen. The first evidence for the contamination and impurity is recorded during FT-IR. Some specimens had contaminants such as talcum powder, alkyd resin, cellophane, aromatic hydrocarbon resin and methyl methacrylate existing at the specimen. A further analysis of the contaminants is made before the processing stage to determine the possible setbacks for the thesis.

SDA 1 - WASTE BAG

SAMPLES	COMPOUND NAME	MATCH PERCENTAGES	MATCH %
S.1	**T.1** PA6/PA66 Blend	63.41	**64.22**
	T.2 PA6/PA66 Blend	65.09	
	T.3 PA6/PA66 Blend	64.15	
S.2	**T.1** PP + 20% talcum powder	66.21	**64.02**
	T.2 PP + 20% talcum powder	65.42	
	T.3 PP + 20% talcum powder	60.42	
S.3	**T.1** PA6/PA66 Blend	76.12	**76.39**
	T.2 PA6/PA66 Blend	76.40	
	T.3 PA6/PA66 Blend	76.64	
S.4	**T.1** Polycarbonate	54.13	**78.47**
	T.2 Polycarbonate	57.50	
	T.3 Polycarbonate	58.41	
S.5	**T.1** PA6/PA66 Blend	78.26	**64.22**
	T.2 PA6/PA66 Blend	77.86	
	T.3 PA6/PA66 Blend	79.29	
S.6	**T.1** Polystyrene	83.83	**78.75**
	T.2 Polystyrene	73.66	
	T.3 Dichlorobis	21.14	
S.7	**T.1** Polycarbonate resin	75.80	**74.50**
	T.2 Polycarbonate resin	73.07	
	T.3 Polycarbonate resin	74.64	
S.8	**T.1** N/A	N/A	**76.92**
	T.2 Polycarbonate resin	77.09	
	T.3 Polycarbonate resin	76.74	
S.9	**T.1** PC/ABS Blend	57.45	**56.92**
	T.2 PC/ABS Blend	57.65	
	T.3 PC/ABS Blend	55.66	
S.10	**T.1** PP + 20% talcum powder	66.47	**66.47**
	T.2 PP + 20% talcum powder	67.66	
	T.3 PP + 20% talcum powder	65.27	
S.11	**T.1** Polystyrene	85.02	**84.16**
	T.2 Polystyrene	83.66	
	T.3 Polystyrene	83.80	
S.12	**T.1** PA6/PA66 Blend	75.61	**76.20**
	T.2 PA6/PA66 Blend	76.86	
	T.3 PA6/PA66 Blend	76.13	

Table 1: The 3-data collection of FT-IR analysis done on 12 selected samples from SDA-1 (Source: Author)

BATCH A. - FLOATING FRACTION

SAMPLES	COMPOUND NAME	MATCH PERCENTAGES	MATCH %
S.1	T.1 Polyethylene/Polypropylene Blend	8.10	9.96
	T.2 Polybutadiene: Acrylonitrile	8.29	
	T.3 Polybutadiene: Acrylonitrile	11.62	
S.2	T.1 Polystyrene	29.68	37.06
	T.2 Polysyrene	34.39	
	T.3 Polystyrene	47.11	
S.3	T.1 Polystyrene	88.81	80.20
	T.2 Polystyrene	88.40	
	T.3 Polystyrene	87.40	
S.4	T.1 Polystyrene	85.77	85.89
	T.2 Polystyrene	85.66	
	T.3 Polystyrene	86.25	
S.5	T.1 PA6/PA66 Blend	74.30	73.58
	T.2 PA6/PA66 Blend	72.68	
	T.3 PA6/PA66 Blend	73.76	
S.6	T.1 Dicarbonylcyclopentadienyl cobalt	12.08	71.01
	T.2 PS: methyl methactylate	78.53	
	T.3 PS: methyl methactylate	63.49	
S.7	T.1 Sodium cyanoborohydride	17.25	67.50
	T.2 PP + 20% talcum	66.81	
	T.3 PP + 20% talcum	68.19	
S.8	T.1 Copper (I) thiocyanate	16.74	67.80
	T.2 Polypropylene	72.06	
	T.3 Polypropylene	63.55	
S.9	T.1 Polystyrene	66.22	66.19
	T.2 Polystyrene	69.26	
	T.3 Polystyrene	63.08	
S.10	T.1 Diiron nonacarbonyl	13.14	55.39
	T.2 Polystyrene	56.22	
	T.3 Polystyrene	54.56	
S.11	T.1 PE/PP Blend	65.63	67.09
	T.2 PE/PP Blend	64.83	
	T.3 PE/PP Blend	70.80	
S.12	T.1 Polyethylene	77.27	74.68
	T.2 Polyethylene	77.47	
	T.3 Polyethylene	69.31	
S.13	T.1 Polystyrene	84.16	68.55
	T.2 Alkyd resin	60.87	
	T.3 Alkyd resin	76.13	
S.14	T.1 PS: vinyl chloride	19.33	38.58
	T.2 Polyester	56.39	
	T.3 PS: vinyl chloride	57.83	
S.15	T.1 Polycarbonate resin	74.79	71.23
	T.2 Polycarbonate resin	73.86	
	T.3 Polycarbonate resin	65.03	
S.16	T.1 Polyacrylonitrile	14.44	83.03
	T.2 N/A	N/A	
	T.3 Polypropylene	83.03	
S.17	T.1 Polystyrene	86.10	86.10
	T.2 Polystyrene	86.10	
	T.3 N/A	N/A	
S.18	T.1 Polypropylene	75.33	74.21
	T.2 Polypropylene	73.09	
	T.3 Talc	28.12	

Table 2: The FT-IR results on 18 selected specimens from density-separated (d: 1.13 g/cm³) first batch (Batch A) from SDA-1 (Source: Author)

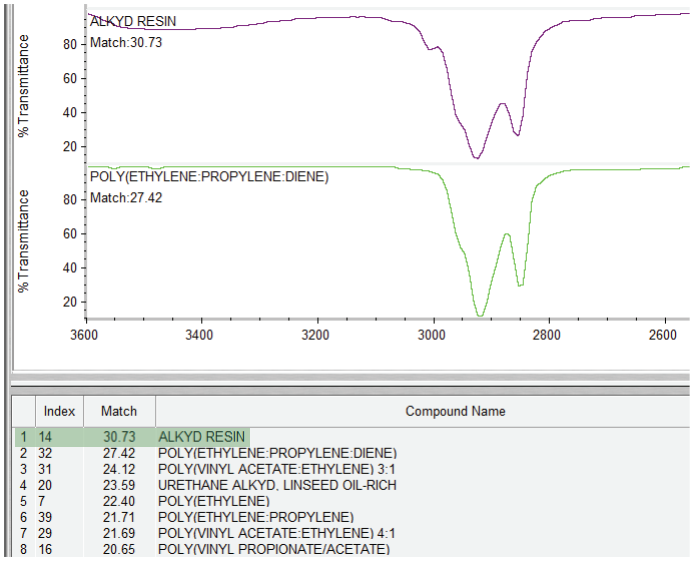
BATCH B. - FLOATING FRACTION

SAMPLES	COMPOUND NAME	MATCH PERCENTAGES	MATCH %
S.1	T.1 PA6/PA66 Blend	64.28	63.05
	T.2 PA6/PA66 Blend	58.74	
	T.3 PA6/PA66 Blend	66.12	
S.2	T.1 Polystyrene	36.15	31.66
	T.2 Polystyrene	36.62	
	T.3 Polystyrene	22.20	
S.3	T.1 Copper thiocyanate	23.92	74.83
	T.2 Polymethyl methacrylate	66.87	
	T.3 Polystyrene	74.83	
S.4	T.1 Polymethyl methacrylate	3.94	N/A
	T.2 PVC	6.19	
	T.3 Polyacrylonitrite	4.46	
S.5	T.1 Polystyrene	86.03	85.83
	T.2 Polystyrene	85.62	
	T.3 PE/PP Blend	31.55	
S.6	T.1 N/A	N/A	N/A
	T.2 N/A	N/A	
	T.3 N/A	N/A	
S.7	T.1 Polystyrene	83.25	81.74
	T.2 Polystyrene	80.22	
	T.3 Bromide	16.99	
S.8	T.1 Polystyrene	86.11	82.07
	T.2 Polystyrene	86.47	
	T.3 Polystyrene	73.63	
S.9	T.1 Polypropylene	89.98	89.56
	T.2 Polypropylene	89.13	
	T.3 PE/PP Blend	39.46	
S.10	T.1 PS: methyl methacrylate	78.98	79.06
	T.2 Potassium dicyanoaurate	26.24	
	T.3 PS: methyl methacrylate	79.13	
S.11	T.1 Polyester urethane	71.40	69.62
	T.2 PA6/PA66 Blend	28.35	
	T.3 Polyester urethane	67.83	
S.12	T.1 Polypropylene	83.26	75.91
	T.2 N/A	N/A	
	T.3 Polypropylene	68.56	
S.13	T.1 N/A	N/A	N/A
	T.2 N/A	N/A	
	T.3 Copper thiocyanate	18.63	
S.14	T.1 PP + 20% talcum	73.76	75.22
	T.2 PP + 20% talcum	76.20	
	T.3 PP + 20% talcum	75.70	
S.15	T.1 Polystyrene	85.77	82.93
	T.2 Polystyrene	87.26	
	T.3 Polstyrene	75.75	
S.16	T.1 Polycarbonate resin	74.66	69.26
	T.2 Polycarbonate resin	65.39	
	T.3 Polycarbonate resin	67.72	
S.17	T.1 Polystyrene	57.47	57.35
	T.2 Polystyrene	57.52	
	T.3 Polystyrene	57.05	
S.18	T.1 Polystyrene	84.18	84.83
	T.2 Polystyrene	84.93	
	T.3 Polystyrene	85.38	

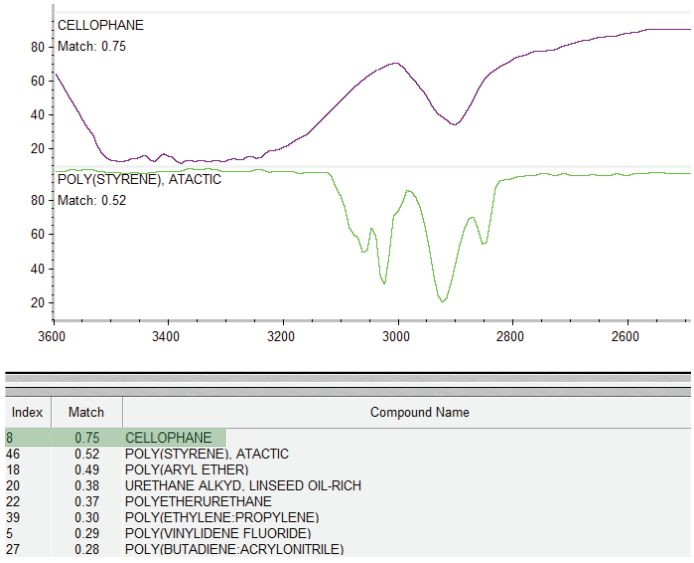
Table 3: The FT-IR results on 18 selected specimens from density-separated (d: 1.13 g/cm³) second batch (Batch B) from SDA-1 (Source: Author)

The contamination check during FT-IR is first done on the spectral region by identifying unexpected peaks at the fingerprint region between 500–1500 cm^{-1} where the deviations are more expected (Mukai et al., 2022). A special focus is given to flame retardants, fillers and colourants after the collected data was matched with the search libraries. For the flame retardants, phosphorus-containing groups were checked during the repetitive data collection. For checking the fillers, Hummel Polymer Library was more reliant on getting some insight on the fillers like talc. For the colourants, especially for the carbon black polymers, as the FT-IR machine also does not show peaks because of near-infrared, a flat spectra was expected.

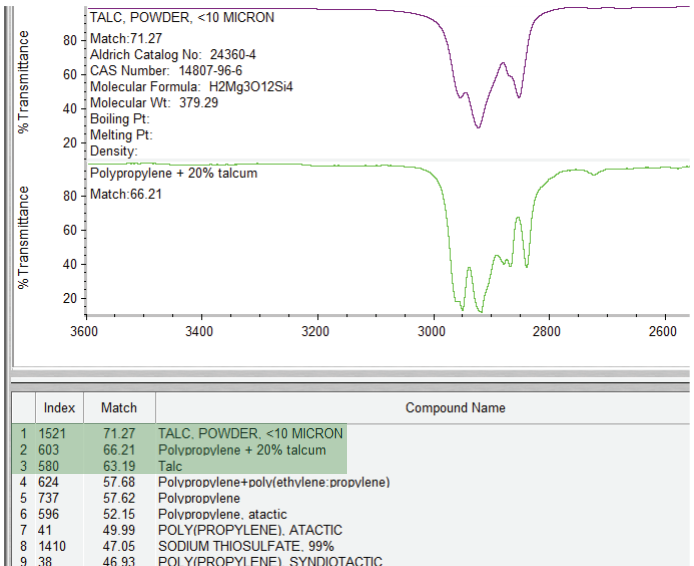
The spectral results associated with the **talcum powder** are characterised by silicate vibrational bands that indicate the presence of inorganic fillers or residues from processing components. The **alkyd resin** is part of ester carbonyl groups or fatty acid groups. The common application for alkyd resin is coatings, which suggests a detection of the external layer with paint or release agent. A **cellophane** is one of the concurrent impurity found in the specimens, which is sourced from carbohydrate-related vibrations that refers to a cellulose-based contaminant. Cellulose-based contaminants are proven to be a hindering effect on especially PS recycling (Leclerc et al., 2024). As cellulose content increases, the simultaneous increase of hydrogen production leads to the hydrogenation of styrene into ethylbenzene. The presence of **aromatic hydrocarbons** and methyl methacrylate is further indication of residues from adhesives or polymerisation. Although these are intentional additives, during the recycling process, they are regarded as contaminated, while it is expected that it will affect the mechanical, thermal and processing parameters of the further recycling steps. Even though there is a high chance of using these additives during the first processing of the virgin polymers to enhance the performance to meet certain requirements, the various inclusion of a wide range of additives is labelled as a risk for process inefficiency.



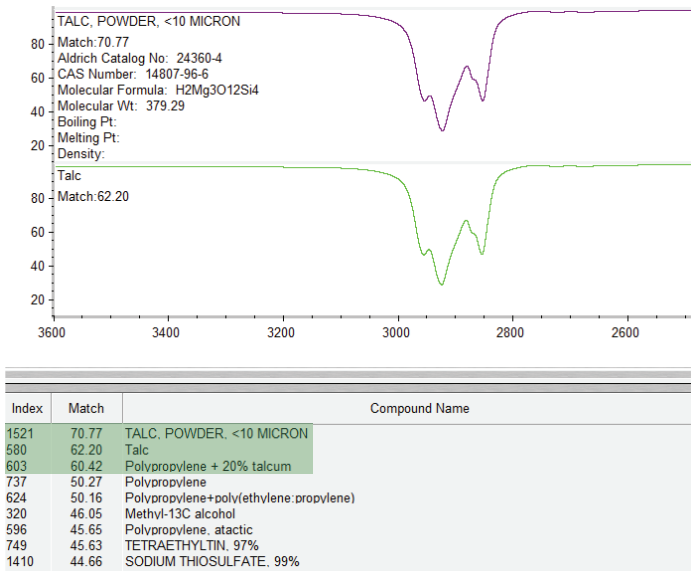
	Index	Match	Compound Name
1	14	30.73	ALKYD RESIN
2	32	27.42	POLY(ETHYLENE:PROPYLENE:DIENE)
3	31	24.12	POLY(VINYL ACETATE:ETHYLENE) 3:1
4	20	23.59	URETHANE ALKYD, LINSEED OIL-RICH
5	7	22.40	POLY(ETHYLENE)
6	39	21.71	POLY(ETHYLENE:PROPYLENE)
7	29	21.69	POLY(VINYL ACETATE:ETHYLENE) 4:1
8	16	20.65	POLY(VINYL PROPIONATE/ACETATE)



Index	Match	Compound Name
8	0.75	CELLOPHANE
46	0.52	POLY(STYRENE), ATACTIC
18	0.49	POLY(ARYL ETHER)
20	0.38	URETHANE ALKYD, LINSEED OIL-RICH
22	0.37	POLYETHERURETHANE
39	0.30	POLY(ETHYLENE:PROPYLENE)
5	0.29	POLY(VINYLIDENE FLUORIDE)
27	0.28	POLY(BUTADIENE:ACRYLONITRILE)



	Index	Match	Compound Name
1	1521	71.27	TALC, POWDER, <10 MICRON
2	603	66.21	Polypropylene + 20% talcum
3	580	63.19	Talc
4	624	57.68	Polypropylene+poly(ethylene:propylene)
5	737	57.62	Polypropylene
6	596	52.15	Polypropylene, atactic
7	41	49.99	POLY(PROPYLENE), ATACTIC
8	1410	47.05	SODIUM THIOSULFATE, 99%
9	38	46.93	POLY(PROPYLENE), SYNDIOTACTIC
10	1460	46.80	LITHIUM TETRACHLOROPALLADATE(II) HYDRATE



Index	Match	Compound Name
1521	70.77	TALC, POWDER, <10 MICRON
580	62.20	Talc
603	60.42	Polypropylene + 20% talcum
737	50.27	Polypropylene
624	50.16	Polypropylene+poly(ethylene:propylene)
320	46.05	Methyl-13C alcohol
596	45.65	Polypropylene, atactic
749	45.63	TETRAETHYLTIN, 97%
1410	44.66	SODIUM THIOSULFATE, 99%
1460	44.18	LITHIUM TETRACHLOROPALLADATE(II) HYDRATE

Table 4: The FT-IR results of proof-of-contamination on several samples from SDA-lines (Source: Nicolet iS50 FT-IR Spectrometer)

The **differential scanning calorimetry (DSC)** device is used to get information on the thermal behaviour of polymers by measuring the heat flows associated with the phase transitions, which are melting, crystallisation and glass transitions, This technique played a critical role during the thesis, as the thermal behaviour is directly related to injection molding cycle. The aim of using DSC is to come up with prior processing conditions which will be matched with the simulations conducted alongside on the product development track.

All measurements were conducted with a PerkinElmer Pyris Series DSC 6000 at the Stevin II Laboratory at the Faculty of Civil Engineering, TU Delft. There is a simple logic behind the DSC device which operates by comparing the required heat flow of a sample pan and a reference pan under controlled heating and cooling stages. Inside a heat sink, based on the assigned temperature and ramp, the heaters heat up the samples. The indication of phase transitions during data collection was visible as the sample either absorbs or releases heat. A precise and clean sample preparation is necessary for trustworthy results of the process.

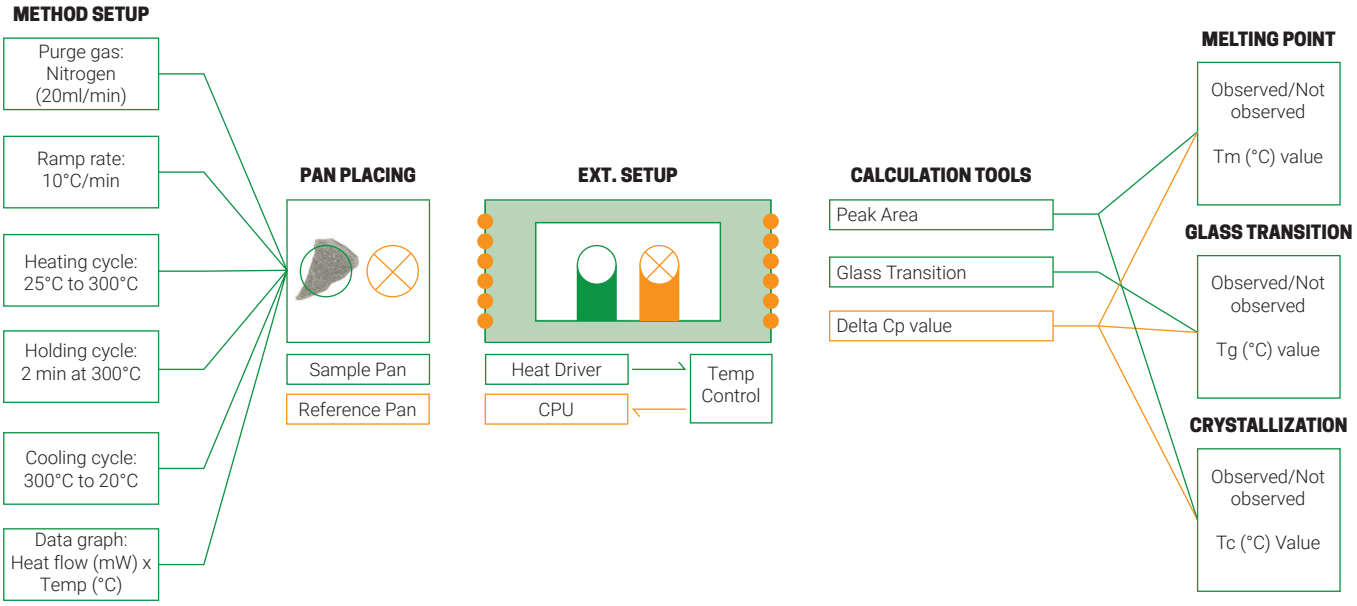


Figure 43: The workflow diagram of Pyris Series - DSC 6000 experiment setup (Source: Author)

Experiment setup: Sample preparation consists of weighing the sample on a METTLER TOLEDO NewClassic precision scale, which should be less than 10 mg. The samples are placed in a PerkinElmer DSC aluminium sample pan -part BO143019-, available in Stevin II Laboratory, and the lid by PerkinElmer -part BO16 9314- is placed on top of the pan carefully. If the extrusions from both the lid and the pan are aligned, it is compressed in a PerkinElmer pan crimper press with 2.4 MPa pressure. After the extrusions are removed because of the pressure head, the samples are ready to be placed on a heat resistor inside the heat sink.

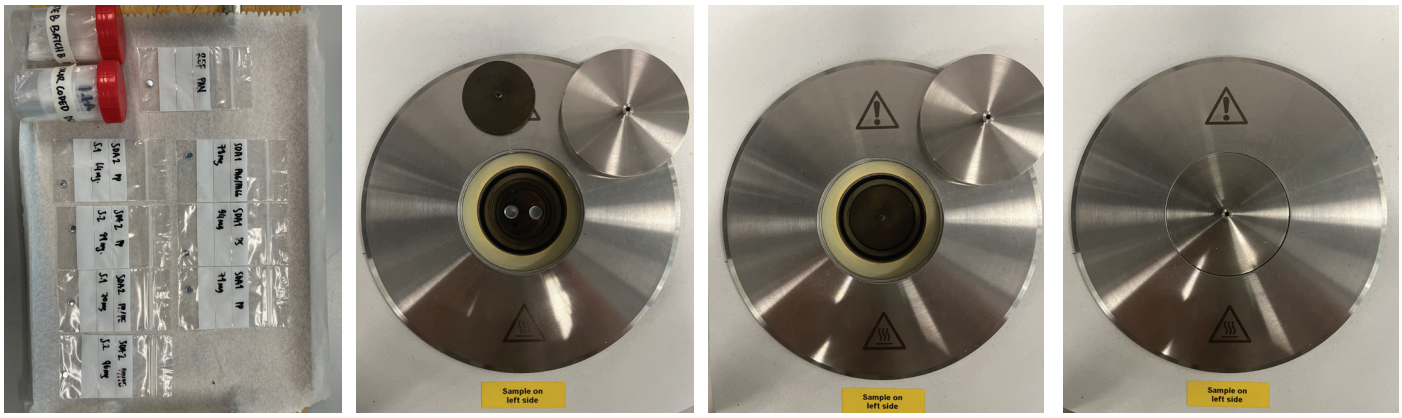


Figure 44: DSC preparation (1) selection of sample, (2) placing sample and reference pan, (3) closing the insulation lid, (4) closing the main lid (Source: Author)

The first experiments are done on the manually selected 9 samples out of all waste bags, with a reference sample that whose polymer type is known. PC reject fraction from MEWA is selected as the reference sample. The first data collection was done on the PC sample to test the workability of the heating/cooling cycle for the polymers. The reliable results from the PC polymers concluded with a semi-adjustable heating/cooling cycle that was tested for all samples. Five samples from two fridge line waste bags and four samples from SDA waste bags, based on manual colour sorting, were selected, and the data were collected. The end temperatures for both the heating and cooling cycles were selected, which covers a wide range of polymers that could be found in WEEE streams. The heating phase, isothermal hold and cooling phase were all performed at a ramp rate of 10 °C/min, which ensured a balanced rate. Nitrogen was selected as the purge gas with a 0.2 ml/min flow rate. The consideration of oxygen and nitrogen was made based on the prevention of oxidative degradation as the minimum temperature the setup can achieve with oxygen is room temperature. Nitrogen gas enabled a reliable setup that would prevent combustion or chemical reaction. To be able to interpret endothermic and exothermic events, the data were plotted as heat flow (mW) against temperature (°C), with endothermic events plotted upwards.

SAMPLES		SAMPLE WEIGHT (mg)	GLASS TRANSITION TEMP.		MELTING BEHAVIOUR		CRYSTALLIZATION	
FRIDGE 1	A1	9.4	**Observed**	Not Observed	**Observed**	Not Observed	**Observed**	Not Observed
	A2	8.7	**Observed**	Not Observed	Observed	**Not Observed**	Observed	**Not Observed**
	A3	6.9	**Observed**	Not Observed	**Observed**	Not Observed	Observed	**Not Observed**
FRIDGE 2	D1	9.5	**Observed**	Not Observed	**Observed**	Not Observed	Observed	**Not Observed**
	D2	8.7	**Observed**	Not Observed	**Observed**	Not Observed	Observed	**Not Observed**
SDA 1	B1	9.9	Observed	**Not Observed**	Observed	**Not Observed**	Observed	**Not Observed**
	B2	5.7	**Observed**	Not Observed	**Observed**	Not Observed	**Observed**	Not Observed
SDA 2	C1	9.8	**Observed**	Not Observed	**Observed**	Not Observed	**Observed**	Not Observed
	C2	9.5	**Observed**	Not Observed	Observed	**Not Observed**	Observed	**Not Observed**

Table 5: The first DSC analysis done on manually selected plastics from each waste bag (Frige 1-2, SDA 1-2) (Source: Author)

The second experiment with DSC was done on the selected four samples after density sorting. The samples are from the floating fraction of lab-scale density-sorted SDA 1 line polymers. The heating/ cooling cycle has initial temperature value as 25°C and the final temperature as 300°C. The ramp rate was selected as 10°C/min. Four different polymer types based on FT-IR were selected to perform the second DSC analysis. The known polymer composition of the samples aided the setup conditions of the heating/cooling cycle. The second data collection aimed to test the accuracy of the scientific data found on the glass transition temperature (Tg), melting temperature (Tm) and/or crystallization temperature (Tc) of the polymers and the data gathered from the experiments. Secondly, the experiment was aimed at being used for the processing stage for detecting the melting temperature of the polymers for the processing cycle.

The final experiments were conducted towards the final stage of the thesis, from the polymer batches which were already tested in the manual plunger-type injection molding machine. The initial and final temperature of the cycles stayed the same whereas the ramp rate increased to 15 °C/min for faster data collection. The polymers are selected from the SDA waste lines, 4 from the SDA line 2, and 2 from the SDA line 1. Based on visual inspection, the similar characteristic polymers that are repeating at the FT-IR and sorted into batches are selected. The numeric values for the glass transition temperature (Tg), melting temperature (Tm) and/or crystallisation temperature (Tc) are collected for comparison with the Edupack polymer data and DSC data.
The numeric data for Tg, Tm, Tc are obtained with the DSC 6000 calculation tools at the software. After the experiment is done, the line at the graph is selected as the active curve. The glass transition calculation tool is used by placing a cross symbol (X) at the left and right limits at the start and end of the glass transition behaviour, which is the first clear endothermic peak of the active curve. As Tg hints at the transition from glassy state to rubbery, it is crucial to examine for semi-crystalline polymers like PP. The numeric value is calculated based on the slopes generated from those points.

	SAMPLE WEIGHT (mg)	FT-IR RESULTS	Tg (°C)	Tm (°C)	Tc (°C)
S.5	7.5	T.1 Polystyrene T.2 Polystyrene T.3 PE/PP Blend	108.10 140.45	N/A	N/A
S.8	6.8	T.1 Polystyrene T.2 Polystyrene T.3 Polystyrene	105.71 143.00	N/A	N/A
S.9	6.6	T.1 Polypropylene T.2 Polypropylene T.3 PE/PP Blend	26.84	162.96	111.10 118.05
S.16	9.3	T.1 Polycarbonate resin T.2 Polycarbonate resin T.3 Polycarbonate resin	143.75	N/A	N/A

	SAMPLE WEIGHT (mg)	FT-IR RESULTS	Tg (°C)	Tm (°C)	Tc (°C)
SDA2.S1	7.0	T.1 PE/PP Blend T.2 PE/PP Blend T.3 PE/PP Blend	142.09	166.48	100.36
SDA2.S2	8.6	T.1 PE/PP Blend T.2 PE/PP Blend T.3 PE/PP Blend	112.95	126.89 162.28	113.78
SDA2.S3	6.4	T.1 Polypropylene T.2 Polypropylene T.3 PE/PP Blend	26.27	165.70	129.45
SDA2.S4	8.8	T.1 Polypropylene T.2 Polypropylene T.3 Polypropylene	27.54	166.18	126.19
SDA1.S1	7.1	T.1 Polypropylene T.2 Polypropylene T.3 Polypropylene	26.61	166.16	124.06
SDA1.S2	9.4	T.1 Polystyrene T.2 Polystyrene T.3 Polystyrene	102.44	9.3	N/A

Table 6: 1. First table showing the DSC analysis and numeric temperature collection for 4-samples from density-separated SDA 1 2. Second table showing the DSC analysis on 2 samples from density-separated SDA 1 and 4 samples from SDA 2 (Source: Author)

The numeric data both for Tm and Tc values are collected with the Peak Area calculation tool that determines the area, starting, mid-, and end point of a peak transition. It is generally used for melting, crystallisation, and curing. The same method of placing cross symbols at the left and right temperature limits (see Fig.45) gives off the maximum value of the manually selected peak in the temperature range. Identification of the melting temperature is done on the endothermic peak after glass transition, and the crystallisation temperature on the exothermic peak during the cooling cycle.

DSC Analysis: The DSC analysis differs on the three experiments that were done with DSC device based on the aim of the study. The first experiments were conducted when the information gathered on the waste streams and the polymer types were limited. Therefore, the main purpose of the first experiment was to identify if the plastics that are repeating at the stream have contamination or immiscibility before conducting other characterization setups. Therefore, the aim of the first experiment is: **(1)** identify a workable heating/cooling cycle for DSC that is applicable for WEEE polymers, **(2)** form an understanding of the amorphous, crystalline and semi-crystalline polymer behaviour, **(3)** identify the immiscible polymer blends and/or contamination. The analysis of the results is classified based on "Observed/Not Observed" options after visually analysing the active curve of the endothermic and exothermic peaks.

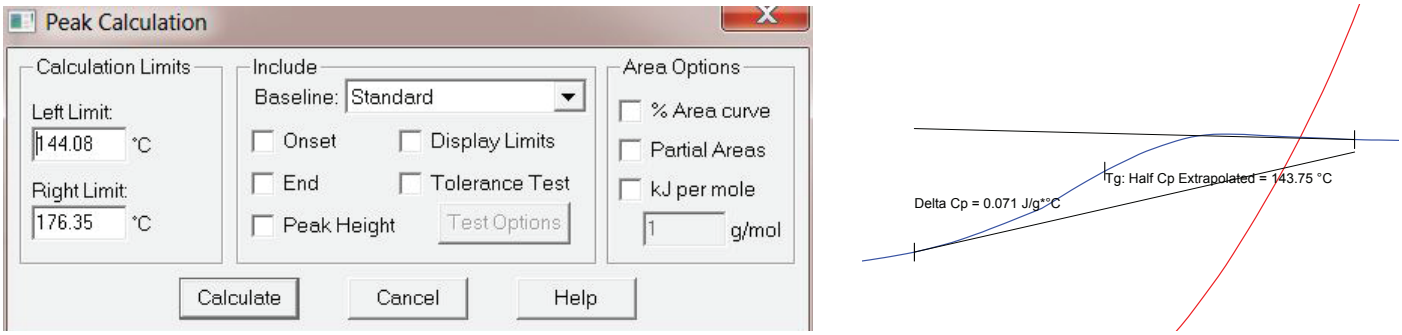
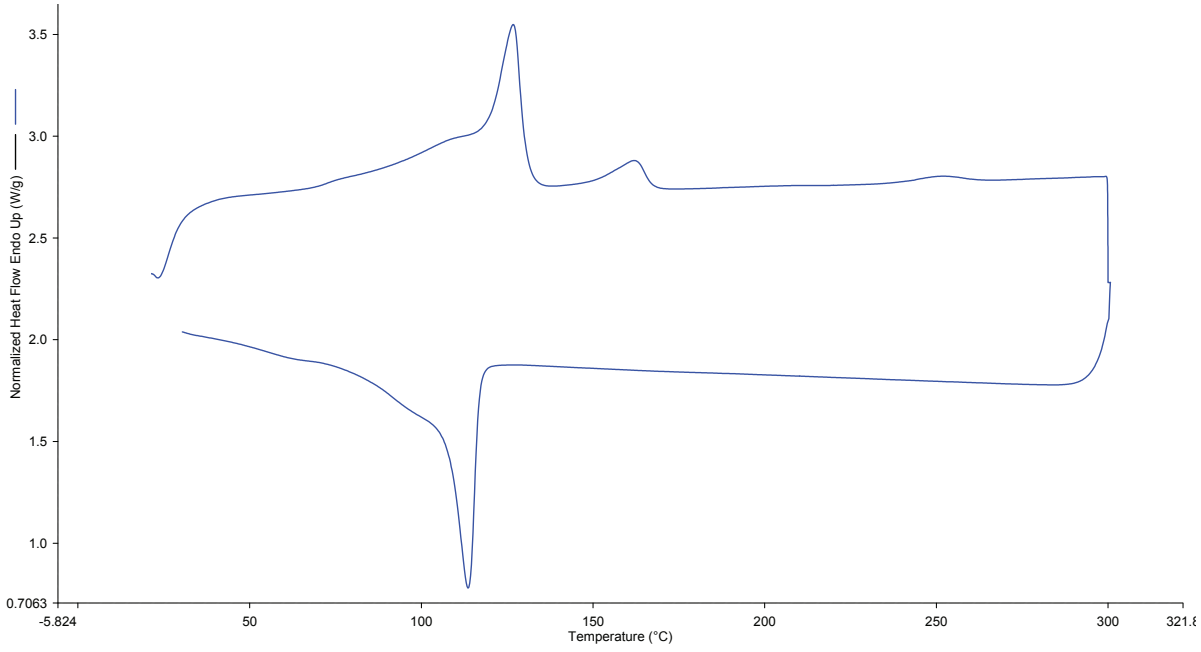


Figure 45: The calculation tools used to obtain numeric temperature values (Peak Area & Tg) (Source: DSC 6000 & Author)

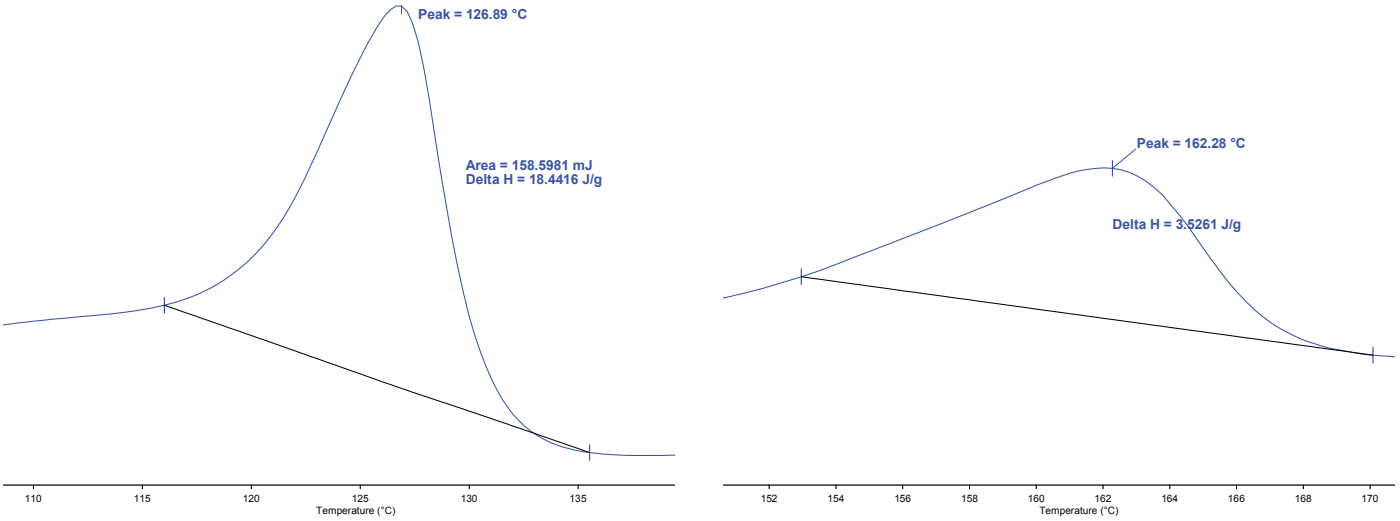
As it can be seen in the Table 4, the selected unknown polymers did not show the expected thermal behaviour. It was thought to have the majority of semi-crystalline polymers, which should include two endothermic peaks and one exothermic peak during the heating/cooling cycle. However, the majority of the polymer was concluded to be amorphous, which suggest polymer selection like PC. The samples A1, B2 and C1 showcased a similar thermal behaviour with an early glass transition, and a distinct melting peak at the temperature ranges of 150-180°C and a crystallisation peak around 170°C. This hints at the semi-crystalline polymer choice that is not a polymer blend, as there was no apparent multiple peak behaviour observed. On the other hand, the samples of B1 and A3 presented a similar amorphous behaviour with only a distinctive glass transition behaviour. D2 presented double glass transition behaviour without melting, which hints at **immiscible polymer blends** because of the clear phase separation (Toledo, 2001). The same immiscibility is observed on A3 that hints at a possible PC/ABS or PC/PS blend. The last behaviour that was noticed on the samples like A2 is the baseline shift that can be observed with a high endothermic peak that lasts through a wide temperature range, which can hint at **immiscibility or contamination**. Even though several outcomes were able to be made from the first experiments. It is concluded that a prior FT-IR test is necessary for clear identification of possible effects of the thermal peaks. Therefore, other two experiments were conducted at the later stages of the thesis to collect numeric data for the processing stage and to check for unexpected thermal behaviour that could cause problems during injection molding setups.

The second experiment (see Table 6.) was done on the four selected polymers from the floating fraction of SDA line 1, selected based on the FT-IR test conducted before. The samples include two PS samples, with overall match percentages of 85.83 and 82.07; PP sample with a match percentage of 89.56; and a PC sample with 69.26 match percentage. The majority of the characterisation results include PP, PS, PC polymer types which were also the types that were selected for DSC analysis. After visual inspection of the active curves, the numeric data on Tg, Tm, Tc characteristics were collected. The comparative analysis was done based on the literature data and the data found with DSC 6000 calculation tools.



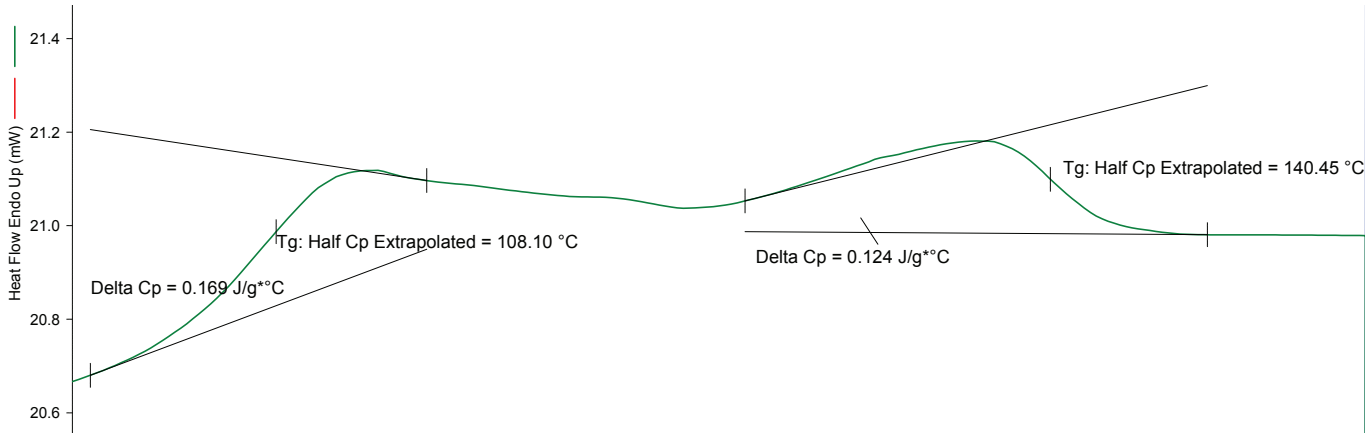
Graph 3: DSC result of SDA2.S2 as PP/PE blend with endo-/exhothermic peaks (Source: DSC 6000 & Author)

As expected, no crystallisation behaviour was observed in the samples S.16,5,8 as they were all found as amorphous polymers. There were two exothermic peaks during crystallisation for S.9, which gave PP and PP/PE results from the FT-IR.



Graph 4: The indication of PP/PE blend with two specific melting behaviour on SDA2.S2 (Source: DSC 6000 & Author)

Based on the literature data, the DSC graphs are analysed and concluded that the multiple glass transition peaks occurring in S.5 and S.8 suggest two separate melting transitions, which led to a phase separation. Both PS samples are found to be immiscible with lower Delta Cp values, hinting at physical ageing. The Delta Cp value on S.9 was found to be lower than the usual range for PP, which also supports the outcome from the crystallisation result that the sample is probably an immiscible PP/PE blend rather than PP. The observed double peak at crystallisation hinted at a higher percentage of having an immiscible polymer blend rather than a single polymer in the sample. Therefore, the PP/PE conclusion for S.9 is regarded as the most probable option. S.16 was FT-IR identified as PC an amorphous polymer; therefore, observing a melting temperature or the crystallization temperature was not expected. A glass transition temperature value between the temperature range 145–150 °C was looked for. Similarly, for S.5, a PS polymer, also only the indication of glass transition behavior and temperature was expected. However, there was also a small endothermic peak after its glass transition, which concluded as a possible indication of contamination.



Graph 5: The indication of PP/PE blend with two specific glass transition behaviours on S.5 (see Table 5.) (Source: DSC 6000 & Author)

The use of additives like **polybutadiene** can cause endothermic bumps. The double endothermic peak behavior was also observed on S.8, which was identified as PS too. The first endothermic peak concluded as the glass transition temperature, whereas the second peak confirmed a similar additives or copolymer use at both S.5 and S.8. There is a high chance the polymer shreds are sourced from the same component of the waste stream or processed similarly. Additionally, there was a small endothermic peak observed around the 50 °C zone during the cooling cycle of S.8, which again might refer to a **residual solvent or additives** existing at the polymer. Overall, the **common WEEE contaminants** like brominated flame retardants, plasticizers, and processing aids can decompose during DSC analysis, causing unexpected endothermic/exothermic behavior of the polymer. The final experiments (see Table 6.) follow the same methodology as the second DSC analysis.

As the selected samples are sourced from polymer batches that were tested at the injection molding experiment setups, the main purposes for this analysis was **(1)** compare the melting temperature at the injection cycle and DSC heating/cooling cycle, **(2)** finding out whether the majority of the polymer blends are miscible, **(3)** finding out if the contamination affects the final performance. SDA2.S2 , a PP/PE polymer blend, showcased two endothermic peaks as melting behaviour. The first peak indicated the melted PE phase, and the second peak indicated the PP phase. Even though this result was expected on both SDA2.S2 and SDA2.S1, SDA2.S1 did not have a distinct endothermic peak with high heat flow, therefore, a double-peak formation was not observed.
Across all three experiments using DSC analysis on heterogeneous WEEE waste streams, the tool helped to define the limitations of the waste input on the processing stages and to characterise the material with its flaws beforehand to relate to the abnormalities after the samples are created during injection moulding setups. The DSC numeric values hand in hand with the literature data found with Edupack Granta and SolidWorks, are referenced while optimising the injection cycle during the setups.

To support the contamination check of the polymers, a **micrograph analysis** was done using the Keyence VHX-7000 digital microscope at the Faculty of Architecture and Built Environment of TU Delft. Micrographs were obtained to examine the surface texture, possible contamination before the processing stage. When combined with the chemical and composition data from FT-IR and DSC, micrograph analysis offered a comprehensive understanding of the waste input.

Figure 46: The micrographs of selected possibly contaminated SDA 1 samples (Source: VHX-7000 & Author)

The first samples were selected during the manual colour sorting of the SDA 1 polymers. Six samples were selected from the floating fraction, selected by the characteristics that were also visible for other polymers in the waste input.

3.2.3 Density Separation

Density separation with sink-float separation is one of the established methods used for mechanical recycling of plastics. The method in its essence is simple where the shredded and pre-cleaned plastics are introduced into a liquid medium, where the density becomes the deciding factor for the plastics that are going to float or sink. The essential part of the density separation is the pre-treatment of the plastics, consisting of pre-cleaning and drying before separation to avoid any water content inside the plastics. Before experimenting, the available data on the polymers of the WEEE stream is looked into. Based on the databases of Granta Edupack and SolidWorks, the densities of the common polymers found in the WEEE stream are compared. The comparison is made based on the injection moldability of the material in line with the product development track. This aided the decision-making process for the target polymer and the density required for the liquid medium.

The polymers that might hinder the efficiency of the density separation, such as ABS and PS, which can exhibit intermediate density values and mostly necessitate well-optimised sink-float systems, were known before the experiments (Meneses Quelal et al., 2022). It was known that the choice of the separating medium is the key to enhancing the recovery percentages for homogeneous streams. In industrial-scale implementations of density

separation, it is also known that polyolefins are separated in low densities, whereas high-density polymers like ABS, PS are recovered as sinking fractions, while overlapping is a common result due to contamination (Thanh Truc & Lee, 2016). Thesis focuses on the floating fraction of density separation as sinking fractions were expected to be highly contaminated with organic and inorganic substances. The first experiments were done targeting PP as, in theory, the density range 0.90–0.96 g/cm³ needs to allow the experiment to work with water as the medium.

Experiment setup: As the waste input is proven to be contaminated and visually inspected as dirty, the pre-cleaning needs to be done before each setup for the density separation to function properly. The reject fraction from the selected fridge or SDA line is washed with detergent by placing the plastics in a 30l container with mixed detergent and water medium. After stirring the mix, plastics are cleaned by the use of kitchen scrubs to remove the removable contamination layer, if it exists. Then, the plastics are dried in an oven at 90°C for two hours or left out in the open for at least 24 hours before density separation.

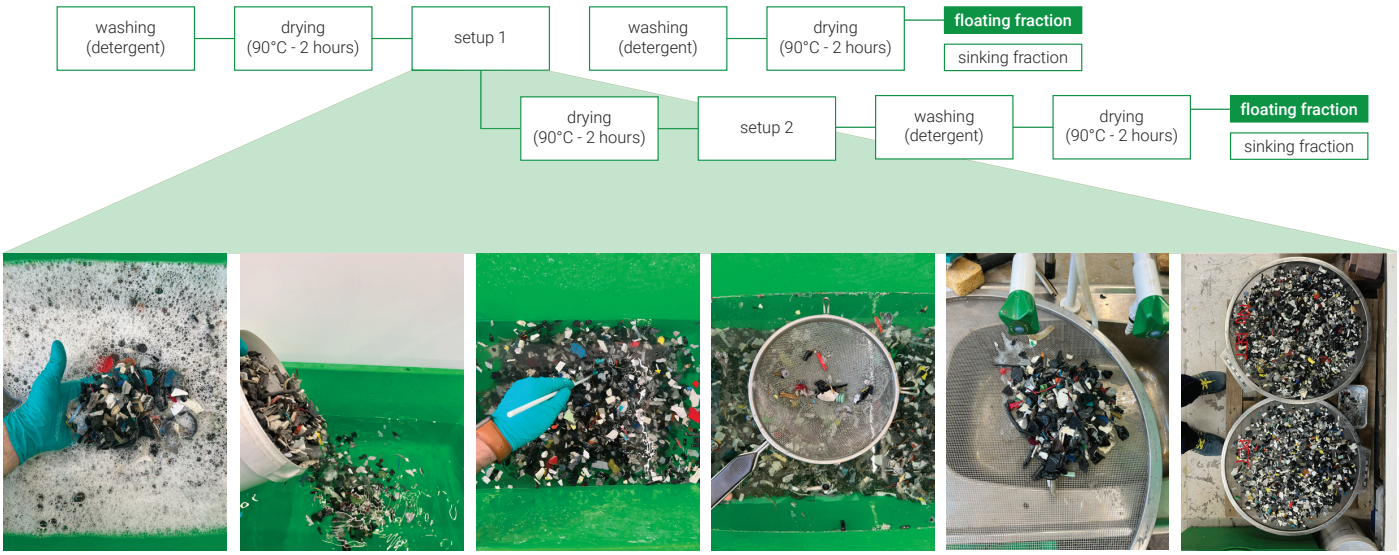
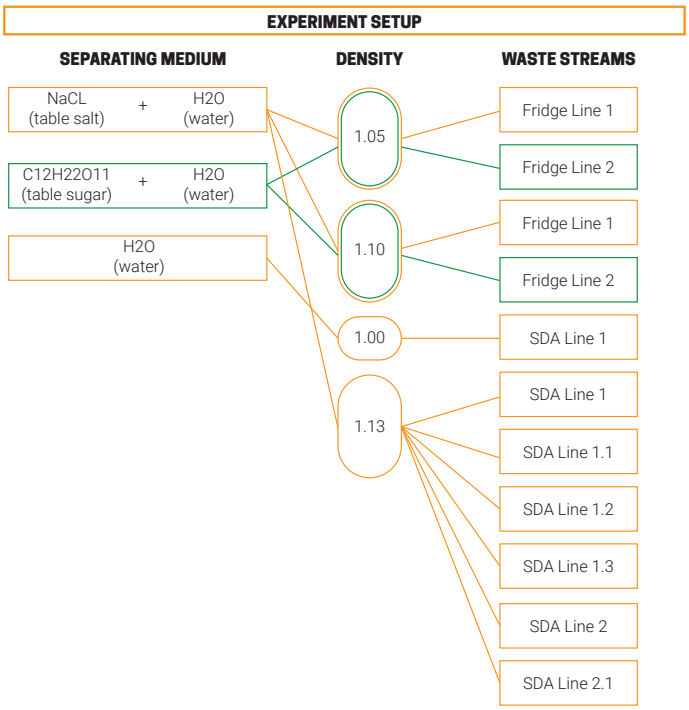


Figure 47: The workflow diagram showing the lab-scale density separation steps (Source: Author)

The separating mediums, consisting of water, table sugar and table salt, and water and table sugar, are prepared based on the "Tables for Sodium Chloride Brine Tables for 15.5 °C" and Hanna Sodium Chloride Refractometer from the Stevin II Laboratory at the Civil Engineering Faculty. Based on multiple checks during the addition of the separator, the liquid medium's target density is achieved. The selected mixed waste is placed in the medium by trials and specific input weight. The floating fraction was collected with a kitchen sieve into a 2mm aperture lab sieve for the removal of salt and sugar stains after the experiment. The floating fraction is washed with detergent and water again and left to dry, which concludes the experiment setup. Density separation played a central role in the material experimentation phase of the thesis. The unknown polymer composition of the waste input on all waste lines and minor information obtained from the first polymer characterisation necessitated a trial-and-error method to conclude a target density and target polymer for the experiments.

Figure 48: The first trial of density separation with Fridge-1 plastics with densities 1.00 and 1.05 g/cm³ (Source: Author)

As there were no solutions available already at the laboratory, table salt and sugar were being used to achieve the target densities. The densities of 1.00 and 1.05 g/cm³ were tested on the fridge line, which had a smaller shred size compared to the SDA line. The first trials were done with 1L of water to test the applicability of the experiments (see Fig.48). Even though the floating fractions of the first experiments were relatively lower than the sinking fractions, the **use of table salt and sugar as the separator** was proven to be used for the following experiments.



EXPERIMENT SETUP			WEIGHT (g)					
SEPARATING MEDIUM	DENSITY	WASTE STREAMS	SEPARATOR	WATER	TRIALS	INPUT WASTE	FLOATING	SINK
NaCL (table salt) + H2O (water)	1.05	Fridge Line 1	72.00	1000	2	100.00	**39.35**	160.65
		Fridge Line 2	100.00	1000	5	100.00	**68.05**	431.95
C12H22O11 (table sugar) + H2O (water)	1.10	Fridge Line 1	165.10	1000	4	100.00	**84.60**	315.40
		Fridge Line 2	240.10	1000	3	100.00	**15.00**	285.00
H2O (water)	1.00	SDA Line 1	-	45000	1	3086.85	**24.50**	2752.20
	1.13	SDA Line 1	4180.00	24000	1	3213.00	**461.80**	
		SDA Line 1.1	6097.00	35000	1	2859.30	**557.30**	2302.00
		SDA Line 1.2	6364.75	35000	1	3990.00	**461.90**	3528.10
		SDA Line 1.3	6364.75	35000	1	5528.10	**1313.50**	4214.60
		SDA Line 2	6637.55	35000	1	6000.00	**8085.00**	6625.00
		SDA Line 2.1	6976.50	42000	1	8710.00		

Table 7: The density separation trials done on all waste bags with floating/sinking weight results (Source: Author)

The target polymer changed after the first experiments done on the fridge lines, based on the feedback loop with the product development track. Several parameters affected the decision to focus on the SDA line waste input. **The smaller shred size** made handling of the polymers for the polymer characterisation difficult. The injection molding simulations done with various polymers hinted at the applicability of targeting PA6/PA66 and PS for the processing stage. Therefore, further trials were done aiming for 1.13 g/cm³, which is higher than both the PA6/PA66 blend and PS densities.

The density of 1.13 g/cm³ of the separating medium is achieved by using table salt on all reject fractions of the SDA line. The promising results, especially with **24.20% efficiency** on SDA Line 1.1 offered a practical lab-scale method for upstream sorting of plastics.

3.2.4 Colour Sorting

Conventional colour sorting in industrial settings is with automated systems with optical sensors, including near-infrared and optical cameras. The automated optical sorting systems are generally preferred over manual colour sorting due to their efficiency for high batches. However, for the thesis, a lab-scale colour sorting is adapted for the small batches of waste input that exist. This enabled the assessment of the feasibility of the system and to conclude whether colour is an indicator for polymer identity and overall quantity.

Experiment Setup: The waste input is collected on a 2mm aperture lab sieve as a mix of plastic, organic and inorganic fractions. The categories include black, white, dark grey, light grey, semi-transparent, multi-colour, rubber, contaminated and foreign. The categorisation was done both by visual inspection and by touching the material to identify. The data is collected in terms of weight, which at the end indicates what colour is found the highest in the waste stream.

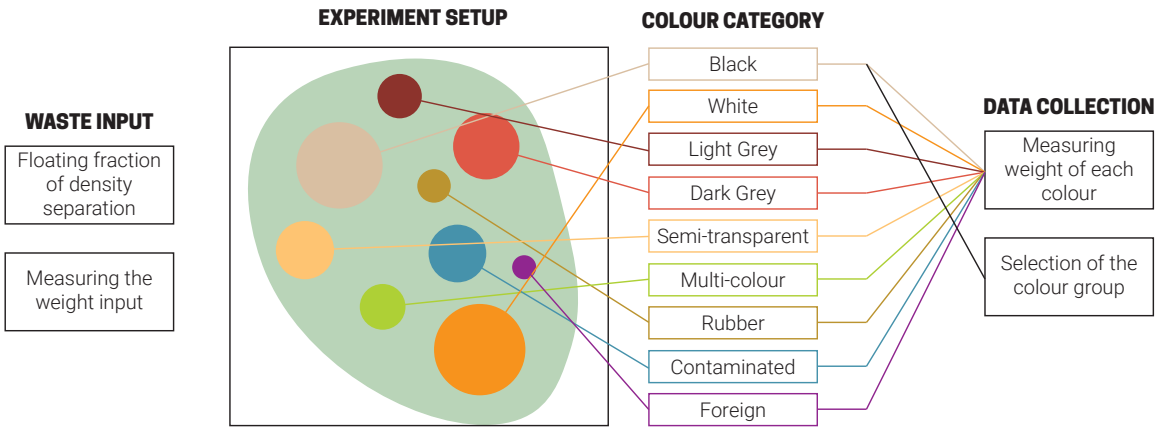


Figure 49: Workflow diagram showing the steps taken for manual colour-sorting setups (Source: Author)

The manual colour sorting was implemented on the waste lines on different steps to test the optimal applicability scenario. First manual colour sorting was implemented on the fridge lines before the density separation. The result of the manual colour sorting as various colour batches, was used for two experiment setups of manual press and pneumatic plunger-type injection moulding for feedback.

The results of the feedback necessitated a change of order for the manual colour sorting which became a complementary step after density separation. The change of order is proven to be efficient in terms of workability and processing results. The limitations of the processing experiments reflected on the use of colour-sorted batches. Relatively bigger shreds were sent to polymer characterisation with FT-IR, and smaller shreds were prepared for manual pressing.

Figure 50: The manual colour sorting setup based on physical characteristics (Source: Author)

		FT-IR IDENTIFIED POLYMER WEIGHTS (g)						
	FIRST BATCH	PP	PE/PP	PS	PA6/PA66	PC	PMMA + PUR	TOTAL WEIGHT (g)
COLOUR SORTED POLYMER CATEGORIES	BLACK	19.52	31.50	15.59	9.53	4.45	9.74	156.31
	WHITE							129.06
	DARK GREY	3.92	18.51	N/A	1.16	N/A	N/A	29.22
	LIGHT GREY	18.98	12.33	8.71	3.44	2.26	0.83	56.18
	SEMI-TRANSPARENT							99.78
	MULTI-COLOUR	17.83	11.69	1.22	2.57	2.62	0.64	42.39
	RUBBER							71.30
	CONTAMINATED							28.11
	FOREIGN							
	SECOND BATCH	PP	PE/PP	PS	PA6/PA66	PC	PMMA + PUR	TOTAL WEIGHT (g)
COLOUR SORTED POLYMER CATEGORIES	BLACK	23.76	45.63	23.74	15.68	5.93	13.28	169.82
	WHITE							136.38
	DARK GREY							N/A
	LIGHT GREY	17.95	22.62	9.86	2.53	1.97	2.60	42.71
	SEMI-TRANSPARENT							80.76
	MULTI-COLOUR	14.43	4.33	2.53	3.06	0.33	2.47	28.29
	RUBBER							72.36
	CONTAMINATED							105.80
	THIRD BATCH	PP	PE/PP	PS	PA6/PA66	PC	PMMA + PUR	TOTAL WEIGHT (g)
	BLACK #1	24.03	55.13	23.63	25.51	28.15	21.63	178.08
	BLACK #2	14.94	35.13	5.48	5.74	2.81	0.89	64.99
	BLACK #3	19.40	67.89	13.69	15.71	3.89	11.68	132.26
	BLACK #4	7.98	23.57	7.50	1.02	N/A	0.35	40.42

Table 8: The polymer datasheet after manual colour sorting & FT-IR analysis (Source: Author)

Carbon black polymers are considered problematic due to their optical properties as the black pigment absorbs the light across ultraviolet, visible and near-infrared spectra during automated colour sorting. This effect significantly lowers the efficiency of conventional sorting techniques that rely on near-infrared spectroscopy during recycling (Signoret et al., 2019).

As the spectral fingerprint is masked by the colour black, the black plastics are frequently missorted and sent to incineration because they are excluded from recycling streams. As the waste input contains reject fractions from mechanical recycling steps which also includes a reject fraction from near-infrared sorting (SDA 1), there is a majority of black plastics available. The limited recyclability of carbon black plastics presented an opportunity within the scope of the thesis, especially for the application of the thesis. Therefore, black plastic reject fractions were prioritised at the later stages to test the applicability for the final injection-moldable recipe.

3.2.5 XRF Analysis

Given that WEEE plastics often contain a range of additives, colourants, and flame retardants, a non-destructive screening tool to detect inorganic elements was conducted with X-ray fluorescence (XRF) spectroscopy. Three sample groups were prepared for the analysis with each group presenting similar surface behaviour to the rest of the final polymer batch before shredding for processing.

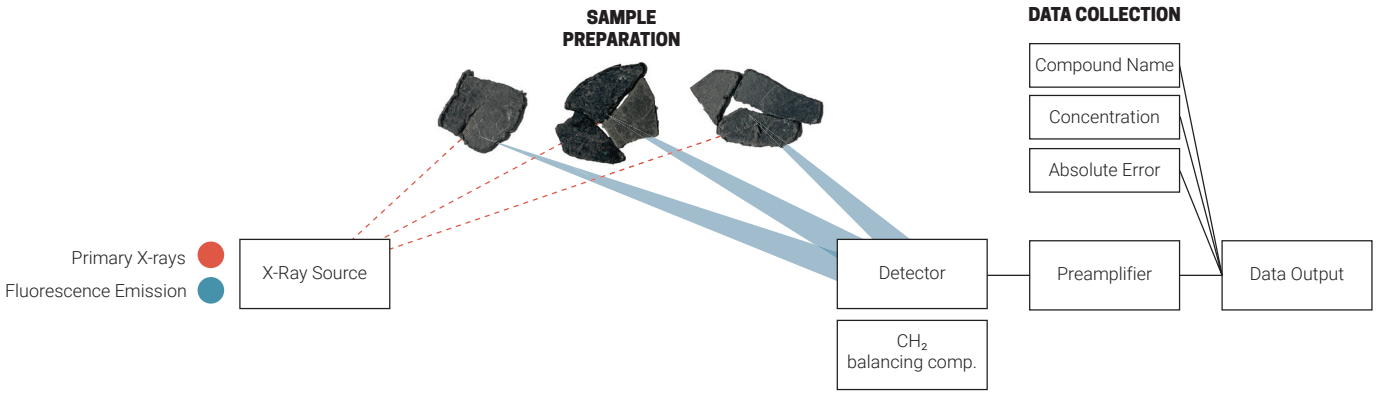


Figure 51: XRF Analysis setup for the three prepared PP/PE blend samples from SDA-2 (Source: Author)

Experiment Setup: The experiment was conducted in the Faculty of Mechanical Engineering (3mE), and Ruud Hendrikx at the Department of Materials Science and Engineering of the Delft University of Technology is acknowledged for the X-ray analysis. The measurements were performed with a Panalytical Axios Max WD-XRF Spectrometer, and the data was evaluated with SuperQ5.0i/Omnian software. The analysis could either be done with powdered samples or samples with a flat surface. CH_2 was used as the balancing compound, which represents the plastic matrix. This enables better matrix correction during elemental quantification.

	SAMPLE 1			SAMPLE 2			SAMPLE 3		
	COMPOUND NAME	CONC. (wt%)	ABS. ERROR (wt%)	COMPOUND NAME	CONC. (wt%)	ABS. ERROR (wt%)	COMPOUND NAME	CONC. (wt%)	ABS. ERROR (wt%)
1	CH2	90.435	-	CH2	92.94	-	CH2	97.979	-
2	Si	4.047	0.06	Na	2.031	0.04	Ti	0.787	0.03
3	Mg	2.603	0.05	Si	1.505	0.04	Na	0.282	0.02
4	Na	1.058	0.03	Mg	1.078	0.03	Si	0.279	0.02
5	Cl	0.647	0.02	Cl	0.782	0.03	Mg	0.245	0.01
6	Al	0.431	0.02	Ba	0.368	0.02	Al	0.152	0.01
7	Ca	0.205	0.01	Ca	0.346	0.02	Cl	0.090	0.009
8	Fe	0.170	0.01	Al	0.281	0.02	Ca	0.044	0.006
9	Ti	0.133	0.01	Ti	0.195	0.01	S	0.041	0.006
10	F	0.119	0.01	S	0.195	0.01	Fe	0.035	0.006
11	S	0.053	0.007	Cu	0.179	0.01	P	0.030	0.005
12	P	0.026	0.005	Fe	0.035	0.006	Cu	0.014	0.004
13	Cu	0.025	0.005	P	0.023	0.005	Cr	0.010	0.003
14	K	0.012	0.003	Sr	0.013	0.003	Co	0.005	0.002
15	Zn	0.011	0.003	K	0.011	0.003	K	0.003	0.002
16	Co	0.007	0.003	Cr	0.005	0.002	Zn	0.002	0.001
17	Mn	0.006	0.002	Zn	0.004	0.002	Br	0.001	0.0008
18	Ni	0.004	0.002	Br	0.004	0.002			
19	Pb	0.003	0.002	Mn	0.002	0.001			
20	Cr	0.002	0.001	Co	0.002	0.001			

Table 9: XRF results for the three samples with inidication of contaminants (green) and Bromine (orange) (Adaped from: Ruud Hendrikx)

The results did not detect significant levels of bromine with 0.004 wt% and 0.001 wt% concentration, which suggests that there was **(1)** no use of halogenated flame retardants at the waste line, **(2)** the use of non-halogenated flame retardants instead, **(3)** or effective cleaning and removal during the sorting steps. The results showcased relatively high concentrations of silicon (Si), magnesium (Mg), sodium (Na), chlorine (Cl), titanium (Ti), aluminium (Al), calcium (Ca), and barium (Ba).

Silicon was among the most highly detected elements in the analysis, which suggests the use of **silica-based fillers** that are commonly found in electronic plastic casings. Magnesium was also one of the highest wt% in the samples, which suggests the use of **non-halogenated flame retardants**, which is common in SDA appliances where fire safety standards apply. Therefore, it is believed that it is one of the reasons why the samples need a higher processing temperature than virgin polymer alternatives. Another possible non-halogenated flame retardant is the result of aluminium, which hints at aluminium hydroxide that is commonly used in thermoplastic casings. Sodium and chlorine were unexpected at the samples as they strongly indicate the **salt residues** (NaCl) from the conducted density separation. Despite the complementary washing with detergent of the floating fraction of the density separation, the residues suggest the imperfection of the lab-scale techniques. It is also believed that the salt residues may be one of the reasons for the **odorous behaviour** of the samples. The detected titanium suggests the use of **UV stabilisers** which is a common application in SDA plastics to achieve colour uniformity. The presence of **fillers** is apparent with the found elements of calcium and barium which might affect flow properties during processing.

In conclusion, the XRF analysis confirmed the presence of **(1)** salt residues from density separation, **(2)** mineral fillers and additives, **(3)** non-halogenated flame retardants which are consistent with typical WEEE plastics.

3.2.6 Experiment Setups

Based on the outcomes of the polymer characterisation, density separation, and manual colour sorting steps, six polymer selection paths were established for further testing: **(1)** colour-sorted polymers, **(2)** density-separated polymers, **(3)** FT-IR-identified polymers/ blends, and **(4)** recycled polypropylene. The suitability of each blend was evaluated in relation to the level of complexity of the injection molding setup, ranging from low-tech to advanced technologies. These connections were determined through a trial-and-error approach, with early-stage failures serving to define processing boundaries and inform polymer selection strategy for each setup.

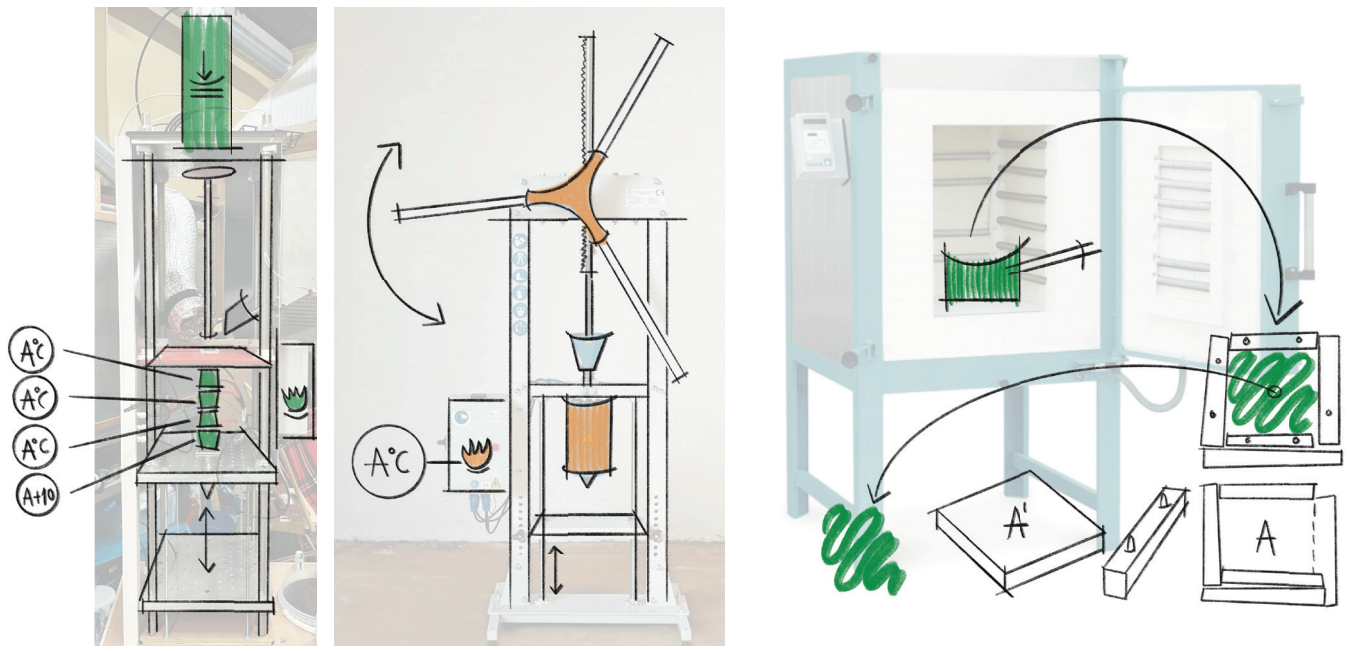


Figure 52: The experiment setups of pneumatic plunger-type injection molding, manual plunger-type injection molding, and manual press respectively (Source: Author)

The categorization of the experiment setups emerged after initial testing with a manual colour-sorted plastic mix (without density separation), specifically sourced from the Fridge-2 line of the WEEE stream. This blend, known to contain a variety of polymers with incompatible melting behaviours, was first tested using the pneumatic plunger-type injection molding machine, the most advanced setup. The unsuccessful result from this trial, due to poor melt homogeneity and visible surface defects, prompted a recalibration of the material–setup matching process, establishing clearer criteria for which polymer types could be tested in which setup. As there was no prior hands-on experience with injection molding, beginning with the most advanced technique using the most heterogeneous mix, unintentionally served as a **critical screening stage**. It revealed the need for more controlled and homogeneous material batches in setups with higher pressure and temperature sensitivity. The manual color-sorted plastic mix contained polymers such as ABS, PC, PP, PS, and PA, which were previously identified in the WEEE stream and confirmed through FT-IR and database comparison. Data gathered from SolidWorks and Granta EduPack indicated distinctive melting temperatures ranging from 230 to 305 °C, while micrograph analysis of selected samples from the same batch showed evidence of contamination.

Generic PC	
Polymer Family	PC
Manufacturer	Generic material
Recommended Melt Temperature	305 °C
Recommended Mold Temperature	95 °C
Maximum Mold Temperature	120 °C
Minimum Mold Temperature	70 °C
Ejection Temperature	125 °C
Thermoset Conversions	Not Available

Generic PP	
Polymer Family	PP
Manufacturer	Generic material
Recommended Melt Temperature	230 °C
Maximum Melt Temperature	280 °C
Minimum Melt Temperature	200 °C
Recommended Mold Temperature	50 °C
Maximum Mold Temperature	80 °C
Minimum Mold Temperature	20 °C

Table 10: The comparative tables for generic PC and PP for recommended melt temperature (Source: SolidWorks)

The boundary setup consisted of three trails with increasing temperature, which resulted in a failure that proved the technical limitations caused by the heterogeneous mix. The iterative approach concluded with a specific polymer selection option for each setup. Based on this, the polymer batches are created specifically for the setups are then tested throughout the second phase of the thesis for sampling. The samples are evaluated based on the five parameters – mixing, morphology, degradation, stability, and smell results- and the results are given as feedback to the product development track simultaneously. The setups and the results are introduced based on their level of advancement for processing after the moulds for the experiments are defined.

3.2.6.1 Mould for Experiments

The moulds for the experiments were made from scrap wood with a unique design that simplifies the sample removal process after processing. The removal of the sample from the mould is prioritised as the samples were expected to be brittle and partially unmelted. The mould is designed with removable sides of the mould as they are supported with wooden dowels. The other sides of the mould is screwed in to prevent plastic flashing during molding. The plug-on/off design enabled quick mold reset between trials, which enabled time efficiency. The dimensions of the molds are given based on the requirements of the standardised mechanical testing and the constraints of the final product design. Two molds with the sizes 100 × 100 × 4 mm and 80 × 100 × 4 mm were used during phase two. The dimensions of the 100 × 100 × 4 mm mold were the result of the ISO 604 guidelines for compressive strength testing of plastics in terms of the length of the mold. The height of the mould was given so that if necessary, the sample can be cut into three pieces, two for Charpy impact testing, one for compressive strength testing. The 80 × 100 × 4 mm mold alternative was selected to align with the design envelope and equal side requirements which were assessed from the product development track. This enabled ease in comparison with the samples from different setups in terms of molding quality.

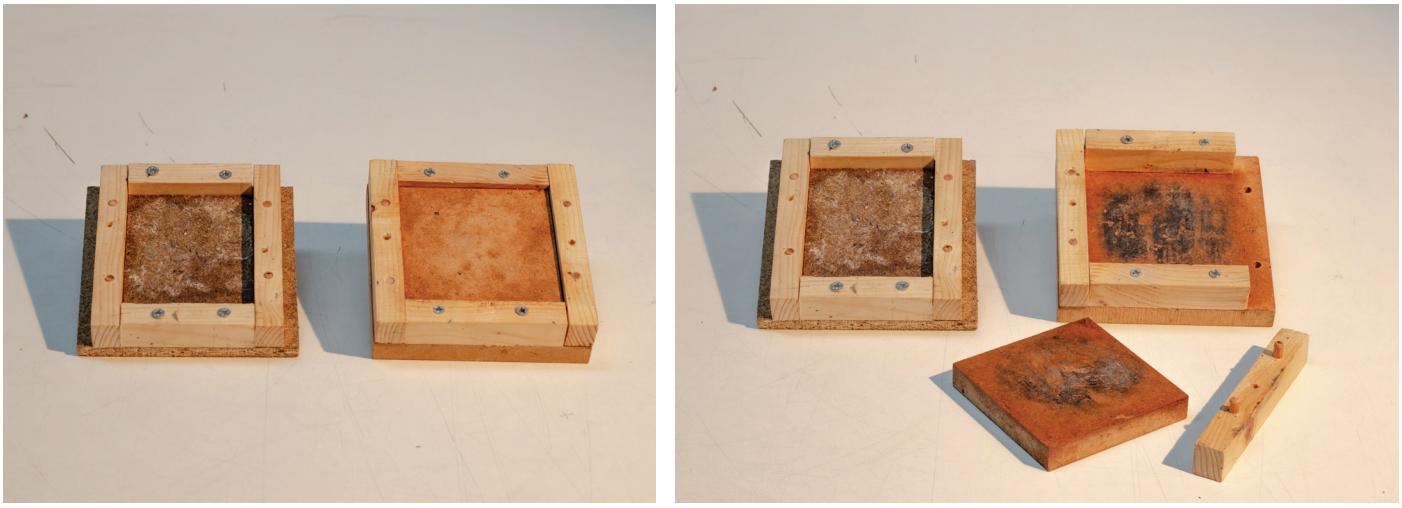


Figure 53: The detachable wood moulds 100 x 100 x 4 mm (see left) and 80 x 100 x 4 mm (see right) (Source: Author)

3.2.6.2 Manual Press

The manual press experiment setup was developed as a low-tech simulation of injection molding principles, adapted by using the ROHDE 1000S kiln at the Stevin Lab II at Civil Engineering, TU Delft. Unlike conventional hot pressing, no heated plates is being used during processing, but rather the plastics are melted at another medium and poured into the mould and pressed just like injection molding, prioritising flow-based behaviour. The material behaviour during injection molding includes cavity filling, flow attributes. The method was crucial in terms of flexibility as a wide range of polymer compositions can be tried and tested rapidly. While the experiments lacked precise measurement of pressure or the injection rate, the failure points and all parameters were easily accessible for evaluation. This enabled rapid refinement of material recipes and polymer selection for the intermediate and advanced processing setups. The manual press setup functioned as the screening tool for the potential of polymer selection for the WEEE stream plastics.

Experiment Setup: The setup consists of straightforward yet with various checkpoints during the setup are designed to simulate injection molding behaviour and refine the processing cycle with low-tech equipment. Each experiment is utilised, starting from the selection of polymers and the mould. The moulds are pretreated with a layer of petroleum jelly to prevent adhesion of the molten plastic to the mold surfaces. After measuring the weight of the polymers, the batch is placed in a steel pot and heated in the ROHDE 1000S kiln with a defined heating and cooling cycle.

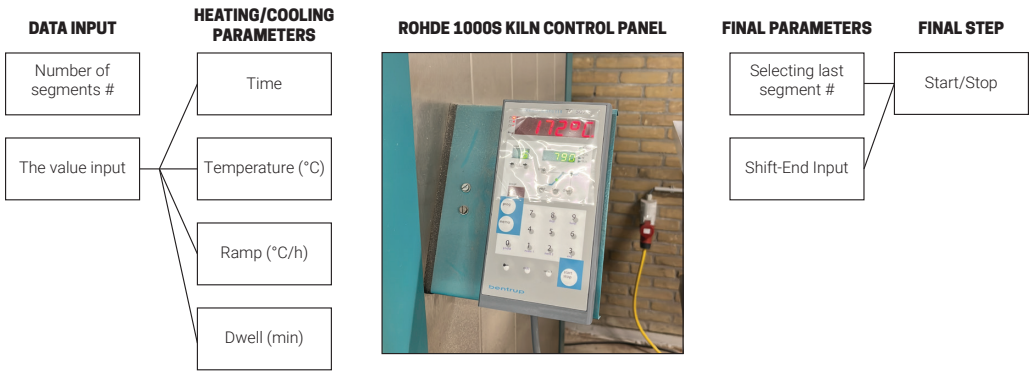


Figure 54: Workflow diagram showing the experiment steps for ROHDE 1000S Kiln for manual press (Source: Author)

During the heating cycle, the oven was periodically opened during the first trials to get used to the heating rate and dwell time polymers need in general. It helped to determine the optimal processing temperature for other blends. When the polymer mix reached the molten state, with the heat-resistant gloves, full-face respirator gas mask and full protective lab wear, the molten plastic was poured into the mold cavity. The top layer of the mold was placed immediately and clamped form all corners for duration for 10 minutes per each sample. After sample solidified, the sample was removed by kitchenware scraper and cleaned to remove residuals of wood and petroleum jelly.

Figure 55: The manual press experiment setup (Source: Author)

This experiment setup was repeated for all the plastic mixes from both fridge lines and SDA line 1, and the adjustments to the heating/cooling cycle were made based on the prior results. The samples are evaluated based on the five performance parameters.

Figure 56: (1) Heating the plastic input in the kiln (2) Putting petroleum jelly on the surfaces of the mould (3) Pouring the molten plastic (4) Clamping the mould (5) Removing the sample from the mould (Source: Author)

3.2.6.3 Manual Plunger-type Injection Molding

A comparison between manual plunger-type injection molding and pneumatic injection molding machines is necessary based on the difference between methodologies. The main difference between them is the method of applying injection pressure. Pneumatic injection molding relies on the compressed air that exerts a continuous and consistent force on the polymer melt. On the other hand, manual injection molding relies solely on the operator and their manual pressure with limited thermal regulation. Based on the available data from Morgan-Press Injection Molder with a model G-100T, a manual plunger-type machines operate with pressures ranging from 0.44 to 0.55 MPa, whereas pneumatic types can go way higher to 160 MPa.

Therefore, in terms of repeatability, dimensional accuracy, and high-volume production, pneumatic injection molding is preferred over manual type (Gupta et al., 2021). For feasibility, small-scale production, and experimental research, the manual-plunger type is preferred. Both types showcase both cases of industrial and experimental types are used during the experimentation phase to conclude a workable recipe.

Firstly, a manual plunger-type injection molding representing an intermediate processing level was designed. Based on the results of the boundary setup, to prevent clogging of the cylinder or malfunctioning, only FT-IR identified polymers or polymer blends were selected for this setup. Therefore, each polymer batch was sorted by density and colour and characterised in the FT-IR machine. As a pre-processing requirement, the polymer batches were shredded into 3 mm shred with a plastic shredder in Stevin II Lab.

Figure 57: 3mm shredded polymer batches for processing (Source: Author)

Experiment Setup: The Arbour Press Injection Machine at Makerlab of TU Delft Science Centre was used as the injection molding medium for the experiment. The machine operates with a single barrel heater with a maximum temperature of 280°C and a hand-operated plunger mechanism, in which the operator rotates a wheel to inject the molten plastic through a nozzle into the mold cavity. For the experiment, the plastic mix was open-air injected into the 100 x 100 x 4 wooden molds after the injection cycle was done. Generally, the preheating process of an injection machine is around 10 minutes operating on standard voltages like 230 V. Therefore, the required preheating cycle was adjusted after the first trial with a 10-minute duration. The final temperature of the preheating process is defined at the temperature controller before the shreds are thrown inside the heating barrel. After preheating the polymer shreds, the wooden mould with pre-treated surfaces was placed at a 10-centimetre distance from the nozzle. After injecting the molten plastic inside the molds, the top layer is clamped from all corners and cooled down for 10 minutes. A kitchenware scraper is used to remove the sample from the mould and cleaned after cooling. The samples were evaluated with the five performance parameters with repetitive trials to conclude a polymer recipe for injection molding and to give feedback to product development track.

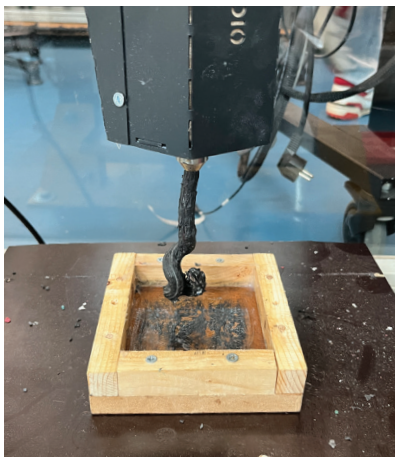


Figure 58: The before and after injection molding using Arbour Press (Source: Author)

Figure 59: The Arbour Press Injection Machine injection molding setup (Source: Author)

3.2.6.4 Pneumatic Plunger-type Injection Molding

The final experiment setup with the most advanced processing technology was the lab-scale pneumatic injection molding machine. Even though the machine was not an industrial scale, it had the essential components of a commercial pneumatic-type machine. Part of the thesis involved the calibration of the machine for the proper alignment of the table plate and upper plate after the boundary setup was conducted. As molding was essential part of the thesis, the mold trials for the complex designs obtained from the product development track was tested in this experiment setup. This experiment was solely dedicated to validating the resin mold for giving feedback to the product development track.

The resin molds emerged as a feasible alternative to the conventional steel moulds used in injection molding. The resin molds enable rapid prototyping and low-volume production, which are mainly generated from epoxy-based resins and high-performance polymers (Zong et al., 2019). As the thesis deals with WEEE stream polymers, the range of melting temperatures varies tremendously. Therefore, high-temperature resin molds are considered which usually involve additives such as aluminium fillers to enhance thermal conductivity and prolong mold life during extended production runs (Kuo et al., 2021). The resin mold option was selected mainly for its economical advantage and to adapt to the iterative design testing during product development. Multiple mold creations necessitated a mold selection with ease of fabrication and economic benefits. This experiment setup served as an official checkpoint between material experimentation and product development tracks for the proof-of-concept and application. The goal was to test the molding capacity for the complex design of reinforcement spacers, the durability for the multiple injection runs and the final injection cycle necessary for this scale of production.

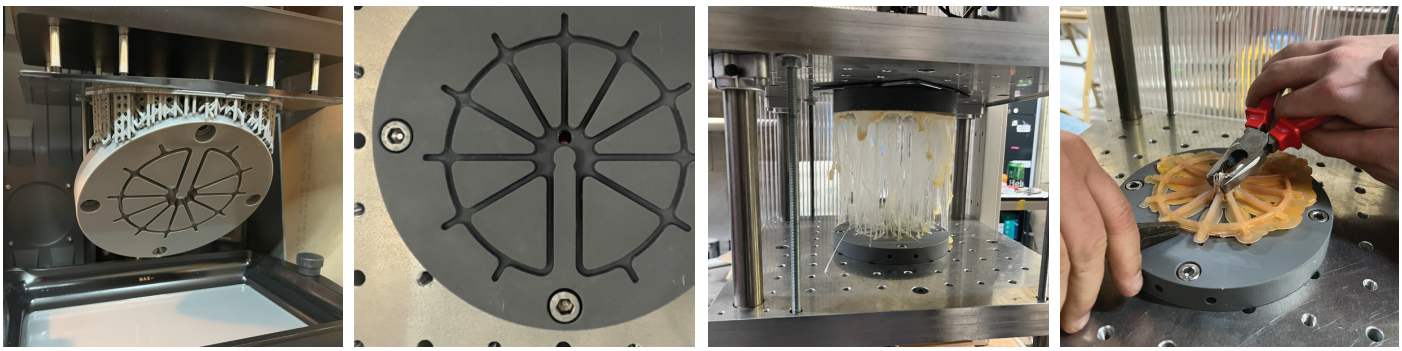


Figure 60: Resin mould setups for the pneumatic injection molding machine (1) 3d printing (2) fixing the mould to plates (3) injection (4) removing the sample (Source: Author)

Experiment Setup: The lab-scale pneumatic-type injection molding machine operates through a compressor connected to the pilot valve of the machine. The heating barrel consists of four heaters, the first three controlled together at the temperature control system, and the last heater controlled individually at the system. Compared to an industrial-scale injection molding machine, it can be deduced that the first three heaters serve as the barrel temperature controller, whereas the fourth heater serves as the nozzle temperature controller. This dual-zone heating system allows fine-tuning and prevents clogging at the barrel. The temperature difference between the first three and the fourth heater is 10°C also because generally there is a heat loss occurring between the heater clamps and the barrel itself (J. Domisse, personal communication, 2025).

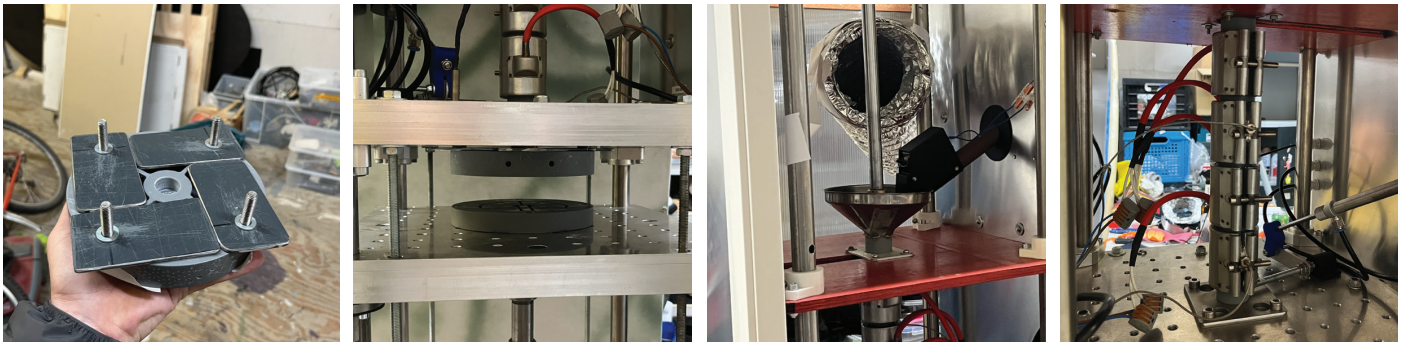


Figure 61: Pneumatic injection molding steps: (1) mould attachment (2) upper & table plate fixing (3) plastic input (4) heating barrel (5) injection (Source: Author)

After the manual calibration of the mold plates for proper clamping and alignment, the preheating cycle generally takes around 20 minutes as the shredded polymer batch is loaded in the barrel. After perfect clamping of the mold plates, the injection was performed under the required air pressure, generally varying from 4 to 8 MPa for this setup. The setup enabled tuning of the requirements of both tracks that provided feedback on the injection cycle, mold type and complexity of the design.

3.2.7 Polymer Processing Results and Discussions

The polymer processing trials are essential to the thesis's material experimentation track. The results and samples from the experiment setups, manual press, manual plunger-type injection molding and lab-scale pneumatic injection molding are analysed to obtain a polymer recipe for the final injection molding with the product development track. The processability and performance of each sample are evaluated based on the evaluation parameters: mixing, morphology, degradation, stability, and smell results. This allows for comparing the results from different setups to establish a working heating/cooling cycle for the polymer selections.

As a baseline understanding is achieved with the DSC, FT-IR and Microscope analyses done prior to experiment setups, the initial processing conditions of the first trials on all three setups were based on the known polymer characteristics. The polymer processing results are categorised based on the blending techniques: **(1)** colour-sorted polymers, **(2)** density-separated polymers, **(3)** FT-IR-identified polymers/blends, and **(4)** recycled polypropylene. For the analysis of the parameters, a combination of visual inspection, sensory assessment and transverse & longitudinal section cutting was applied. For both mixing and morphology results, a longitudinal section parallel to the material flow direction and a transverse section perpendicular to the flow direction were created to examine the flow lines, phase separations, fiber formations and the domains. For the degradation result, the visual indicators suggesting decomposition and color change were observed. The stability result was assessed by trying to deform the sample under manual pressure and the smell result was assessed by identifying the odors both during and after processing.

3.2.7.1 Colour-sorted Polymer Blend

The manually colour-sorted polymer blend trails were tested on manual press and pneumatic plunger-type injection molding experiment setups. The first experiment was conducted with the polymer acquired from the Fridge 1 -reject fraction of water separation tables-. The white coloured polymers are sorted with manual colour sorting from the waste bag. This was the first experiment ever conducted during the thesis; therefore, based on the results of this trial, boundary conditions for testing different blends based on different experiment setups were identified.

SETUP 1 - MANUAL COLOUR SORTED POLYMER INPUT

TRIALS	TRIAL 1	TRIAL 2	TRIAL 3
POLYMER IDENTITY	Fridge Line 2 - Colour sorted all polymer blend		
MOULD TYPE	Open-air injecting		
APPLIED PRESSURE (MPa)	0.4	0.6	0.6
HEATERS 1-2 (°C)	270	270	310
HEATER 3 (°C)	280	280	320
HEAT - COOL CYCLE (min)	20	10	20
MIXING RESULT	Immiscibility - Heterogeneous blend		
MORPHOLOGY RESULT	Air traps - Visible melt flows - Clear phases		
DEGRADATION RESULT	Discoloration - Burnt areas		
STABILITY RESULT	Visible warping		
SMELL RESULT	Mild burnt smell		

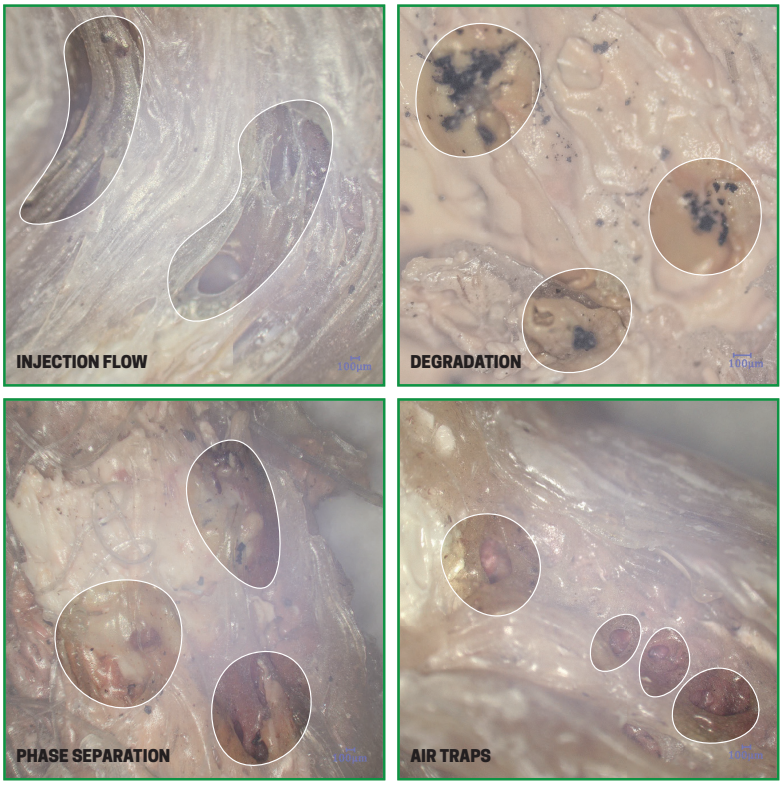


Table 11: First experiment setup with pneumatic plunger-type injection molding and parameter analysis (Source: Author)

Open-air injection with the pneumatic injection molding machine was conducted with three trials with an increase in both pressure and temperature with the 200-gram polymer input. Even after increasing both pressure and temperature of the heating cycle, the polymers were stuck at the heating barrel, which suggested failure of the setup. The nozzle blockage caused by the thermally degraded plastics caused smoke during the third trial. The results of the setup were analysed by removing the heating barrel from the machine and manually removing the sample inside the barrel.

The boundary conditions limited the testing of blending all polymers at the plunger-type injection molding setups and only allowed the use of a manual press for sampling. Therefore, the manually colour-sorted black and grey polymers from Fridge 2 were tested at the manual press setup to evaluate the samples. For the manual pressing, two sample collections take place: one directly taken from the melted plastic from the pot, and one taken from the pressed sample at the wood mold.

SETUP 2 - FRIDGE LINE 2 MANUAL COLOUR SORTED

TRIALS	TRIAL 1: BLACK COLOUR BLEND	TRIAL 2: GREY COLOUR BLEND
POLYMER IDENTITY	Fridge line 2 manul colour sorted polymer blend	
WEIGHT (g)	34.65	47.50
MOULD TYPE	80x100x4 mm wood mould	
HEATING CYCLE		
HEATING RATE (°C/h)	250	250
START TEMP (°C)	25	240
DWELL TIME (min)	60-60-60	120
END TEMP (°C)	240-260-300	300
COOLING CYCLE		
HEATING RATE (°C/h)	250	250
START TEMP (°C)	300	300
END TEMP (°C)	25	25
CONTROLLED TEMP (°C)	240-260-300	260
MIXING RESULT	Immiscibility - Heterogeneous blend	Immiscibility - Heterogeneous blend
MORPHOLOGY RESULT	Clear phase domains	Clear phase domains
DEGRADATION RESULT	Thermal degradation	Thermal degradation
STABILITY RESULT	Fragile	Fragile
SMELL RESULT	Mild burnt smell	Mild burnt smell

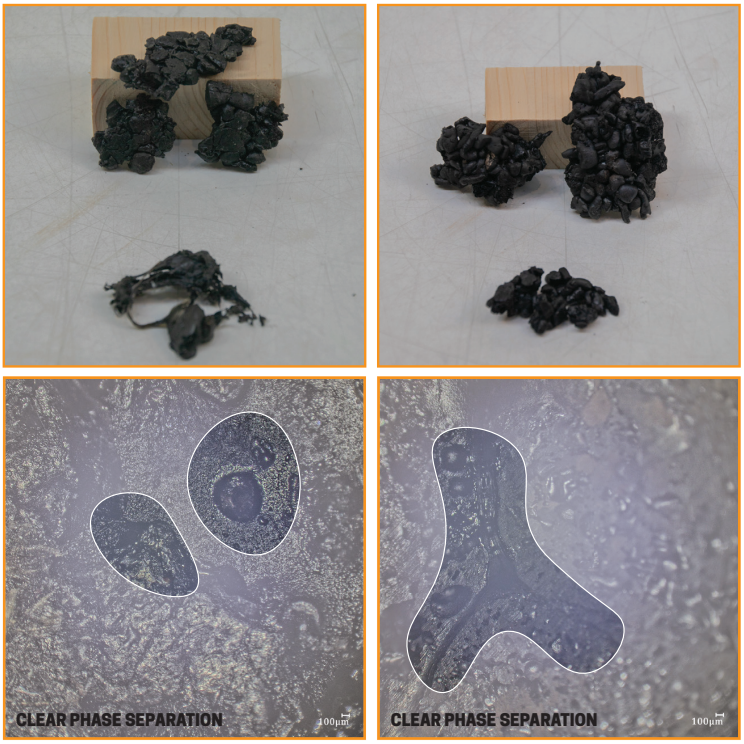


Table 12: Second experiment setup with manual press with heating-cooling cycles and parameter analysis (Source: Author)

The first trial of the manual press was also conducted to define a working heating/cooling cycle for the oven that ensures proper mixing and melting of the plastics. Therefore, during the heating cycle, the oven was opened and the temperature of the molten plastic was measured with an infrared (IR) thermometer. Based on the actual plastics' temperature in relation to the temperature set in the oven, adjustments were made. The analysis of the sample proved the immiscibility of all polymer blends, as the phase separation was distinctive in both samples. Therefore, the **necessity for density separation** was proven.

3.2.7.2 Density-separated Polymer Blend

As it was stated, the four densities were tried for the separating medium including 1.00, 1.05, 1.10, and 1.13 g/cm³ to obtain a floating fraction to be used for processing on all waste lines. The first setup was done by combining the floating fraction of the 1.05 and 1.10 g/cm³ densities because of the low quantity of floating fractions. As the densities were used on the fridge lines, all polymer blend was tried without colour sorting.

	SETUP 3 - FRIDGE LINE 2 DENSITY SORTED (1.05 + 1.10 g/cm3)		SETUP 4 - FRIDGE LINE 1 DENSITY SORTED (1.05 + 1.10 g/cm3)
TRIALS	**TRIAL 1: ALL POLYMER BLEND**	**TRIAL 2: ALL POLYMER BLEND**	**TRIAL 1: ALL POLYMER BLEND**
POLYMER IDENTITY	Fridge line 2 floating fraction (1.05 + 1.10 g/cm3) polymer blend		Fridge line 1 floating fraction (1.05 + 1.10 g/cm3)
WEIGHT (g)	47.10		85.60
MOULD TYPE	80x100x4 mm wood mould		80x100x4 mm wood mould
HEATING CYCLE			
HEATING RATE (°C/h)	200	200	200
START TEMP (°C)	28	220	28
DWELL TIME (min)	120	60	90 - 60 - 60
END TEMP (°C)	220	260	220 - 240 - 260
COOLING CYCLE			
HEATING RATE (°C/h)	200	200	200
START TEMP (°C)	220	260	220 - 240 - 260
END TEMP (°C)	25	25	25
CONTROLLED TEMP (°C)	170 - 250	260	220 - 240 - 260
MIXING RESULT	Immiscibility - Heterogeneous blend	Immiscibility - Heterogeneous blend	Immiscibility - Viscous flow
MORPHOLOGY RESULT	Clear phase domains	Agglomeration	Clear phase domains - Fibers
DEGRADATION RESULT	Thermal degradation	Surface carbonization	Little carbonization - Little degradation
STABILITY RESULT	Deformation under light pressure	Deformation under light pressure	Deformation under light pressure
SMELL RESULT	Mild burnt smell	Mild burnt smell	Mild burnt smell

Table 13: Third and fourth setups with manual press and samples from both Fridge lines 1-2 (Source: Author)

The samples from the Fridge 2 polymers still resulted in failing results with a fully heterogeneous and immiscible blend. The micrographs of the samples revealed the presence of hair-like fibres in the matrix. These thin fibres are caused either by immiscibility or existing contamination, like textiles or glass fibres, that might have caused the results. The increased temperature for the heating cycle for the Fridge 1 polymers already gave a better

result in terms of the flow behaviour of the matrix. It was noticed that some polymers were acting like binders for other incompetent polymers in the matrix. There was still a formation of thick fibres in between the phase domains.

The other experiments with the density-separated polymers were conducted with the SDA 1 polymers, containing all polymer blends and manually colour-sorted polymer blends. The polymers were selected and sorted from the density sorting done by the 1.13 g/cm³ medium. The floating fraction was expected to have similar behaviour to polymers with melt temperatures; therefore, a heating/cooling cycle with pre-defined conditions, with pre-defined end temperatures, and heating rate was identified.

SETUP 5 - SDA LINE 1 DENSITY SORTED (1.13 g/cm3)

TRIALS	TRIAL 1: ALL COLOUR BLEND	TRIAL 2: BLACK COLOUR BLEND	TRIAL 3: WHITE COLOUR BLEND
POLYMER IDENTITY	SDA line 1 floating fraction (1.13 g/cm3) blend	SDA line 1 floating fraction (1.13 g/cm3) blend	SDA line 1 floating fraction (1.13 g/cm3) blend
WEIGHT (g)	33.85	34.98	41.30
MOULD TYPE		80x100x4 mm wood mould	
HEATING CYCLE			
HEATING RATE (°C/h)	250	250	250
START TEMP (°C)	25	220	220
DWELL TIME (min)	120	120 - 60	45
END TEMP (°C)	260	260	260
COOLING CYCLE			
HEATING RATE (°C/h)	250	250	250
START TEMP (°C)	260	260	260
END TEMP (°C)	25	25	25
CONTROLLED TEMP (°C)	220	260 - 260	260
MIXING RESULT	Partial compatibility	Partial compatibility	Partial compatibility
MORPHOLOGY RESULT	Medium indication of phase domains	Matte surface finish	Matte surface finish
DEGRADATION RESULT	Little yellowing on some polymers	No visible degradation	Little discolouration on some polymers
STABILITY RESULT	Stable geometry	Stable geometry	Stable geometry
SMELL RESULT	Mild burnt smell	Mild burnt smell	Mild burnt smell

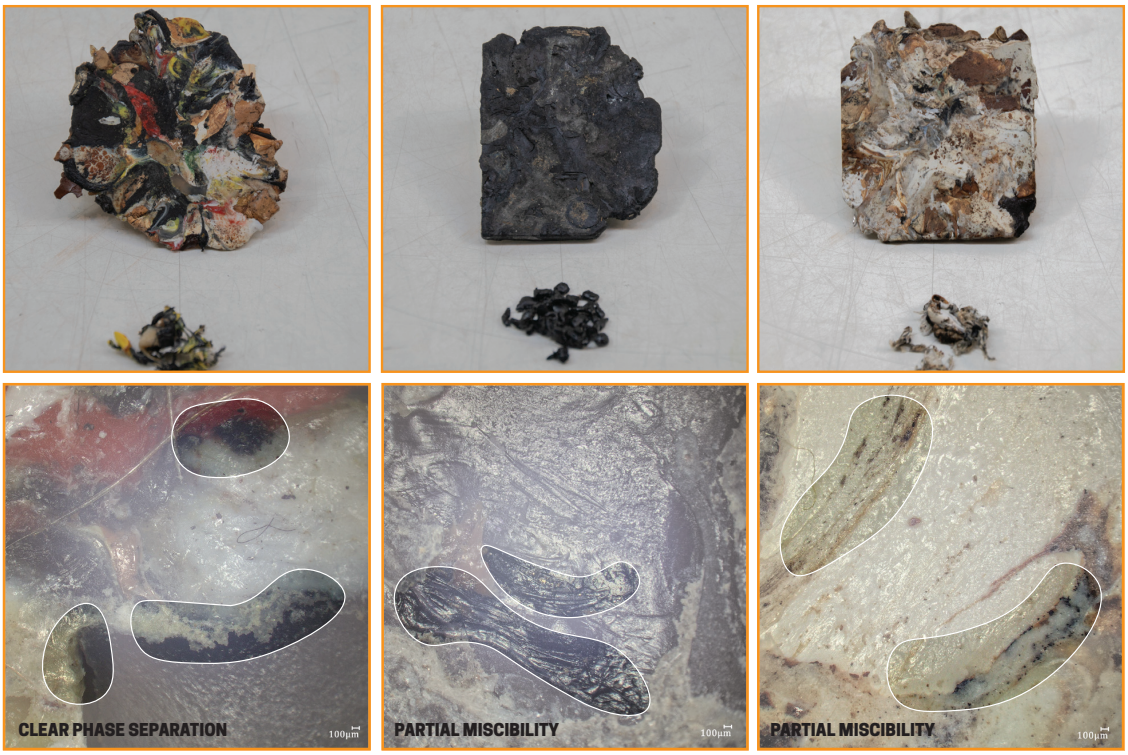


Table 14: Fifth setup with manual press and three categorized samples from SDA line 1 (Source: Author)

A partial compatibility was achieved on all samples with stable geometry, which proved a working processing condition for the manual press setup. The degradation was minimised even though the phase separation was still clear. The next experiment was aimed at proving a workable heating/cooling cycle especially for white and black colours, which were the majority during manual colour sorting.

SETUP 6 - SDA LINE 1 DENSITY SORTED (1.13 g/cm3)

TRIALS	TRIAL 1: BLACK COLOUR BLEND	TRIAL 2: WHITE COLOUR BLEND	TRIAL 3: SEMI-TRANSPARENT BLEND
POLYMER IDENTITY	SDA line 1 (1.13 g/cm3) < 5mm shred samples	SDA line 1 (1.13 g/cm3) < 5mm shred samples	SDA line 1 (1.13 g/cm3) < 5mm shred samples
WEIGHT (g)	40.00	40.00	20.00
MOULD TYPE	100x100x4 mm wood mould		
HEATING CYCLE			
HEATING RATE (°C/h)	250	250	250
START TEMP (°C)	25	240	240
DWELL TIME (min)	120	120	120
END TEMP (°C)	260	260	260
COOLING CYCLE			
HEATING RATE (°C/h)	250	250	250
START TEMP (°C)	260	260	260
END TEMP (°C)	25	25	25
CONTROLLED TEMP (°C)	220	260 - 260	260
MIXING RESULT	Partial compatibility	Partial compatibility	Homogeneous blend
MORPHOLOGY RESULT	Less indication of phase domains	Clear phase domains	Occuring transparency
DEGRADATION RESULT	Some fume emission	Oxidative breakdown	Discolouration
STABILITY RESULT	Stable geometry	Stable geometry	Stable geometry
SMELL RESULT	Mild burnt smell	Mild burnt smell	Strong burnt smell

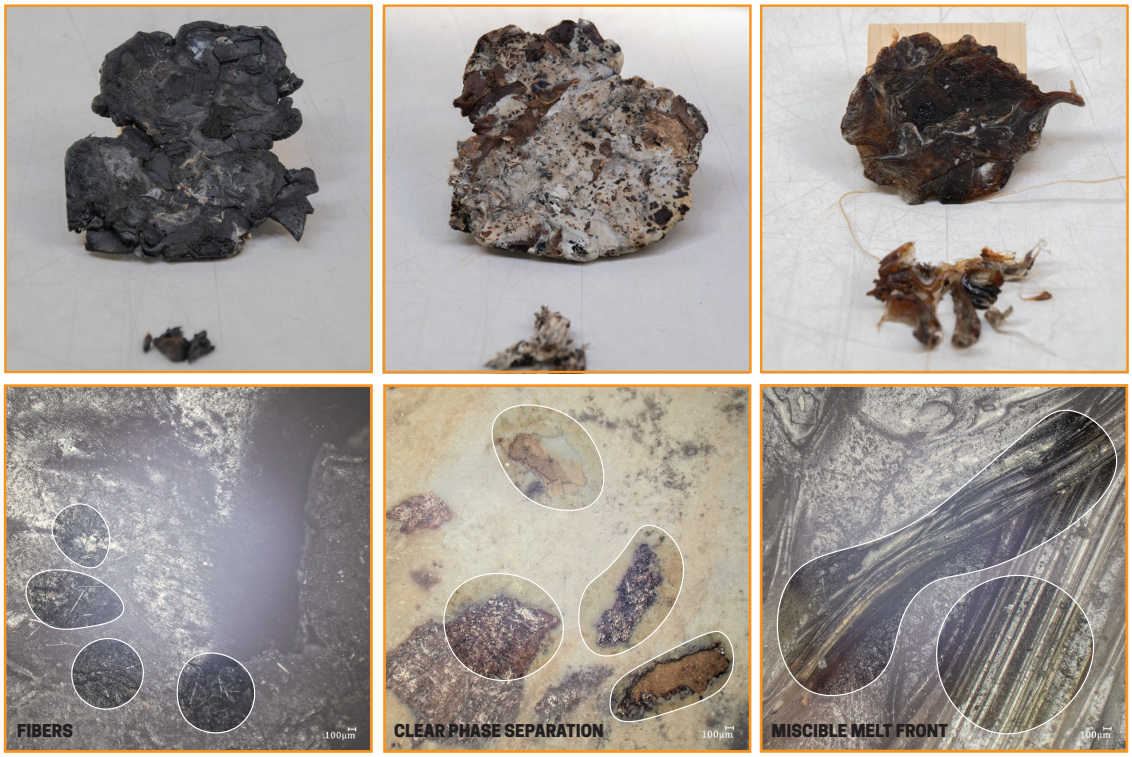


Table 15: Fifth setup with manual press and three categorized samples from SDA line 1 (Source: Author)

A similar behaviour with partial compatibility with definite phase domains was observed. The polymer characterisation done on the semi-transparent polymers resulted differently in all trials without giving any coherent result. However, the mixing and morphology results on the semi-transparent blend sample showcased a homogeneous blend with similar melt flow characteristics to industry-scale injection molding. Even though the odour during the molding stage was stronger compared to other trials, the sample before and after processing was miscible and stable while still achieving partial transparency at the end.

3.2.7.3 FT-IR Identified Polymer/Polymer Blends

Because of the boundary conditions defined after the first failed pneumatic injection molding setup, the FT-IR identified polymers/polymer blends were tested in the manual plunger-type injection molding machine. The FT-IR analysis of the density-sorted SDA 1 polymers was conducted with a special setup for time efficiency, as the waste input generally contained small shreds. The number of scans was lowered to 12 scans, and the data collected for one shred was reduced to one rather than three. The highest matching percentage for one shred was taken as the true polymer identity, and batches containing PP, PE/PP blend, PC, PA6/PA66 blend, PS, and PMMA were created.

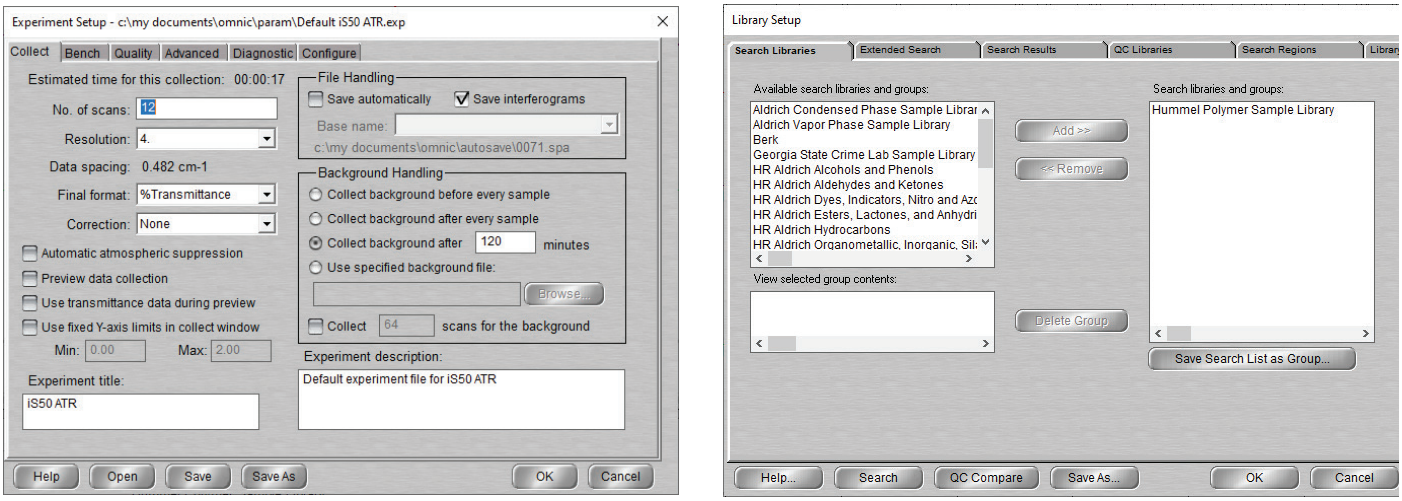


Figure 62: Adjusted FT-IR experiment setup and Library setup (Source: Nicolet iS50 FT-IR Spectrometer)

Figure 63: 50x50 mm transverse and longitudinal cut scenario of samples after processing (Source: Author)

The polymer batches were shredded into 3mm shreds and based on the weight of the batches, the batch with the highest weight -PP, PP/PE blend, PS- got tested at the setup. The first trial was done to define a working heating/cooling cycle for the manual plunger-type injection molding machine with PP. The plastic was injected to the mould with a 10 cm distance in between the nozzle and the bottom of the mold. Similar to manual press, a sample directly from the nozzle and the sample pressed inside the 100x100x4 mm wood mold were collected for analyses.

The analyses of the longitudinal and transverse sections were crucial and informative to evaluate the mixing and morphology results. Partial miscibility was achieved for all samples, but with fairly different morphologies. A melt flow was visible both on the skin layer and the core layer of the PS sample. The uneven melting with a clear domain was visible on the micrographs taken on the PP sample. A persistent, strong chemical smell was noticed after the processing stage.

The final experiments were done for fine-tuning the PP/PE, PP and PS shreds, which were found in the highest quantities during FT-IR identification. Adjustments on the temperature and the pre-heat duration were made for fine-tuning.

SETUP 7- FT-IR IDENTIFIED POLYMER INPUT SDA LINE 1

TRIALS	TRIAL 1: PP	TRIAL 2: PS
POLYMER IDENTITY	SDA 1 (1.13 g/cm3) PP 3mm shred	SDA 1 (1.13 g/cm3) PS 3mm shred
WEIGHT (g)	56.60	37.84
MOULD TYPE	100x100x4 mm wood mould	
PRE-HEAT DURATION (min)	25	5
DWELL DURATION (min)	15	15
HEATER (°C)	205-220-225	230
DISTANCE TO MOULD (cm)	10	10
MIXING RESULT		
SECTION 1.	Partially miscible blend	Layered blend
SECTION 2.	Partially miscible blend	Layered blend
MORPHOLOGY RESULT		
SECTION 1.	Uneven melting	Visible melt flow
SECTION 2.	Uneven melting - Some phase domains	Visible melt flow
DEGRADATION RESULT	Odor change during processing	Odor change during processing
STABILITY RESULT	Stable geometry	Stable geometry
SMELL RESULT	Persistent strong chemical smell	Persistent strong chemical smell

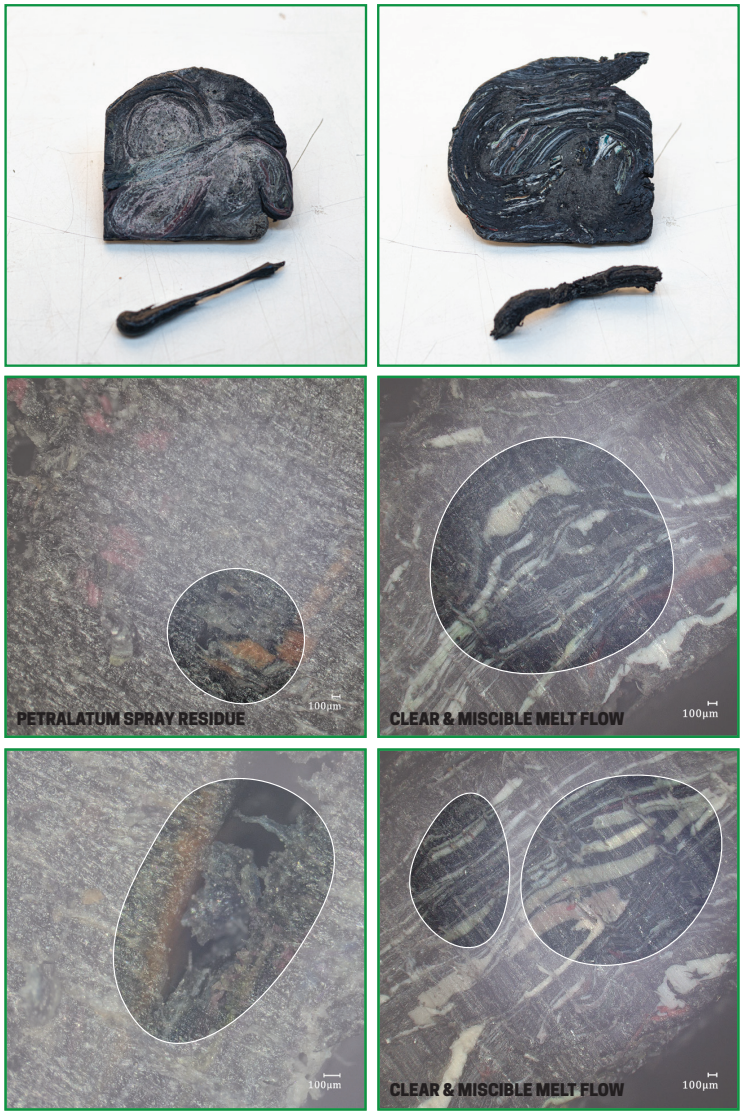


Table 16: Seventh setup with manual plunger-type injection molding with PP-PS input (Source: Author)

SETUP 8- FT-IR IDENTIFIED POLYMER INPUT SDA LINE 1

TRIALS	TRIAL 3: PP/PE BLEND	TRIAL 4: PP/PE BLEND	TRIAL 5: PP/PE BLEND
POLYMER IDENTITY	SDA 1 (1.13 g/cm3) PP/PE 3mm shred	SDA 1 (1.13 g/cm3) PP/PE 3mm shred	SDA 1 (1.13 g/cm3) PP/PE 3mm shred
WEIGHT (g)	107.00	107.00	29.79
MOULD TYPE		100x100x4 mm wood mould	
PRE-HEAT DURATION (min)	15	5	5
DWELL DURATION (min)	15	15	15
HEATER (°C)	225	230	230
DISTANCE TO MOULD (cm)	10	10	10
MIXING RESULT			
SECTION 1.	Homogeneous blend - Partially miscible	Clear phase domains	Homogeneous blend - Partially miscible
SECTION 2.	Homogeneous blend - Partially miscible	Homogeneous blend - Partially miscible	Layered blend
MORPHOLOGY RESULT			
SECTION 1.	Visible melt flow	Uneven melting - Visible melt flow	Visible melt flow
SECTION 2.	Visible melt flow	Uneven melting - Visible melt flow	Visible melt flow
DEGRADATION RESULT	Odor change during processing	Odor change during processing	Odor change during processing
STABILITY RESULT	Stable geometry	Stable geometry	Stable geometry
SMELL RESULT	Persistent strong chemical smell	Persistent strong chemical smell	Persistent strong chemical smell

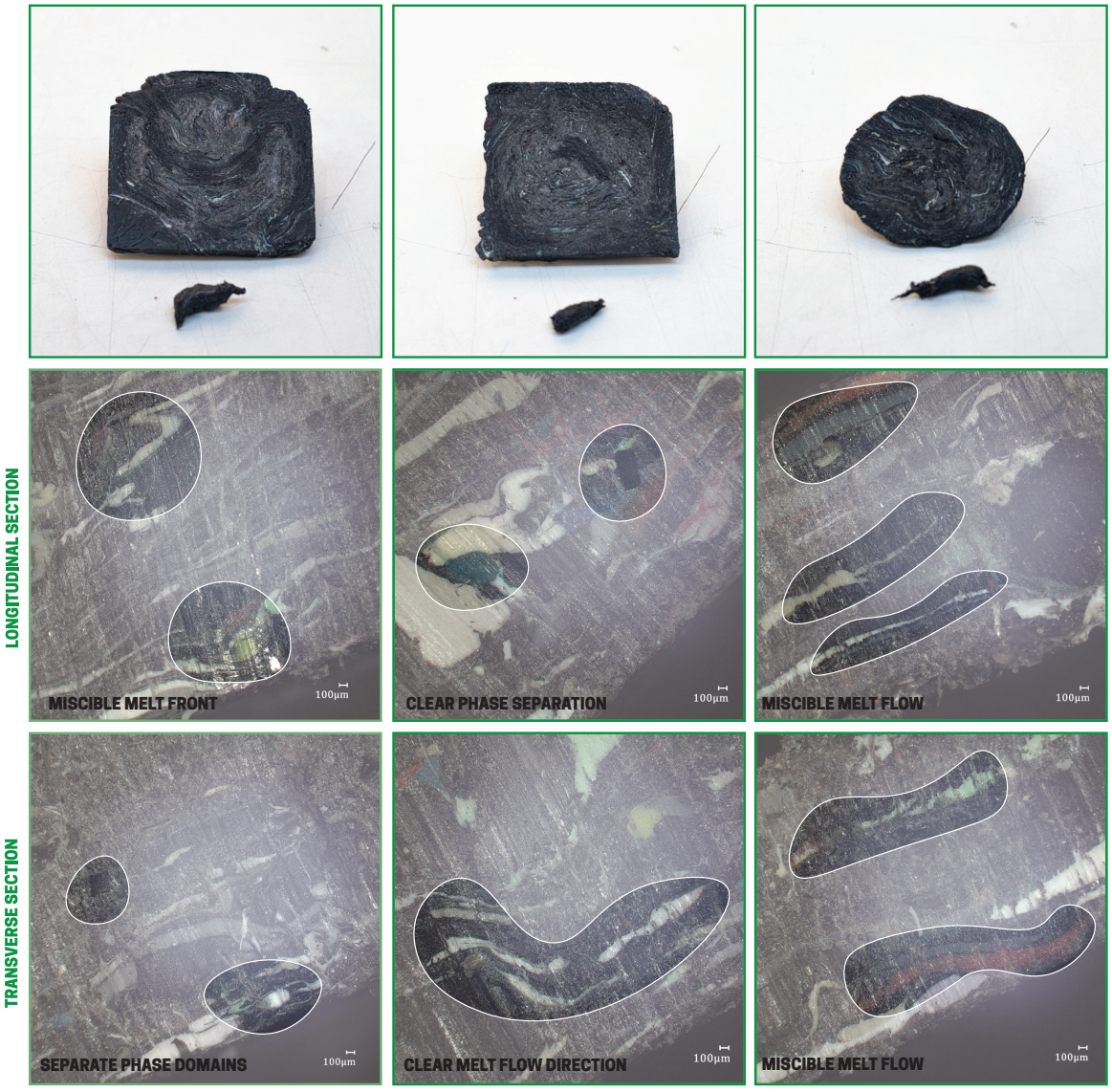


Table 17: Eigth setup with manual plunger-type injection molding with PP/PE blend input (Source: Author)

3.2.7.4 Recycled Polypropylene

The experiment was conducted with recycled PP from an unknown waste stream was crucial as this was the official checkpoint of the thesis, where both material experimentation and product development track gave feedback on the application phase of the thesis. As the high-temperature resin and ABS-like resin were used for creating an alternative to the aluminium moulds, the pneumatic plunger-type injection molding setup tested the potential of feasible resin molds replacing aluminium molds with PP, which had already proven in terms of processability before. As there were high quantities of PP, PS and PP/PE blends that were planned to be used for the final recipe, testing the resin molds, the complex shape of the spacer and the material properties were crucial to determine applicability.

As the experiment setup is lab-scale, with trial-and-error, a heating/cooling cycle for injection molding with a mould was created.

SETUP 9 - RECYCLED PP INPUT

TRIALS	TRIAL 1	TRIAL 2	TRIAL 3
POLYMER IDENTITY	Anonymous source - recycled PP		
MOULD TYPE	Resin mould	Open-air	Resin mould
APPLIED PRESSURE (MPa)	0.8	0.8	0.5
HEATERS 1-2 (°C)	250	250	240
HEATER 3 (°C)	260	260	250
HEAT - COOL CYCLE (min)	20 + 0.5	5	20 + 5
CLAMP DISTANCE (mm)	1	N/A	1
MIXING RESULT	Miscible - Homogeneous blend		
MORPHOLOGY RESULT	Flashing - Visible knit lines - Air traps		
DEGRADATION RESULT	No degradation		
STABILITY RESULT	Stable geometry		
SMELL RESULT	No odor		

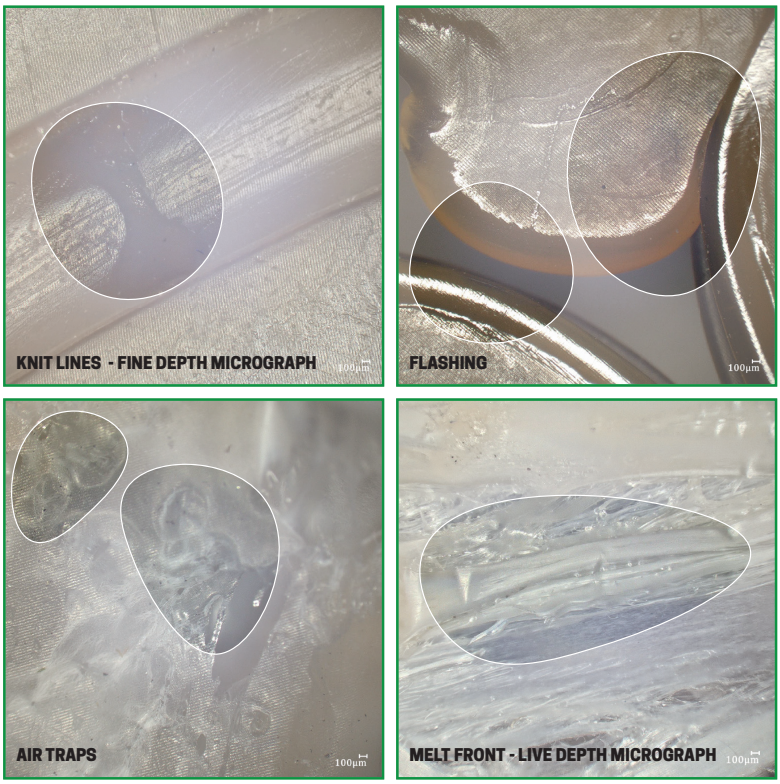


Table 18: Ninth setup with pneumatic plunger-type injection molding with rec-PP input (Source: Author)

It was concluded that the time duration for the injected plastic to cool down is as crucial as the injection cycle, as the first trial resulted in several air traps and flashing. The melt front of the first trial showcased the importance of the cooling duration of injection. Therefore, based on SolidWorks' maximum cooling time predictions on the design was applied which resulting in a successful result. The defect of the result includes flashing, possibly due to the fact that there were no venting channels on the mold and also knit lines. The micrograph shows how two melt fronts meet with each other, forming a possible deformation area. Nevertheless, the homogeneous mixing and morphology proved the applicability of the resin molds and plastics injection, which behave similarly to PP.

3.2.8 Final Recipe and Injection Cycle

The final recipe selected for the application is PP/PE, PP and PS from the SDA-2 waste line. The target colour for the polymers is carbon black plastics from a floating fraction of the 1.13 g/cm³ density separation. The targeted colour was selected to showcase the potential of processing black-coloured polymers, which can normally not be identified during the sorting stage because of the inability of NIR technology. As the processability of the PP/PE blend was proven at the manual plunger-type injection molding setups, again, 3 mm shred batches were created.

The injection cycle selected for the final experiment consists of 15 min preheating - 230°C barrel temperature – 15 min dwell time for the plastic input.

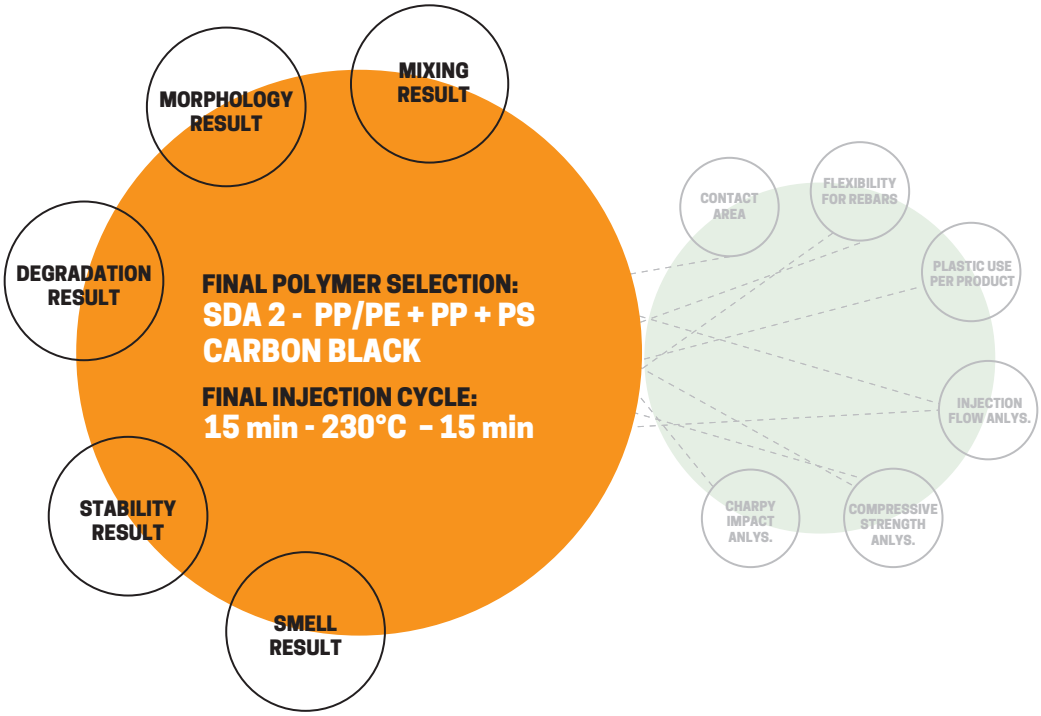
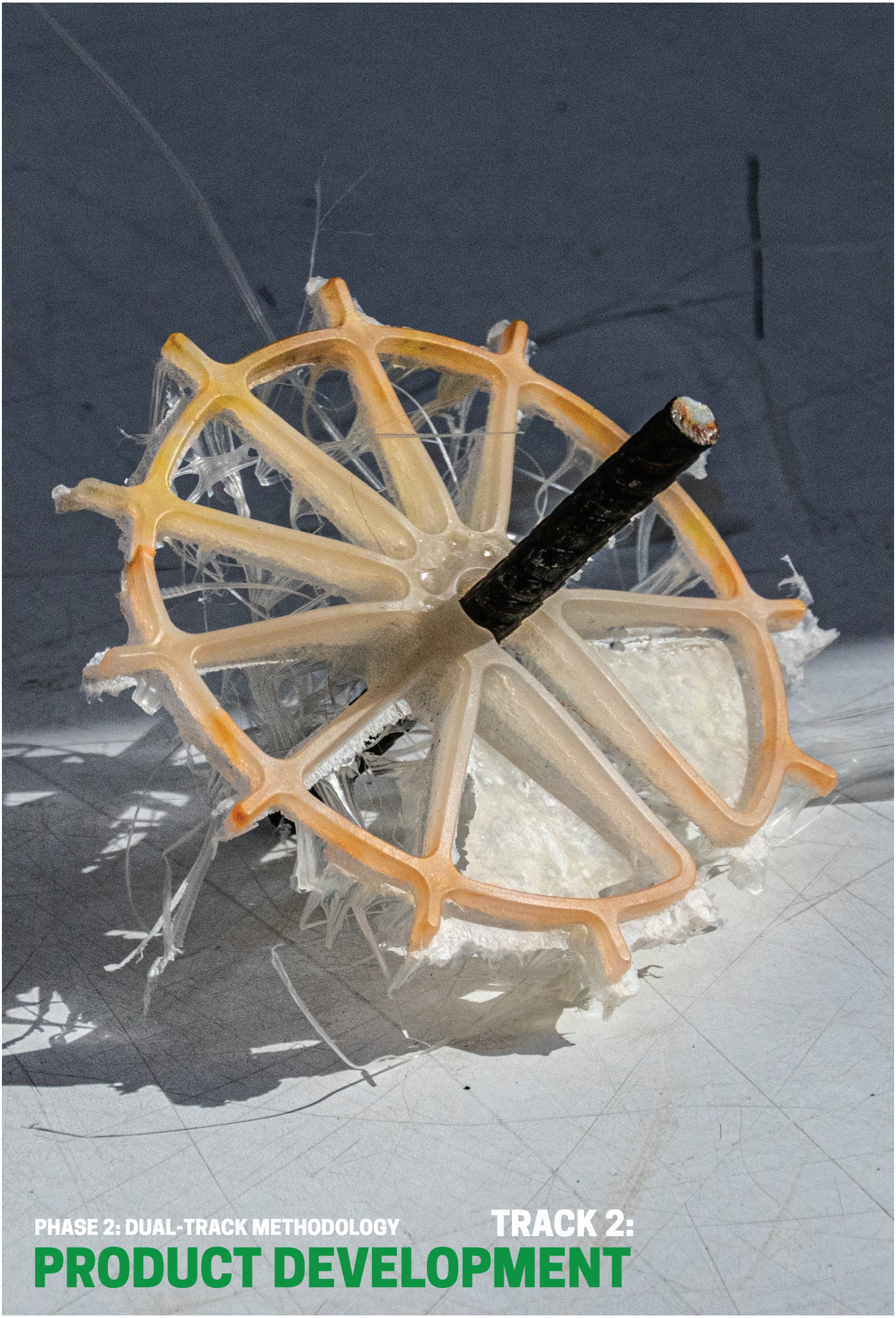


Figure 64: The dual-track diagram showing the results of the Material Experimentation track (Source: Author)



PHASE 2: DUAL-TRACK METHODOLOGY

TRACK 2: PRODUCT DEVELOPMENT

3.3 Product Development Track

The product development track of the dual-track methodology mainly focuses on the design optimisation of the selected reinforcement spacer that is used in reinforced concrete construction. While the material experimentation track investigates the feasibility of transforming unrecycled WEEE plastic into an injection-moldable recipe, this track explores how that selected waste polymer can be translated into functional building components through a parameter-driven iterative design process. The parameters include: **(1)** contact area, **(2)** flexibility for rebars, **(3)** plastic use per product, **(4)** injection flow analysis, **(5)** compressive test analysis, **(6)** charpy impact analysis. These parameters are evaluated by physical testing or by digital simulations to assign an overall grade for each design iteration.

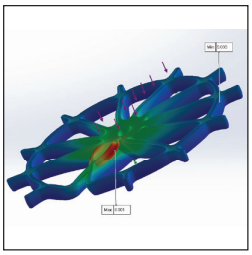
Following the parameter definition, there are two verification stages assigned throughout the track. The first verification stage is used to determine the application of the selected reinforcement spacer type. As the wheel spacer can be applied to both the beam and the column, for the mechanical testing to fit the timeline, a specific application had to be selected. The first batch of design alternatives is tested based on the injection flow analysis and compressive strength analysis to finalise the application scenario.

The unique designs are developed based on the current reinforcement spacers and ISO guidelines for reinforced concrete construction. Each design is evaluated based on the parameters with simulation tools and physical prototypes that enable multidimensional comparison. In parallel, the constant feedback loop is sustained from the material experimentation track for the polymer input.

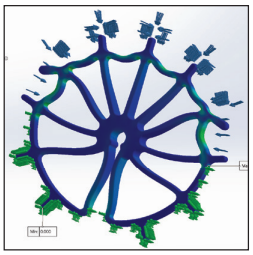
The second and final verification stage consists of a weighted evaluation model which is optimised to grade each design iteration. Weight value is assigned to each parameter based on the importance in regards to the final use and material performance. As the molding is checked at the official checkpoint of the dual-track methodology, the top-performing design is adapted to the mold fabrication for resin printing. Therefore, the final outcome of the track is a design optimised, injection-moldable reinforcement spacer design that will be combined with the final polymer recipe at the third phase of the thesis: application.

DUAL TRACK METHODOLOGY:

PRODUCT DEVELOPMENT



COLUMN



BEAM

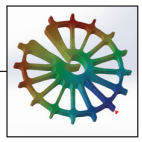
PARAMETERS

- Contact Area
- Flexibility for Rebars
- Plastic use per Product
- Injection Flow Analysis
- Compressive Test Analysis
- Charpy Impact Analysis

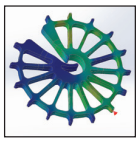
PARAMETERS	PHYSICAL TEST
Contact Area	Surface Test with 3D Print
Flexibility for Rebars	Rebar Test with PET-G Print
Plastic use per piece	Volume of the design

SIMULATION

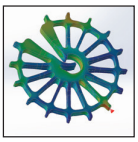
Injection Flow Analysis



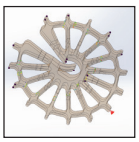
Fill Time



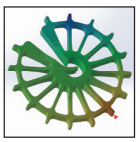
Pressure



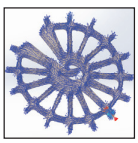
Temperature



Weld lines & Air Traps

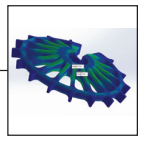


Shear Stress

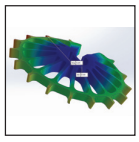


Velocity Vector

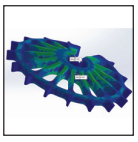
Compressive Strength Analysis



Stress

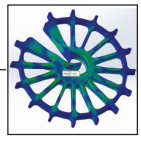


Displacement

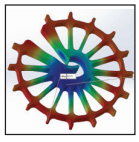


Equilavent Strain

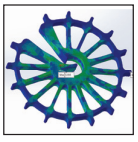
Charpy Impact Analysis



Stress



Displacement



Equilavent Strain

Manual Score

Auto Score

FINAL SCORE ANALYSIS

FINAL DESIGN
FINAL APPLICATION

3.3.1 Definition of Design Parameters

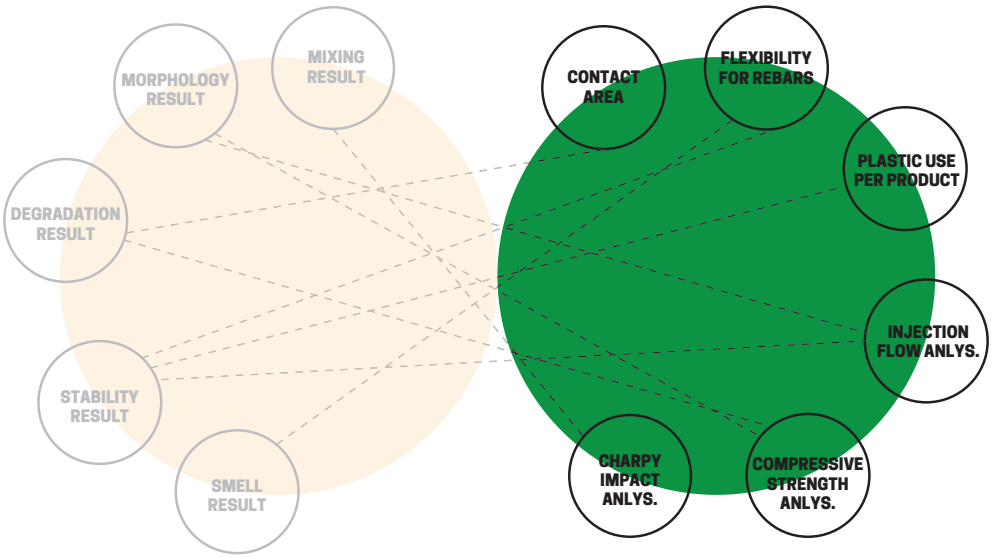


Figure 65: The indication of product development design parameters (Source: Author)

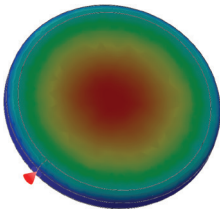
The product development track initiates with defining an original set of product evaluation parameters based on the literature and industry requirements. The parameters include:

Contact Area: This parameter refers to the area that the reinforcement spacer touches within the formwork and how much of the reinforcement spacer will be exposed at the concrete finish. This is evaluated with a 3D PLA or PET-G print which is tested physically.

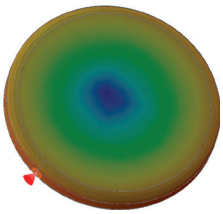
Flexibility for Rebars: During the iterative design process, the created design batches are also tested with PET-G print physically for the snapping action and rebar engagement. As PET-G exhibits a higher elongation at break compared to PLA, it represents the real-life scenario better where thermoplastics will be used. Maintaining the shape under mechanical stress was essential for this parameter so PET-G 3D print was tested for retention mechanism.

Plastic Use per Product: This parameter is important for the real-life scenario, as it concerns the production rate and price-performance ratio. This parameter is tested mainly during the design phase of the spacers in which the volume of the spacer is collected and compared between the market design data and the other design iterations.

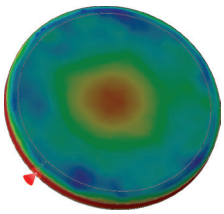
Injection Flow Analysis: This parameter is a critical as it evaluates the moldability and production feasibility of the design iterations. SolidWorks Plastics simulation tool is used which provides both numeric and graphic data on how the selected prototype will behave during the injection molding process. The sub-parameters data are collected as a graphic representation, and with the minimum and maximum values for it. The sub-parameters of this analysis are defined as below:



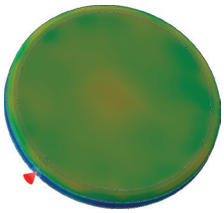
Fill Time: The fill time refers to the duration its required for the molten plastic to fill the mold cavity. A consistent fill time across the cavity is desired as the short fill or longer fill may result in weld lines. In addition to the data collected for all sub-parameters a filling video is also evaluated for the performance of the design. The video data showing the filling of the mold is also analyzed to observe the behavior of flow front.



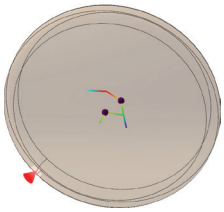
Injection Pressure: This is a very critical sub-parameter that is a boundary condition of the experiment setups. The maximum pressure the setups can reach is limited to maximum of 10 MPa, and the min/max data achieved from this part indicates whether the design restricts the applicability or not. The pressure at the end of the fill represents how evenly the cavity has been filled.



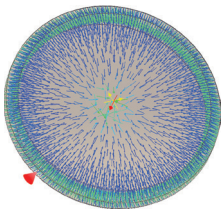
Temperature: This sub-parameter evaluates the design's flow behaviour, showing the regions where the mold gets cool quickly then other regions which might lead to incomplete filling. This parameter is critical for the selection of blends and recycled polymers, which can cause degradation under uneven temperatures. The formation of the frozen layer is dependent on the difference between melt front and mold temperature.



Shear Stress: This refers to the frictional force between the molten plastic and the mold wall during injection. The graphic data aids in identifying brittle zones which might affect the mechanical performance of the design. As resin moulds are being used for the molds, the maximum shear stress is crucial to test the applicability of resin molding.



Weld Lines & Air Traps: It is a common injection molding trait when two flow fronts meet that form imperfect polymer fusion. Due to the complex shape of the reinforcement spacer, this trait is expected from most of the designs.The air traps occur as the air in the mold cavity cannot be vented to the atmosphere during injection. The air traps occur when the air traps itself inside the mold, which affects injection efficiency.



Velocity Vector: The sub-parameter shows the molecular orientation at the end of fill of the melted plastic. The graphic data obtained from this parameter aids the process of achieving a uniform filling pattern of the molten plastic as it gives data on the speed and direction of the melt front based on the ejector location.

Compressive Strength Analysis: This parameter firstly aids the decision-making process for the suitable application of the spacer and then, is used for determining whether the spacer can maintain its functionality and shape under the loadings from poured concrete and reinforcing bars. The simulation results for stress, displacement and equivalent strain are examined by both min/max and graphic data to understand each design's mechanical response based on current EN 1992-1-1 standards.

Charpy Impact Analysis: The parameter tests the ability of the spacer to absorb the impact energy without permanent deformation. It is done by adapting SolidWorks' Drop Test tool to generate an impact energy within the EN 13586 range of 1-50 Joules. The numeric and visual data from stress, displacement, equivalent strain was similarly examined during design optimization process.

The parameters are used as guidelines both before and after the design process. Based on the literature and experimental research, these parameters are generated as the most crucial factors for selecting an optimal design for the specific case.

3.3.2 Definition of Design Optimization Tool

The product evaluation parameters of the product development track is used inside a customized weighted evaluation model which serves a verification method during the track. This optimization tool is used to objectively compare and asses the spacer designs based on a tier-based grading system. As the product development track includes parameters and sub-parameters which are not equally critical, the weighting system is assigned in the tool based on their impact on applicability and functionality. The weights are based on the interpretation of the construction guidelines and existing research on spacers. Based on the literature like Neamat & Shamsborhan, most critical parameters and sub-parameters are identified. Product development track uses physical testing or simulation results for the parameters, the results are transferred into the tool either by scoring it manually or by autoscoring based on the percentile-based tier thresholds which at the end results in four scoring options: **ideal (10), acceptable (7), risky (4), and failure (0**). As there is both numeric and graphic data collected from the simulations, a unique dual-data scoring system is generated. The visual data is analysed based on the range classes assigned for the four scoring options – ideal, acceptable, risky, failure- at the critical locations where a spacer is most expected to fail. This hybrid evaluation ensures a reliable selection of the final spacer design.

The optimization tool is created by combining in Excel with individual spreadsheets which are created for the main evaluation dashboard, and for the parameters that includes sub-parameters and more than one data for analysis. The optimization of the systems allows for more comprehensive and interconnected evaluation of all the data collected from different testing methods including physical and simulation.

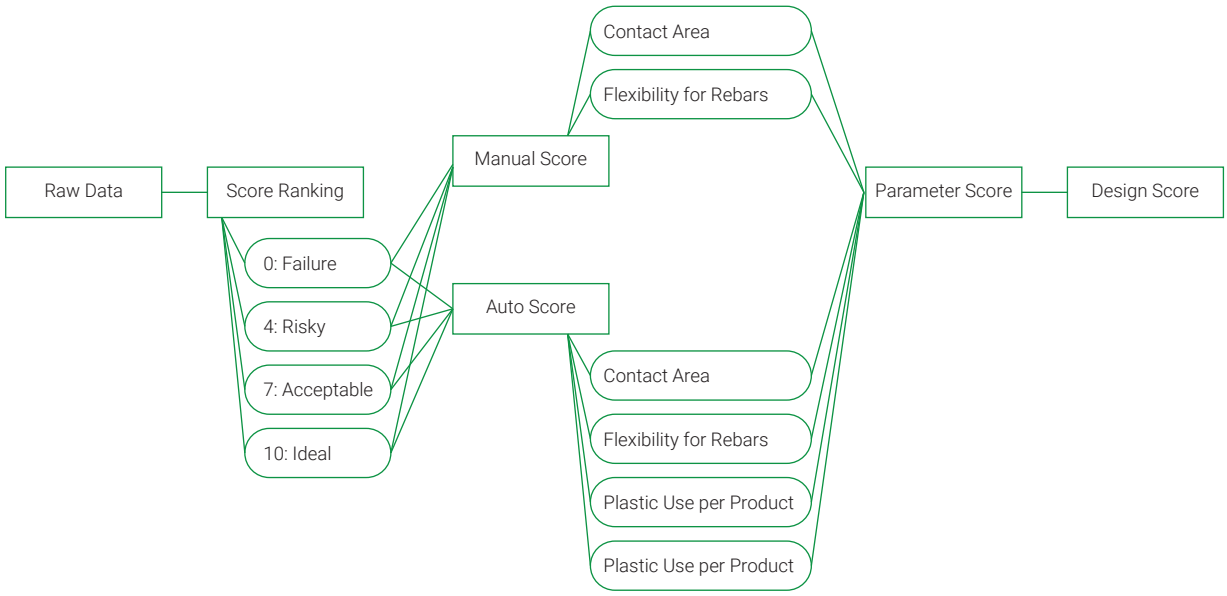


Figure 66: Workflow diagram indicating the interconnected parameter analysis of design optimization tool (Source: Author)

For creating a coherent system starting from individual sub-parameter and parameter scoring to selection of the optimal design, several strategies are implemented to the tool: **(1)** autoscoring, **(2)** manual scoring, **(3)** weight-based scoring.

Autoscoring is an important part of the design optimization as it is based on percentile-based thresholds rather than absolute benchmarks. This was done by integrating Phyton "numpy" library with Excel's "IFS ()" scoring formula. A percentile threshold tool was necessary to create a comparative tool for the min/max values for grouping them to fit the four scoring options; 10,7,4,0. Either minimum or maximum data from the simulation results are inputted based on the sub-parameter. The data is transferred into groups for 25, 50,75 percentiles to represent 10, 7, 4 scores respectively. For instance, the maximum simulation data is taken for the fill time, pressure, temperature, shear stress, weld lines & air traps sub-parameters, and the minimum data is taken for the velocity vector to use the script to identify the best-performing percentiles.

Fill Time: [5.2786, 3.4292, 0.7704, 3.9858, 1.8899, 5.9485, 6.0483, 6.6475, 2.5370]
Pressure: [2.19, 6.32, 2.63, 7.23, 4.42, 2.84, 2.35, 2.19, 10.04]
Temperature: [230.02, 230.08, 230.14, 230.10, 230.93, 230.01, 230.02, 230.00, 230.86]
Shear Stress: [0.04, 0.08, 0.08, 0.08, 0.10, 0.10, 0.06, 0.07, 0.13]
Weld Lines & Air Traps: [137.650, 149.180, N/A, 149.170, N/A, 129.860, 144.480, 95.040, 146.900]
Velocity vector: [29.1789, 57.2777, 60.8905, 51.3741, 189.2124, 87.6201, 26.5677, 29.56, 207.7365]

The values are calculated with "percentiles = np.percentile(fill_time_values, [25, 50, 75])". Then, the four thresholds obtained from the script are identified with IFS () formula from 10 to 0. If the simulation result for each sub-parameter is withing the best-performing 25 percentile, then it satisfies the condition of scoring the sub-parameters as 10. If the result is between 50 and 75 percentile then it gets the score 7. The results not satisfying the 25,50,75 percentile thresholds receive the score 0.

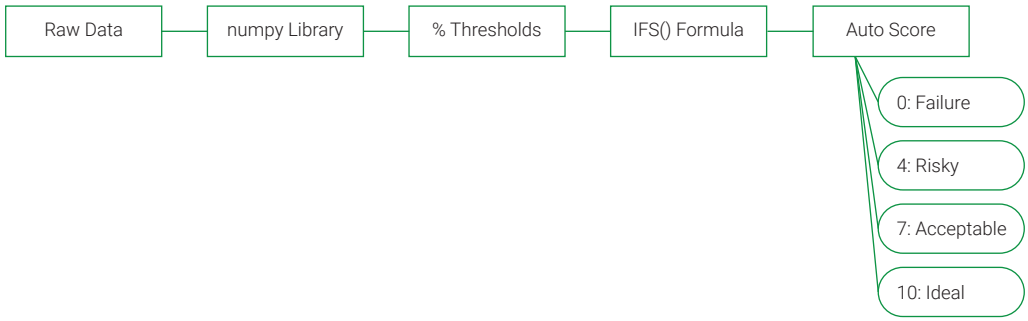


Figure 67: Workflow diagram showing data collection and ranking system (Source: Author)

The autoscore is combined with manual scoring to enable weight-based scoring system. The manual tier score is inputted for two scenarios: for scoring the result of the physical testing, and for scoring the visual simulation results. The four scoring options are used to determine the satisfactory level of the results. The manual scoring of the visual simulation results is done for the sub-parameters of injection flow analysis, compressive strength analysis, and charpy impact analysis. The range class is assigned based on the critical locations of the spacer.

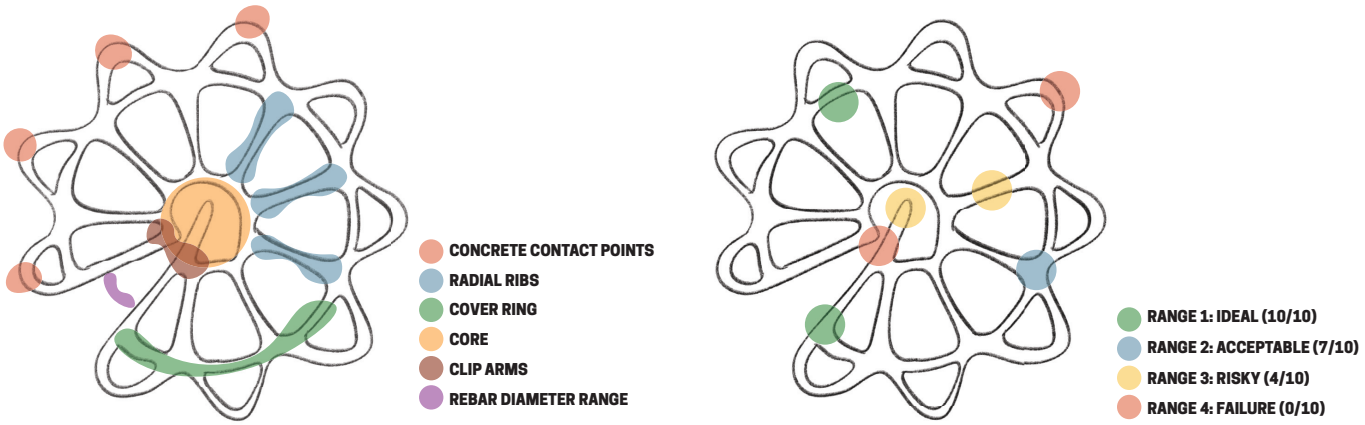


Figure 68: (1) Components of wheel spacer, (2) Diagram showing what range class a low data collection represents based on the location on the design (Source: Author)

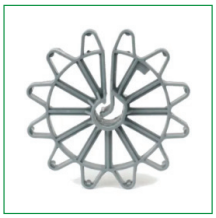
Finally, the weight-based scoring is an essential strategy to determine the final scores of both the designs and the sub-parameters differently. During the scoring of the sub-parameters, 75% weight is assigned to the auto score, and 25% weight is assigned to the manual tier score. The weights are given so that the final score ensures that quantitative data is prioritized over qualitative data. After each of the six parameter's final score is determined, a weight is assigned also to the each parameter score for finalizing the overall scoring of the design. The weights are assigned based on their relative significance on the implementation of the spacer. The most critical parameters and less critical parameters are selected based on the importance of them for both material experimentation and product development track in line with the construction applicability. Therefore, injection flow analysis, and contact area have the 25% weight for each; plastic use per product, and flexibility for rebars have 15% weight for each; compressive strength analysis and charpy impact analysis have 10% weight for each. The given hierarchy with the weights, finalize the final score for all 9 spacer designs. The one with the best scores out of 10 is selected for final optimization for the third phase of the thesis: application.

3.3.3 Design Development

The target product selected from the category of reinforcement spacers is wheel reinforcement spacers. Based on the options spacer with clip-on/off action, tower spacer, wheel spacer, cementitious block spacer, continuous line spacer and steel wire chairs; the product that suited the plastic material choice, and injection molding processing technique was the wheel spacer. This choice was also based on multiple factors like the suitability of both column and beam application scenarios, the full circumferential support for the rebars, and the minimal contact to the concrete cover. The waste input being contaminated and mixed, requires the evaluation of how hidden the target product will be for health and comfort of the construction and users. Because of its unique geometric complexity, the exposure of the wheel spacer out of concrete is minimal, therefore this showcased a great potential to choose it as target product for the thesis.

Additionally, the processing technique of injection molding creates an opportunity to create complex shapes. The complexity of the wheel spacers was an ideal challenge to validate the injection molding setups created for the waste input. The parameters and sub-parameters identified for the product development track enabled the selection of a target product in which all parameters could be tested and verified. After selecting the target product, the mainstream wheel spacer products are analyzed based on their characteristics and differences. The mainstream wheel spacer types have various adaptation to the must-have components (see Table 19) of a wheel spacer. The typical components existing in a wheel spacer includes: **(1)** core, **(2)** clip arms, **(3)** radial ribs, **(4)** cover ring, **(5)** concrete contact points, and **(6)** rebar diameter range. The wheel spacer types were first analysed based on these components before generating designs.

WHEEL SPACER TYPES



STANDARD WHEEL SPACERS
Standard wheel spacers can be used for both beam and column applications. These high quality spacers are generally used for vertical surfaces. The components are generally larger compared to other wheel spacer types. The core is wider resulting in a stronger and stable spacer. It meets the guidelines BS7973-1. *(Adapted from Euro Accessories)*

STANDARD WHEEL SPACERS
The lap wheel spacer types are designed to provide an ideal cover support with the ability to accommodate two spacers parallel with each other. *(Adapted from Euro Accessories)*

SMALL WHEEL CIRCLES
This type of wheel spacers have two types that have similar retention mechanism with three axes snapping action. These are meant for small diameter rebars ranging from 3-8mm. *(Adapted from Euro Accessories)*

HEAVY DUTY WHEEL SPACERS
These wheel spacers are used generally for heavy duty applications both for column and beam applications. *(Adapted from Euro Accessories)*

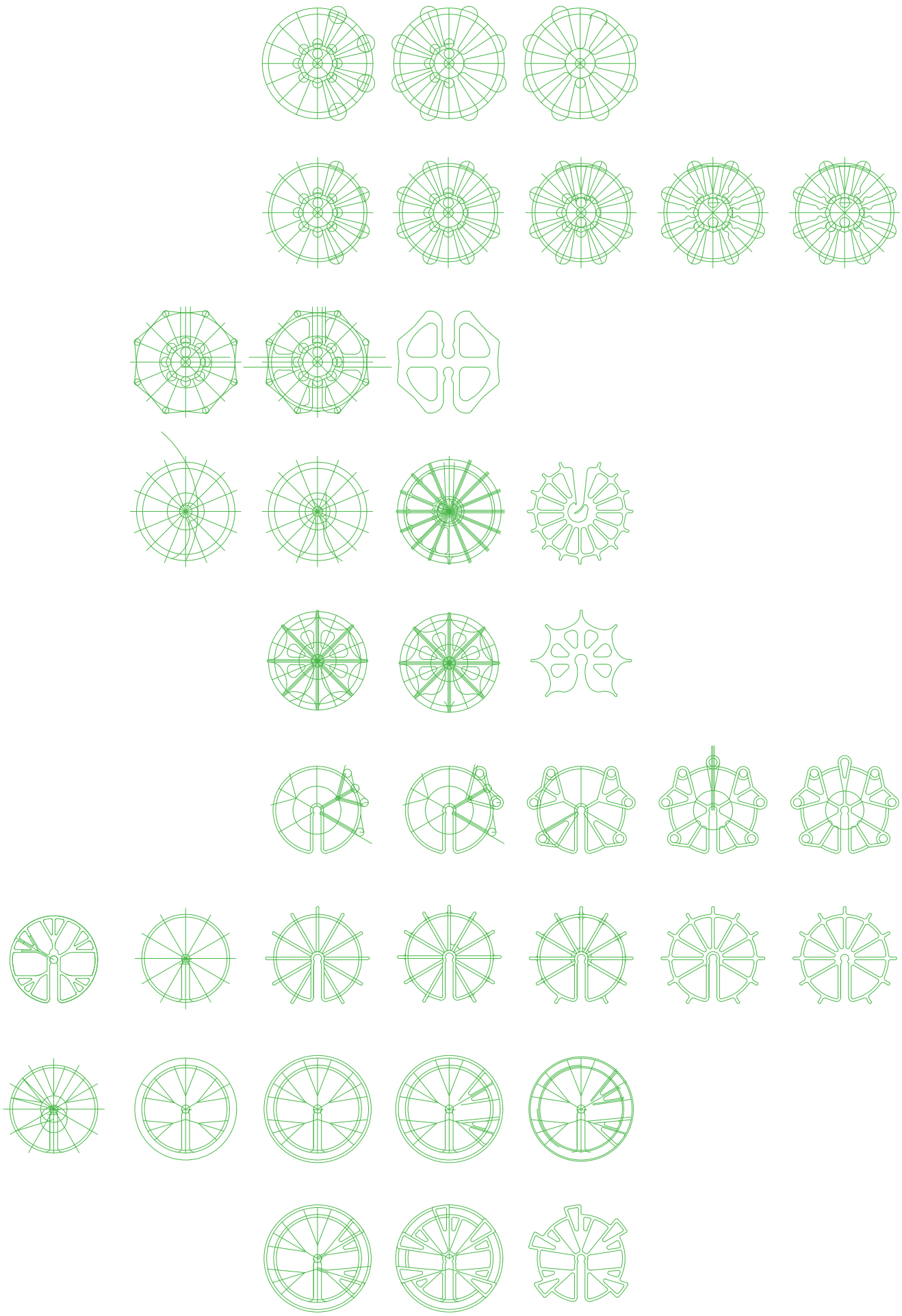
Table 19: Mainstream wheel spacer type reinforcement spacers and their applicacation scenarios (Source: Author)

Several standardised wheel spacers are found in Netherlands-based and worldwide manufacturing companies. The standard wheel spacer type includes a large core with one clip arm that creates a retention mechanism. The span of the radial ribs is small compared to other types because of the large core. The concrete contact points are sustained with a unique wavy design that creates minimal exposure. The main advantage of the standard design compared to other mainstream types is the ability to host a wide range of standard rebar diameters. Other common types generally have linear elongated spikes to control the concrete contact, which proves the functionality of the minimal designs. Generally, the core is the component that differentiates one type from another, while the retention mechanisms designed for wheel spacer types are all unique. The core component varies from the most basic snapping action to the locking mechanism, where the necessity of adjustment in-place increases.

The variants were taken into consideration during design development. Significant attention was given to designing a simple but functional wheel spacer considering the application scenario and processing technologies. As the injection molding setups are lab-scale prototypes, the complexity of the components is lowered compared to the spacers that are manufactured in industrial machines. In addition, the practical usability during the construction phase was critical for the design development. Generally, large quantities of wheel spacers are installed on-site without a lot of care, and a fast and easy application scenario was imagined. Therefore, the developed design could be suitable for large-scale applications of concrete construction following the guidelines like EN 1992-1-1 and EN 13369.

The design development phase includes, firstly, the development of nine unique designs with the necessary components that are found in mainstream wheel spacer types. The designs are evaluated based on the product evaluation parameters, and an optimal design with the best score is selected with the design optimisation tool. Each wheel spacer design was created focusing more on one of the evaluation parameters in mind.

The designs include different variations in order to satisfy different concrete covers and a rebar diameter range suitable for that cover. The rebar diameter range is decided based on Euro Accessories' standard wheel spacer type with Polypropylene (see Fig.69)

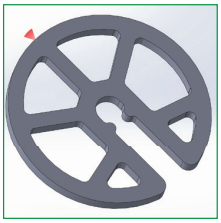


3.3.4 Simulation and Physical Testing
3.3.4.1 Injection Flow Analysis

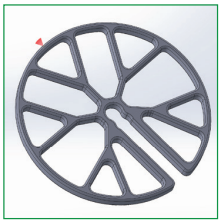
Product Code	Cover (mm)	Bar Dia. (mm)	Pack Size	Pallet Size
PCS200412	20	4-12	2000	60000
PCS250812	25	8-12	1000	40000
PCS251220	25	12-20	1000	36000
PCS300812	30	8-12	1500	30000
PCS301220	30	12-20	1000	20000
PCS351220	35	12-20	500	10000
PCS400412	40	4-12	750	13000
PCS400816	40	8-16	750	13500
PCS401220	40	12-20	500	14000
PCS450816	45	8-16	500	10000
PCS500816	50	8-16	250	7500
PCS501220	50	12-20	250	7500

Figure 69: Plastic wheel spacer datasheet (Source: Euro Accessories)

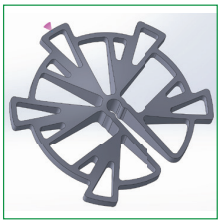
DESIGNS



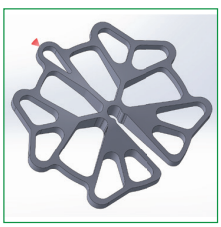
SPACER 1
The first spacer is created with the first attempt of the unique retention mechanism for the core component in which the snapping action is highly reliant on the flexibility of the material rather than the shape of the design. The necessary attention to the minimum concrete contact was not given during this stage of the design phase.



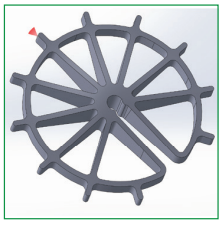
SPACER 2
The second spacer was created based on how the SolidWorks Plastic simulation tool operates. The radial ribs are created with the injection location which creates easy branching out of plastic during injection. However, similar to the first spacer, the necessary attention was not given to the concrete contact points.



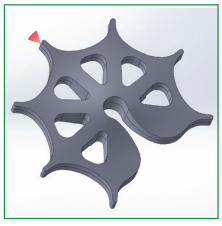
SPACER 3
A general curvilinear design approach is observed for the mainstream wheel spacer types. Therefore, for spacer 3, a design with straight lines and sharp corners was generated.



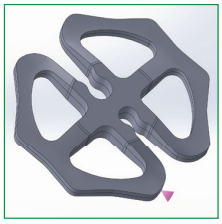
SPACER 4
The design approach focuses on generating a thick radial rib design to ensure structural stability and better distributed loading. An aesthetic focus was given to this design as well.



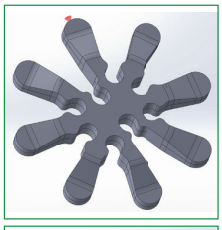
SPACER 5
The fifth spacer is crucial for the thesis as this design is used for the checkpoint of the thesis, where the main feedback loop is created between material experimentation and product development tracks. The similarity of the design to the mainstream types, with adaptation of the unique retention mechanism, makes the spacer a proof-of-concept during the thesis.



SPACER 6
With a negative cover ring design and short span of the radial ribs, an efficient design with minimal plastic use was generated. The core was kept simple and the retention mechanism was tried to be achieved by making the radial ribs that takes the rebar curvilinear which mimics squeezing.



SPACER 7
A unique approach compared to the mainstream wheel spacer types was taken for this spacer. A multiple core design that is specifically for the two rebar diameters that is used for the selected concrete cover enables a simple yet functional approach.



SPACER 8
The unique approach was repeated for this spacer, where the in-between area of each radial rib creates a core for the rebar. The application scenario for this spacer was also imagined for the extreme scenarios where multiple rebar connections might be necessary for special cases. This spacer was imagined to prevent the use of another spacer in those situations.

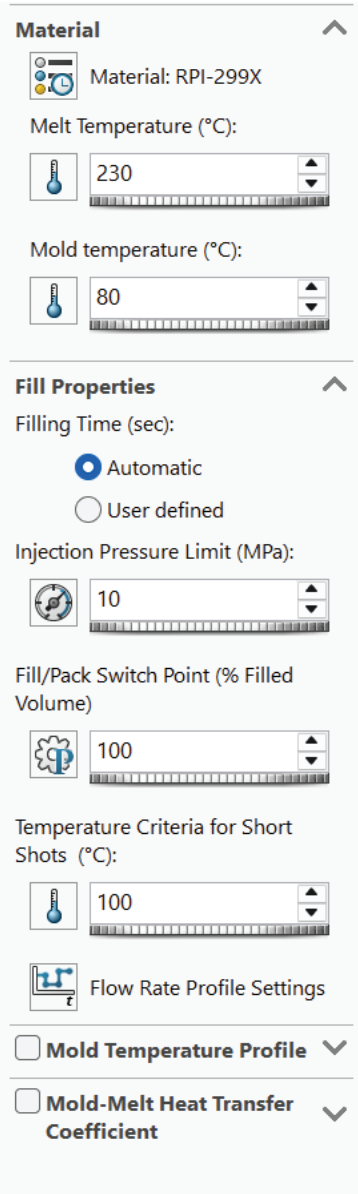
SPACER 9
The generic core design of the standard wheel spacer type is analysed and mimicked for the core of this spacer. The quantity of the radial ribs was increased as well as the concrete contact points, to ensure that the exposure of the product outside of the concrete is minimised. The increase in radial ribs is imagined to ensure better structural stability than the standard types.

Table 20: Designed wheel spacers and their descriptions for their design approaches (Source: Author)

The Plastic Injection Analysis tool in SolidWorks Plastics shows how the flow behaviour of the selected polymer at the defined injection scenario. The injection flow analysis was one of the parameters that were tested hand-in-hand with the material experimentation track. The results from the polymer characterisation and sorting processes give feedback to the product development track about the polymer types for defining polymer parameters for injection. This tool served as a prior step before injection moulding setups, which pointed out expected results and behaviours beforehand. As the polymer selection is prioritised, if the injection flow analysis is done within the feedback loops from material experimentation track.The design is adapted to give successful injection results.

Analysis Setup: The generated solid design is selected for the single-material injection process. Based on the feedback from the material experimentation track, the polymer is selected. The polymers that have been selected throughout the thesis include **(1)** PA6/PA66 blend by DOMO Engineering Plastics, **(2)** Generic PS by SolidWorks, **(3)** Generic PP by SolidWorks, **(4)** PE/PP blend by RESEARCH Polymers, respectively.

The database for the polymer selection includes useful characteristics like thermal conductivity, viscosity and polymer-material parameters. At the polymer-material table for each polymer, the recommended melt and mold temperature, and maximum shear stress are considered while defining the temperature values based on the boundary conditions of the experiment setups. Another crucial aspect is the injection pressure limit that is solely related to the experiment setup. For example, 10 MPa is assigned as the pressure limit of the pneumatic plunger-type injection molding machine to represent real-life data (see Fig.70).



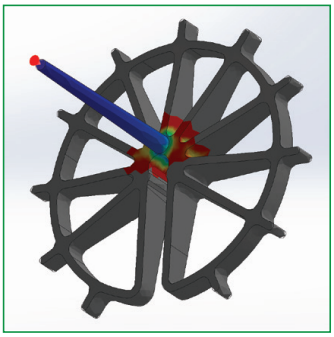
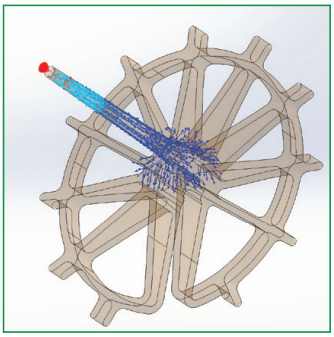
Then, as the boundary condition of the simulation, an injection location is defined. The injection location is assigned based on the selection between manual or pneumatic injection molding setups. This was one of the boundary conditions of the thesis because the selection of the optimal injection location was not possible, while the experiment setups necessitated specific injection locations because of the mould availability. For the pneumatic plunger-type injection molding machine, a central location, closer to the centre of gravity of the design, was possible, whereas for the manual-plunger type injection molding, a top-end location was possible for injection.

The last step before the analysis was transforming the solid body into a curvature-based mesh, which was the main indicator of getting finer results that gives a closer result to the real-life scenario. The created mesh was put to the simulation and both the numeric and graphic results are analysed quantitatively and qualitatively with the design optimization tool.

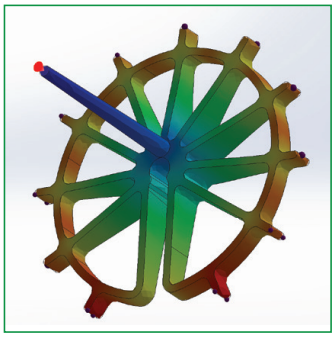
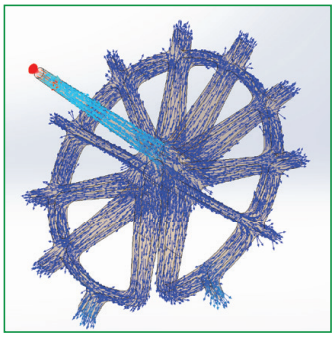
First Analysis:
The first analysis was conducted during the first polymer characterisation trials where several polymers from each waste bag were selected. It is conducted for the pneumatic injection molding setup. The majority of the characterised polymers were PP and PA6/PA66 blends. Therefore, the first analysis was done on a selected design with and without a runner to test the applicability of a runner for the complexity of the prototypes. These analyses were meant to establish a baseline understanding of the expected material behaviour when adjustments were made on the data, such as temperature, injection location, and polymer selection.

Figure 70: SolidWorks Plastics injection parameters (Source: SolidWorks)

INJECTION LOCATION : RUNNER SYSTEM - PA6/PA66

FILL TIME	VELOCITY VECTOR
	

INJECTION LOCATION : RUNNER SYSTEM - PP

FILL TIME	VELOCITY VECTOR
	

INJECTION LOCATION : CENTER - PP

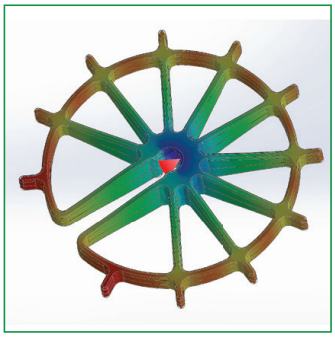
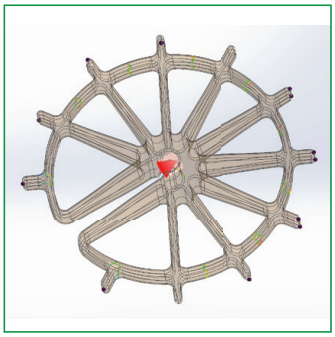
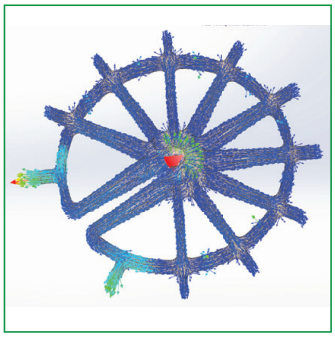
FILL TIME	WELD LINES & AIR	VELOCITY VECTOR	EASE OF FILL
			

Table 21: First analysis results on several sub-parameters (Source: Author)

The results showcased the minimal effect a temperature change on the simulation makes, whereas a change in the polymer selection and causes a tremendous shift in flow behaviour (see Table.17). With the limited injection pressure limit assigned on the simulation with existing runners, PP setups performed better with passing results. For the designs without runner systems, all PP and PA6/PA66 blends had passing results.

Second Analysis:

The second analysis was done after all the density sorting and polymer characterisation were done at the material experimentation track. Based on the feedback from the track, PE/PP blend was used as the material with an injection pressure limit of 10 MPa. The melt and mould temperature for all simulations was kept as they are suggested by SolidWorks. As the manual plunger-type injection molding setup was selected for the analysis with a defined injection location, all nine wheel spacer designs were simulated and put into design optimisation tool.

The graphic and numeric data were collected for optimisation. The spacers 3 and 5 failed the injection flow simulation. The failing results were caused by limited injection pressure and/or the injection location. Because of the setup, the injection locations are placed at the concrete contact points, which in the case of the spacers 3 and 5 were long, elongated spikes. This probably caused difficulty for the melt front to travel and distribute throughout the cavity.

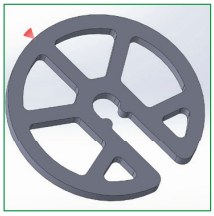
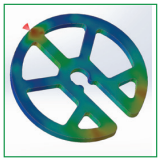
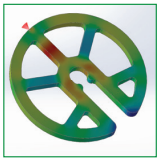
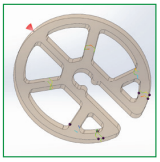
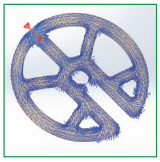
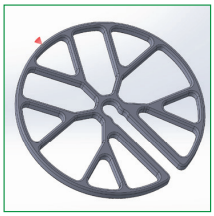
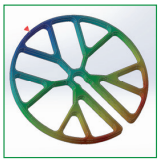
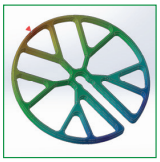
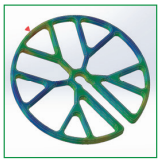
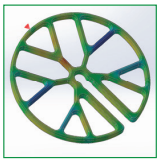
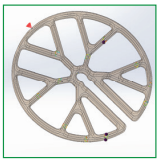
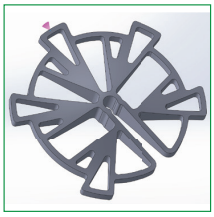
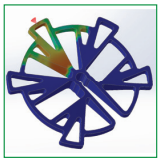
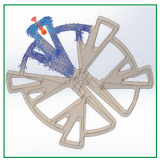
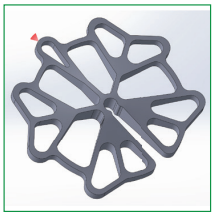
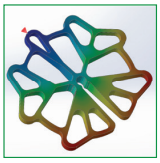
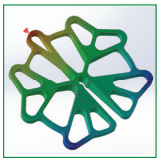
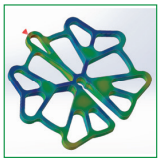
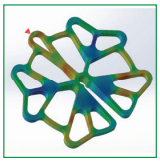
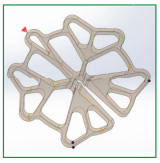
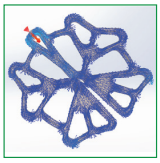
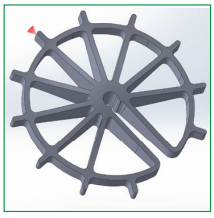
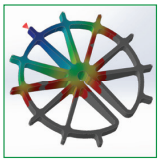
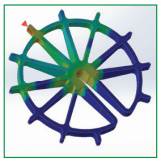
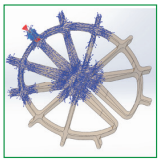
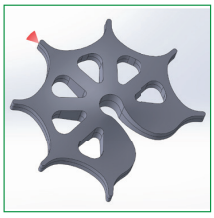
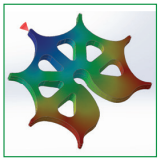
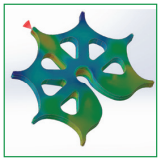
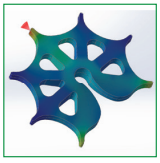
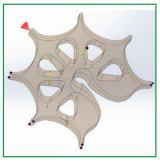
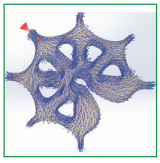
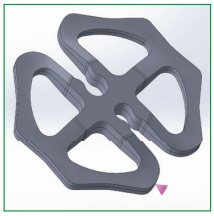
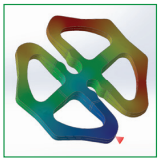
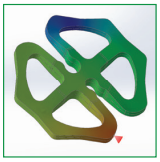
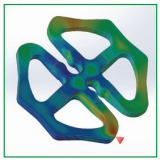
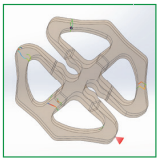
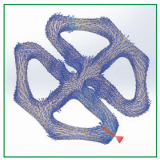
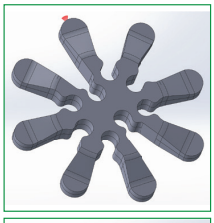
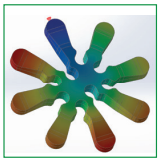
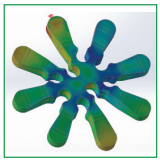
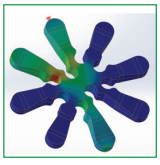
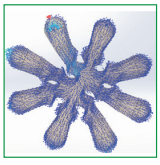
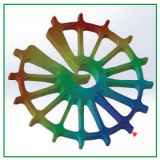
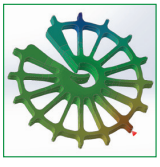
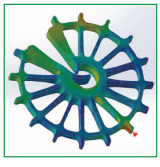
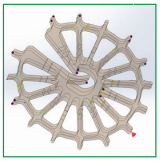
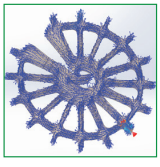
DESIGNS	PROPERTIES	FILL TIME	PRESSURE	TEMPERATURE	SHEAR STRESS	WELD LINES & AIR	VELOCITY VECTOR
	**SPACER 1** Height(mm): 93 Cover(mm): 32 Bar Dia. (mm): 6 Volume(cm3):20.88	**min:** 0.0011 sec **max:** 5.2786 sec 	**min:** 0.10 MPa **max:** 2.19 MPa 	**min:** 103.07°C **max:** 230.02°C 	**min:** 0.00 MPa **max:** 0.04 MPa 	**min:** 1.610° **max:** 137.6500° 	**min:** 0.0201 m/s **max:** 29.1789 m/s 
	**SPACER 2** Height(mm): 100 Cover(mm): 42 Bar Dia. (mm): 8 Volume(cm3): 20.96	**min:** 6.512e-04 sec **max:** 3.4292 sec 	**min:** 0.10 MPa **max:** 6.32 MPa 	**min:** 90.87°C **max:** 230.08°C 	**min:** 0.00 MPa **max:** 0.08 MPa 	**min:** 0.7700° **max:** 149.1800° 	**min:** 0.0116 m/s **max:** 57.2777 m/s
	**SPACER 3** Height(mm): 120 Cover(mm): 42 Bar Dia. (mm): 8 Volume(cm3): 31.31	**min:** 5.159e-04 sec **max:** 0.7704 sec 	**min:** 0.10 MPa **max:** 2.63 MPa 	**min:** 80.00°C **max:** 230.14°C 	**min:** 0.00 MPa **max:** 0.08 MPa 	N/A	**min:** 0.0141 m/s **max:** 60.8905 m/s 
	**SPACER 4** Height(mm): 123 Cover(mm): 45 Bar Dia. (mm): 8 Volume(cm3): 27.50	**min:** 6.425e-04 sec **max:** 3.9858 sec 	**min:** 0.10 MPa **max:** 7.23 MPa 	**min:** 91.55°C **max:** 230.10°C 	**min:** 0.00 MPa **max:** 0.08 MPa 	**min:** 0.1500° **max:** 149.1700° 	**min:** 0.0227 m/s **max:** 51.3741 m/s 
	**SPACER 5** Height(mm): 118 Cover(mm): 42 Bar Dia. (mm): 8 Volume(cm3): 28.55	**min:** 3.878e-04 sec **max:** 1.8899 sec 	**min:** 0.10 MPa **max:** 4.42 MPa 	**min:** 80.00°C **max:** 230.93°C 	**min:** 0.00 MPa **max:** 0.10 MPa 	N/A	**min:** 0.0034 m/s **max:** 189.2124 m/s 
	**SPACER 6** Height(mm): 82 Cover(mm): 35 Bar Dia. (mm): 10 Volume(cm3):15.31	**min:** 4.068e-04 sec **max:** 5.9485 sec 	**min:** 0.10 MPa **max:** 2.84 MPa 	**min:** 83.50°C **max:** 230.01°C 	**min:** 3.382e-07 MPa **max:** 0.10 MPa 	**min:** 0.9100° **max:** 129.8600° 	**min:** 2.871e-04 m/s **max:** 87.6201 m/s 
	**SPACER 7** Height(mm): 88 Cover(mm): 35 Bar Dia. (mm): 8-10 Volume(cm3):21.60	**min:** 0.0011 sec **max:** 6.0483 sec 	**min:** 0.10 MPa **max:** 2.35 MPa 	**min:** 98.68°C **max:** 230.02°C 	**min:** 2.499e-04 MPa **max:** 0.06 MPa 	**min:** 2.1400° **max:** 144.4800° 	**min:** 0.0026 m/s **max:** 26.5677 m/s 
	**SPACER 8** Height(mm): 89.5 Cover(mm): 30 Bar Dia. (mm): 8 Volume(cm3):21.22	**min:** 0.0090 sec **max:** 6.6475 sec 	**min:** 0.10 MPa **max:** 2.19 MPa 	**min:** 91.86°C **max:** 230.00°C 	**min:** 4.794e-08 MPa **max:** 0.07 MPa 	**min:** 12.2100° **max:** 95.0400° 	**min:** 0.00 m/s **max:** 29.56 m/s 
	SPACER 9 Height(mm): 86 Cover(mm): 27 Bar Dia. (mm): 6-8 Volume(cm3):13.41	**min:** 1.272e-04 sec **max:** 2.5370 sec 	**min:** 0.10 MPa **max:** 10.04 MPa 	**min:** 84.58°C **max:** 230.86°C 	**min:** 1.146e-07 MPa **max:** 0.13 MPa 	**min:** 0.1000° **max:** 146.9000° 	**min:** 0.0016 m/s **max:** 207.7365 m/s 

Table 22: Second analysis results with the min/max value with graphic data collection (Source: Author)

3.3.4.2 Physical Tests

Physical testing was used mainly for the parameters of Contact Area and Flexibility for Rebars. 3D printing technology was used to generate 1:1 scale prototypes to assign a numeric value for the manual tier score of the design optimisation tool. The 1:1 scale models were printed first with PLA as it was found to be optimal for testing the contact area parameter. For analysing concrete contact points of each design, the 3D print was placed on a horizontal surface. The distribution of the surface area on the horizontal surface represents the exposed area of the component at the concrete finish.

For evaluating the "flexibility for rebars" parameter, the snap-fit action and the retention mechanism were crucial therefore, it was intended to find a similar performing polymer for 3D printing that would represent the polymer selections from the material experimentation track. As **PP and PP/PE blends** are recovered highly, another filament selection was made to represent similar mechanical properties: PET-G (polyethylene terephthalate glycol-modified). PLA is a brittle polymer which has low impact resistance, whereas PET-G has higher impact resistance and has similar yield strength as PP and PP/PE blends. The expected flexible gripping behaviour was better achieved with PET-G because of its lower modulus.

The manual tier score of 0, 4, 7, 10 were given based on the performance of each design and inputted into the design optimization tool for selecting the optimal design.

Generic PETG	
Polymer Family	PETG
Manufacturer	Generic material
Recommended Melt Tempe	255 °C
Maximum Melt Temperature	290 °C
Minimum Melt Temperature	220 °C
Recommended Mold Tempe	15 °C
Maximum Mold Temperature	30 °C
Minimum Mold Temperature	10 °C
Ejection Temperature	60 °C
Thermoset Conversions	Not Available
Transition Temperature	80 °C
Viscosity : 7-Parameters Mo	3.86184e+25 323.15 0 64.52 51.6 724170 0.1563
PVT : Modified Tait Equatior	0.000795 5.3e-07 2.38e+08 0.00408 0.0007944 2.65e-(
Density	Not Available
Specific Heat : Constant	2050 J/(Kg-K)
Thermal Conductivity : Cons	0.2 W/(m-K)
Elastic Modulus : Constant	2125 2125
Poisson's Ratio : Constant	0.443 0.443
Coefficient of Thermal Expa	7.485e-05 7.485e-05
Shear Relaxation Modulus	Not Available
Heat of Reaction	Not Available
Induction Time Constants	Not Available
Curing Model	Not Available

RPI-299X	
Polymer Family	PE+PP
Manufacturer	RESEARCH Polymers
Recommended Melt Tempe	230 °C
Recommended Mold Tempe	80 °C
Ejection Temperature	120 °C
Thermoset Conversions	Not Available
Transition Temperature	100 °C
Viscosity : 5-Parameters Mo	0.019 5390 37300 0.34 0
PVT : Constant	900 Kg/m3
Density	Not Available
Specific Heat : Constant	2200 J/(Kg-K)
Thermal Conductivity : Cons	0.16 W/(m-K)
Elastic Modulus : Constant	2600 2600
Poisson's Ratio : Constant	0.38 0.38
Coefficient of Thermal Expa	9.5e-05 9.5e-05
Shear Relaxation Modulus	Not Available
Heat of Reaction	Not Available
Induction Time Constants	Not Available
Curing Model	Not Available
No-Flow Temperature	Not Available
Melt Flow Rate	Not Available
Filler Properties	Not Available
Max. Shear Rate	100000 1/s

Table 23: The polymer datasheets of PET-G and PP/PE blends for compatibility (Source: SolidWorks)

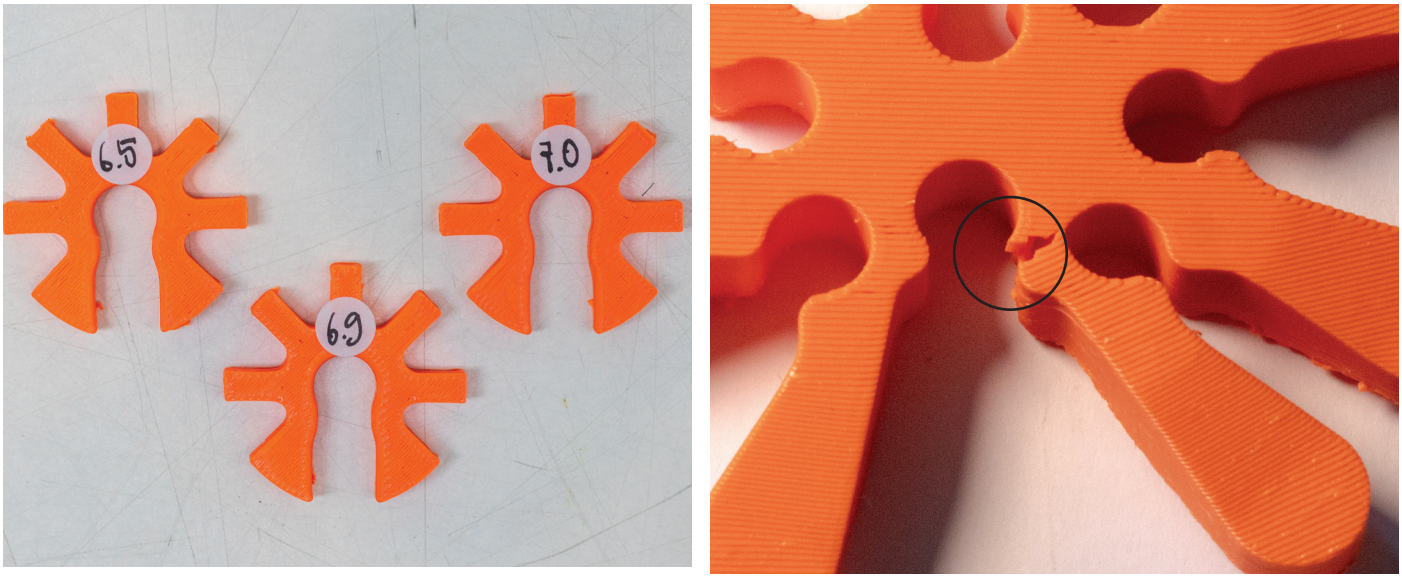


Figure 71: (1)The rebar retention mechanism tests and (2) Failed rebar test on the Spacer 8 (Source: Author)

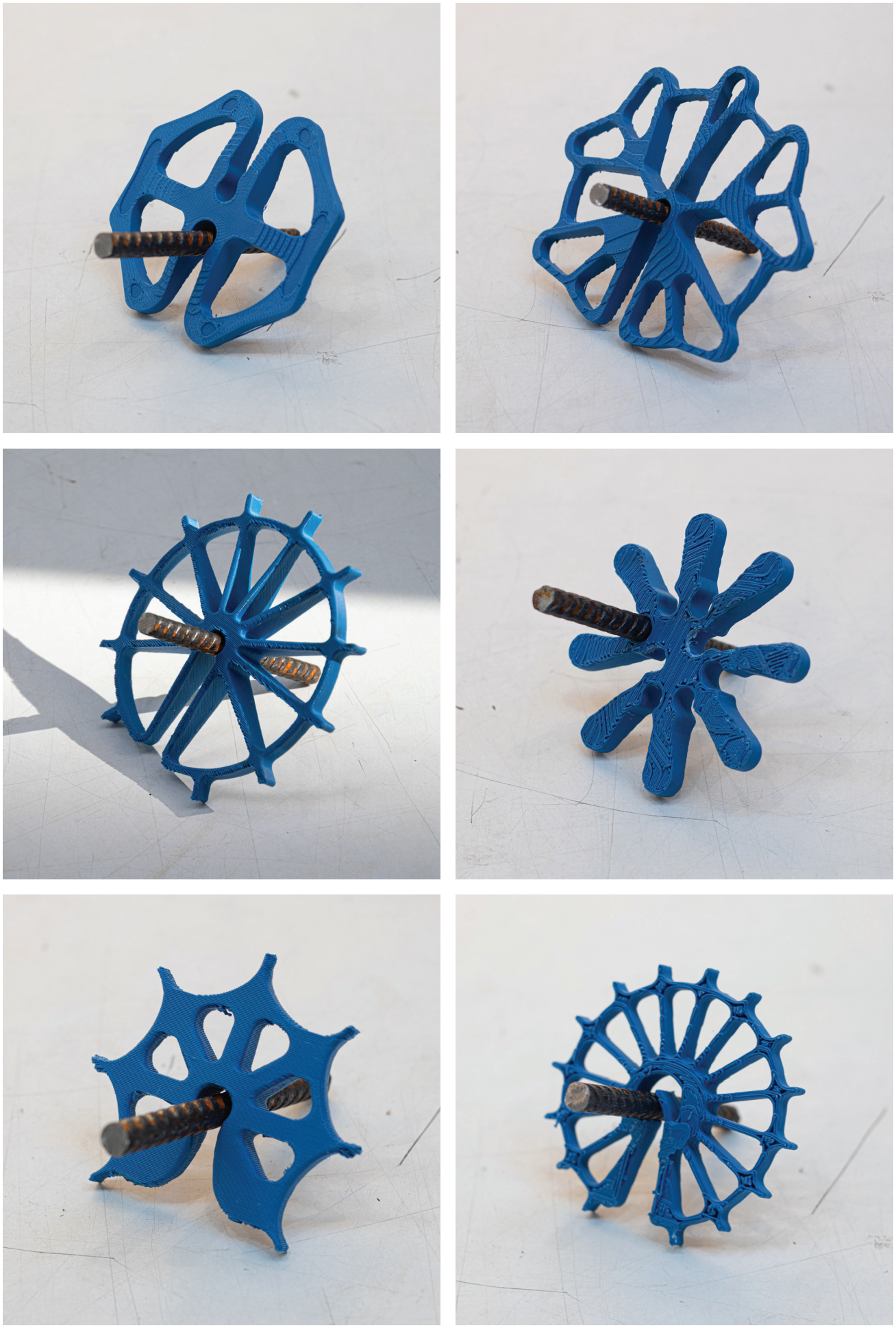


Figure 72: Physical tests with 6mm rebars on Spacers 7, 4, 5, 8, 6, 9 (Source: Author)

3.3.4.3 Compressive strength and Charpy Impact

The validation of the mechanical performance of the designs is done by looking at the compressive strength and Charpy impact behaviours of the designs using SolidWorks. As wheel spacers are temporary supports mainly to sustain the correct positioning of the rebar until concrete sets. The simulations were enough to evaluate their mechanical performance for applicability. The main considerations for the mechanical performance includes **(1)** hydrostatic pressure of the wet concrete, **(2)** the possible deformation during concreting, **(3)** on-site impact conditions.

Analysis Setup: The compressive strength was first used to determine the target application scenario of a beam or column. For selecting the optimal scenario, a low-rise residential building was selected with a column with the dimensions 230 mm x 230 mm x 1000 mm, and a beam with 230 mm x 300 mm and 1000 mm. These assumptions are made based on the EN 1992-1-1 guidelines that suggest low axial loading requirements and the span/10 rule for beams. The loading scenario consisted of self-weight and also the hydrostatic pressure from wet concrete, where three spacers are considered to be used for each element. A safety factor of 2 was applied based on the EN 1990 guidelines. As there was no guideline for the compressive strength requirements of the reinforcement spacers, the DBV Merkblatt "Abstandhalter" guideline was taken into consideration, which requires spacers to withstand 200-400 N without significant deformation.

The hydrostatic pressure from the wet concrete is calculated based on the fluid pressure formula:

$$p=\rho \times g \times h$$

where:
p = hydrostatic pressure (N/m^2)
ρ = density of fresh concrete (~2400 kg/m^3)
g = gravitational acceleration (9.81 m/s^2)
h = vertical height of the fresh concrete above the point considered (m)

	CONDITIONS	STANDARDS	FORCES	LOAD RANGE	PER SPACER
COLUMN	Residential buildings (low-rise) C25/30 class	**EN 1992-1-1** 230 x 230 x 1000 mm low axial loads	self-weight + lateral pressure of wet concrete	**Safety factor 2-3x** 4 spacer per column	Total weight of concrete/4 = **200 N**
BEAM	Residential buildings (low-rise) C25/30 class	**EN 1992-1-1** 230 x 300 x 1000 mm span/10 rule	self-weight + lateral pressure of wet concrete	**Safety factor 2-3x** 3 spacer per beam	Total weight of concrete/3 = **1100 N**

Table 24: Compressive strength simulation setup for column-beam applications (Source: Author)

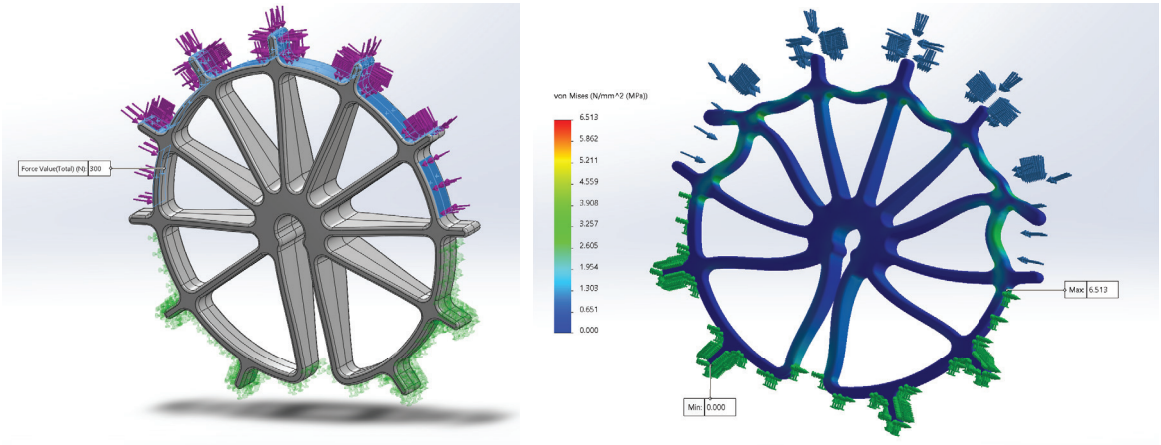


Figure 73: Exemplary setup for compressive strength and final stress results for beam application on Spacer 5 (Source: SolidWorks)

The numeric data obtained from the calculations were inputted into SolidWorks' nonlinear dynamic simulation setup. Firstly, the solid body was fixed at the necessary surfaces based on column or beam application to mimic the real-life scenario. At the opposite direction, a force representing the wet concrete force was assigned. Based on the feedback from the material experimentation track, a material was selected. As there was no polymer selection of PP/PE blend, the similar behaving PE-HD polymer in the SolidWorks database was selected and the minor material differences were neglected during thesis. Finally, the solid body was converted into a curvature-based mesh model and the simulation was conducted.

Property	Value	Units
Elastic Modulus	1070	N/mm^2
Poisson's Ratio	0.4101	N/A
Shear Modulus	377.2	N/mm^2
Mass Density	952	kg/m^3
Tensile Strength	22.1	N/mm^2
Compressive Strength		N/mm^2
Yield Strength		N/mm^2
Thermal Expansion Coefficient		/K
Thermal Conductivity	0.461	W/(m·K)
Specific Heat	1796	J/(kg·K)
Material Damping Ratio		N/A

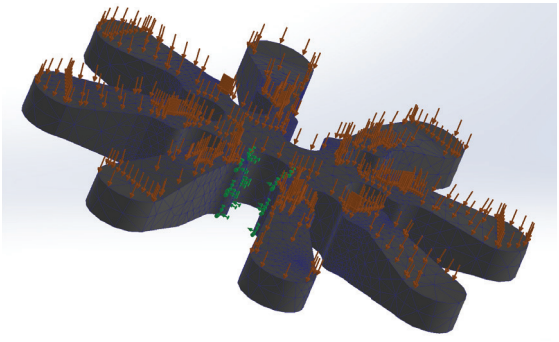


Figure 74: PE-HD polymer datasheet (see left) and compressive strength setup of the forces (see right) (Source: SolidWorks)

The maximum forces were given to the analysis setup to test the extreme conditions for both application scenarios. Based on the graphic and numeric data gathered from the analysis, the application scenario is decided as a column for further mechanical testing that was conducted. The graphic data was the main indicator for the decision for the application scenario as well as the fact that this component is mainly used for column applications. The second analysis was done on all nine spacers to get the stress-displacement-strain behaviour to input in the design optimization tool (see Appendix for other six analyses results).

COMPRESSIVE STRENGTH SIMULATION ANALYSIS RESULTS FOR COLUMN APPLICATION

	STRESS (MPa)	DISPLACEMENT (mm)	EQUIVALENT STRAIN
SPACER 7	**min:** 0.012 **max:** 8.168	**min:** 0.000 **max:** 0.743	**min:** 0.000 **max:** 0.006
SPACER 8	**min:** 0.011 **max:** 11.367	**min:** 0.000 **max:** 1.003	**min:** 0.000 **max:** 0.009
SPACER 9	**min:** 0.000 **max:** 12.519	**min:** 0.000 **max:** 0.689	**min:** 0.000 **max:** 0.009

Table 25: Exemplary compressive strength analysis results collection for Spacers 7-8-9 (Source: Author)

The Charpy impact analysis was conducted mainly to test the on-site impact conditions and to test the durability of the wheel spacer for accidental dynamic loads. In theory, Charpy impact test measures the energy that is absorbed by the material because of the impactor. While SolidWorks does not simulate the exact principles of the Charpy impact test, the Drop Test setup measures the localised energy input and material behaviour of the wheel spacer if adjusted correctly. Therefore, a scenario of wet concrete falling onto the spacer was created for the analysis. The impact energy is sustained within the 1-50 J range defined for the plastic components under ISO 179, Charpy impact tests for plastics.

Analysis Setup: The solid body is selected for the Drop Test setup, where firstly the impact surface is selected. To be able to stimulate impact scenario, an initial velocity was applied with the gravity to represent a 3kg concrete falling from a 1-meter height as the impactor. After the material is selected based on the material experimentation track, the solid body was transferred into a curvature-based mesh for the simulation. The potential energy and the impact velocity are calculated with the following formula:

$$PE=m\times g\times h$$

where:
PE = Potential energy (Joules, J)
m = Mass (kg)
g = Gravitational acceleration (9.81 m/s²)
h = Height (m)

$$v=2gh$$

where:
v = Impact velocity (m/s)
g = Gravitational acceleration (9.81 m/s²)
h = Height (m)

The numeric and graphic data were collected for inputting into the design optimisation tool, together with compressive strength data. Three results, including stress, displacement and equivalent strain, were analysed, where minimum and maximum data are identified at the visuals for manual tier scoring.

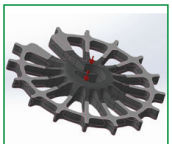
	CONDITIONS	SCENARIO	INITIAL VELOCITY	SCENARIO	RESULTS
COLUMN	**On-site impact conditions** ISO 179 EN 13586	Drop Test Interval for plastics: 1-50 J	**4.43 m/s** Moderate energy impact: 29.4 J		**Displacement** **Stress** **Strain**

Table 26: Charpy impact simulation setup (Source: Author)

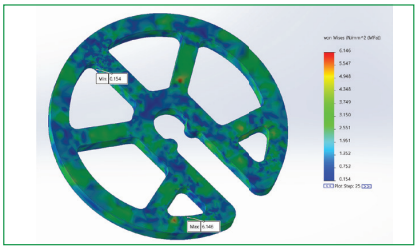
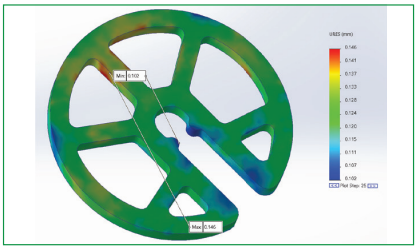
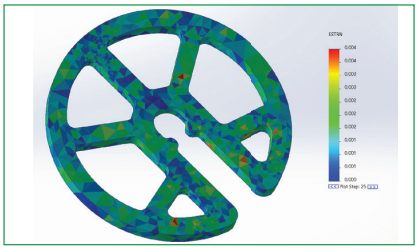
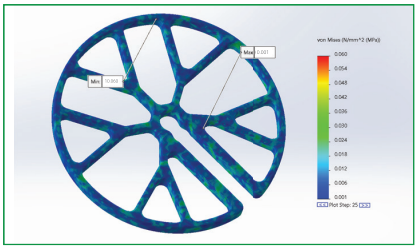
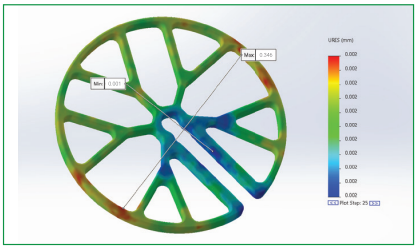
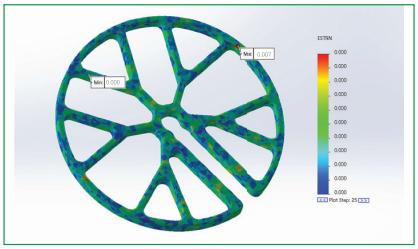
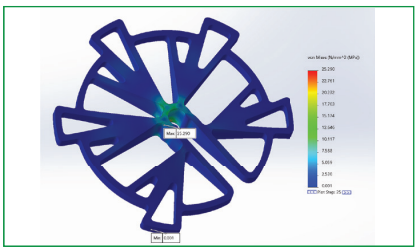
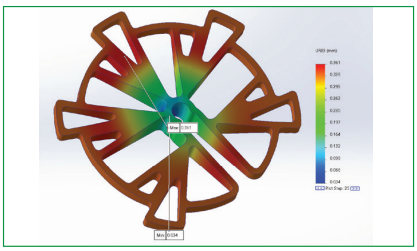
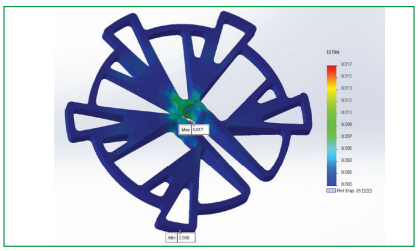
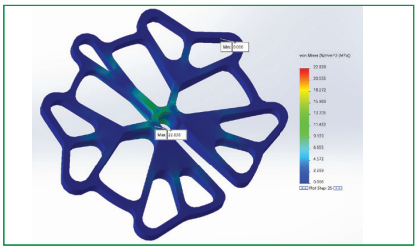
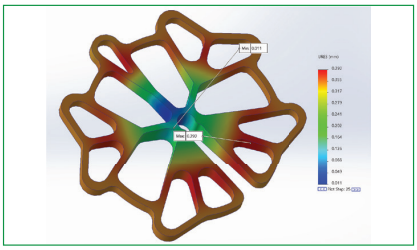
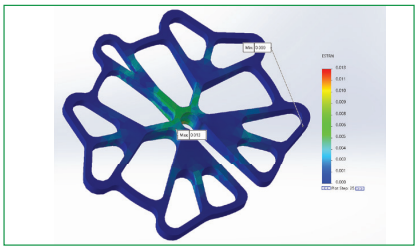
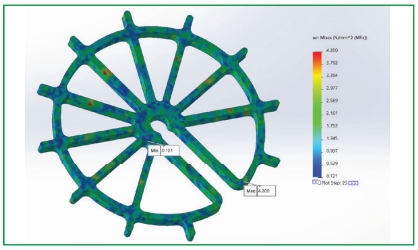
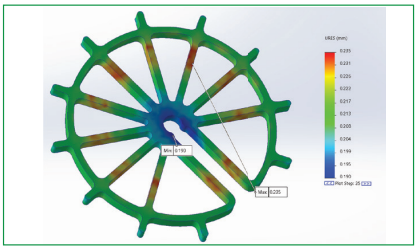
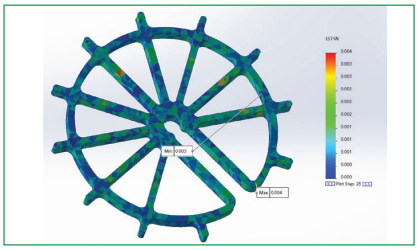
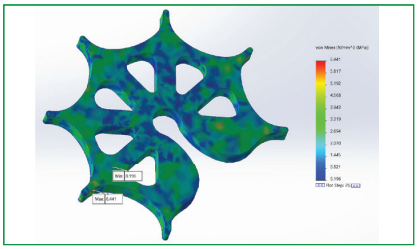
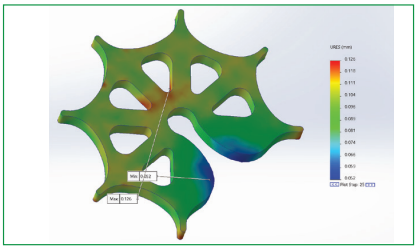
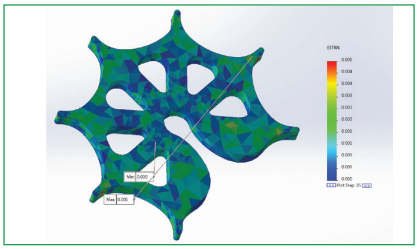
	CHARPY IMPACT SIMULATION RESULTS FOR COLUMN APPLICATION		
	STRESS (MPa)	**DISPLACEMENT (mm)**	**EQUIVALENT STRAIN**
SPACER 1	**min:** 0.154 **max:** 6.146	**min:** 0.102 **max:** 0.146	**min:** 0.000 **max:** 0.004
			
SPACER 2	**min:** 0.001 **max:** 10.060	**min:** 0.001 **max:** 0.346	**min:** 0.000 **max:** 0.007
			
SPACER 3	**min:** 0.001 **max:** 25.290	**min:** 0.034 **max:** 0.361	**min:** 0.000 **max:** 0.017
			
SPACER 4	**min:** 0.006 **max:** 22.838	**min:** 0.011 **max:** 0.393	**min:** 0.000 **max:** 0.013
			
SPACER 5	**min:** 0.121 **max:** 4.200	**min:** 0.190 **max:** 0.235	**min:** 0.000 **max:** 0.004
			
SPACER 6	**min:** 0.196 **max:** 6.441	**min:** 0.052 **max:** 0.126	**min:** 0.000 **max:** 0.005
			

Table 27: Exemplary Charpy Impact analysis results collection for Spacers 1-2-3-4-5-6 (Source: Author)

3.3.5 Mould Trials

To validate the official checkpoint of the thesis, a resin molding technique was used to replace the conventional aluminium molds purely because of feasibility. Based on the timeline of the thesis, for the official checkpoint of thesis Spacer 5 was selected as the optimal design that would be tested for resin printing a complex shape and also to prove its applicability for injection molding. The custom resin mold includes an upper part with Phrozen TR300 Ultra high-temperature resin and a bottom part SUNLU ABS-Like dark grey resin. These resins were selected based on their thermal resistance and mechanical strength to be able to satisfy higher temperatures for injection molding. The evaluation of the suitability of the resin molds were made based on the analysis of the crack formations after the experiment setup with recycled PP.

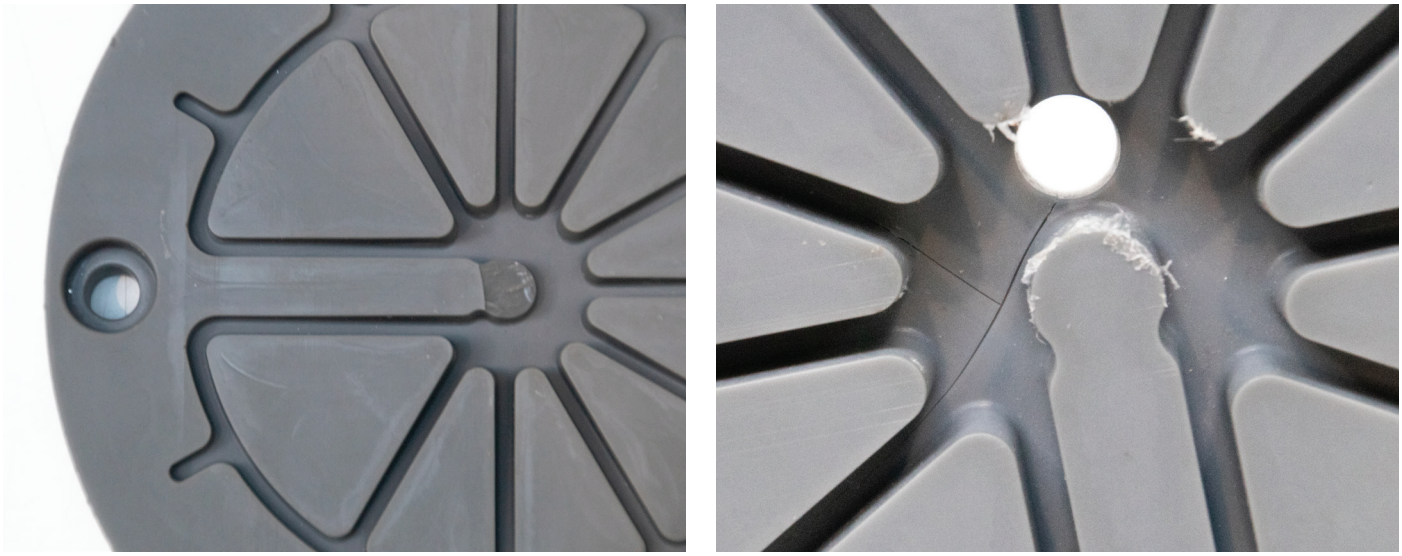


Figure 75: The crack formations on the upper plate resin mould (see right) and bottom plate resin mould (see left) (Source: Author)

After injecting two samples with the same custom resin mold, there was formation of cracks in between the two radial ribs at several locations on the Phrozen resin mold. Whereas, similar crack formation was also visible on the SUNLU resin mold in addition to the deformation and cracking at the central location. It was deduced that the pressure sustained from the injection location caused the defects (see Fig.75). Additionally, the clamp distance and absence of ventilation channels might be another cause of the defects. Overall, because of the successful result of the plastic sample, the applicability of the 3D resin printing was proved, and ABS-like resin was selected for the mould for the final design.

Another crucial step for the molding was the adjustment of the proper clamp distance at the lab-scale pneumatic injection molding machine. For a perfect result for injection molding, the mold surfaces need to be perfectly flat and aligned together for successful results. Therefore, manual calibration of the custom resin molds until a 1 mm distance in between was achieved for the experiment setup.

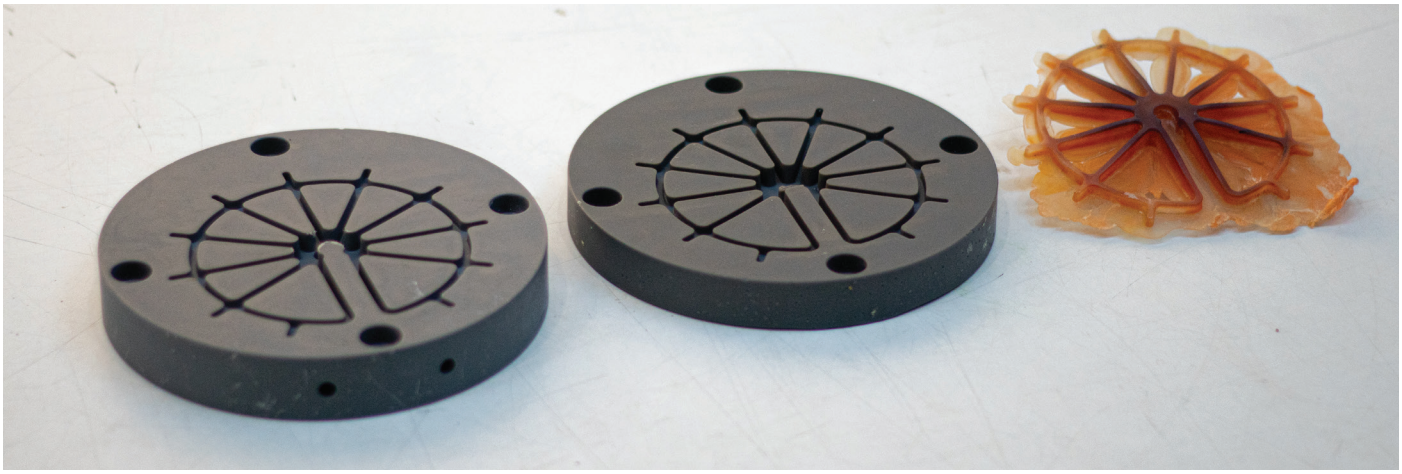


Figure 76: The resin printed moulds and the injection molded Spacer 5 on lab-scale pneumatic plunger-type machine (Source: Author)

Following on the initial resin mould evaluations done for the applicability of Phrozen TR300 Ultra high-temperature resin and a bottom part SUNLU ABS-Like dark grey resin, the final mould phase is adapted using the ABS-Like resin as a low-cost alternative to other mould types. Despite the lower glass transition temperature compared to industrial grade resins, the selected resin performed good under thermal and mechanical stress under pre-defined injection cycle. For the evaluation of the final mould, **(1)** the ability to withstand repeated injection cycles, **(2)** thermal expansion causing warping or cracking, and **(3)** surface softening and deformation were considered.

Figure 77: Final ABS-like resin printed mould used for the injection molding Spacer 10 (Source: Author)

Design Setup: Based on the results of the injection molded samples with the first resin moulds, special attention was given to shaping the geometry of the mould to adapt it to both less resin use and better injection flow. Adaptations were made to the STL insert templates available at the Sustainable Design Studio website for the used 100 mm × 100 mm × 50 mm cavity mould. The main modifications of the mould were made for (1) sprue, (2) draft angles, (3) mould supports. As the injection was only possible at the concrete contact points of the spacer, the current 6 mm diameter sprue was not realistic. Therefore, while preventing the pressure build-up, a tapered sprue design from 6 mm to 2.5 mm was designed for the resin mould. Secondly, a 2-degree draft angle was given to all surfaces of the mould to prevent any friction during injection. To be able to use less resin and at the same time have support for the mould surface, a hexagonal grid texture was implemented to provide localized reinforcement.

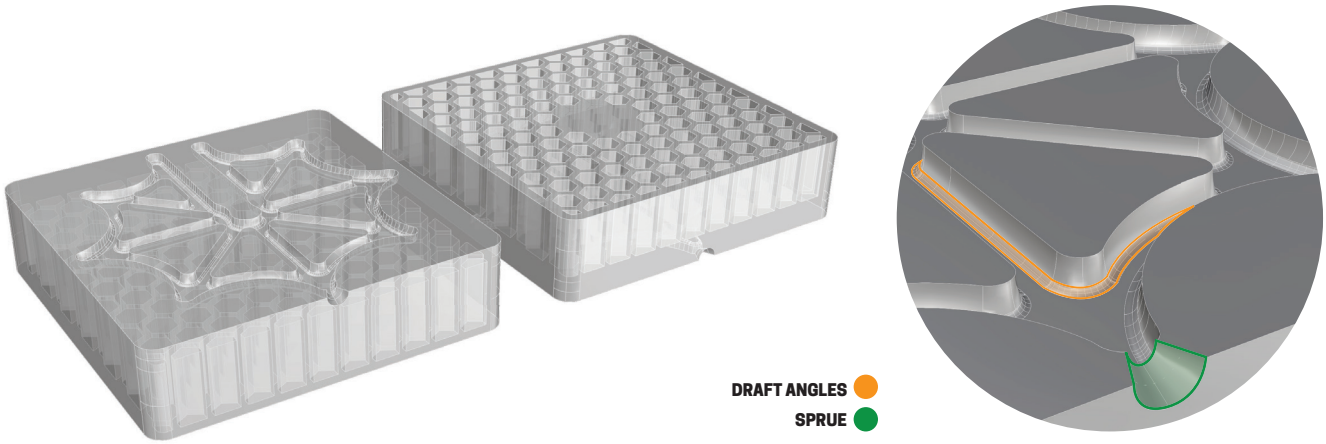


Figure 78: The model of final resin mould with necessary adjustments for better injection molding (Source: Author)

In an industry-scale injection molding application, and as suggested by SolidWorks Plastics, the moulds were required to be preheated at 80°C to ensure optimal flow and reduced injection pressure. However, this suggestion is mainly done for CNC-milled aluminium moulds, which was not the case for the custom-made mould that was used at room temperature. Therefore, the predefined injection cycle allowed moulds to cool down between each injection to be able to maintain dimensional accuracy as much as possible. The mould withstood 30 injection cycles, **maintaining structural integrity with minimal defects**. There was progressive warping on the facing mould surfaces, which led to extreme flashing formations at the samples. The major defects that affected the samples were the crack that developed at one of the radial ribs, and also the surface deformation that impacted the surface quality of the injected samples.

Figure 79: The injection molding process with the resin mould (1) tightening the mould (2) placing the mould to the table plate (3) fixing the mould into the 6mm diameter nozzle (4) injecting (5) removing the mould (6) removing the bolts (7) removing the sample (Source: Author)

While the resin-printed mould cannot fully replicate the industry conditions achieved by using aluminium moulds, Sustainable Design Studio's 3D-printed insert holder aluminium mould at the Maker Lab provided a buffer effect between the resin mould and nozzle. The buffer effect significantly extended the lifespan of the mould by protecting the mould from heat concentration and thermal shock. Overall, the use of resin mould showcased a potential for hybrid moulding strategies, which is cost-effective, especially for research.

Figure 80: The deformation of the mould after 30 injection molding trials (1) surface deformation (2) cracking (3) flashing in-between two moulds (4) warping of the mould (Source: Author)

3.3.6 Design Evaluation and Final Selection

As discussed in chapter 3.3.2, the manual and auto scores were input into the design optimisation tool based on their respective parameters and sub-parameters. Firstly, the transition from Python to Excel was made for obtaining the auto-scores. This enables a mimicked multi-criteria decision analysis (MCDA) that combines both manual and auto score inputs. The assigned weights and the defined four range classes (0, 4, 7, 10) follow the weighted sum model (WSM) algorithm combined with a tiered scoring system. Therefore, a complex evaluation of each spacer was achieved to be able to focus on a specific, unique design for the proof of application.

The weights given for each parameter were based on their importance for the functionality of the wheel spacer and the applicability with a manual plunger-type injection molding setup. The limited technology of the available facilities necessitated a higher weight percentile given to the Injection Flow Analysis and Contact Area as 25%, a middle weight percentile to Flexibility for Rebars and Plastic Use per Product as 15%, and finally lower weight percentile for Compressive Strength and Charpy Impact Analysis as 10% for the final evaluation dashboard that will give the final scores.

Design	Parameter	Plastic Use (g)	Auto Score
Spacer 01	Plastic Use per Product	20.88	10
Spacer 02	Plastic Use per Product	20.96	7
Spacer 03	Plastic Use per Product	31.31	0
Spacer 04	Plastic Use per Product	27.5	4
Spacer 05	Plastic Use per Product	28.55	0
Spacer 06	Plastic Use per Product	15.31	10
Spacer 07	Plastic Use per Product	21.6	4
Spacer 08	Plastic Use per Product	21.22	7
Spacer 09	Plastic Use per Product	13.41	10

Table 28: Auto scores for the spacers based on their plastic use (g) (Source: Author)

Design	Parameter	Sub-Parameter	Min/Max Value	Manual Tier Score	Auto Score	Final Score
Spacer 01	Charpy Impact Analysis	Stress (MPa)	6.146	4	10	8.50
Spacer 02	Charpy Impact Analysis	Stress (MPa)	10.049	4	7	6.25
Spacer 03	Charpy Impact Analysis	Stress (MPa)	25.29	10	0	2.50
Spacer 04	Charpy Impact Analysis	Stress (MPa)	22.838	10	0	2.50
Spacer 05	Charpy Impact Analysis	Stress (MPa)	4.2	4	10	8.50
Spacer 06	Charpy Impact Analysis	Stress (MPa)	6.441	4	10	8.50
Spacer 07	Charpy Impact Analysis	Stress (MPa)	9.4	4	7	6.25
Spacer 08	Charpy Impact Analysis	Stress (MPa)	12.97	7	4	4.75
Spacer 09	Charpy Impact Analysis	Stress (MPa)	11.356	10	4	5.50
Spacer 01	Charpy Impact Analysis	Displacement (mm)	0.146	10	10	10.00
Spacer 02	Charpy Impact Analysis	Displacement (mm)	0.346	4	4	4.00
Spacer 03	Charpy Impact Analysis	Displacement (mm)	0.361	0	4	3.00
Spacer 04	Charpy Impact Analysis	Displacement (mm)	0.393	0	0	0.00
Spacer 05	Charpy Impact Analysis	Displacement (mm)	0.235	7	10	9.25
Spacer 06	Charpy Impact Analysis	Displacement (mm)	0.126	7	10	9.25
Spacer 07	Charpy Impact Analysis	Displacement (mm)	0.343	7	7	7.00
Spacer 08	Charpy Impact Analysis	Displacement (mm)	0.402	7	0	1.75
Spacer 09	Charpy Impact Analysis	Displacement (mm)	0.271	4	7	6.25
Spacer 01	Charpy Impact Analysis	Equivalent Strain	0.004	4	10	8.50
Spacer 02	Charpy Impact Analysis	Equivalent Strain	0.007	4	7	6.25
Spacer 03	Charpy Impact Analysis	Equivalent Strain	0.017	10	0	2.50
Spacer 04	Charpy Impact Analysis	Equivalent Strain	0.013	10	0	2.50
Spacer 05	Charpy Impact Analysis	Equivalent Strain	0.004	7	10	9.25
Spacer 06	Charpy Impact Analysis	Equivalent Strain	0.005	7	10	9.25
Spacer 07	Charpy Impact Analysis	Equivalent Strain	0.007	4	7	6.25
Spacer 08	Charpy Impact Analysis	Equivalent Strain	0.008	4	4	4.00
Spacer 09	Charpy Impact Analysis	Equivalent Strain	0.008	10	4	5.50

Table 29: The manual-tier scores, auto scores and the final scores for the sub-parameters of Charpy Impact Analysis (Source: Author)

Design	Parameter	Sub-Parameter	Min/Max Value	Manual Tier Score	Auto Score	Final Score
Spacer 01	Injection Flow Analysis	Fill Time	5.2786	7	4	4.75
Spacer 02	Injection Flow Analysis	Fill Time	3.4292	7	7	7.00
Spacer 03	Injection Flow Analysis	Fill Time	0.7704	0	10	7.50
Spacer 04	Injection Flow Analysis	Fill Time	3.9858	7	7	7.00
Spacer 05	Injection Flow Analysis	Fill Time	1.8899	0	10	7.50
Spacer 06	Injection Flow Analysis	Fill Time	5.9485	4	4	4.00
Spacer 07	Injection Flow Analysis	Fill Time	6.0483	7	0	1.75
Spacer 08	Injection Flow Analysis	Fill Time	6.6475	4	0	1.00
Spacer 09	Injection Flow Analysis	Fill Time	2.537	7	10	9.25
Spacer 01	Injection Flow Analysis	Pressure	2.19	4	10	8.50
Spacer 02	Injection Flow Analysis	Pressure	6.32	7	4	4.75
Spacer 03	Injection Flow Analysis	Pressure	2.63	0	7	5.25
Spacer 04	Injection Flow Analysis	Pressure	7.23	4	0	1.00
Spacer 05	Injection Flow Analysis	Pressure	4.42	0	4	3.00
Spacer 06	Injection Flow Analysis	Pressure	2.84	10	7	7.75
Spacer 07	Injection Flow Analysis	Pressure	2.35	7	10	9.25
Spacer 08	Injection Flow Analysis	Pressure	2.19	4	10	8.50
Spacer 09	Injection Flow Analysis	Pressure	10.04	4	0	1.00
Spacer 01	Injection Flow Analysis	Temperature	230.02	4	10	8.50
Spacer 02	Injection Flow Analysis	Temperature	230.08	4	7	6.25
Spacer 03	Injection Flow Analysis	Temperature	230.14	0	4	3.00
Spacer 04	Injection Flow Analysis	Temperature	230.1	7	4	4.75
Spacer 05	Injection Flow Analysis	Temperature	230.93	0	0	0.00
Spacer 06	Injection Flow Analysis	Temperature	230.01	7	10	9.25
Spacer 07	Injection Flow Analysis	Temperature	230.02	4	10	8.50
Spacer 08	Injection Flow Analysis	Temperature	230	7	10	9.25
Spacer 09	Injection Flow Analysis	Temperature	230.86	7	0	1.75
Spacer 01	Injection Flow Analysis	Shear Stress	0.04	4	10	8.50
Spacer 02	Injection Flow Analysis	Shear Stress	0.08	4	7	6.25
Spacer 03	Injection Flow Analysis	Shear Stress	0.08	0	7	5.25
Spacer 04	Injection Flow Analysis	Shear Stress	0.08	4	7	6.25
Spacer 05	Injection Flow Analysis	Shear Stress	0.1	0	4	3.00
Spacer 06	Injection Flow Analysis	Shear Stress	0.1	10	4	5.50
Spacer 07	Injection Flow Analysis	Shear Stress	0.06	4	10	8.50
Spacer 08	Injection Flow Analysis	Shear Stress	0.07	4	10	8.50
Spacer 09	Injection Flow Analysis	Shear Stress	0.13	10	0	2.50
Spacer 01	Injection Flow Analysis	Weld Lines & Air Traps	137.65	4	7	6.25
Spacer 02	Injection Flow Analysis	Weld Lines & Air Traps	149.18	4	0	1.00
Spacer 03	Injection Flow Analysis	Weld Lines & Air Traps		0		0.00
Spacer 04	Injection Flow Analysis	Weld Lines & Air Traps	149.17	4	0	1.00
Spacer 05	Injection Flow Analysis	Weld Lines & Air Traps		0		0.00
Spacer 06	Injection Flow Analysis	Weld Lines & Air Traps	129.86	0	10	7.50
Spacer 07	Injection Flow Analysis	Weld Lines & Air Traps	144.48	10	7	7.75
Spacer 08	Injection Flow Analysis	Weld Lines & Air Traps	95.04	4	10	8.50
Spacer 09	Injection Flow Analysis	Weld Lines & Air Traps	146.9	4	4	4.00
Spacer 01	Injection Flow Analysis	Velocity Vector	29.1789	0	10	7.50
Spacer 02	Injection Flow Analysis	Velocity Vector	57.2777	4	10	8.50
Spacer 03	Injection Flow Analysis	Velocity Vector	60.8905	0	10	7.50
Spacer 04	Injection Flow Analysis	Velocity Vector	51.3741	4	10	8.50
Spacer 05	Injection Flow Analysis	Velocity Vector	189.2124	0	0	0.00
Spacer 06	Injection Flow Analysis	Velocity Vector	87.6201	7	10	9.25
Spacer 07	Injection Flow Analysis	Velocity Vector	26.5677	4	10	8.50
Spacer 08	Injection Flow Analysis	Velocity Vector	29.56	7	10	9.25
Spacer 09	Injection Flow Analysis	Velocity Vector	207.7365	10	0	2.50

Table 30: The manual-tier scores, auto scores and the final scores for the sub-parameters of Injection Flow Analysis (Source: Author)

Designs	Injection Flow Analysis	Compressive Stregth Analysis	Charpy Impact Analysis	Contact Area	Flexibility for Rebars	Plastic Use per Product	Final Score
Spacer 01	7.33	2.00	9.00	0	0	10	4.43
Spacer 02	5.63	1.92	5.50	0	4	7	3.80
Spacer 03	4.75	3.75	2.67	0	4	0	2.43
Spacer 04	4.75	4.50	1.67	4	4	4	4.00
Spacer 05	2.25	8.25	9.00	10	7	0	5.84
Spacer 06	7.21	8.50	9.00	10	4	10	8.15
Spacer 07	7.38	8.75	6.50	4	7	7	6.47
Spacer 08	7.50	7.00	3.50	7	10	7	7.23
Spacer 09	3.50	8.00	5.75	10	7	10	7.30

Table 31: Final Evaluation Dashboard for 6-main parameters and the final score for the Spacers (Source: Author)

The final scores obtained from the design optimisation tool finalised the selection of the best-performing wheel spacer with a score of 8.15/10. As shown at the parameter-sub parameter tables, Spacer 6 performed high based on the range tier both in manual and autoscoring. Based on the weight values assigned, the spacer performed the best for the contact area parameter and one of the best for the injection flow analysis. Therefore, the multi-criteria decision-making process was concluded, and the Spacer 6 was refined for the final application phase.

Figure 81: The best-performing design (Spacer 6) (Source: Author)

Figure 82: Modified design for application (Spacer 10) (Source: Author)

The final modification on the Spacer 6 included making the radial ribs slimmer to increase the whole for aggregate penetration. Secondly, the concrete contact points were made more bulky to satisfy the processing conditions of a manual plunger-type injection molding machine. The clip arms were refined to enable a better performing retention mechanism of the spacer. The PET-G model was again made to test the manual parameters once again before printing the high-temp resin mold.

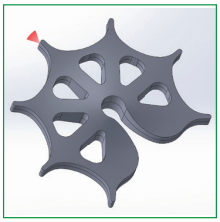
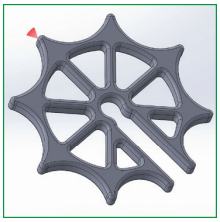
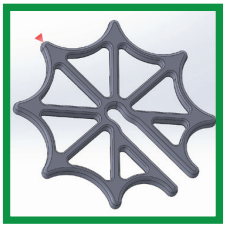
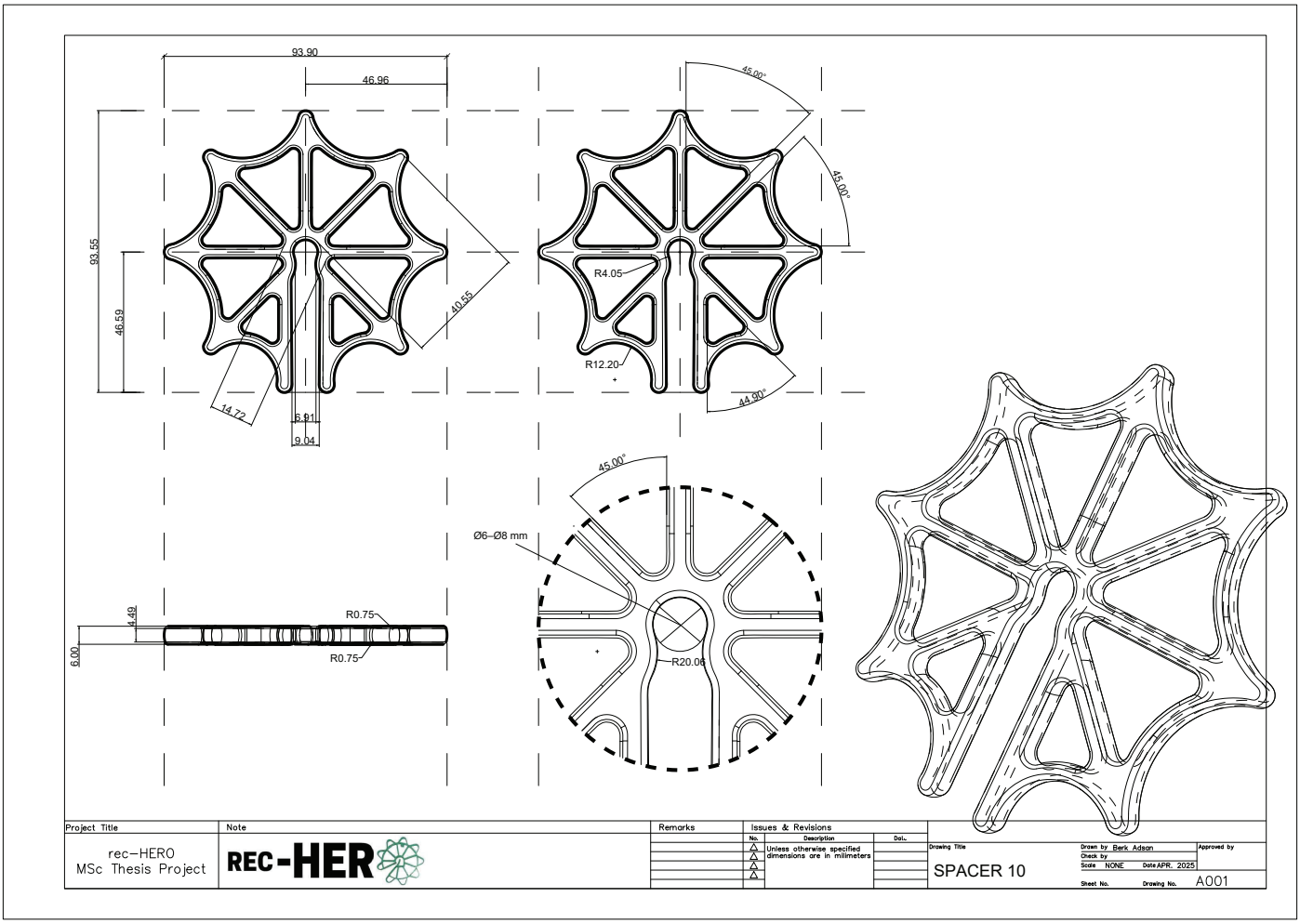
MODIFICATION	PROPERTIES	FILL TIME	PRESSURE	TEMPERATURE	SHEAR STRESS	WELD LINES & AIR	VELOCITY VECTOR
	**SPACER 6** Height(mm): 82 Cover(mm): 35 Bar Dia. (mm): 10 Volume(cm3):15.31	**min:** 4.068e-04 sec **max:** 5.9485 sec	**min:** 0.10 MPa **max:** 2.84 MPa	**min:** 83.50°C **max:** 230.01°C	**min:** 3.382e-07 MPa **max:** 0.10 MPa	**min:** 0.9100° **max:** 129.8600°	**min:** 2.871e-04 m/s **max:** 87.6201 m/s
	**SPACER 6.1** Height(mm): 92 Cover(mm): 40 Bar Dia. (mm): 6-8-10 Volume(cm3):19.89	**min:** 0.0016sec **max:** 5.5859 sec	**min:** 0.10 MPa **max:** 2.64 MPa	**min:** 91.92°C **max:** 230.02°C	**min:** 0.06 MPa **max:** 3.459e-05 MPa	**min:** 2.1500° **max:** 148.4100°	**min:** 0.0016 m/s **max:** 5.5859 m/s
	**SPACER 10** Height(mm): 92 Cover(mm): 40 Bar Dia. (mm): 6-8 Volume(cm3):12.63	**min:** 3.308e-04 sec **max:** 3.8485 sec	**min:** 0.10 MPa **max:** 4.78 MPa	**min:** 98.81 °C **max:** 230.14°C	**min:** 6.986e-05 MPa **max:** 0.09 MPa	**min:** 5.3800° **max:** 149.9400°	**min:** 0.0032 m/s **max:** 88.5547 m/s

Table 32: The injection flow analysis result comparison between first - modified Spacer 6 design (Source: Author)

The PET-G model and injection flow analysis concluded that the modified spacer 6 was functioning better than before. Some component designs of other spacers are also implemented to the new design like the rebar retention mechanism of Spacer 7 which was proven to be successful. By keeping the main design elements, Spacer 6 became more suitable for the final processing with manual plunger-type injection molding while the maximum pressure and fill time is relatively low compared to the older design.



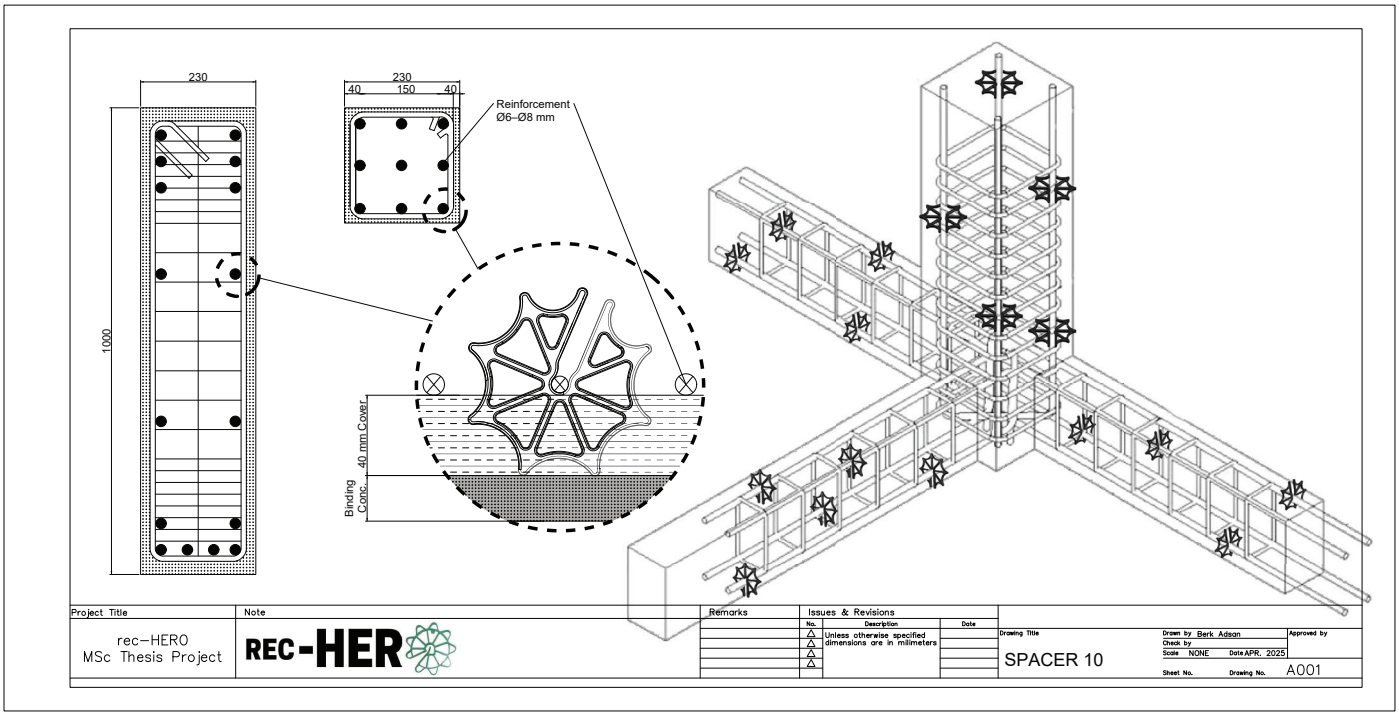


Figure 83: Technical datasheet of Spacer 10 (Source: Author)

PHASE 3: APPLICATION

4.1 Proof of Concept

The final phase of the thesis is meant to showcase the result and applicability of the dual-track methodology with material experimentation and product development tracks. The dual-track feedback between the tracks throughout the thesis enabled a comprehensive understanding of the applicability of a problematic plastic source in an architectural application that is not exposed but crucial for the reinforced concrete construction. Final polymer selection, injection cycle, spacer design, and application were collected as a conclusion from both tracks to be used for the final phase: application.

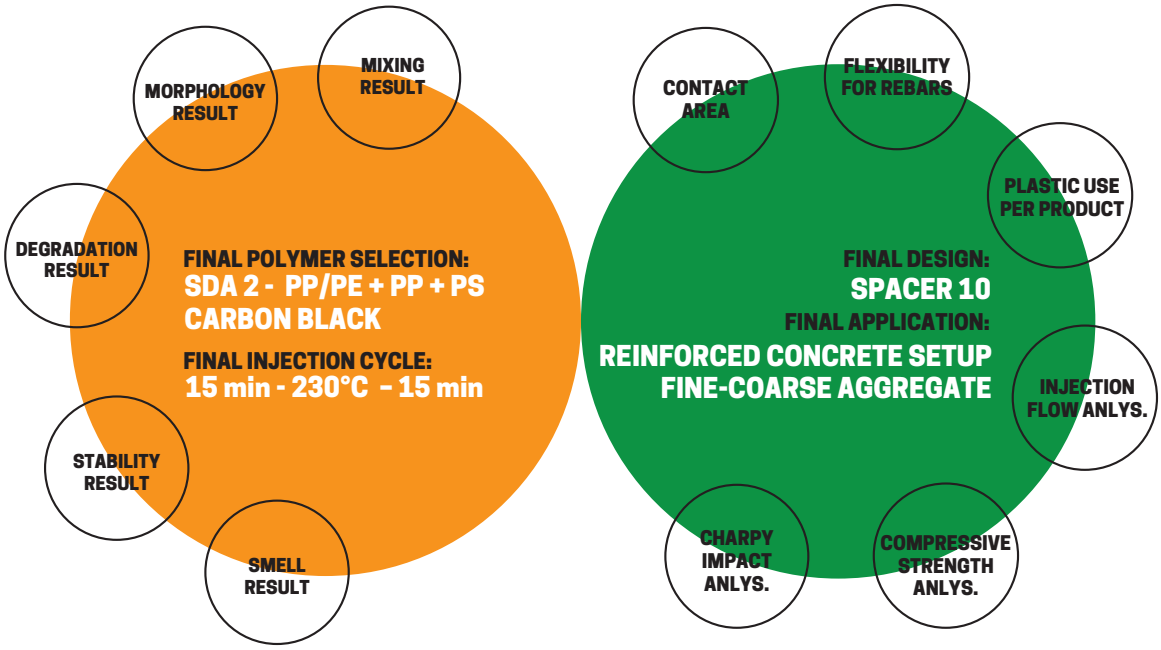


Figure 84: The dual-track diagram showing the results of both tracks of Phase 2 (Source: Author)

The initial feedback from the material experimentation track proving both visible and characteristic contamination in all waste bags improved the decision-making process for the application scenario and building component. As the mechanical recycling steps were repeated in a lab-scale, the potential of using the impure and mixed plastic source increased. The density trials that could be achieved in lab-scale with salt and sugar was already limited compared to advanced sorting techniques like magnetic density sorting, therefore for all mimicked mechanical recycling steps, the trials were conducted starting from the most low-tech to advanced. The design development of the spacers based on the generic wheel spacer types were getting constant feedback from material experimentation track for the early simulations of injection flow analysis and mechanical strength simulations. This enabled understanding of injection behaviour and possible adaptations to the designs that would enable continuous processing in injection molding machine. Shaping up to the final design was influenced from the parameters of both tracks which enabled the proof of concept.

Given the level of advancement of the injection molding technologies and setups that were available during the thesis, the goal of the proof of concept was to provide an alternative iteration to the existing commercial wheel spacer products that can be produced with the “waste of the waste polymers” and low-tech injection molding technologies.

The point out the possibility of the carbon black polymers not being able to get detected during near-infrared sorting stages of mechanical recycling, black plastics from SDA 2 waste bags were sorted for the final application. As it was already proven that there was a high majority of black plastics in the reject fractions, the most time-consuming process was the FT-IR identification of the plastic shreds one by one before processing.

Then, the shredder at the Stevin II Lab at Civil Engineering at TU Delft was used to shred the plastic pieces into 3 mm shreds for the processing stage. The manual plunger-type injection molding machine, the Arbour Press Injection Machine at Makerlab of TU Delft Science Centre was used as the main experiment setup for the proof of concept. Although the setup lacks the precision of the lab-scale pneumatic plunger-type injection molding machine, the system provides enough pressure and temperature for validation. The 100 x 100 x 50 mm cavity 3D-printed insert holder aluminium mould from Sustainable Design Studio is available only at the manual plunger-type experiment setup, therefore, this makes the processing stage closer to the industry. Based on the volume of the Spacer 10, and the densities of the polymer types, the mass of the each required specimen is calculated. The required plastic weight needed for each polymer type is: (1) PP/PE blend: 12.9 grams, (2) PP: 11.7 grams and (3) PS: 13.7 grams. To account for any process-related material losses like some shred plastic getting stuck at the heating barrel, slightly larger batches of 15 and 20 grams were prepared for injection.

Figure 85: (1) Shredded 3 mm polymer batches for the PP, PS, PP/PE blend (2) 15-20 g injection-ready batches (Source: Author)

The final result of the proof of concept, serving as the proof of dual track methodology, concluded the real-life applicability of combining **final polymer selection**, **final injection cycle**, and the **final design**.

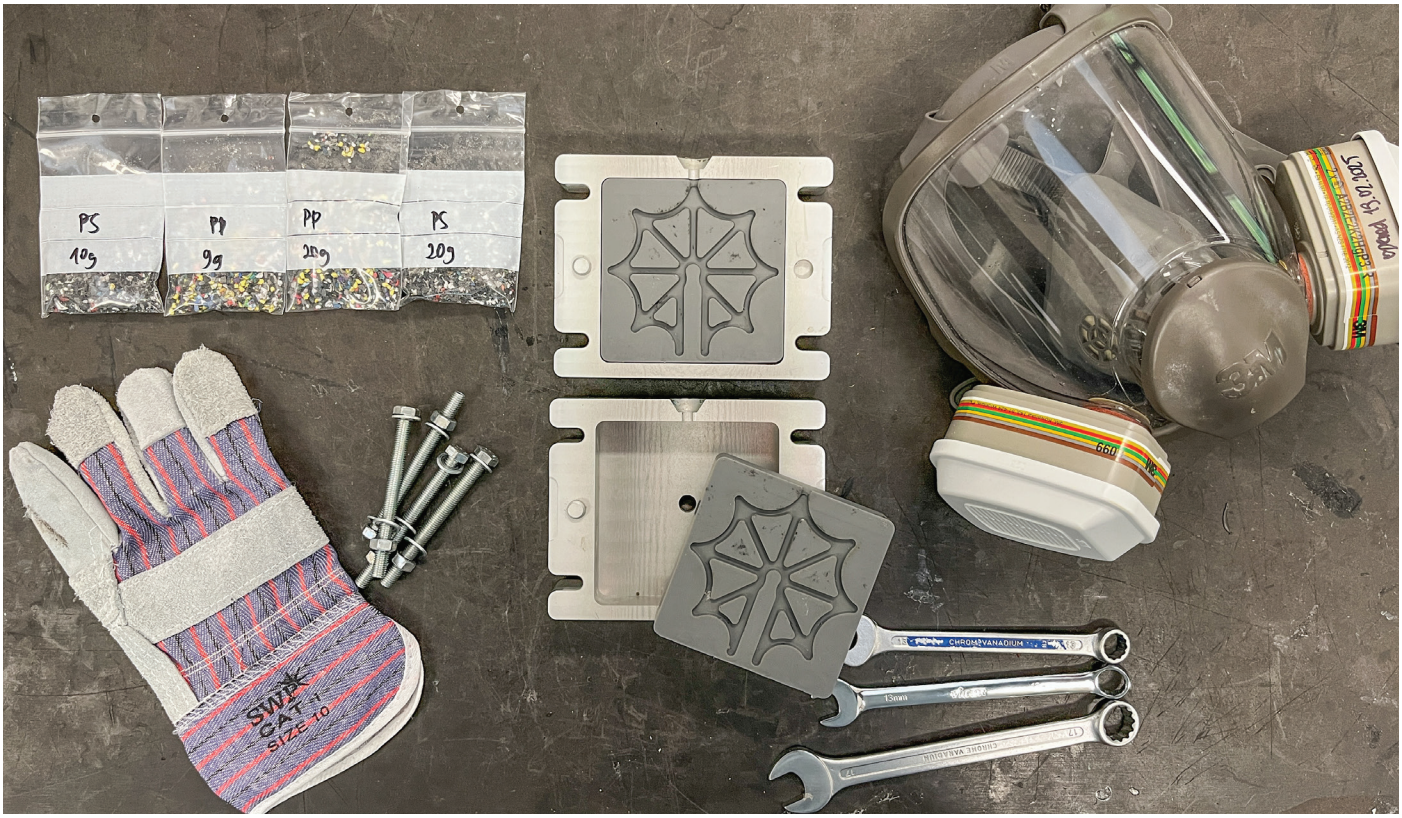


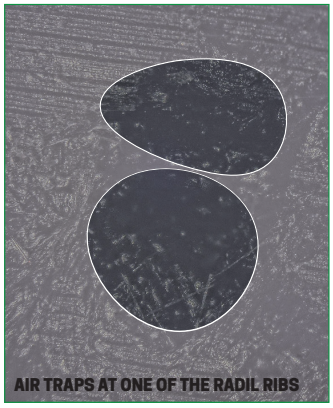
Figure 86: Injection molding setup (Source: Author)

The first trials 1-11 served to tailor **(1)** the manual pressure needed, **(2)** validate the weight input, **(3)** validate the injection cycle, **(4)** prove the **processability of 100% WEEE recycling residues for injection molding**.

TRIAL 1: rec-PP CARBON BLACK INPUT

WEIGHT (g)	20 + 10
MOULD TYPE	Aluminium Cavity + ABS-like Resin Moulds
INJECTION CYLE (min)	30
DWELL DURATION (min)	15
HEATER (°C)	230
MIXING RESULT	Miscible blend
MORPHOLOGY RESULT	Rough texture and semi-molten phases
DEGRADATION RESULT	Possible thermal degradationa at flashing
STABILITY RESULT	Stable geometry
SMELL RESULT	Persistent strong chemical smell

TRIAL 2: rec-PP/PE BLEND CARBON BLACK INPUT

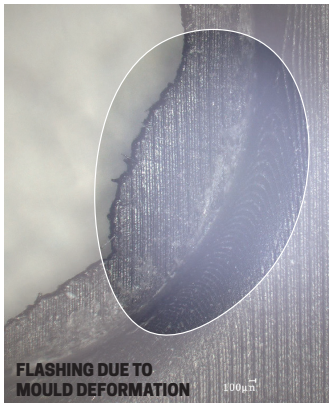


WEIGHT (g)	20
MOULD TYPE	Aluminium Cavity + ABS-like Resin Moulds
INJECTION CYCLE (min)	20
DWELL DURATION (min)	15
HEATER (°C)	240
MIXING RESULT	Miscible blend
MORPHOLOGY RESULT	Very rough texture, fibrous surface
DEGRADATION RESULT	Possible thermal deradation bc. of temperature
STABILITY RESULT	Brittle geometry
SMELL RESULT	Persistent strong chemical smell

TRIAL 3: rec-PP/PE BLEND CARBON BLACK INPUT

WEIGHT (g)	20
MOULD TYPE	Aluminium Cavity + ABS-like Resin Moulds
INJECTION CYCLE (min)	20
DWELL DURATION (min)	15
HEATER (°C)	240
MIXING RESULT	Miscible blend
MORPHOLOGY RESULT	Surface irregularities becase of deformed mould
DEGRADATION RESULT	Some warping
STABILITY RESULT	Flashing causing stronger geometry
SMELL RESULT	Persistent strong chemical smell

TRIAL 4: rec-PP/PE BLEND CARBON BLACK INPUT



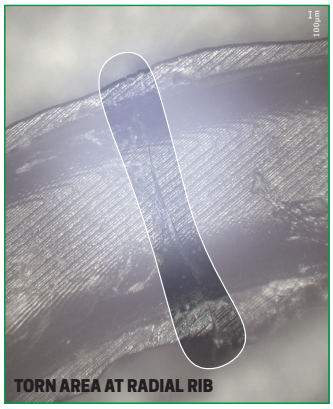
WEIGHT (g)	15
MOULD TYPE	Aluminium Cavity + ABS-like Resin Moulds
INJECTION CYCLE (min)	20
DWELL DURATION (min)	15
HEATER (°C)	240
MIXING RESULT	Better miscibility
MORPHOLOGY RESULT	Resin mould creeping, fibers at flashing
DEGRADATION RESULT	Some warping
STABILITY RESULT	Semi-brittleness
SMELL RESULT	Persistent strong chemical smell

Table 33: Trials 1-4 of injection molding of Spacer 10 with microscopic inspection and parameter evaluation (Source: Author)

TRIAL 5: rec-PS CARBON BLACK INPUT

WEIGHT (g)	14
MOULD TYPE	Aluminium Cavity + ABS-like Resin Moulds
INJECTION CYLE (min)	20
DWELL DURATION (min)	15
HEATER (°C)	240
MIXING RESULT	Miscible blend
MORPHOLOGY RESULT	Clear surface irregularities
DEGRADATION RESULT	Possible thermal degradation at injection end
STABILITY RESULT	Stable geometry
SMELL RESULT	Persistent strong chemical smell

TRIAL 6: rec-PS CARBON BLACK INPUT

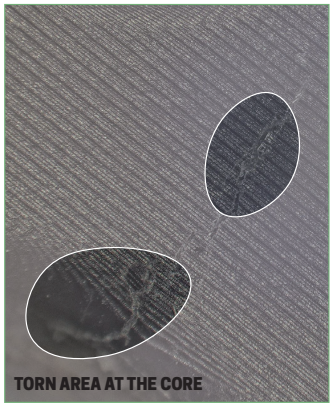


WEIGHT (g)	15
MOULD TYPE	Aluminium Cavity + ABS-like Resin Moulds
INJECTION CYCLE (min)	20
DWELL DURATION (min)	15
HEATER (°C)	240
MIXING RESULT	Miscible blend
MORPHOLOGY RESULT	Very rough texture, fibrous surface
DEGRADATION RESULT	Possible thermal deradation bc. of temperature
STABILITY RESULT	Brittle geometry
SMELL RESULT	Persistent strong chemical smell

TRIAL 7: rec-PP/PE BLEND CARBON BLACK INPUT

WEIGHT (g)	20
MOULD TYPE	Aluminium Cavity + ABS-like Resin Moulds
INJECTION CYCLE (min)	20
DWELL DURATION (min)	15
HEATER (°C)	240
MIXING RESULT	Miscible blend
MORPHOLOGY RESULT	Surface irregularities becase of deformed mould
DEGRADATION RESULT	Flashing at the ribs
STABILITY RESULT	Brittle behaviour after rebar test
SMELL RESULT	Persistent strong chemical smell

TRIAL 8: rec-PP/PE BLEND CARBON BLACK INPUT



WEIGHT (g)	30
MOULD TYPE	Aluminium Cavity + ABS-like Resin Moulds
INJECTION CYCLE (min)	20
DWELL DURATION (min)	15
HEATER (°C)	240
MIXING RESULT	Better miscibility
MORPHOLOGY RESULT	Better surface results, Rough texture
DEGRADATION RESULT	No thermal degradation
STABILITY RESULT	Brittle behaviour after rebar test
SMELL RESULT	Persistent strong chemical smell

Table 34: Trials 5-8 of injection molding of Spacer 10 with microscopic inspection and parameter evaluation (Source: Author)

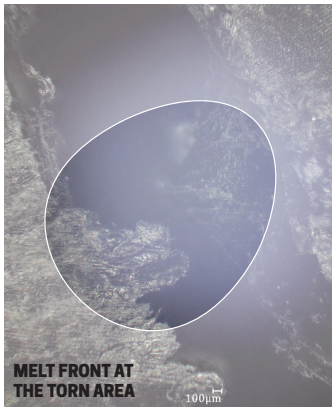
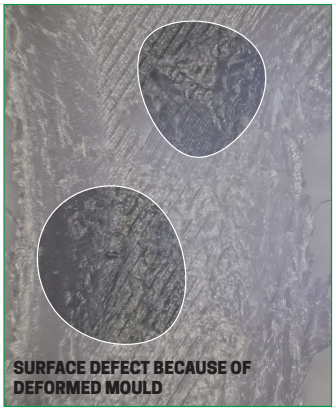
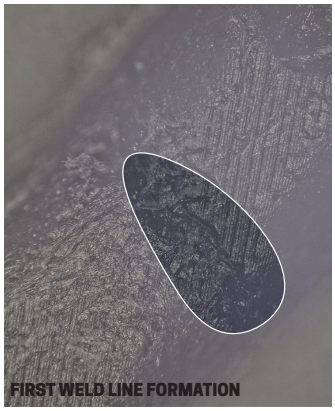
TRIAL 9: rec-PP/PE BLEND CARBON BLACK INPUT			
		WEIGHT (g)	20
		MOULD TYPE	Aluminium Cavity + ABS-like Resin Moulds
		INJECTION CYLE (min)	20
		DWELL DURATION (min)	15
		HEATER (°C)	240
		MIXING RESULT	Miscible blend
		MORPHOLOGY RESULT	Increased surface irregularities
		DEGRADATION RESULT	No thermal degradation at melt front
		STABILITY RESULT	Brittle behaviour
		SMELL RESULT	Persistent strong chemical smell
TRIAL 10: rec-PP/PE BLEND CARBON BLACK INPUT			
		WEIGHT (g)	20
		MOULD TYPE	Aluminium Cavity + ABS-like Resin Moulds
		INJECTION CYCLE (min)	20
		DWELL DURATION (min)	15
		HEATER (°C)	240
		MIXING RESULT	Miscible blend
		MORPHOLOGY RESULT	Increased surface irregularities
		DEGRADATION RESULT	No thermal degradation
		STABILITY RESULT	Semi-brittle geometry
		SMELL RESULT	Persistent strong chemical smell
TRIAL 11: rec-PP/PE CARBON BLACK INPUT			
		WEIGHT (g)	20
		MOULD TYPE	Aluminium Cavity + ABS-like Resin Moulds
		INJECTION CYCLE (min)	20
		DWELL DURATION (min)	15
		HEATER (°C)	240
		MIXING RESULT	Miscible blend
		MORPHOLOGY RESULT	Increased surface irregularities
		DEGRADATION RESULT	No thermal degradation
		STABILITY RESULT	Semi-brittle geometry
		SMELL RESULT	Persistent strong chemical smell

Table 35: Trials 9-11 of injection molding of Spacer 10 with microscopic inspection and parameter evaluation (Source: Author)

The first modification was made to the heater temperature, which necessitated the use of **240 °C** for better melt flow. The prepared 15-gram polymer batches for processing were adjusted according to the success rate of the previous injection. If the pressure was not enough, the plastics inside the barrel were still used for the next injection. The main limitation of the manual plunger-type machine was the **uncertainty of the necessary pressure** to inject without causing flashing. Therefore, the results vary from trial to trial, which at the end concluded that a **20-gram polymer input** is optimal for one injection cycle to fill the mould. The rebar retention mechanism check with 8mm rebar mostly concluded with the identification of critical areas at multiple samples which concluded the brittle nature of the samples at specific locations. The torn areas or the weld lines occurred at the two specific locations at the radial ribs (see Trials 6 and 11) which were generally caused by the **surface deformation of the resin mould**, that made the skin layer of the melt front already deformed right after processing.

The **injection flow analysis done during the product development track was verified** with the first trials as the weld line formations and critical areas occurred at the exact locations SolidWorks predicted.

Overall, 100% WEEE input samples provided processable, miscible blends that formed a **critical benchmark** for the thesis. Out of five evaluation parameters (mixing, morphology, degradation, stability, smell), only negative results were achieved for the stability (see Table 35) Because of the brittle behaviour of the samples, a second experiment setup with polymer blending by mixing 70 wt% WEEE PP/PE shreds and 30 wt% packaging PP shreds was conducted to compare the results.

The decision-making on the weight ratios of the blend was based on the existing research done by Tai et al., Mourad, and Han et al. As the performance requirement of the reinforcement spacer is low, the aim was to **increase the impact strength and brittleness** of the samples slightly to be able to resist the expected forces. The blending trials were mainly based on mixing virgin and recycled polymers. However, as the secondary plastic shreds sourced from packaging waste already present cleaner and less visually contaminated characteristics, the **polymer blending was done again with 100% secondary plastics input**, **mixing WEEE and packaging waste**. The same shred size of 3mm semi-transparent PP and carbon black PP/PE blend was processed. The trials 12-16 showcased the blending possibilities of the thesis's polymer selection.

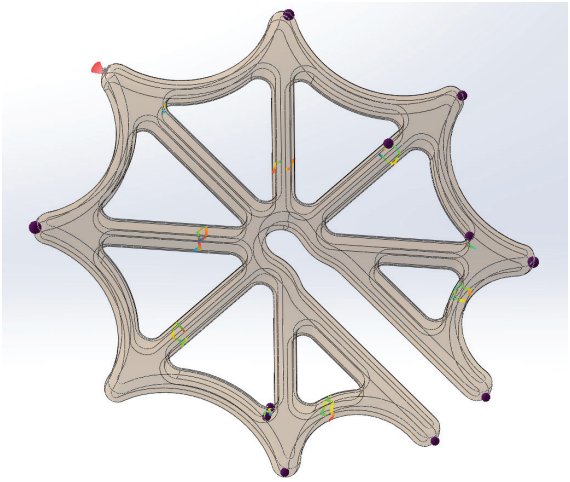
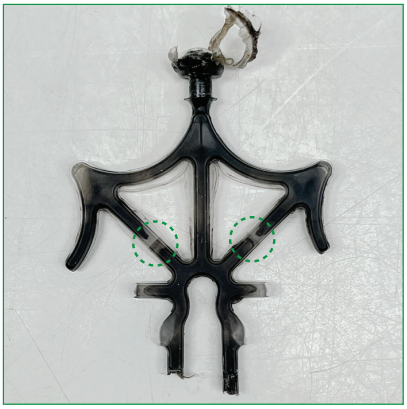


Figure 87: Weld line formation and air traps of Spacer 10 (Source: SolidWorks)

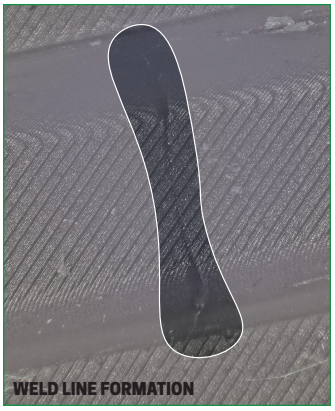
Figure 88: (1) 3 mm PP shreds -semi transparent- (2) 5-15 mm PP shreds -mixed colour- both from packaging waste from Precious Plastic (Source: Author)

TRIAL 12: %70 rec-PP/PE BLEND + %30 rec-PP (PRECIOUS PLASTIC)

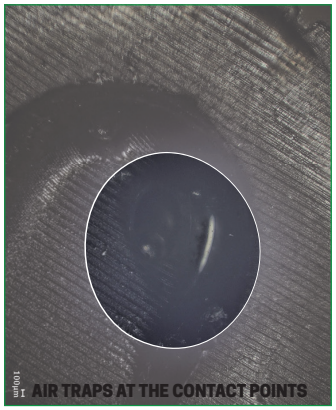


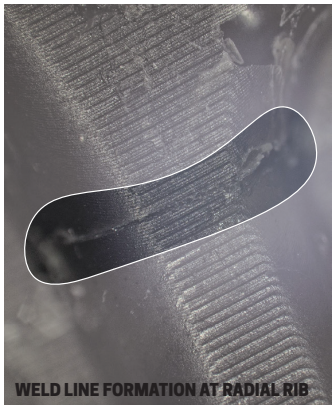
WEIGHT (g)	10.5 + 4.5
MOULD TYPE	Aluminium Cavity + ABS-like Resin Moulds
INJECTION CYLE (min)	20
DWELL DURATION (min)	15
HEATER (°C)	220
MIXING RESULT	Miscible blend
MORPHOLOGY RESULT	Identifiable phase domains
DEGRADATION RESULT	Thermal degradation bc. of long injection cycle
STABILITY RESULT	Stable geometry
SMELL RESULT	Less strong chemical smell

TRIAL 13: %70 rec-PP/PE BLEND + %30 rec-PP (PRECIOUS PLASTIC)



WEIGHT (g)	10.5 + 4.5
MOULD TYPE	Aluminium Cavity + ABS-like Resin Moulds
INJECTION CYLE (min)	15
DWELL DURATION (min)	10
HEATER (°C)	220
MIXING RESULT	Miscible blend
MORPHOLOGY RESULT	Identifiable phase domains - Better surface
DEGRADATION RESULT	No thermal degradation
STABILITY RESULT	Stable geometry
SMELL RESULT	Less strong chemical smell

TRIAL 14: %70 rec-PP/PE BLEND + %30 rec-PP (PRECIOUS PLASTIC)			
		WEIGHT (g)	17.5 + 7.5
		MOULD TYPE	Aluminium Cavity + ABS-like Resin Moulds
		INJECTION CYLE (min)	15
		DWELL DURATION (min)	10
		HEATER (°C)	220
		MIXING RESULT	Miscible blend
		MORPHOLOGY RESULT	Air traps at the contact points, Flashing
		DEGRADATION RESULT	No thermal degradation
		STABILITY RESULT	Stable geometry
		SMELL RESULT	Less strong chemical smell

TRIAL 15: %70 rec-PP/PE BLEND + %30 rec-PP (PRECIOUS PLASTIC)			
		WEIGHT (g)	17.5 + 7.5
		MOULD TYPE	Aluminium Cavity + ABS-like Resin Moulds
		INJECTION CYLE (min)	15
		DWELL DURATION (min)	10
		HEATER (°C)	220
		MIXING RESULT	Miscible blend
		MORPHOLOGY RESULT	Extreme flashing, Resin mould deformation
		DEGRADATION RESULT	No thermal degradation
		STABILITY RESULT	Stable geometry
		SMELL RESULT	Less strong chemical smell

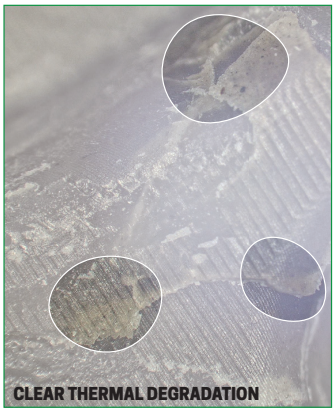
TRIAL 16: %70 rec-PP/PE BLEND + %30 rec-PP (PRECIOUS PLASTIC)			
		WEIGHT (g)	10.5 + 4.5
		MOULD TYPE	Aluminium Cavity + ABS-like Resin Moulds
		INJECTION CYLE (min)	20
		DWELL DURATION (min)	15
		HEATER (°C)	220
		MIXING RESULT	Miscible blend
		MORPHOLOGY RESULT	Inconsistent colour dispersion
		DEGRADATION RESULT	Yellowing, Discolouration
		STABILITY RESULT	Stable geometry
		SMELL RESULT	Less strong chemical smell

Table 36: Trials 12-16 of injection molding of Spacer 10 with microscopic inspection and parameter evaluation (Source: Author)

The injected samples already presented better stability and mixing results. Even though the phase domains were visible, the melt flow of PP and PP/PE was miscible. There was a significant **reduction in odour** after processing. The main improvement of the blended samples was the stability necessary for the rebar retention mechanism. The samples proved successful results after multiple trials of rebar snapping. The deformation of the mould also reflected on the samples' behaviour at the concrete contact points, where there were multiple air traps suggested by SolidWorks (see Fig. 87) and warping formations . Additionally, the weld line formation at the radial ribs and the cover ring was more visible under microscopic inspection. The polymer blending with different waste stream polymers was concluded to be the optimal route to have better performing samples under the lab-scale conditions of the thesis. The injection cycle of 15 minutes was adequate for the polymer blend with a heater at 220°C .

To showcase also the processability of different coloured polymers to assess whether colour sorting has any tangible effect on injection moulding behaviour was conducted for the trials 17-19 with 100% WEEE origin PP and PS shreds.

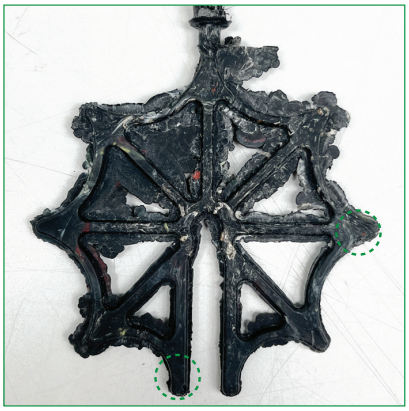
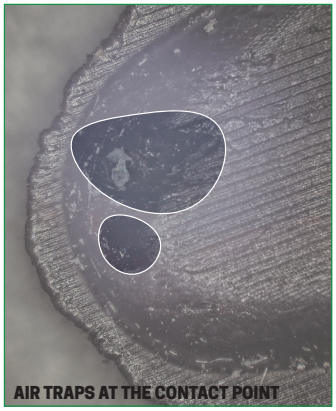
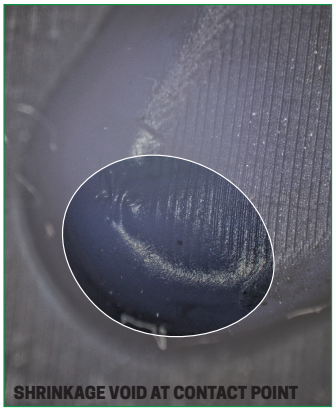
TRIAL 17: rec-PS MIXED COLOUR INPUT		
	WELDINE FORMATION AT RADIAL RIB	**WEIGHT (g)** 20 **MOULD TYPE** Aluminium Cavity + ABS-like Resin Moulds **INJECTION CYLE (min)** 20 **DWELL DURATION (min)** 15 **HEATER (°C)** 240 **MIXING RESULT** Miscible blend **MORPHOLOGY RESULT** Clear phase separation, Rougher texture **DEGRADATION RESULT** No degradation **STABILITY RESULT** Semi-brittle geometry **SMELL RESULT** Persistent strong chemical smell
TRIAL 18: rec-PP MIXED COLOUR INPUT		
	AIR TRAPS AT THE CONTACT POINTS	**WEIGHT (g)** 20 **MOULD TYPE** Aluminium Cavity + ABS-like Resin Moulds **INJECTION CYLE (min)** 20 **DWELL DURATION (min)** 15 **HEATER (°C)** 240 **MIXING RESULT** Miscible blend **MORPHOLOGY RESULT** Clear melt flow, Rougher texture **DEGRADATION RESULT** No degradation **STABILITY RESULT** Semi-brittle geometry **SMELL RESULT** Persistent strong chemical smell
TRIAL 19: %52 rec-PS MIXED COLOUR INPUT + %48 rec-PP MIXED COLOUR INPUT		
	 AIR TRAPS AT THE CONTACT POINT	**WEIGHT (g)** 10+9 **MOULD TYPE** Aluminium Cavity + ABS-like Resin Moulds **INJECTION CYLE (min)** 20 **DWELL DURATION (min)** 15 **HEATER (°C)** 240 **MIXING RESULT** Miscible blend **MORPHOLOGY RESULT** Clear melt flow **DEGRADATION RESULT** No degradation **STABILITY RESULT** Semi-brittle geometry **SMELL RESULT** Persistent strong chemical smell

Table 37: Trials 17-19 of injection molding of Spacer 10 with microscopic inspection and parameter evaluation (Source: Author)

Compared to the trials 1-11, these samples showcased similar physical and injection behaviour. The only difference between old and new trials with 100% WEE origin samples was the formation of air traps and warping effect at the contact points. This proved the **deformation of the resin mould** that causes uneven shrinkage during the cooling process, as the resin mould cannot be preheated before injection.

Trials 20-23 were done to assess **(1)** the possibility of PP/PP blending with WEEE and packaging waste, and **(2)** the influence of larger shred size during processing. The 70 wt% WEEE-sourced 3mm PP polymers were blended with 30 wt% packaging waste PP polymers with varying shred sizes from 5-15 mm. The carbon black polymers were blended with blue-dominated mixed colour shreds.

TRIAL 20: %70 rec-PP + %30 rec-PP (PRECIOUS PLASTIC)

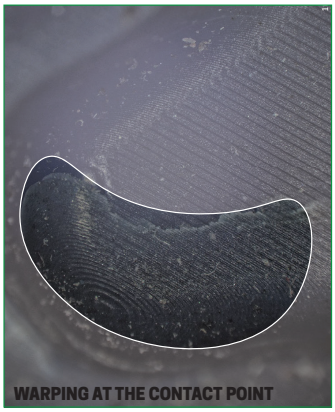


WEIGHT (g)	14+6
MOULD TYPE	Aluminium Cavity + ABS-like Resin Moulds
INJECTION CYLE (min)	18
DWELL DURATION (min)	15
HEATER (°C)	220
MIXING RESULT	Miscible blend, Better plastic flow
MORPHOLOGY RESULT	Smoother surface
DEGRADATION RESULT	No thermal degradation
STABILITY RESULT	Stable geometry
SMELL RESULT	Less strong chemical smell

TRIAL 21: % 70 rec-PP + %30 rec-PP (PRECIOUS PLASTIC)

WEIGHT (g)	14+6
MOULD TYPE	Aluminium Cavity + ABS-like Resin Moulds
INJECTION CYLE (min)	18
DWELL DURATION (min)	15
HEATER (°C)	220
MIXING RESULT	Miscible blend, Better plastic flow
MORPHOLOGY RESULT	Smoother surface, Extreme flashing
DEGRADATION RESULT	No thermal degradation
STABILITY RESULT	Stable geometry
SMELL RESULT	Less strong chemical smell

TRIAL 22: %70 rec-PP + %30 rec-PP (PRECIOUS PLASTIC)



WEIGHT (g)	14+6
MOULD TYPE	Aluminium Cavity + ABS-like Resin Moulds
INJECTION CYLE (min)	18
DWELL DURATION (min)	15
HEATER (°C)	220
MIXING RESULT	Miscible blend, Better plastic flow
MORPHOLOGY RESULT	Smoother surface, Extreme flashing
DEGRADATION RESULT	Warping due to mould deformation
STABILITY RESULT	Stable geometry
SMELL RESULT	Less strong chemical smell

TRIAL 23: %70 rec-PP + %30 rec-PP (PRECIOUS PLASTIC)

WEIGHT (g)	14+6
MOULD TYPE	Aluminium Cavity + ABS-like Resin Moulds
INJECTION CYLE (min)	18
DWELL DURATION (min)	15
HEATER (°C)	220
MIXING RESULT	Miscible blend
MORPHOLOGY RESULT	Possible shrinkage void
DEGRADATION RESULT	Warping due to mould deformation
STABILITY RESULT	Stable geometry
SMELL RESULT	Less strong chemical smell

Table 38: Trials 20-23 of injection molding of Spacer 10 with microscopic inspection and parameter evaluation (Source: Author)

The evaluation parameter results performed similarly to the trials 12-16 with better melt flow and degradation results. The same injection cycle for trials 12-16 was repeated with slight adjustments on the duration of the injection cycle by reducing it to 18 minutes. The samples for the first polymer blending trials started to show signs of thermal degradation approaching to the last samples (see Trial 16), therefore, faster injection proved to be possible with the new trials. The warping and weld line formations were similar to previous polymer blend trials. However, there was a formation of the torn area even without the rebar snapping test at Trial 23, which was probably due to extreme flashing in addition to mould deformation. Nevertheless, the larger shred size is also found to be optimal for thesis's injection cycle and dwell duration.

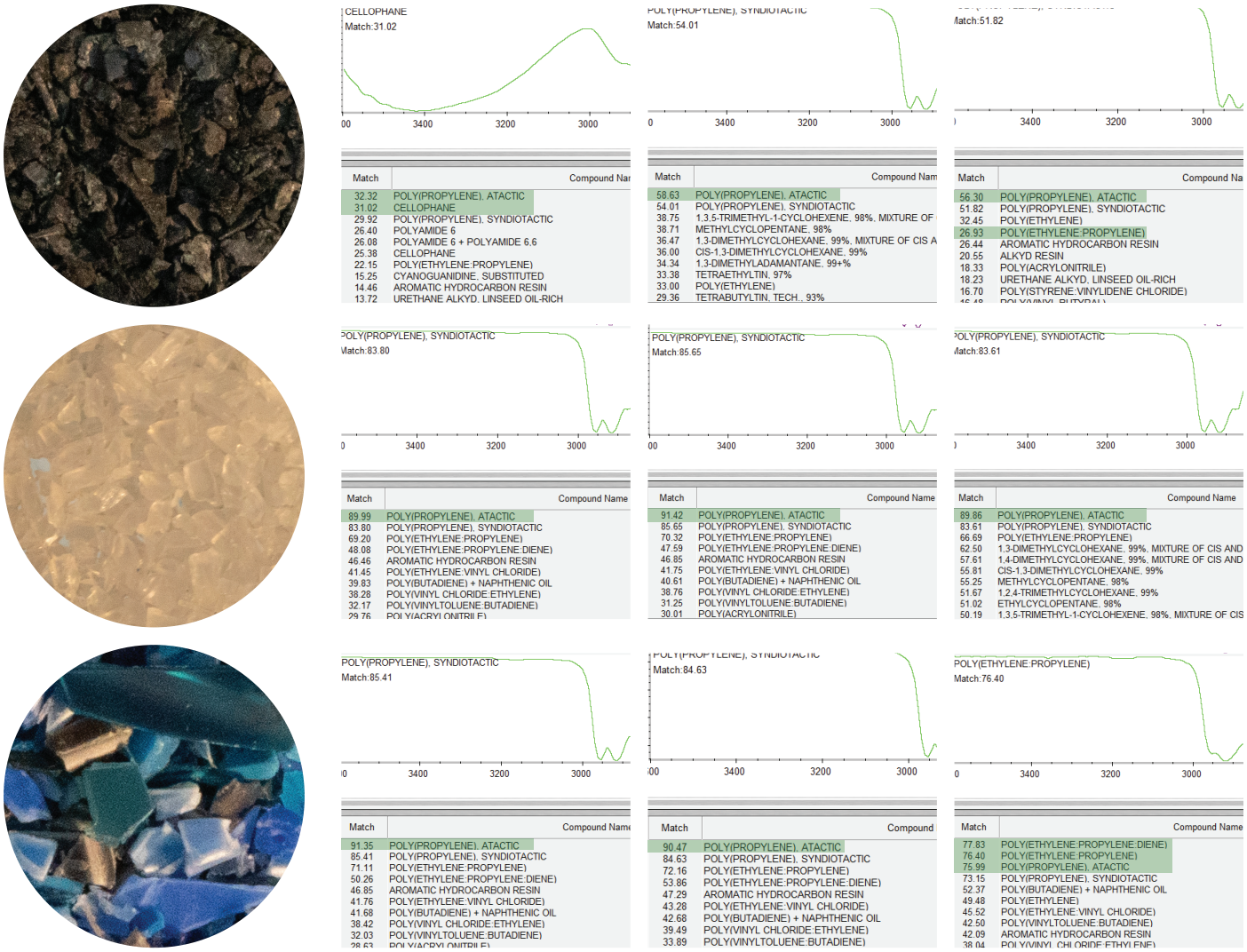


Table 39: FT-IR Analysis done on the (1) WEEE PP shreds (2) rec-PP packaging 3 mm shreds (3) rec-PP packaging 5-15 mm shreds (Source: Nicolet iS50 FT-IR Spectrometer & Author)

The assess the cleanness and purity of the rec-PP shreds from the packaging waste compared to WEEE plastic shreds, and additional FT-IR analysis was conducted. The conclusions for the cleanness were made based on the **(1)** maximum numeric match percentages and the **(2)** secondary high percentage polymers found in the selected samples. It is verified that both packaging waste polymer shreds have very high percentage results compared to WEEE ones without any contamination like cellophane. The FT-IR results of the WEEE polymers show distinctively lower match percentages compared to packaging waste. An interesting result was gathered on the blue plastic shreds where some results also included PP/PE blend as the highest match. This was already expected as the blue shreds are mixed compared to semi-transparent shreds.

Overall, the blended plastic shreds from packaging waste were proven to be purer and cleaner compared to the WEEE shreds. Therefore, it can be deduced that blending cleaner recycled polymers with the contaminated ones would also create applicable results rather than blending it with virgin polymers.

In conclusion, five different polymer recipes were validated for the proof of concept: **(1)** 100 wt% WEEE-sourced PP/PE blend, **(2)** 100 wt% WEEE-sourced PP, **(3)** 100 wt% WEEE-sourced PS, **(4)** 70 wt% WEEE-sourced PP/PE blend and 30 wt% packaging waste PP and **(5)** 70 wt% WEEE-sourced PP and 30 wt% packaging waste PP.

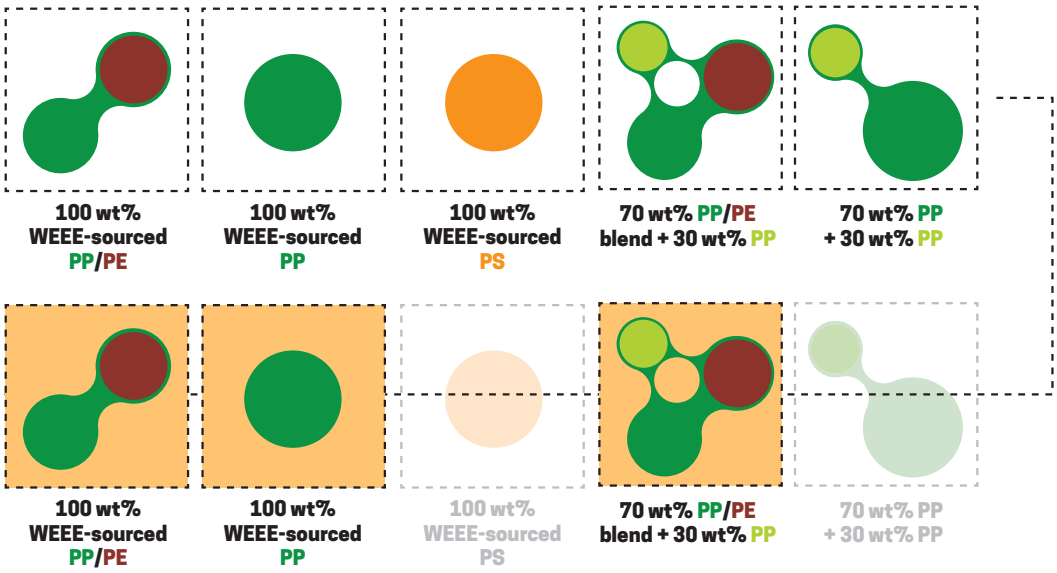
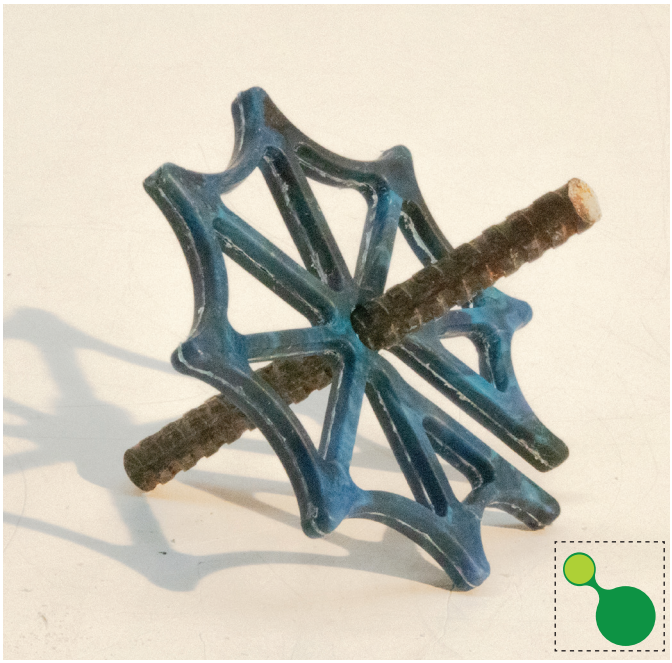
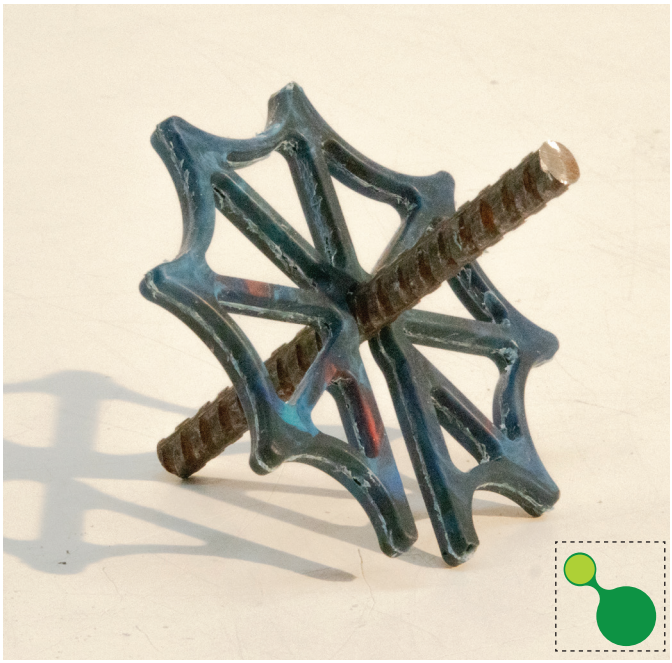


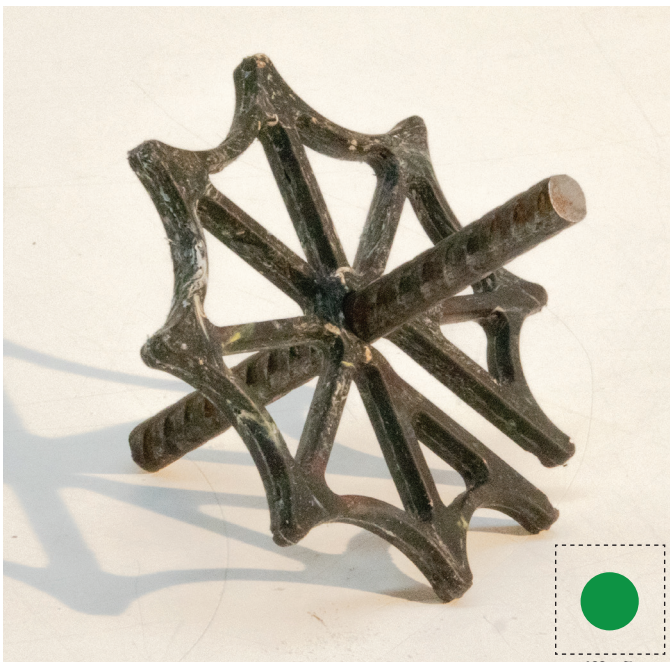
Figure 89: (First row) Validated polymer recipes (Second row) Selected polymer recipes for the proof of application (Source: Author)

As flashing was a recurring use encountered in the majority of the samples during the proof of concept trials, an additional post-processing step was introduced to manually remove the excess material. By using precision blades, the flashing was carefully removed to ensure the geometry was still preserved. While this manual intervention introduces a potential risk of micro-cracks at the surface or localised stress concentrations, the samples retained sufficient mechanical integrity. Successful processed samples from the recipes 1,2 and 4 were selected to be used in the proof of application.

Figure 90: The setup for the removal of flashing for the succesful injection molded samples (Source: Author)







Recipes 4 and 5 were crafted as an **adaptive strategy to accommodate the limitations of lab-scale mechanical recycling and lab-scale injection molding setup**, where industrial injection molding conditions cannot be fully replicated. As the 100% WEEE-sourced polymer selections were validated with successful processing, the thesis' conclusions are centered upon **recovering 100% WEEE-sourced plastic recycling residues**.

The final proof of concept validation is evaluated based on the **(1)** the performance of the resin-printed moulds for industry-scale applications, **(2)** the validation of injection moldable polymer recipe sourced by WEEE recycling residues **(3)** the injection cycle for processing.

Figure 91: The material flow starting from SDA-2 waste input to the proof-of concept (Source: Author)

Two resin-printed mould alternatives were tried during the thesis, including SUNLU ABS-like resin and the high-temperature Phrozen TR300. Overall, they offered a **low-cost, affordable alternative to aluminium moulds**, especially for research. While **warping, flashing, and cracking** were inevitable over time, the ABS-like resin mould endured over **30 injection cycles** when supported with an aluminium insert holder mould. The aluminium support mitigated the excessive heat and ensured better clamp pressure. As injection molding was selected as the processing technique for the thesis during the design optimisation phase, resin-printed mould offered processability verification of multiple spacer designs throughout the thesis.

The thesis tackled a **challenging waste stream** compared to other secondary plastic streams. Secondly, the focus on **carbon black polymers**, which are invisible to most sorting technologies, was another challenge the thesis tackled to prove processability. The polymer types with the highest quantity at the floating fraction of density sorting – **PP/PE, PP, PS**- were processed at the **same injection cycle** applicable for all these polymers. A workable material behaviour and successful parameter results were observed for the defined application scenario of reinforcement spacers. Using **100 wt% WEEE recycling residue plastics** to process them into a **low-grade construction component** is a viable scenario.

The defined injection cycle for the manual plunger-type injection molding machine at the Maker Lab was adjusted slightly after resin-printed moulds, rather than wood moulds, were being used. Final injection cycle applicable for all PP/PE, PP and PS polymers, concluded as a **20-minute injection cycle with a 15-minute dwell duration and 240°C heater temperature**. The adaptation of the increased temperature of the heater, opposed to the predefined temperature of the material experimentation track, was necessary to accommodate the sustained better melt flow at thin sections and manual pressure. The duration of the injection cycle can be easily lowered if a pneumatic plunger-type injection molding machine is used.

4.2 Proof of Application

The proof of application serves as an additional verification step to assess the designed wheel spacer's (Spacer 10) performance under real-life construction conditions. The objective is the physically test the **spacer's behaviour during and after concrete casting**, which simulates a reinforced concrete scenario at 1:1 product scale. This also verifies the mechanical strength simulations of Charpy impact and compressive tests as well as the applicability of the parameter scoring. The realistic construction scenarios by mimicking lateral pressure of wet concrete and on-site impact conditions within C20/25 strength class aligned with Eurocode standards. The following performance indicators are assessed during proof of application: **(1)** the rebar retention mechanism while snapping the rebar in place, **(2)** the visible surface exposure of the contact areas of the spacer at the concrete finish, and **(3)** the penetration of most common aggregate types in-between hollow areas of the spacer compared to the generic one.

Experiment setup: The proof of application was carried out at MicroLab in Stevin II, Civil Engineering Department at TU Delft, using available concrete mixing facilities. Three 15 x 15 x 15 cm moulds were used with three different concrete recipes to test three different polymer-origin spacers in comparison with a commercial generic wheel spacer. The three Spacer 10 variants tested are made from PP, PP/PE, and 70 wt% PP/PE and 30 wt.% PP.

The generic wheel spacer of Gerrijn with the same cover made from virgin PE polymer was used. In consultation with Maiko van Leeuwen and Abraham Gebremariam from Civil Engineering, three distinct concrete recipes for 20-litre were designed: **(A) fine aggregates, (B) regular coarse aggregates (4-16 mm), (C) recycled coarse aggregates (4-5 mm)**. The **inclusion of both conventional and recycled aggregates** enables a possible application scenario also for circular construction practices. The choice of 20-litre volume for the concrete mix was to ensure a consistent mixing ratio and sufficient concrete flow.

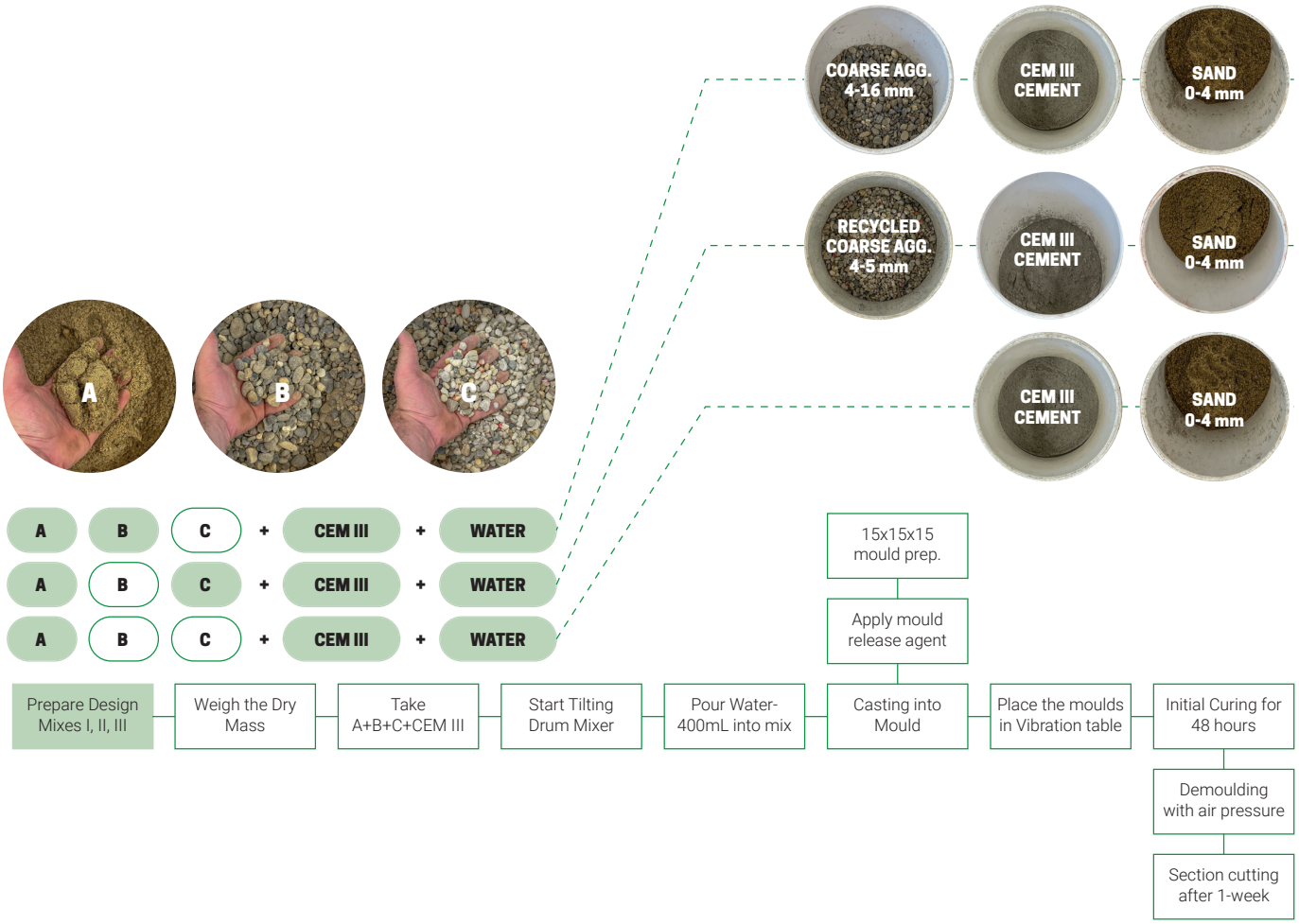
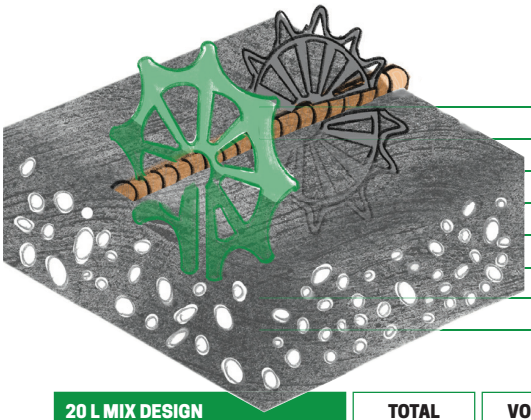


Figure 92: The experiment setup for the proof of application (Source: Author)



RECIPE INFORMATION (REF. 1000L MIX)

Based on the consultation with Maiko van Leeuwen at MicroLab

Norm	NEN-EN 206/NEN 8005	**Water content**	173.4 kg
Strength Class	C20/25	**Absorbed water**	27.7 L
Water-binder factor	0.550	**Total gravel mass**	1041.7 kg
Water-cement factor	0.550	**Total sand mass**	793.7 kg
Required strength	31.6 MPa	**Total air content**	15 L
Calculated strength	41.2 MPa	**Chloride content**	0.075% M/M
Binder content	315 kg	**Alkali content**	2.46 kg
Cement content	315 kg	**CO2 equivalents**	0.095 ton

20 L MIX DESIGN FOR REGULAR AGGREGATES	TOTAL VOLUME %	VOLUME (L)	DRY MASS (kg)	MASS TO BE DOSED (kg)	VOLUME TO BE DOSED (L)	VOLUME FINE (L)	MOISTURE FRACTION %	ABSORPTION FRACTION %
CEM III CEMENT	**10.69**	0.2138	**6.30**	6.30	2.14	2.138	0.0	00
SAND (0-4 mm)	**30.18**	0.6036	**14.98**	15.96	6.04	0.482	0.6	0.6
COARSE AGGREGATES (4-16 mm)	**39.91**	0.7982	**20.84**	21.30	7.98	-	2.2	2.2
WATER AND SLUDGE	**17.72**	0.3544	-	3.66	-	0.076	-	-
AIR	1.5	0.0300	-	-	-	-	-	-

Recycled aggregates received from Abraham Gebremariam at Civil Engineering

20 L MIX DESIGN FOR RECYCLED AGGREGATES	TOTAL VOLUME %	VOLUME (L)	DRY MASS (kg)	MASS TO BE DOSED (kg)	VOLUME TO BE DOSED (L)	VOLUME FINE (L)	MOISTURE FRACTION %	ABSORPTION FRACTION %
CEM III CEMENT	**10.69**	0.2138	**6.30**	6.30	2.14	2.138	0.0	00
SAND (0-4 mm)	**30.18**	0.6036	**14.98**	15.96	6.04	0.482	0.6	0.6
COARSE AGGREGATES (4-5 mm)	**39.91**	0.7982	**20.84**	21.30	7.98	-	2.2	2.2
WATER AND SLUDGE	**17.72**	0.3544	-	3.66	-	0.076	-	-
AIR	1.5	0.0300	-	-	-	-	-	-

20 L MIX DESIGN FOR FINE AGGREGATES	TOTAL VOLUME %	DRY MASS (kg)	MASS TO BE DOSED (kg)	MOISTURE FRACTION %	ABSORPTION FRACTION %
CEM III CEMENT	**22.22**	**4.5**	4.5	0.0	0.0
SAND (0-4 mm)	**66.66**	**13.5**	13.5	0.6	0.6
WATER AND SLUDGE	**11.11**	**2.25**	-	-	-

Table 40: Reference Recipe Information and 20 L Mix Design recipes with numeric data for the experiments (Source Author)

Material Preparation: The dry mix components were sourced from the Simatic HMI recipe control panel (see Table 41) based on three pre-defined design mixes. Mixing was performed in a tilting drum mixer, allowing for a uniform blending until the desired workability and viscosity were achieved, which was checked by Ton Blom at MicroLab. After casting into the moulds, the used facilities were cleaned before preparing the next batch.

RECIPE SIMATIC HMI PANEL

Based on the receipt panel at Micro Lab

SILO 1. Portland Cement CEM I 52.5R		**SILO 8.** Sand 0.125-0.250 mm		**SILO 15.** Broken Sand 0-4 mm	
SILO 2. Slug		**SILO 9.** Grind 4-8 mm		**SILO 16.** Iron-bearing Slag	
SILO 3. Slug		**SILO 10.** Sand 0.250-0.500 mm		**SILO 17.** Non-ferrous Slag	
SILO 4. Blast F.Cement CEM III/B 42.5N	6.3 + 6.3	**SILO 11.** Sand 2-4 mm		**SILO 18.** Recycled Aggregate 4-5 mm	20.8
SILO 5. Blast F.Cement CEM III/A 52.5N		**SILO 12.** Sand 1-2 mm		**SILO 19.** Gravel 4-16 mm	
SILO 6. Fly Ash		**SILO 13.** Sand 0.5-1 mm	15.8 +15.8 + 13.5	**SILO 20.** Recycled Sand 0-4 mm	
SILO 7. Grind 8-16 mm		**SILO 14.** Broken Gravel 4-16 mm	20.8	**SILO 21.** Dust	

Table 41: The quantity of dry mass selection on the Recipe simatic HMI Panel (Source: Author)

Figure 93: Material preparation steps (1) Collecting dry mass (2) Mixing dry materials (3) Adding water (4) Cleaning after use (Source: Author)

Mould Preparation: Accurate rebar placement was essential for assessing the performance indicators of the proof of application. Each 8 mm rebar was tightened with a steel rod and secured at both ends with modelling clay. This ensured the rebar to not float while casting, and also the achieve necessary concrete cover for both spacers. The spacers were attached before applying the mould release agent. The cured mockups were removed from the mould with air pressure and were cut using a waterjet cutting facility at Micro Lab.

Figure 94: Mould preparation steps (1) Fixing the rebar and snapping the spacers (2) Pouring the design mix(3) Vibration table (4) Leaving the mould to cure (Source: Author)

The removal of the mockups enabled the assessment of **(2)** the visible surface exposure of the contact areas of the spacer at the concrete finish, and **(3)** the penetration of most common aggregate types in-between hollow areas of the spacer compared to the generic one.

Figure 95: (1) The mockups left for curing (2) The setup to remove the mockups from mould (3) The mockups after removal from the moulds (Source: Author)

Figure 96: The contact point exposure inspection of Spacer 10 (Source: Author)

The parameter (2) was assessed through visual inspection of the generic wheel spacer and Spacer 10 at the concrete finish. Spacer 10 outperformed the generic type with minimal exposure that was observed at the fine aggregate mix design. In contrast, the coarse aggregate mockups revealed clear exposure of the generic type while Spacer 10 remained nearly fully embedded (see Fig.96). According to Alzyoud et al., the air gaps occurring between the spacer and the concrete matrix lead to chloride ion penetration, localized corrosion or deterioration at the exposed interface. The experiment confirms that Spacer 10 is suitable for use in common concrete mix designs. In addition, the results validate the manual grading system integrated into the design optimization tool.

Figure 97: The penetration results on the cut-mockups of (1) fine (2) recycled coarse (3) regular coarse aggregates (Source: Author)

Testing the penetration of common aggregate types in-between the spacer geometry (3) was a critical step in evaluating whether the modified version of Spacer 6 allows proper matrix flow between the radial ribs during casting. Spacer 10 accommodated coarse aggregates up to 16 mm. As shown in Fig. 97, the cut mockups across all three mix designs showed successful matrix penetration comparable to the generic spacer. This concludes the Spacer 10 to achieve **effective cover depth and structural compatibility**.

4.3 Proof of Sustainability

The sustainability performance of the proposed wheel reinforcement spacer is evaluated based on a crafted Environmental Product Declaration **(EPD)-based methodology**. EPD is a third-party verified document over the environmental impact of a product based on Life Cycle Assessment. To ensure **reliable and comparable data**, all quantitative data were directly derived from EPD for reinforcement spacers by Spritz-Plast GmbH, which was developed in accordance with EN 15804 and ISO 14025 (Spritz-Plast GmbH, 2024). The selected EPD focuses on the plastic spacers that were manufactured by a **100% secondary plastic blend of PP/PE blends from packaging waste** thus the numeric data closely aligns with the polymer selection of the thesis. However, as **(1)** the recycled feedstock of the thesis is the SDA recycling residues of the WEEE waste line, and **(2)** only lab-scale mechanical recycling and processing technologies are being used, there was a need for a crafted sustainability path in which only the **credible system values** were taken into account to estimate a potential environmental impact.

Environmental Product Declaration

EPD®
THE INTERNATIONAL EPD® SYSTEM

ECO PLATFORM EPD VERIFIED

EPD INTERNATIONAL EPD SYSTEM

In accordance with ISO 14025:2006 and EN 15804:2012+A2:2019/AC:2021 for:

Plastic spacer

(EPD of multiple products, based on the average results of the product group)

from

Spritz-Plast GmbH

Spritz·Plast KUNSTSTOFFVERARBEITUNG

Programme:	The International EPD® System, www.environdec.com
Programme operator:	EPD International AB
EPD registration number:	EPD-IES-0015611
Publication date:	2024-11-29
Valid until:	2029-11-29

An EPD should provide current information and may be updated if conditions change. The stated validity is therefore subject to the continued registration and publication at www.environdec.com

Figure 98: Spritz-Plast's EPD Data (Source: Spritz-Plast)

Therefore, two system diagrams for Coolrec's current scheme and thesis' proposed scheme were made based on Spritz Plast's existing LCA calculations to evaluate sustainability better. The environmental impact of the proposed product was assessed, focusing on the **A1-A3 (Product stage) and D (Resource Recovery Stage) stages** of the system diagram.

The cradle-to-gate approach of Spritz-Plast considers the manufacturing of PP,PE, and PP/PE blend secondary plastics. The product composition covers the quantity of all reinforcement spacers produced at the production site within the geographical scope of Europe. For the LCA calculations the German residual waste data was used. For the module A2, the calculation was done for the transportation with EURO 6 truck, and the manufacturing, A3 was done for the processing technique of injection molding. Therefore, the EPD data was considered reliable to develop conclusions.

The selected system boundaries from A1-A3, align with the cradle-to-gate scope of the research while **avoiding speculative assumptions**. The numeric data obtained from the lab-scale experiments and results are combined with the EPD values to define a functional unit, **Spacer 10** to evaluate the environmental impact not for 1 kg of product but specifically for the designed wheel spacer.

Functional Unit Definition: The final manufactured products of the thesis were established with the use of **100% secondary PP, PP/PE blend and PS**. Therefore, the mass of product for each polymer selection was made to assess the impact values for the volume of 12.63 cm^3 based on the material densities. As Spritz Plast's EPD data on environmental impact is done for 100% recycled PP/PE blend reinforcement spacers, based on three product alternatives of the thesis **PP/PE blend was focused** to reflect a realistic result of the proposed recycling loop. From the existing impact results, GWP-fossil (Global Warming Potential from fossil fuels), ADP-fossil (Abiotic Depletion for fossil resources) and WDP (Water Deprivation Potential) results were taken into consideration as others were found to be less critical for the scope of the thesis.

As the selected EPD-IES 0015611 provides a standardised module D (Reuse-Recovery-Recycling potential) based on 100% recovery from the secondary plastic, the study adapts the **actual recycling/recovery rate** of the lab-scale mechanical recycling process. This adapted numeric data represents **(1)** the constraints of dealing with **low-grade WEEE plastic residues** compared to packaging residues, and **(2)** the realistic efficiency of adapting low-tech lab-scale technologies to mechanically recycle.

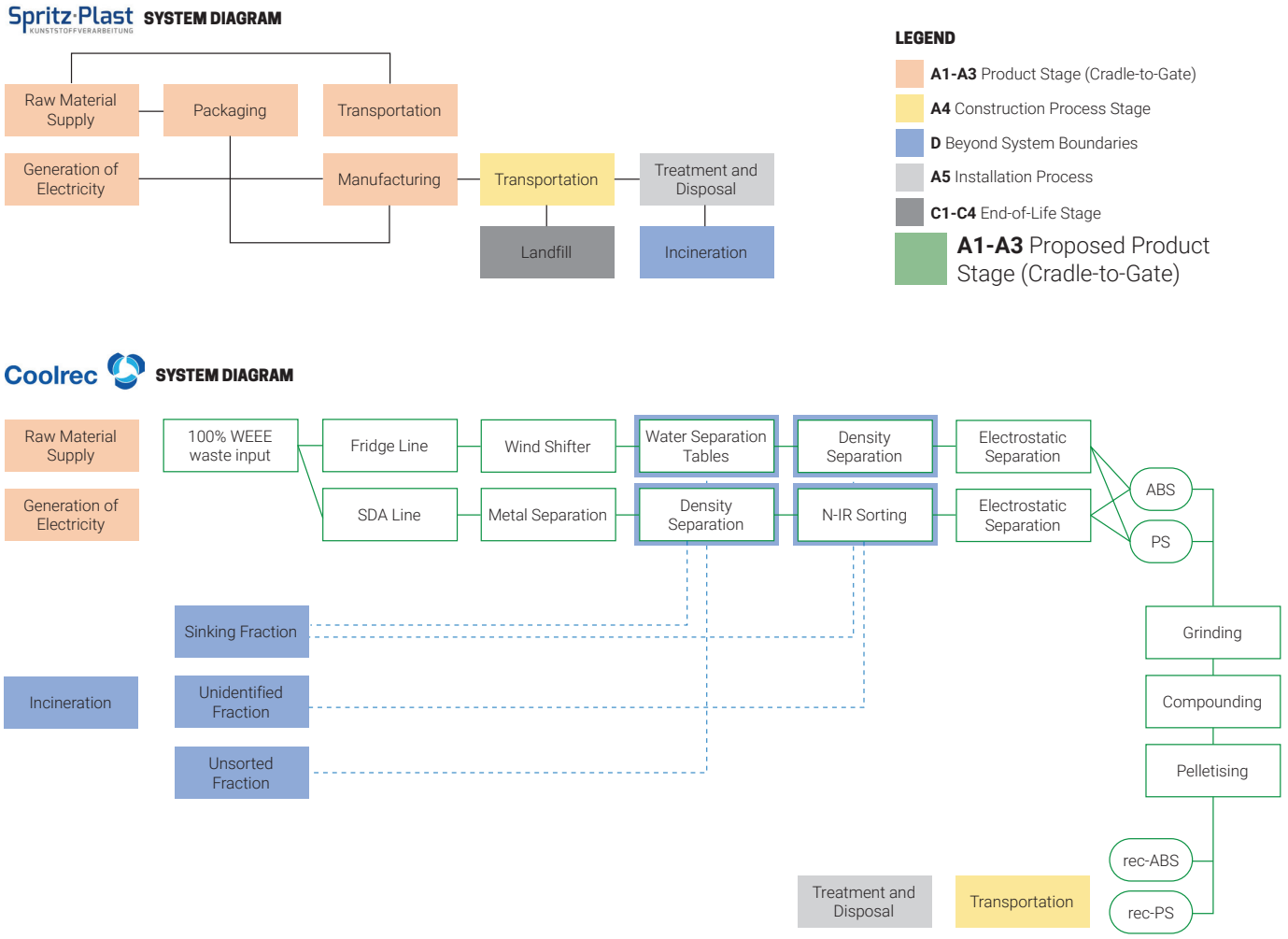


Figure 99: System diagrams of (1) Spritz-Plast, (2) Coolrec, (3) Rec-Hero (Adapted from Spritz-Plast) (Source: Author)

The calculation is done for the numeric data from the mechanical recycling of SDA Line 2 with the waste input of 14.710 grams. The mechanical recycling implemented for the SDA Line 2 targeted carbon black polymers, therefore the numeric data found for the module D reflects a very specific scenario crafted for the timeline of the thesis. Therefore, two D values are created based on the efficiencies of **(1)** thesis' specific scenario (D1), **(2)** close to industry scenario which considers the efficiencies until density separation, in which six different workable polymers can be recovered for processing (D2).

The values for both modules D1 and D2 were scaled according to the recovery rates and then to the mass of the Spacer 10:

Adjusted Dscenario=Original D×Recovery Rate
Module Dspacer=Adjusted Dscenario×0.01149

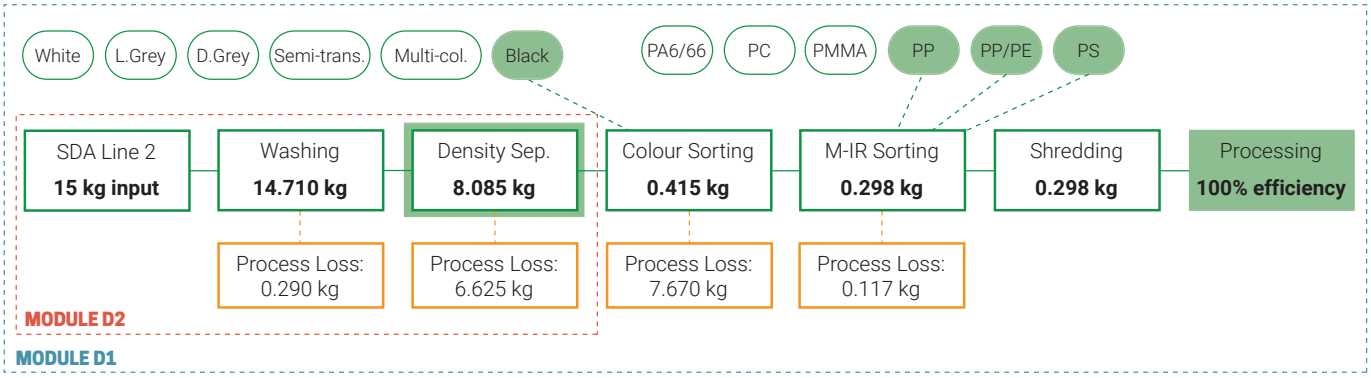


Figure 100: Recycling/Recovery rate for Module D1 (Thesis' scenario) and Module D2 (Industry scenario) (Source: Author)

PRODUCT TYPE BASED ON POLYMER		WEIGHT (g)	WEEE RECYCLING RESIDUE RATE	BIOGENIC MATERIAL WEIGHT
P.1	Polypropylene	11.37	**100%**	0%
P.2	Polypropylene/Polyethylene	11.49	**100%**	0%
P.3	Polystyrene	13.26	**100%**	0%

Results per 1 kg of plastic spacer made of secondary material *(Adapted from Spritz Plast)*

INDICATOR	UNIT	A1-A3	A4	A5	C2	C4	D
GWP-fossil	kg CO2 eq.	**1.47E+00**	8.12E-03	4.42E-03	3.83E-03	2.94E-02	**-2.83E-02**
ADP-fossil	MJ	**1.43E+01**	1.07E-01	2.32E-02	5.05E-02	4.97E-01	**-5.06E-01**
WDP	m3	**8.61E-02**	1.26E-04	1.05E-02	5.93E-05	3.80E-03	**-3.13E-03**

Results for PP/PE (P.2) wheel spacer made of WEEE recycling residues *(Source: Author)*

INDICATOR	UNIT	A1-A3	A4	A5	C2	C4	D1 & D2
GWP-fossil	kg CO2 eq.	**1.689E-02**	9.330E-05	5.079E-05	4.401E-05	3.37Ee-04	**-6.460E-06**
ADP-fossil	MJ	**1.643E-01**	1.229E-03	2.666E-04	5.802E-04	5.711E-03	**-1.155E-04**
WDP	m3	**9.893E-04**	1.448E-06	1.206E-04	6.814E-07	4.366E-05	**-7.145E-07**

LEGEND

A1-A3	A1: Raw Material Supply A2: Transport A3: Manufacturing
A4	Transport
A5	Construction Installation
C2	EoL Transport
C4	EoL Disposal
D	Reuse-Recovery Recycling Potential

RECYCLING/RECOVERY RATE

D1 - Thesis Scenario	D2 - Industry Scenario
-6.460E-06	-1.753E-04
-1.155E-04	-3.134E-03
-7.145E-07	-1.938E-05
Low Recovery (1.99%)	**High Recovery (53.9%)**

Table 42: The numeric results of A1-A3 & D modules of Spritz-Plast and thesis (Source: Author)

The evaluation of the cradle-to-gate (A1-A3) and D modules proves the environmental and material recovery achieved by the lab-scale mechanical recycling. **As the existing recovery rate of SDA recycling is near 50%, the D2 module achieved a comparable recovery rate with 53.9%** (A. Neiva, personal communication, 2024). The numeric results achieved for the specific scenario tailored for the thesis presents a low recovery rate which underlines the need for efficient separation and sorting technologies rather than manual lab-scale implementations.

The EPD-based proof of sustainability concludes the possibility of upstreaming the WEEE plastic recycling residues as an alternative path for incineration. The lowered emission values for the proposed application and optimised design showcase the scalability of the lab-scale mechanical recycling into a real-life industry scenario within the same facility. The proposed system diagram (see Fig.99), **integrates only an inclined friction washer to the facility** to be able to **recover two more polymers (PP and PP/PE) with 53.9% recovery efficiency**. This friction washer technology includes friction washing and drying functions, which are imagined to be placed between density separation and N-IR sorting to output even better purity results than the lab-scale outcome.

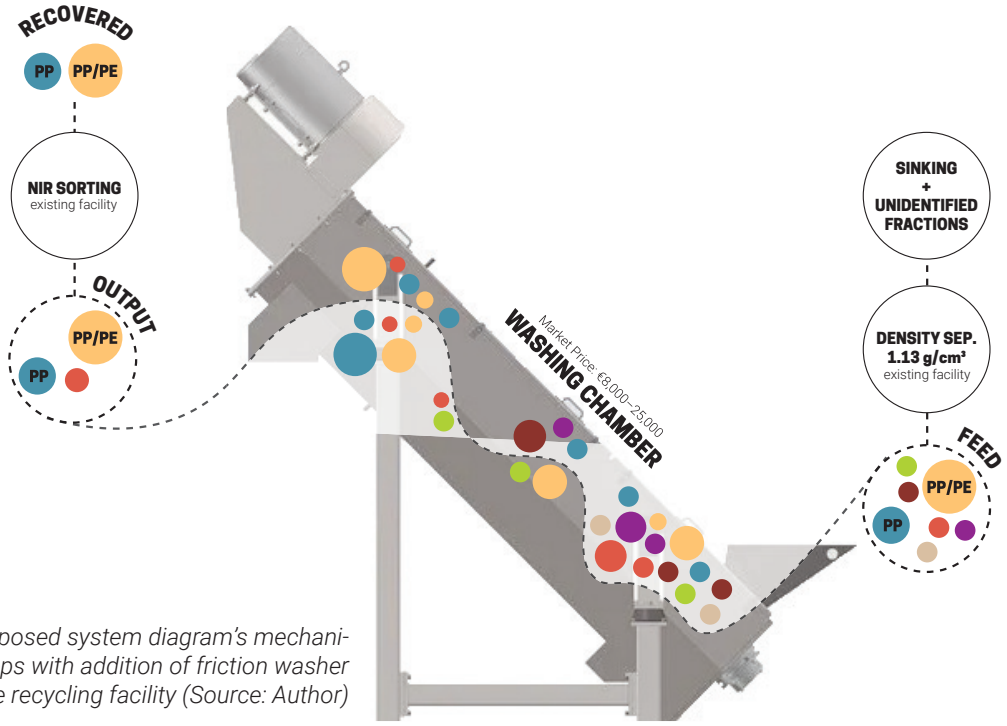


Figure 101: Proposed system diagram's mechanical recycling steps with addition of friction washer at the recycling facility (Source: Author)

The first step of the proposed system involves **secondary density separation with a higher separating medium density of 1.13 g/cm³**, using either existing industrial float-sink tanks or with low-tech table salt solution. The second step involves the **friction washer**, which is regarded as a critical step after concluding the contamination level of the reject fractions. It is believed that one of the main reasons of the low sorting efficiencies is the less efficient cleaning technologies that limit the identification of target polymers. Therefore, even though the proposed targeted polymers of PP and its copolymers do not necessitate higher densities, based on conducted trials (see Appendix.) they floated only with 1.13 g/cm³. The critical step with the friction washer is envisioned to increase the overall efficiency of the second recycling line. The next step of using the existing N-IR sorting facility was decided based on the energy use of the systems and the low need for having precise polymer batches. **The final low-grade application scenario enabled a minimal intervention with high systemic impact on recycling**.

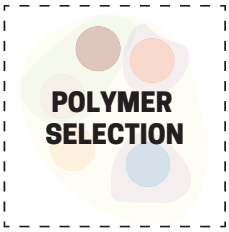
In essence, the proposed system **closes a mismanaged material loop** that is currently broken not due to technological limitations but due to a lack of market-driven applications for low-grade plastics. The thesis proves an application scenario and a product that is optimal for using contaminated recycling residues to offer the plastic another service life.

RESEARCH CONCLUSION &REFLECTION

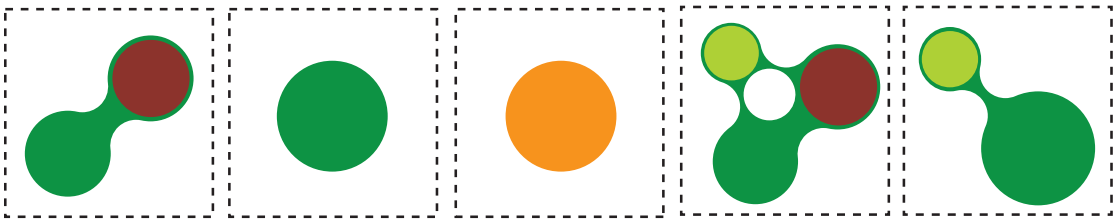
5 Research Conclusion & Reflection

The thesis focuses on the technical, material, and processability-based insights from the dual-track methodology that sub-branches into polymer selection, injection parameters, design optimisation, and applicability. The results and insights achieved because of the thesis are evaluated based on **(1) scientific and (2) high-level conclusions**. The scientific conclusions focus on polymer science, polymer sorting and characterization, polymer blending, structural performance, the injection molding behaviour, and architectural application. Whereas, the high-level conclusions focus on the status of the thesis within a broader perspective that evaluates the systematic challenges that plastic recycling faces. The market limitations, regulations, the sustainability goals are evaluated to point out the industry gaps on plastic recycling.

Overall, working a difficult waste stream of WEEE that contains various impurities, blends and contaminants in the waste stream proved extreme difficulty at the earlier stages of the thesis. The unpredictable composition, the available lab-scale facilities, the characterization and sorting of the plastics proved the difficulty of recycling WEEE plastic in the industry. Nevertheless, the combination of bottom-up and top-down methodologies, hand in hand with material experimentation and product development tracks, validated a **"rec-HERO"** that unlocked a new potential and a business case for using plastic reject fractions from recycling as a hidden but essential building component for architectural applications.

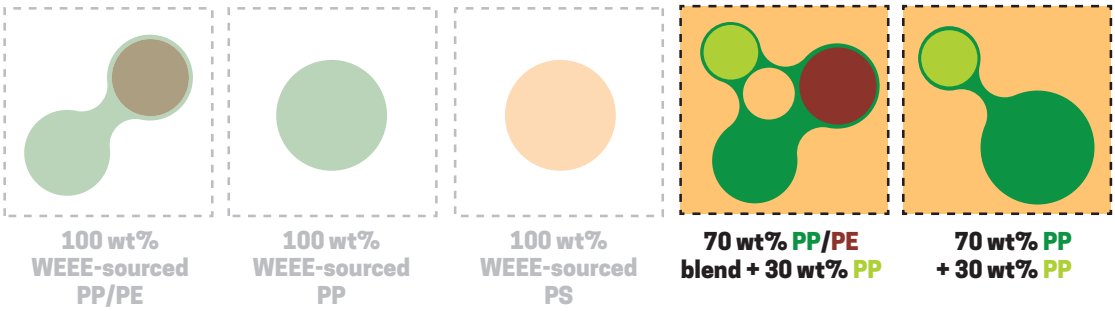


The first sub-track of material experimentation track highlighted the the complexity and unpredictability of WEEE plastic waste. This sub-track will be evaluated based on **(1)** polymer science, **(2)** polymer sorting and characterization and **(3)** polymer blending conclusions. To understand the gaps of the industry-scale mechanical recycling of plastics, the same strategies are repeated in a lab-scale, with a waste input being the reject fractions of recycling processes. The experiments are conducted firstly with the fridge lines to test the applicability of the lab-scale mechanical recycling steps. These tests provided information on the applicability of the experiments which then repeated at small domestic appliances (SDA) lines which provided better workability because of larger plastic pieces. Mainly based on the size of the shreds and as the SDA lines were reported to have lower recycling efficiencies, the focus was given to the SDA line polymers. The main sorting tools were density separation and manual colour sorting, and the main characterization tools were FT-IR, XRF, micrographs and DSC analyses. The repeated tests and long durations spent at the FT-IR identification of each polymer resulted in finding a potential polymer selection that was tested in injection molding setups to prove processability.

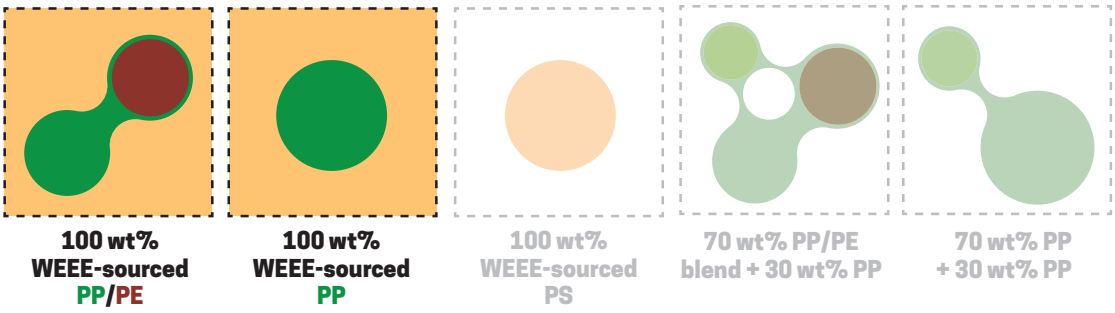


At the end, five different polymer recipes were tested for processability based on the lab-scale mechanical recycling steps: **(1)** 100 wt% WEEE-sourced PP/PE blend, **(2)** 100 wt% WEEE-sourced PP, **(3)** 100 wt% WEEE-sourced PS, **(4)** 70 wt% WEEE-sourced PP/PE blend and 30 wt% packaging waste PP and **(5)** 70 wt% WEEE-sourced PP and 30 wt% packaging waste PP. The selection of PP/PE, PP and PS polymers from SDA-2 was mainly because they were recovered with highest quantity as carbon black with the **recovery rates of %43.71, %15.96, %12.10** respectively (see Table.8). **PA6/PA66 blend** was the other higly recovered polymer with the recovery rate of %11.54. However, because of the high injection molding temperature suggested for the design by SolidWorks with 285°C, the manual plunger-type injection molding could not reach that temperature with the use of resin mould. The selected 100 wt% WEEE-sourced recipes 1,2,3 concluded with succesful results for processability. The thesis' aim to recover the mismanaged contaminated plastic waste to be able to process was achieved. However, the use of lab-scale injection molding

setups with ABS-like resin mould, concluded with brittle behaviour of the majority of WEEE-sourced samples which concluded with cracking at the weld lines or where the resin mould warped. Therefore, the thesis adapted a strategy tailored for the lab-scale conditions and created again with **100 wt.% recycled plastic recipe** by combining cleaner packaging waste with contamianted WEEE plastics. The weight percentages were identified based on the existing research by Tai et al., Mourad, and Han et al., who blended virgin and recycled polymers. On the other hand, it was believed that a 100% recycled recipe was still possible even by **blending cleaner shreds with contaminated ones with varying shred sizes**.



The injection molded samples with the recipes (4) and (5) already gave better results in terms of especially **stability and smell results** of the evaluation parameter. Even though the smell results are neglected because of the application scenario as a hidden building component, it is concluded that the recipes (4) and (5) that blended WEEE and packaging plastic gave more applicable results for the function of reinforcement spacers with the **available lab-scale facilities** for mechanical recycling and injection molding.



However, as the brittle behaviour of the injection molded samples mainly caused by external factors like feasibility, limited technology; different high-level conclusion can be made for the polymer selection sub-track. Therefore, **100 wt% PP/PE and PP injection molded reinforcement spacers** are selected as the **most applicable recipes** that can be implemented in industry-scale recycling and processing techniques. Possible upgrades to the used technologies would result in a sucessful implementation of the recipes (1) and (2) in industry-scale applications:

1. PP/PE and PP already had better recovery results compared to PS but with also using a magnetic density separation at the facility would give much better recovery results.
2. Including a friction washer to the WEEE recycling facilitity would give a cleaner and better-sorted plastic output for recovery.
3. Rather than using plunger-type injection molding facilities, screw or twin-screw injection molding machine with possible addition of a static mixer would allow for more miscible and mixed injection melt front which would lower the risk of failures such as air traps, weld lines, warping or fiber formations.
4. Using aluminum mould with a chance to pre-heating before injection molding would increase the velocity of the melt front which would give better morphologies of the samples.

The complexity and unpredictability of the waste input necessitated boundary conditions to be set at three main experiment setups for injection molding: manual press, manual plunger-type injection molding, and pneumatic plunger-type injection molding. To be able to develop a workable polymer recipe, the experiment trials, starting from mixed polymer blends to targeting one specific colour polymers, were tested at the respective experiment setups, varying from low-tech to more advanced. The iterations on the heating/cooling cycle, pressure and dwell time were the main parameters that validated the injection cycle specific for each experiment setup. The results on the setups, proved that the injection behaviour of the selected polymers was solely dependent on the complexity of the geometry rather than the plastic input. The heating/cooling cycle on the polymer selection was proved by fine-tuning the processing conditions.

At the end, a injection cycle that is **adaptable to three polymer types PP, PP/PE and PS** were validated with the use of manual plunger-type injection molding machine. The injection cycle that was concluded at the material experimentation track got slightly adjusted for accomodating better injection flow for the thin sections of the resin mould and the dimension of the nozzle. The injection cycle of **15 min - 240°C - 15 min** can be implemented for the use of resin mould with cavity aluminum moulds for the geometries that necessitates **maximum 10 MPa** if manual plunger-type machine is being used for **100 wt.% WEEE-sourced recycling residues**. On the other hand, for the polymer blending done with packaging waste, **15 min - 220°C - 10 min** found to be the optimal cycle that can be used if the polymer blending is done with purer and cleaner plastic with thesis polymers.

The **top-down approach** was essential for the dual-tracks to function simultaneously. Based on the first analysis of the waste stream, it was concluded that the mixed plastic can be used for plastic building components that are situated in **buildings' internal shearing layer**. The selected design is crucial in reinforced concrete construction and in use with high quantities per construction. As there is no necessity of high mechanical performance expected from the component, it proposed a good business case to prove the applicability with mixed and contaminated waste polymers. Firstly, the application scenario of the design was validated with simulations and physical tests, and then the proposed alternative design scenario for the generic wheel spacers was tested by iterative designs that focuses on functional requirements of a spacer. The tailored design optimization tool that combines weighted sum model algorithm and tiered scoring system principles aided the selection of the best-performing design for the business case. While including all the functional requirements of the selected reinforcement spacer, the design is tailored for the use of contaminated heterogeneous polymers with less advanced processing technologies.

The final design of Spacer 10 concluded as **simple, lightweight alternative** to the generic, commercial-scale wheel spacers. The simple rebar retention mechanisms and concrete contact points gave successful results. The only **future modification** that could be done is for the re-design of radial ribs as the critical areas are located at where the weld lines form. An adaptation could be made for the radial ribs near the core which might help achieve better results even with lab-scale recycling and processing technologies.

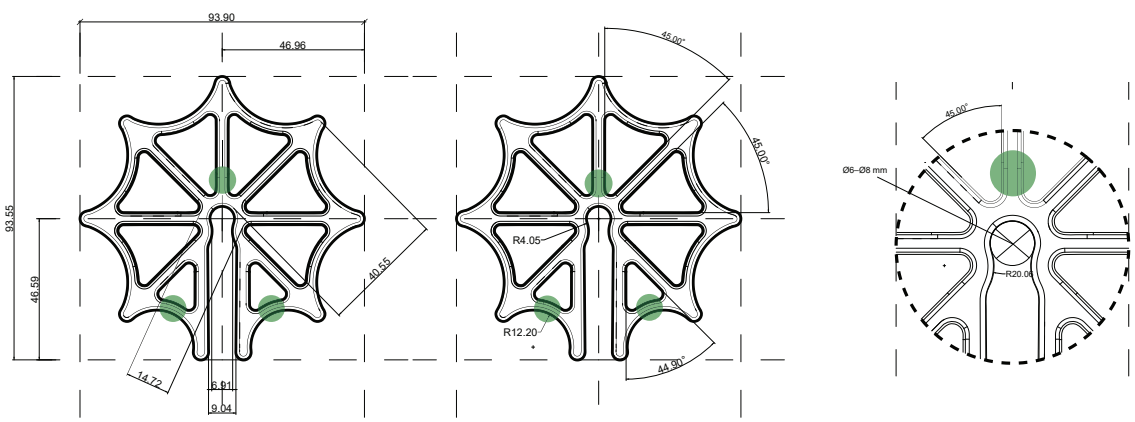


Figure 102: The possible locations where modifications can be considered (Source: Author)

The use of **SolidWorks** for the simulations was successful as the critical areas were all suggested during the injection flow simulations done on the Spacer 10. Therefore, SolidWorks is a great tool to test injection molded products that necessitates two-step verification. Overall, **design optimization tool** is validated and found applicable for future use especially for reinforcement spacers and their variants.

The applicability and the validation of the design scenario were aimed to prove the real-life construction requirements in a 1:1 scale concrete mockups and a sustainability analysis with EPD-based methodology. Mimicking the real-life concreting process with different uses of aggregates -fine, regular coarse aggregates and recycled coarse aggregates- to confirm compressive and impact response, concrete penetration within the wheel spacer, spacer's retention mechanism before and after concreting **validated the simulations and physical tests**. The comparative analysis will be made with a generic wheel spacer with same rebar cover of 40 mm from Gerrijn to evaluate the performance of the products. The applicability proves the use of the **"waste of the waste" plastics in a non-exposed layer of construction that offers a new circular route for reject fractions that supposedly meant to be sent to energy recovery**.

The proof of sustainability comparison was based on Spritz-Plast's injection molded reinforcemet spacer with 100% secondary plastic blend of PP/PE blends from packaging waste. This provided reliable numeric data for the A1-A3 Product and D Resource recovery stages of the Spacer 10. The analysis proved the applicability and realistic industry scenario of another mechanical recycling steps to recover PP and PP/PE for manufacturing rec-heroes. The **high recovery rate of 53.9% of plastic** on top of ~50% recycled SDA line of plastic recycling proves the possiblity of the proposed business scenario by only purchasing a friction washer into the recycling facility. The final low-grade application scenario enabled a **minimal intervention with high systemic impact on recycling**. The possible sustainability proof would be to provide a material-flow diagram for the proposed system diagram for the rec-hero. The material-flow model would indicate the specific flows in and out of the system if a plastic recycling company collaborates with the data input.

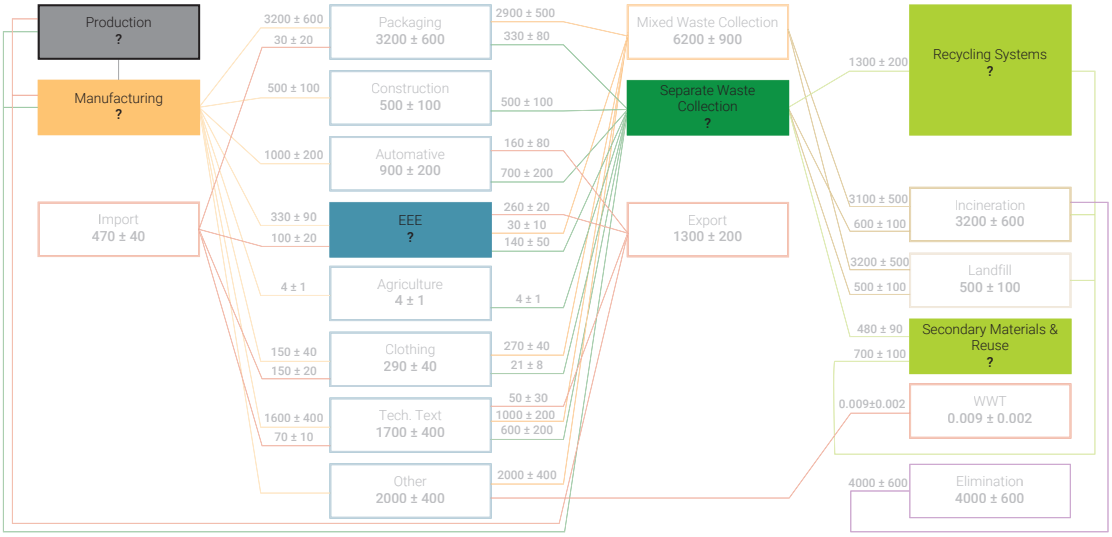


Figure 103: The proposed material-flow model adapted from Kawecki et al. focusing on WEEE (Source: Author)

The validated aggregate penetration tests with better exposure of spacer at the concrete finish compared to generic wheel spacer, the thesis proposed an opportunity for the future of circular concrete construction. The use of rec-heroes with 100 wt.% WEEE-based plastics, recycled coarse aggregates and Electric Arc Furnace (EAF) rebar would propose a new market for the 100% recycled concrete recipes that could be scaled up. In conclusion, two appicability paths for a **(1) low-tech, lab-scale rec-HERO and (2) high-tech, industry-scale rec-HERO** were defined during the thesis.

The information on the specific mechanical recycling step each waste bag was rejected **became available only midway** through thesis. Therefore, the initial experiments and analyses were conducted under assumptions based on the recycling line they belong to -either Frige line or SDA line-. As a result, the conclusions should be interpreted within these initial assumptions and scope on the waste origin.

FRIDGE 1-2

Fridge 1: Reject fraction of water separation tables
Fridge 2: Sink fraction of density sorting

The Fridge-1 samples were collected as the reject fractions of water separation tables. Based on initial visual inspection, the samples had fewer contaminants and impurities and stronger polymers compared to the Fridge-2 polymers. The polymers had moisture and water content existing at the waste bag, which already suggested a pre-cleaning being done at the recycling steps. The stronger polymer behaviour already suggested higher PS, ABS content, which was known to be difficult to process with injection molding. Therefore, the plastic input was mostly **used to shape the processing parameters**. The Fridge line 2 showcased a smoother polymer behaviour, which already suggested the potential of high PP, PE, and PA6 content. Therefore, the first trials of density separation were done with this line to conclude a **working density separation setup** for other waste bags. The characterisation done on both fridge line polymers gave an overall polymer characteristic that can be generalised for fridge line reject fractions. As the fridge line was already reported as efficient in terms of recycling rates, and the shred sizes are smaller and hard to handle, the processability focus was not given.

SDA 1

SDA 1: Reject fraction of near infra-red sorting after SDA 2

This waste line **proved the potential to use recycling residues** for injection molding regardless of their impurities. First **successful density separation results** were obtained with this waste line with a high percentage of lab-scale injection moldable polymers like PP, PS, and PP/PE blends. The heavy fractions like PC, PVC which were not targeted because of their toxic behaviour during melting were successfully avoided by density separation. The high content of **carbon black** polymers showcased the limitations of the sorting technologies as well as the potential for them to be used in secondary service life. As PS and ABS are known to be targeted during the compounding step of Coolrec, the majority of the polymers characterised resulted in **PP-based polymers**, which gave feedback to the polymer selection phase. The polymer selection for the application phase was concluded based on the experimental results from SDA Line 1 polymers.

SDA 2

SDA 2: Sink fraction of density sorting

The 15 kg waste input from the sink fraction of density separation of SDA plastics was fully utilised to be used as the third phase of application. The proven density separation techniques, the manual colour sorting mechanism, the FT-IR characterization, DSC analysis setups were repeated to acquire a **carbon black PP/PE, PP and PS batches** with **recycling/recovery efficiency of 1.99%** ready for processing. The injection cycle with a manual plunger-type injection molding machine that was proven with SDA-2 PP/PE, PP, PS polymers was repeated with the pre-defined heating/cooling cycle. The **SDA recycling line has the most potential to increase the overall efficiency of plastic recycling** as the industry scale **recycling/recovery efficiency concluded as 53.9%**. Processing them into micro-level plastic components for the second-highest plastic-demanding sector of construction industry is validated.

FOREIGN MATERIALS & CONTAMINATION

Sourced from manual sorting of floating fraction of density separated SDA 2

The most crucial findings of the thesis were the extent of the contamination, impurity and identification of the foreign materials. The density separation setups during the thesis and the manual colour sorting done on the floating fractions prove the efficiency of the metal separation done at the first mechanical recycling, while the majority was wood chips, foams and rubber. The **high quantity of rubber and nylon** which are undetectable by near-infrared sorting, confirmed the challenges of the mixed plastic residues during lab-scale mechanical recycling. The contamination was validated by **(1) FT-IR analysis, (2) random peaks and thermal behaviour differences during DSC analysis and (3) microscopic inspection, (4) XRF analysis and (5) smell results during injection molding**. Overall, the implemented physical, chemical, and thermal analyses on the contamination proved the existence of organic and inorganic contamination inside all waste lines including:

1. **Identification of talcum powder, alkyd resin, cellophane and aromatic hydroocarbons were made with FT-IR results.**
2. **The use of possible additives like polybutadiene, residual solvents and polymer blends were identified by DSC results.**
3. **The foreign materials glued/stuck at the samples and discolouration were identified by microscopic inspection.**
4. **The detection of silica-based fillers, non-halogenated flame retardants, and UV stabilisers were made by XRF analysis.**
5. **The strong odorous behaviour during injection molding validated the salt resdiues from density separation and other organic/inorganic contamination from prior polymer characterization tools.**

CARBON BLACK - PP/PE, PP and PS

From the injection molding batch of FT-IR identified sorted and characterized SDA 2 carbon black polymers

The final polymer selection for the application phase is carbon black PP/PE blends, PP and PS from SDA-2 waste line with **recovery rates of %43.71, %15.96, %12.10** respectively. The high quantity of processable polymers found at the floating fraction of density separation with 1.13 g/cm³ were sorted and characterized for processing stages of the thesis. However, despite the pre- and post-washing treatments done on the samples, there is still a **visible contamination layer** adhered to the surface. The dirtiness is clearly visible by comparing the final plastic shreds of PP, PP/PE and PS with PP shreds from packaging waste. It is concluded that the reason for the persistent chemical smell was caused by the contamination layer which suggests presence of volatile compounds or additives proven during material experimentation phase. The contamination presences of talcum powder, polybutadiene, alkyd resin and residual solvent caused some immiscibility on various DSC-tested PP/PE blends in terms of thermal behaviour. The immiscibility was validated during the comparison made with 100 wt.% WEEE-based samples and 70 wt.% WEEE-based samples during proof of concept. However, the melting behaviour which is crucial for the processing, represented trust-worthy results for both lab-scale and industry-scale injection molding.

5.1 Discussion and Conclusion

The discussions and the conclusions will be shared based on the scientific and high-level perspectives on the sub-questions and research question of the thesis.

Sub-question 1 What is the state of the art of plastic manufacturing and plastic recycling?

Scientific conclusion: The high flexibility and the low manufacturing cost of plastics will continue to grow with its manufacturing typically relying on natural materials like oil, coal, natural gas and crude oil. After the evaluation of the process-chains for plastic manufacturing, it was deduced that the main difference between various life cycles are plastics are caused from different sorting techniques and schemes. The magnetic and sensor-based sorting system hand-in-hand with additional frictionw washers found to be the **optimal path for highly mixed waste streams** going through mechanical recycling. Feasible alternatives like implementing same sorting system repeteadly by targeting other polymers also found to be applicable for low-budget interventions.

High-level conclusion: The state of art of plastic manufacturing is **still extremely reliant on the use of virgin and fossil-based polymers**. It was deduced that by TNO's Sankey diagram on the lifecycle of plastic waste that the fossil-based plastics are nearly eight times high then recyclates. This proves that even though mechanical recycling is a widely adopted technology that produces high volumes of secondary plastics, out of 990 kilotons of manufactured plastics, only 124 kilotons of it are secondary plastics (Wijngaard et al., 2020). Even though the Netherlands is performing as one of the best countries to recycle post-consumer plastics, it is **fully reliant on the incineration method for the end-of-life of plastics** after targeting one/two polymers at a recycling facility. This idea can be shifted with a **different business model** that targets plastic recycling residues to mechanically recycle into a micro-scale application with low-tech methods.

Sub-question 2 What are the primary challenges of recycling plastics from one waste stream?

Scientific conclusion: The process of open-loop mechanical recycling on the plastic recycling residues posed challenges because of the **unknown polymer composition**, and **lack of technology** available at lab scale. The advanced sorting and separation techniques are required to effectively acquire workable polymers for processing and to offer another service life to the plastic waste. The selection of the waste stream is crucial to increase the effectiveness of upstream sorting of plastics. For a **waste stream which has common use of additives and colourants**, alternative recycling methods like chemical recycling would offer comparable recovery results with possibly fewer polymer losses that would convert unrecycled plastics into a feedstock.

High-level conclusion: The common waste streams, including WEEE, C&D, ELV and industrial plastics all have their own limitations to obtain a secondary plastic. The primary challenges that the waste streams face are being minimised by Dutch regulations, which prioritise waste reduction, reuse and recycling. The problems plastic recyclers are facing are also caused by different types of waste collection systems, including **source separation and commingled collection**. The efficiency of plastic recycling is solely dependent on the waste input. The classification and screening steps taken before the waste input during waste collection defines the overall efficiency of the recycling, therefore **switching to CC schemes in the Netherlands** would already impact the plastic recycling efficiency in general.

Sub-question 3 What are the material characteristics of WEEE plastic waste?

Scientific conclusion: The overall composition of the WEEE stream has nearly **16% of plastic content** and based on OECD 2060 scenarios, the e-waste will exponentially grow, which are mostly treated with recycling and incineration. As fridges and small domestic appliances (SDA) are big part of WEEE, the focus on the fridge and SDA waste lines proved the **material characteristics expected from WEEE**. The target waste line being SDA, it is proven that the majority of the polymers include **high-density polymers like PC, ABS** based on the comparison between the floating-sinking fraction. However, the separator medium also proved that there are still **low-density thermoplastics apparent in the waste stream**, optimal for processing with injection molding. It was noted that even though pre-cleaning and drying were done to the samples before each experiment, there was still an **existing contamination layer or water content** that might cause the polymers to not float on the usual densities assigned during mechanical recycling.

However, as the separating medium can be reused at every density separation trial, readjusting the separator medium will not affect the applicability of the recycling waste of waste. The technologically advanced systems, like **inclined friction washer**, can be used to offer several mechanical recycling steps with minimum economic effect to recover more WEEE polymers.

High-level conclusion: The rapid growth of WEEE worldwide and the inadequacy of the global policies results in high rates of e-waste flow. The **UN's E-waste Monitor** concluded the need to encourage manufacturers to design the components with recycling in mind. The high content of existing PP/PE blends and PA6/PA66 blends at the waste stream showcases the need to **rethink the whole life cycle of plastics**. The legislation that is mainly focuses on WEEE is **REACH** which prevents hazardous waste to end up at the recycling process. Therefore, the s**econdary plastics can only have 20% impurity** which supports the EN 71-3 standards. However, for the thesis, REACH still allows a research possibility that can showcase the potential of using WEEE waste alternatively to prove a secondary life cycle. The thesis showcases a micro-scale application with a polymer blend that suggests impurity based on the morphology, mixing, and smell results inside a shearing layer of a construction. As the design will not be exposed to exterior it will not cause damage to human health and it will still be functional as a reinforcement spacer.

Sub-question 4 What are the technical requirements and limitations of injection molding for plastics?

Scientific conclusion: Unlike hot pressing, injection molding requires **consistent melt flow** inside the heating barrel that is pushed out with pressure inside a cavity in-between upper and table plate. Even at the lab-scale or manual plunger-type version of the injection molding techniques, the risk of using polymer blends have high risk to cause defects to the processing system. Therefore, the **polymer input needs to be carefully adjusted** by their thermal and chemical properties so that a compatible blend is achieved at the melt front. Therefore, during the thesis, a **long duration of time was given to FT-IR analysis to characterize plastics input shreds** that create a batch with the same polymer type. This was the main limitation discovered with injection molding. On the other hand, injection molding proves great potential to be used for complex shapes with easy setup that only requires four main parameters to be defined – dwell time, preheating time, temperature of the heating barrel, and pressure- to be able to injection mold in the simplest way. Another limitation that injection molding faces is the feasibility of the system and the moulds. Better results are achieved with aluminium moulds for **preventing delamination and sink marks**. However, the alternative method of using 3d-printed resin moulds for the one-cavity mould system was proven with the thesis **proposing an alternative method for lab-scale injection molding.**

High-level conclusion: The main limitation of injection molding in industry is how the technique is optimised for **virgin or known-recycled polymers**. The exemplary injection cycle conditions are defined for known polymers, which necessitated a tailored injection cycle based on trial-and-error and SolidWorks' simulation data. The Design for Recycling can enable the addition of **material databases** that include secondary plastics for simulation and data collection as well. This would make the manufacturing process and usability of waste polymers easier.

Sub-question 5 How does the presence of contamination and unknown polymer composition affect the injection molding behaviour of WEEE plastic waste?

Scientific conclusion: The scientific data obtained from the experiment setups showcased the limits of WEEE plastic with the trial-and-error method. The necessity of the detailed sorting and characterization of the polymers was deduced after inputting a mixed colour sorted polymer blend in a pneumatic plunger-type injection molding setup. The difference in melting behaviours of the polymers, as well as the presence of degradation, resulted in the polymer batch being stuck at the heating barrel, which **malfunctioned the setup**. Therefore, there needs to be an available platform where different polymers can be tested and proven to be usable with injection molding.

High-level conclusion: The main inhibitor of the injection moldability of WEEE plastics is the REACH legislation which necessitates the industry to chemically characterize each polymer input and comply with the restrictions on reuse. There needs to be **broader exemptions for non-exposed injection-molded plastic components at low-risk applications** which would integrate the secondary plastics into mainstream production.

Sub-question 6 **What architectural applications are suitable for contaminated and mixed plastic?**

Scientific conclusion: Non-exposed components, which are **situated mainly at the internal shearing layer of the buildings**, are suitable for contaminated and mixed plastic applications. As the use of blends and impurities affect the mechanical and structural behaviour of the end product, a **semi-structural or temporary component** without load-bearing expectations would be suitable application scenario. **(1) Temporary bracing systems like adjustable props or wedge clamps that are removed after construction, (2) different types of rebar spacers, (3) drainage components, (4) or plastic fasteners** could be another potential application suitable for contaminated and mixed plastics.

High-level conclusion: As the construction industry has the second highest demand for plastics with an average **lifespan of a plastic component exceeding 35 years**, the recycled plastics has great potential to apply low-grade secondary plastics into the industry. There are so many areas where recycled hidden heroes can step in for the construction industry. This will reduce e-waste, maximize material recovery while promoting environmental responsibility.

Sub-question 7 **What parameters influence the structural performance, moldability and concrete compatibility of reinforcement spacers?**

Scientific conclusion: The main parameters of the product development track, **(1)** contact area, **(2)** flexibility for rebars, **(3)** injection flow, **(4)** Charpy impact, **(5)** compressive strength, **(6)** plastic use per product are proven to be significant indicators that influence the applicability of the reinforcement spacers. The application setup with concrete mockups also proves the influence of the **(1)** rebar retention mechanism, **(2)** spacer's surface exposure at the concrete finish, **(3)** the penetration of aggregates in-between the hollow areas of the spacer.

High-level conclusion: The parameters concluded during the thesis are adaptations of what current market standards seek from a reinforcement spacer. The alternative design scenario with a bulkier design option that still functions as a reinforcement spacer with simpler geometry and processability option at a lab-scale and manual plunger-type injection molding machines concludes that the top-down approach that gets its foundations from Design for Recycling can shift the real-life scenario of the industry. The tailored processing steps for **contaminated mixed polymers into an injection molded component** can be adapted to other possible applications with design optimization.

Research question: How can plastic residues from WEEE recycling be processed into an optimized injection-moldable building component?

Scientific conclusion: The thesis demonstrates how plastic residues from WEEE recycling can be processed into a design-optimised injection molded building component through a **combination of bottom-up and top-down dual-track methodology**. By using various reject fractions from distinct mechanical recycling steps from both SDA and fridge recycling lines enabled a complex and comprehensive analysis of the possibility of using plastic residues as an injection molded building components essential for reinforced concrete construction.

Material experimentation track proved the applicability of mimicking mechanical recycling on the plastic residues by conducting a lab-scale experiments that validates the characterized and sorted plastic in three defined experiment setups from less advanced to more advanced in order to come up with workable polymer recipes without addition of compatibilizer or powder to the mix. This allowed to conclude a foundation point that leaves room for improvement for the business case. Parallel to the material track, the product development track resulted with a optimized reinforcement spacer design with the simulations and physical testing conditions created from the dual-track feedback loop after each sampling and characterization. The proven use of lab-scale injection molded setup with resin printed moulds conformed a low-tech and lab-scale alternative to commercial-scale products as **non-exposed recycled hero from contaminated and mixed WEEE polymers**.

High-level conclusion: The thesis highlights a significant gap on the current secondary plastic production schemes, the regulations, and the recycling infrastructure. Whilst understanding the feasibility of sending plastic reject fractions to energy recovery, the potential of the plastic residues is apparent and can be reintroduced to the market with some modifications to the existing frameworks.

An alternative design path is created for the thesis, which embraces the flaws and impurities of the waste input and optimises a building component with these factors in mind. This opens up a potential for low-grade recyclates and their use as hidden heroes that make the WEEE recycling practices more circular. This design path necessitates altered restrictions for the waste of the waste plastics by the WEEE Directive and REACH legislations that would support strategic material flow opportunity for secondary plastics.

5.2 Reflection

5.2.1 Relevance Reflection

What is the relation between your graduation project topic, your master track (A, U, BT, LA, MBE), and your master programme (MSc AUBS)?

The core of the thesis is centred around innovation-driven material research and building product innovation with an emphasis on research-by-design and design for recycling approaches. The material testing, laboratory work and structural validation fall within the scope of Building Technology. Whereas the focus on practical implementation of the selected design in the built environment and attention to circularity strategies align with the goals of the Architecture faculty, Moreover the design proposal addressing societal, industrial and scientific challenges related to sustainability, waste management and innovation in construction materials aligns with the goals as well. The integration of the processing technique of injection molding with product design that takes its foundation points from the material research done on recycling residues rather than virgin materials represents a novel convergence between structural design and building product innovation.

5.2.2 Academic Reflection

How do you assess the value of your way of working (your approach, your used methods, used methodology)? How do you assess the value of the transferability of your project results?

As the thesis aimed to give equal importance to both material experimentation and product development tracks of its dual track methodology from the start, an iterative process with complex feedbacks in the dual-track methodology was necessary. The use of a bottom-up approach for material experimentation was due to the unknown polymer compositions, contaminants and unpredictable degradations of the waste input. Throughout the thesis, the waste is identified, sorted, characterized and refined step-by-step until a workable polymer recipe was achieved for the selected processing technique: injection molding. The same bottom-up approach was also used to define various experiment setups for injection molding while the processing technique has strict boundaries on what polymers it can process without malfunctioning. Therefore, having varying setups from less to more advanced injection molding inevitably helped to make the conclusions based on the evaluation parameters. On the other hand, the top-down approach was followed for the product development track while the waste input necessitated specific application scenarios in order to have a functional, non-risky building component. Based on the processing technique and material behaviour, an optimal selection was made that showcased the potential in low-grade plastic recycling. The custom evaluation system and design optimization tool showcased the potential of generating a design from both product and material perspective.

The complexity of the thesis required the use of a wide range of facilities to sustain continuous feedback loops between the dual tracks for laboratory and computer work. Therefore, the scheduling of the thesis was crucial to be able to have a coherent flow to provide conclusions for each evaluation parameter of material experimentation and product development track.

Through the lab-scale setups in combination with simulation data, the thesis demonstrated how design for imperfection can still lead to optimized, functional hidden recycled heroes situated inside the concrete layer of our walls and floors.

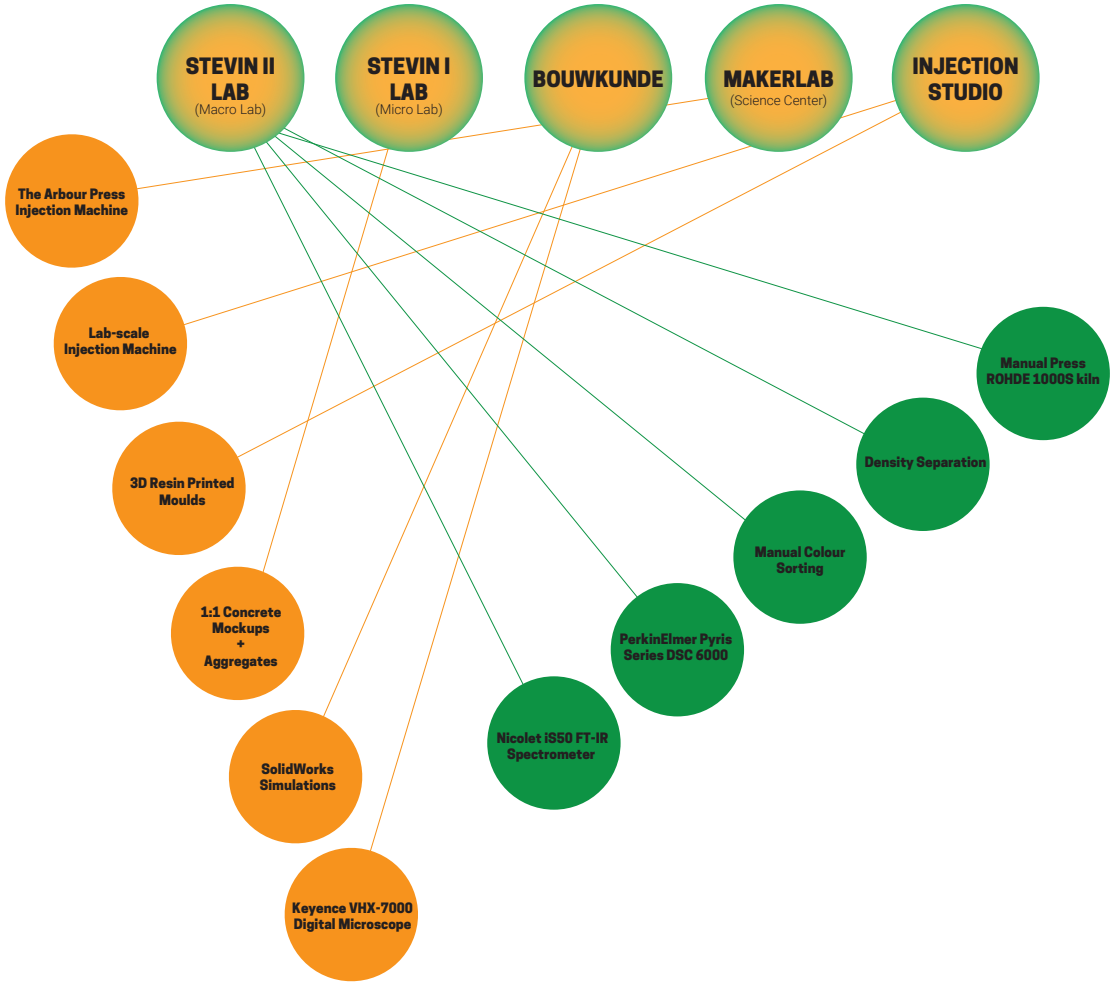


Figure 104: The various facilities and the locations they were being used (Source: Author)

5.2.3 Socio-cultural Reflection

How do you assess the academic and societal value, scope and implication of your graduation project, including ethical aspects?

Tackling with the "waste of the waste" with the growing accumulation of plastic waste reframes a socio-environmental challenge as a design opportunity rather than a disposal option. With the Netherlands' legislative effort to eliminate the take-make-dispose economy model for plastic waste streams, the thesis highlights the necessary awareness of the global waste flows and points out the current defects and potentials of a critical and problematic waste stream of WEEE. The OECD's Baseline scenario pointed out the drivers that will increase the secondary plastics use in daily lives. The economic growth, structural change and technological change drivers were tested during the thesis which questioned the current recycling schemes while offering an alternative recycling scheme for the future of mechanical recycling and upstream sorting of plastics. This would support the TNO's proposed lifecycle of the plastic waste in the Netherlands and propose a better alternative. The efforts of the thesis aligns with the future CO2 emission mitigation goals as well as the Green Deal and Circular Economy Action Plan as it aims to reduce the reliance on virgin plastics.

One of the biggest concerns of the thesis was in regards to the comfort and health regulations and the legislations specifically targeting the WEEE stream. While REACH places strict limitations on recycling e-waste plastics, the legislation still leaves room for the low-exposure applications, encouraging circular economy goals. Therefore, the selection of reinforcement spacers is qualified as a non-exposed, low-risk application, which in theory complies with Article 3(23) of REACH, which suggests the feasibility of this new recycling scheme for this specific product within the regulatory limits. The thesis offers another life cycle for the secondary plastics that was meant to be incinerated at the construction industry, which has the second highest plastic demand, showcases that the regulation needs to guide innovation, do not restrict it.

5.2.4 Industry-scale Reflection

How do you assess the academic and societal value, scope and implication of your graduation project, including ethical aspects?
To what extent is the outcome of the thesis scalable beyond the experimental setup, and what adjustments would be necessary?

The thesis proposes a scalable business case by using plastic residues from WEEE recycling processes for the application in the second-highest plastic-demanding sector: the construction industry. As the selected design of reinforcement spacers do not necessitate advanced mechanical strength, or high-strength polymers, the defined application scenario offers a untapped recycling scheme to make use of contaminated and mixed polymers for another life cycle. The proved applicability of the resin printed cavity moulds and manual plunger-type injection molding methods showcased a feasible, less technologically advanced alternative to the current industry standards which can easily be scaled up.

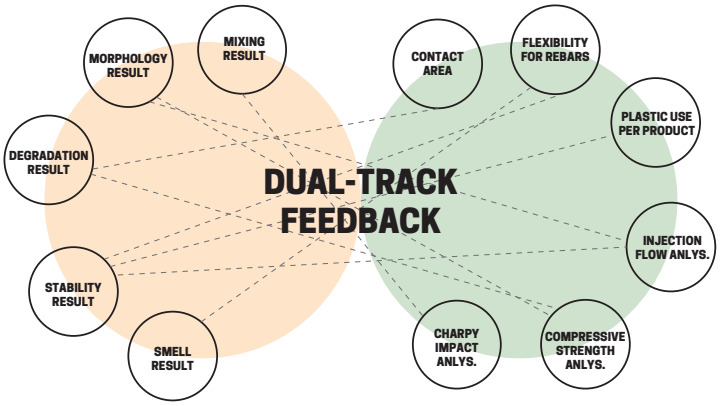
One of the main reasons for selecting carbon black PP/PE, PP and PS polymers for the application phase of the thesis is to highlight the current challenge carbon black plastics face as they are mostly visible to many conventional sorting systems due to their absorption behaviour. Mainly due to this reason, the carbon black polymers in my waste input was in high quantity compared to other colours. Because of low-tech manual colour sorting method, the carbon black polymers were able to be sorted. The mechanical recycling facilities need to shift their sorting technologies which mainly uses near-infrared technology to mid-infrared range sorting, which can separate carbon black polymers. The advanced measuring accuracy will enable more efficient sorting of all plastic waste streams of today. The generic mechanical recycling steps taken for the plastics can be adjusted to offer a potential even for the reject fractions. Placing the size reduction steps at the earlier stages of mechanical recycling limits the opportunity to handle the reject fractions as it contain small shreds of highly mixed materials. As the targeted polymer of the recycling facility is known beforehand, the adjustments to the size reduction systems can be further pushed until the last stages to enable another mechanical recycling that can be done on the reject fractions to become a recycled hero for other industries.

The scalability of the secondary mechanical recycling for the plastic recycling residues is another concern in regards to emissions. The power a facility uses needs to be directly proportional to the waste input. Therefore, alternative small-scale solutions for startups, individuals can be the solution to start dealing with the “waste of the waste” plastics to achieve sustainability goals. Compounding is an essential step for the processing stage, which is highly cost and time-dependent. For the small-scale applications or R&D works, therefore micro-compounders and mobile or handheld measuring devices for polymer characterisation are the future to achieve better results.

Finally, introducing an alternative reinforcement spacer design to the construction industry that was shaped by the waste input and its melt flow characteristics could offer a different business approach to handle contaminated and mixed plastics. The difference of material behaviour between virgin and recycled polymers necessitates a simpler but functional design alternative that offers an application scenario for the low-grade plastics.

5.2.5 Design-Research Reflection

How did your research influence your design/recommendations and how did the design/recommendations influence your research?

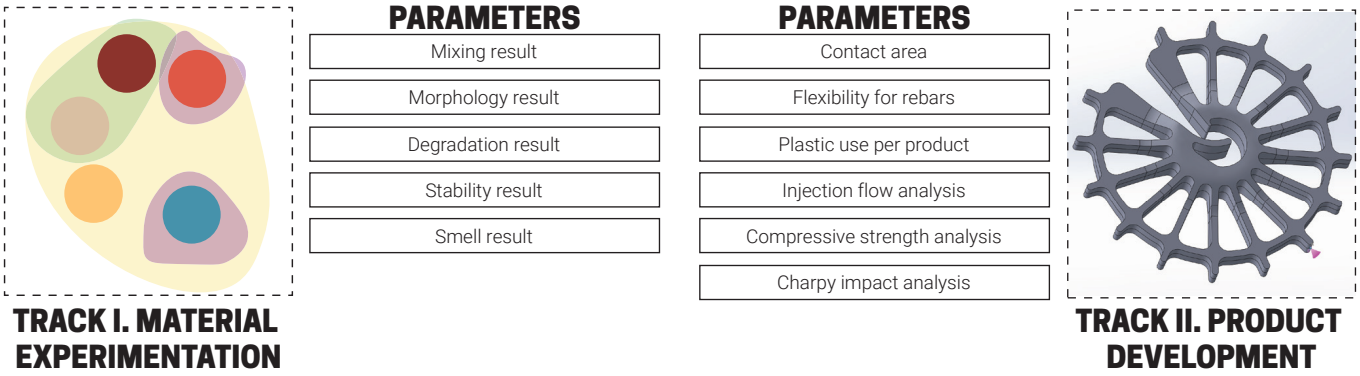


Because of the dual-track methodology that was followed throughout the thesis, there were constant points where research influenced design and where design influenced the research.

1. The material characterisation and sorting setups during material experimentation directly restricted the geometric decisions and shaped the product into bulkier, forgiving geometries.
2. The injection molding setups' pressure and temperature constraints shaped the design of each spacer after simulations.
3. The unpredictability of the plastic based on thermal and chemical behaviour led to prioritising the FT-IR characterization of each plastic shred to have processable plastic for the product.
4. Both the simulation tools and lab-scale tools constantly gave feedback to possible design adjustments to the component.
5. The complexity of the selected reinforcement spacer necessitated a refined and validated injection cycle for each injection molding setups to come up with proper conclusions.
6. The components of the reinforcement spacer and the necessary retention mechanism restricted the selection of durable and stiff thermoplastics to target.
7. The official checkpoint of the thesis where a selected spacer design was tested at the pneumatic plunger-type injection molding setup with two types of 3d-printed resin mould led to key findings on the necessary pressure, applicability of low-cost mould alternatives and the validation of injection molding complex shapes by lab-scale injection molding.

The iterative feedback loop of the dual-track methodology resulted in a successful implementation of material experimentation and product development that can co-evolve and prove the scalability of the thesis in industry-scale implementation.

5.3 Evaluation of Parameters and Optimization Tool



Defining evaluation parameters on the material experimentation and product development track was essential to establish a systematic and comparable dual-track methodology and was able to conclude **(1)** final polymer selection, **(2)** final injection cycle, **(3)** final design, and **(4)** final application that formed the **rec-HERO**. The main reason for the coherent data collection based on thes defined parameters on both tracks. The parameters acted as boundary conditions to comment, give feedback and conclude results at the end. Various improvements can be made on parameters of the dual-track to have more concrete results on the four conclusions.

(1) The timeline to implement XRF analysis can be pushed earlier to have a solid understanding of the existence of flame retardants. If a high-density polymer were targeted during the thesis, it would be hard to reach optimal densities with salt and sugar. Therefore, better sorting technologies like magnetic density separation available at the Stevin II Lab of Civil Engineering can be used for further studies. Currently, the magnetic density separator is calibrated for metal separation, not plastics. Therefore, necessary adjustments have to be sustained for long-term research.

(2) The final injection cycle for all experiment setups are valid for wide range of WEEE polymers especially for the manual press. As multiple blends and mixed polymers were tested at the manual press at the ROHDE 1000S kiln with a specific heating/cooling cycle, this setup can be used as a starting point for future research.

(3) The design optimisation and evaluation tool for the wheel spacers based on manual tier-based scoring system, percentile thresholds and weight-based auto scoring functions efficiently for the thesis. However, the optimization tool has very specific boundary conditions to function which was specified for the reinforcement spacers. Therefore, this tool still can be used for other types of reinforcement spacers but need adjustments on sub-parameter equations if different simulation software then SolidWorks will be used. More proof-based manual tier-scoring can be possible for different building components that has wide range of scientific data available.

(4) The odorous behaviour of the injection molded samples hinting at the organic/inorganic contaminants were not additionally tested specifically for odour because of the selected application scenario. As the injection molded product is destined to end up at the concrete matrix during its' life cycle, the smell results were disregarded after concluding the occurence of the chemical smell. Additional gas chromatography or sensory testing at the SenseLab of TU Delft can be made if the same polymer input is considered to be used for future research.

5.4 Recommendations

For future research, there are several recommendations in regards to WEEE recycling and dealing with plastic recycling residues:

1. As polymer blending of cleaner and contaminated plastic shreds gave successful results by mixing two waste streams of WEEE and packaging plastics, a further analysis solely focusing on the mechanical behaviour of same final product with different waste stream plastics inputs is possible. This would compare the expected purity and contamination levels of plastic waste streams as well as give hints at the possible application scenario based on the mechanical tests.
2. If dealt with heavier waste inputs and plastic intakes, magnetic density separation needs to be considered. The company, myne, is currently collaborating with Civil Engineering Faculty of TU Delft for separating different materials. This can be a potential for plastics as the facility is already located at Stevin II Lab.
3. The hot pressing technique available at the Aerospace Faculty of TU Delft can be another processing alternative to injection molding, which may recover a higher content of plastics because of its flexible working conditions. With that, the use of compatibilizers or additives can be researched to be able to increase the final blending of different recovered polymer types.
4. As WEEE is one of the hardest plastic waste streams to deal with, the reject fractions and recycling residues from packaging waste can be a safer start for this new proposed recycling scheme and upstream sorting.
5. For future research that would like to focus on injection molding regardless of the final shape, there are several aluminum moulds at the MakerLab with an availability to pre-heat the moulds before injection molding. This wil not focus purely on product development but for testing the processability of polymer recipe close to the industry-scale techniques, the available moulds would be optimal.

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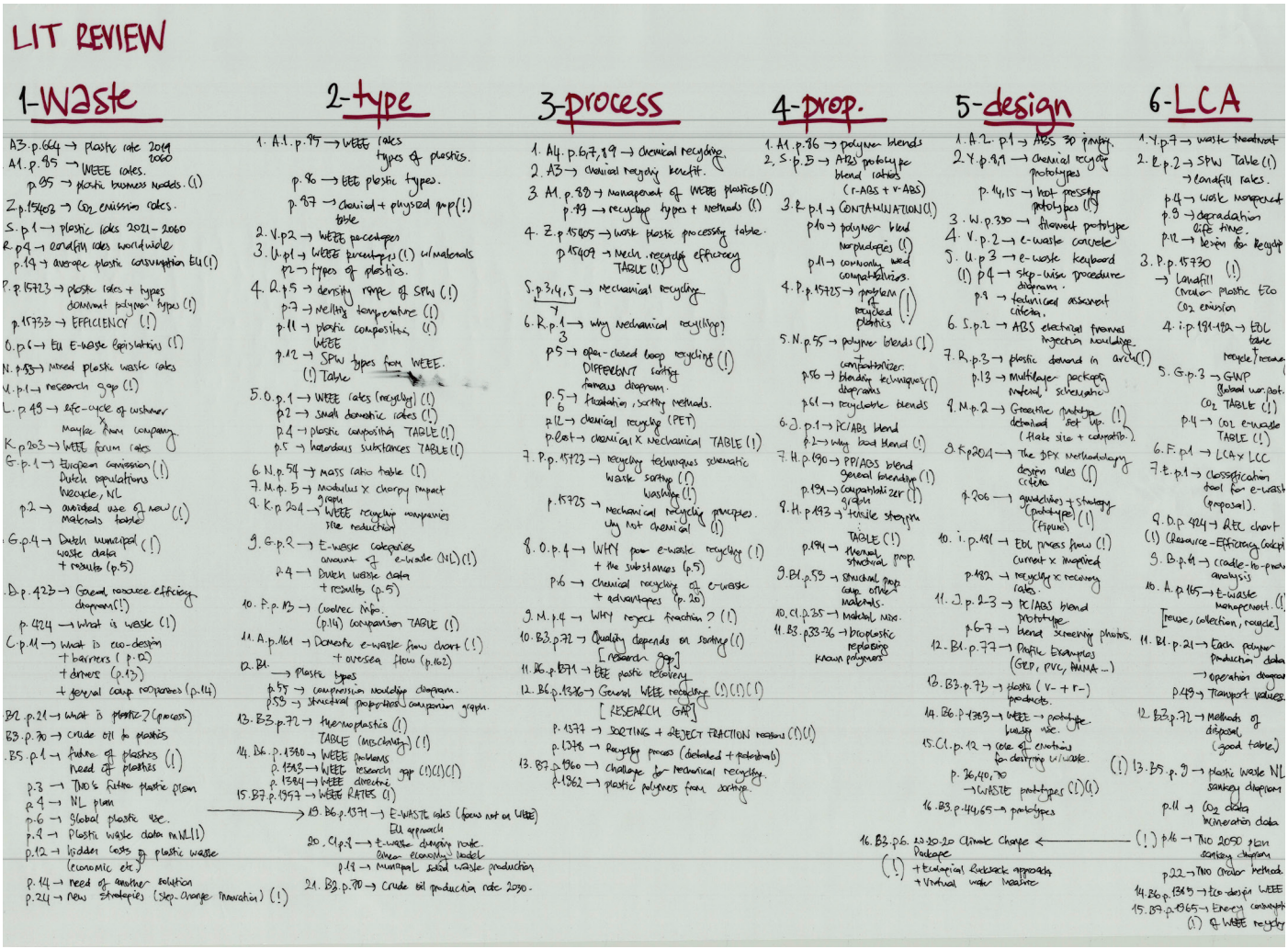
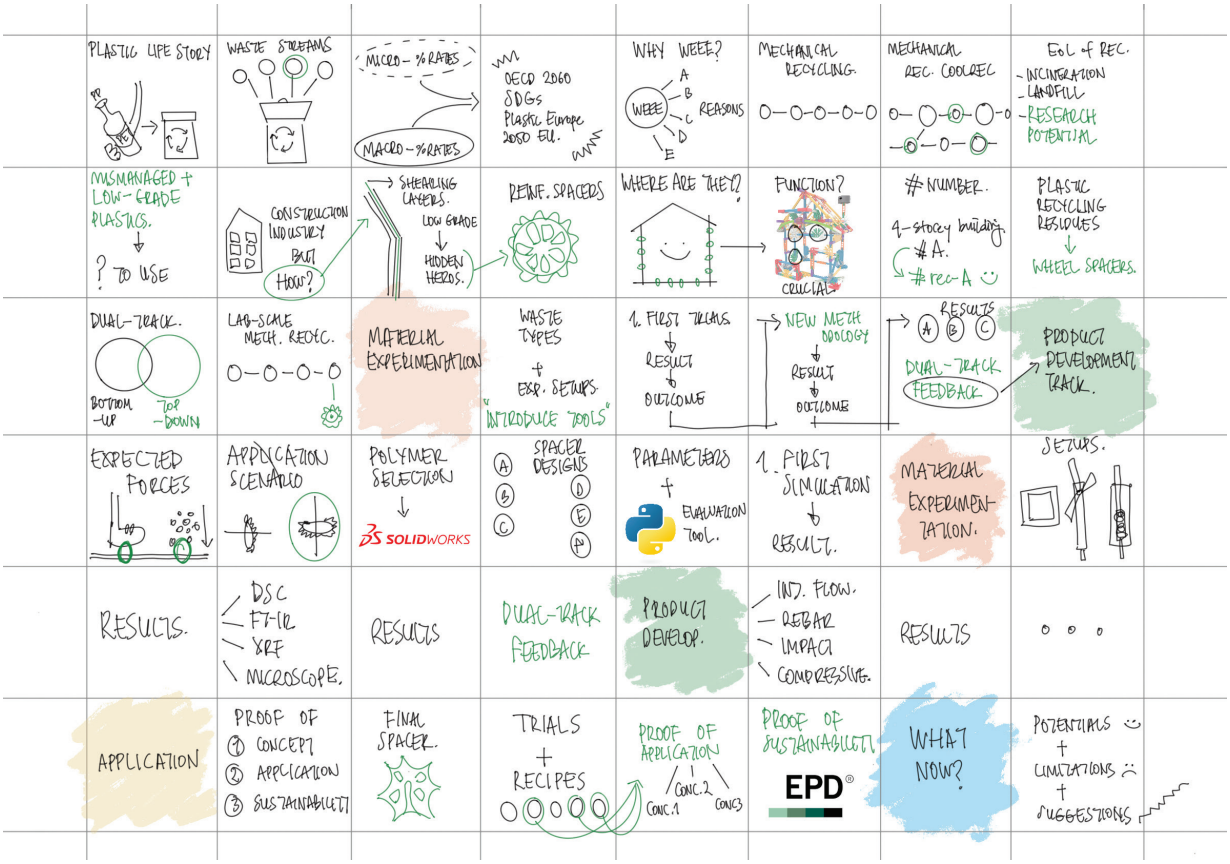
APPENDIX



Appendix.1 The literature review based on categorization

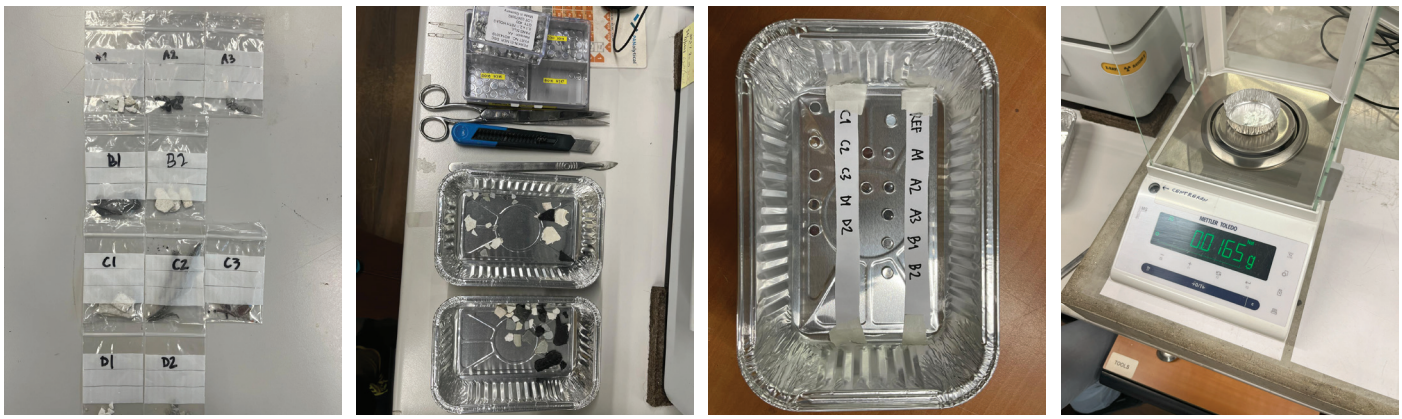


Appendix.2 The story line of the thesis

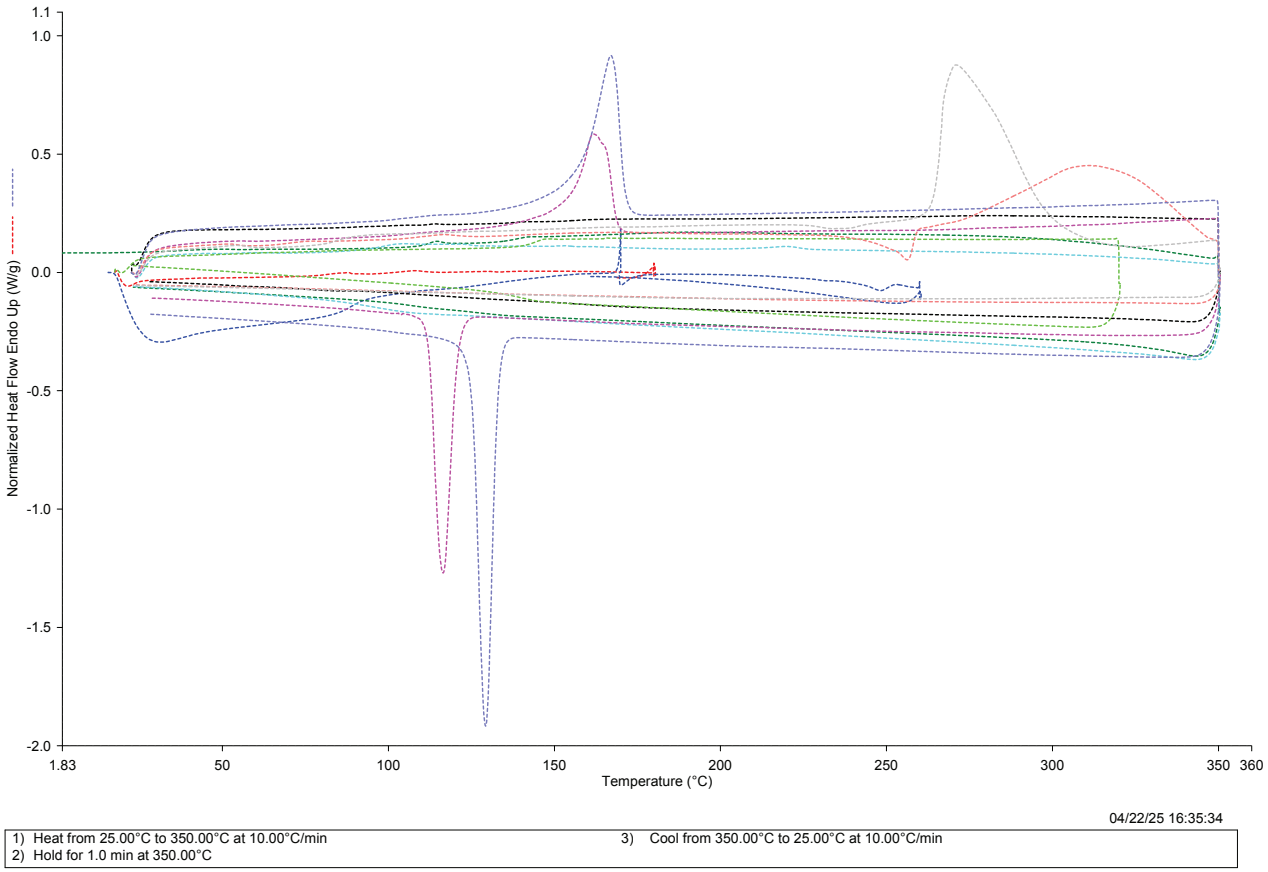
Appendix.3 Large-scale water separation steps (1)input weight, (2)density bath, (3) sink/floating fraction, (4) weighing floating fractions before drying

Appendix.4 Density separation results with (1) d: 1.13 g/cm³ (2) 1.10 g/cm³, (3) 1.05 and 1.10 g/cm³

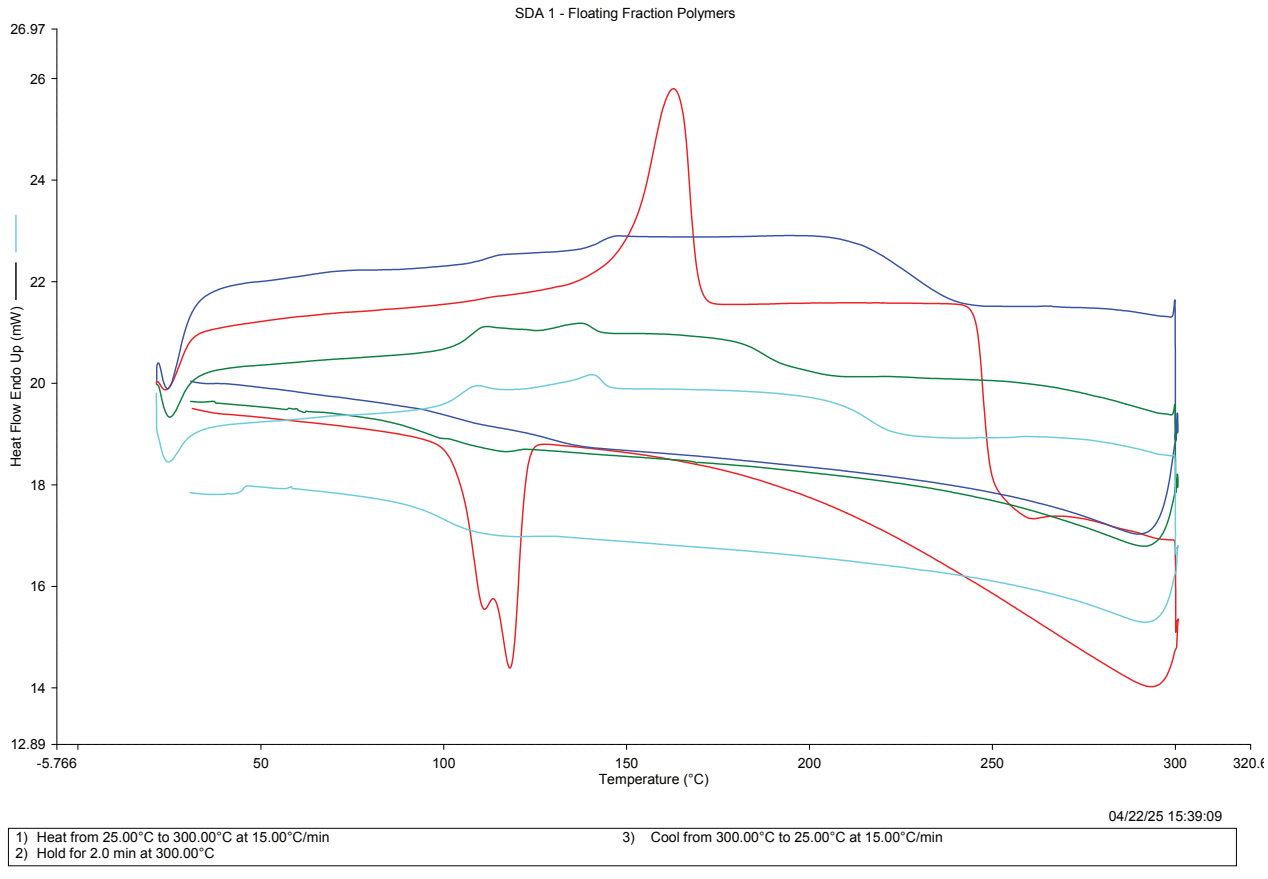
Appendix.5 The density separation setups done on Fridge1-2 and SDA-1 waste input



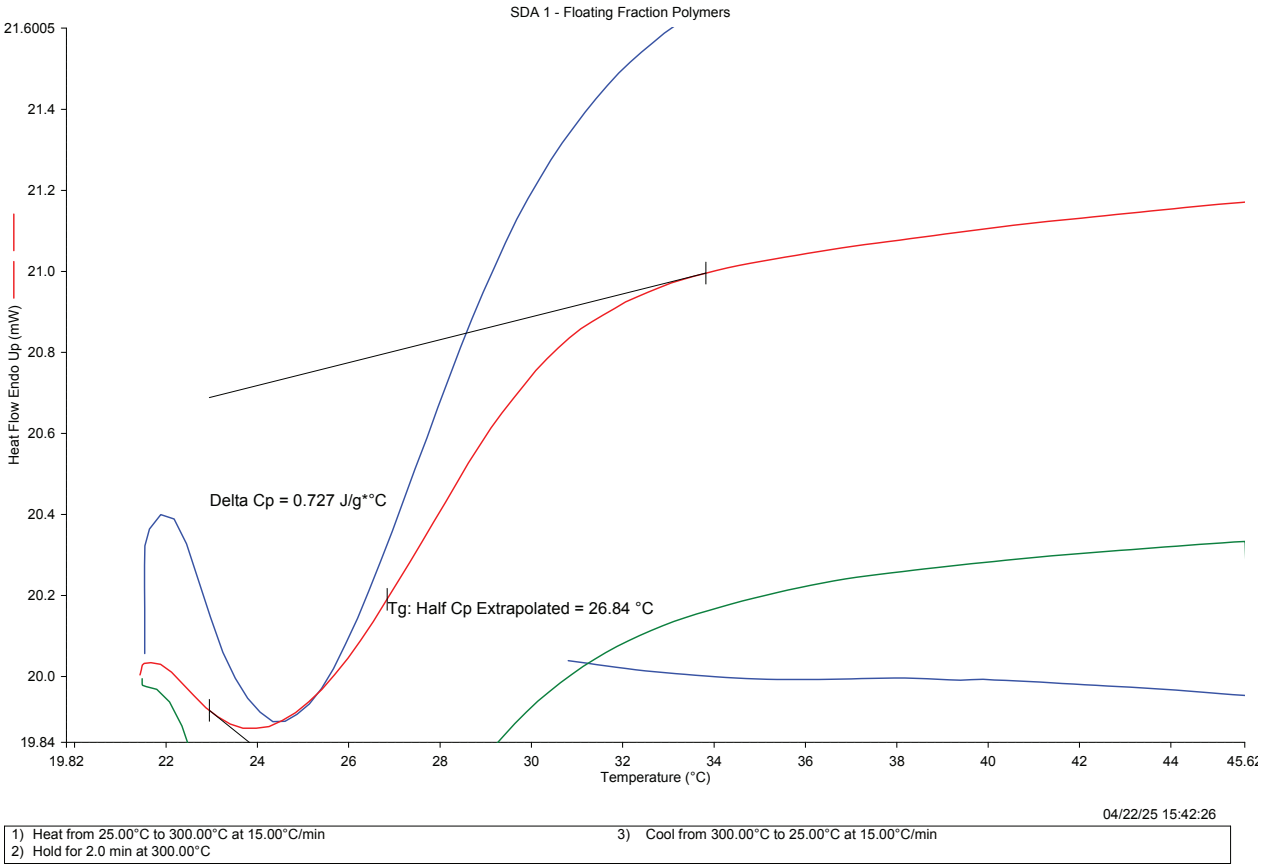
Appendix.6 DSC preparation (1) sample selection, (2) cutting samples, (3) sealing them inside a sample pan, (4) weight collection of each sample



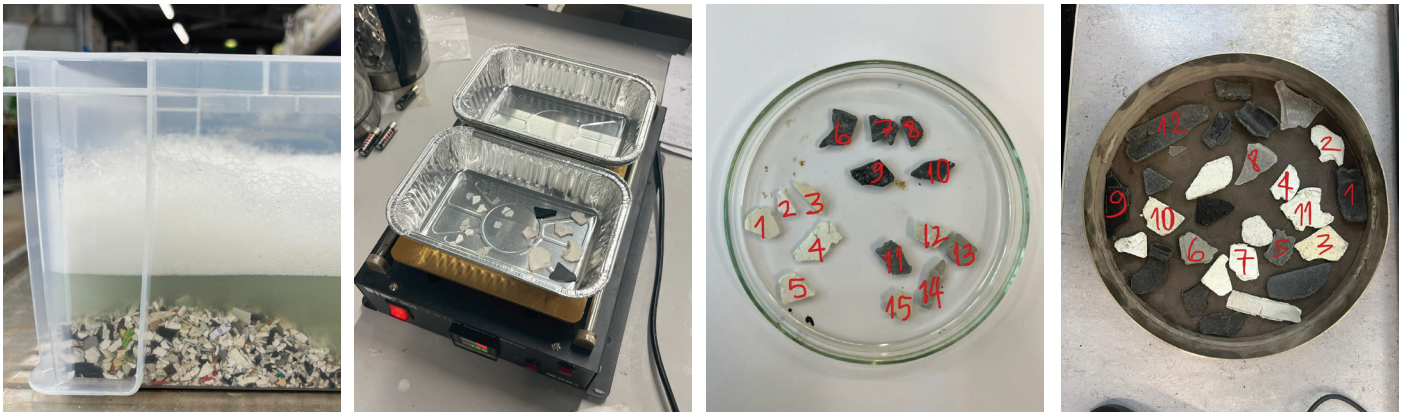
Appendix.7 DSC curves on the first experiment setup done on selected samples from each waste line



Appendix.8 DSC curves on the second experiment done for the samples of SDA-1

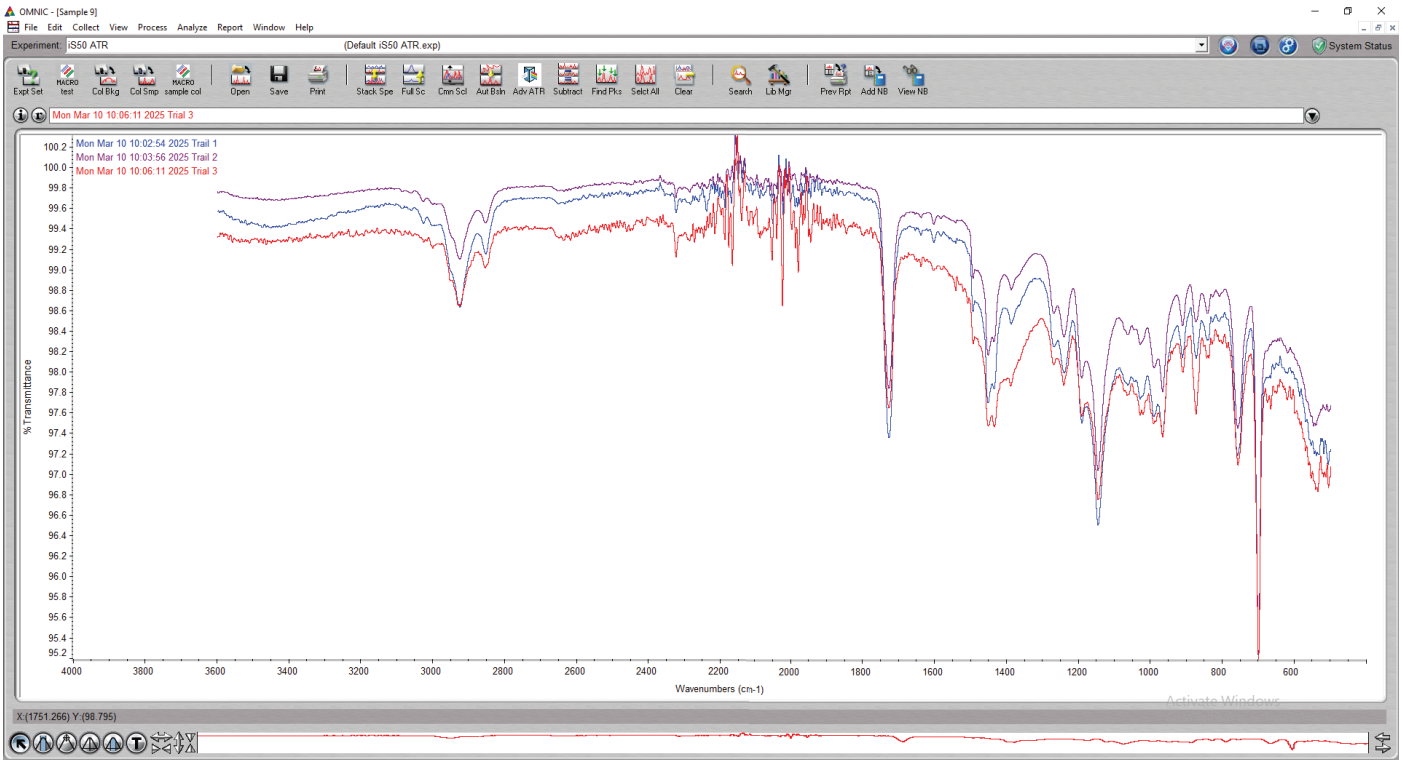


Appendix.9 DSC analysis showing the glass transition of SDA-1 Sample 16



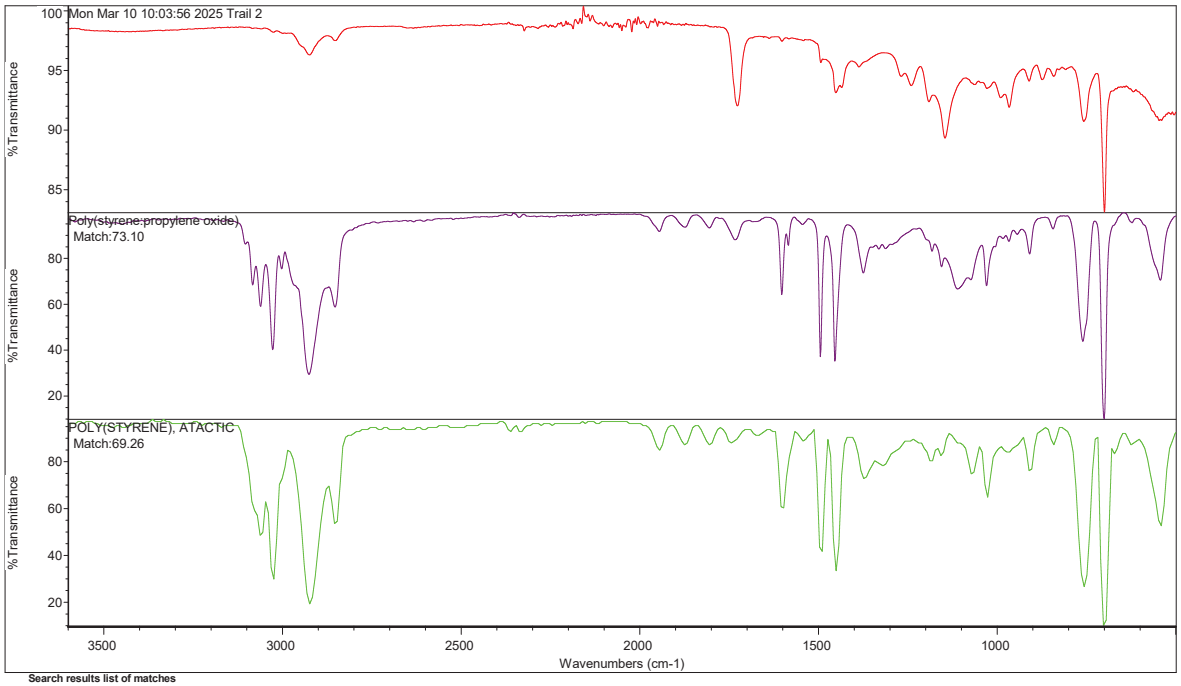
Appendix.10 FT-IR analysis preparation (1) washing samples with detergent, (2) drying the samples, (3)(4) numbering the sample before characterization

Appendix.11 The samples for FT-IR analysis (1) SDA-1, (2) SDA-2, (3) SDA-2, (4) Fridge-1 and Fridge-2



Appendix.12 The FT-IR curves for the 3 trials for density separated SDA-1 sample

Search results for: Mon Mar 10 10:03:56 2025 Trail 2
Date: Mon Mar 10 10:08:31 2025 (GMT+01:00)
Search algorithm: Correlation
Regions searched: 3949.50-455.13



Search results list of matches

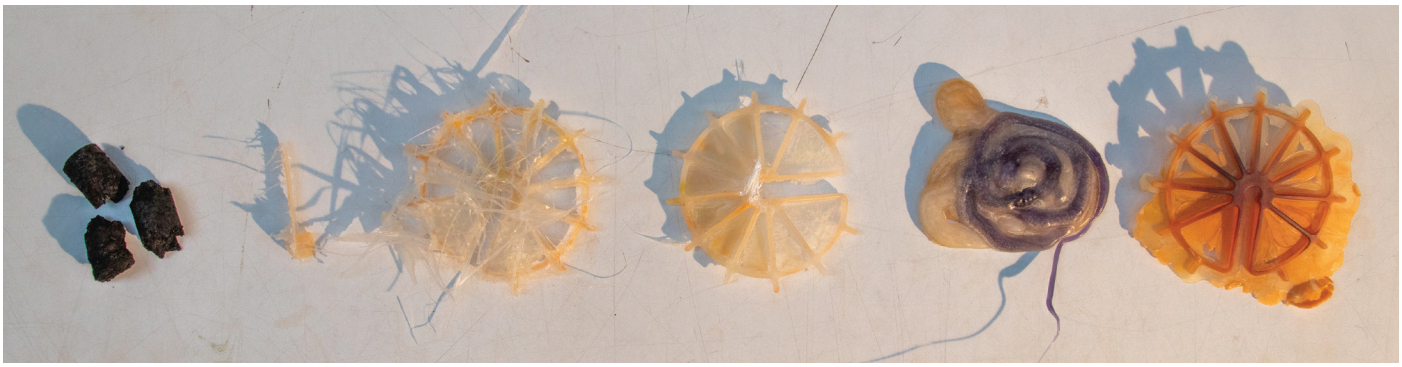
	Index	Match	Compound Name	Library Name
1	469	73.10	Poly(styrene:propylene oxide)	HR Nicolet Sampler Library
2	46	69.26	POLY(STYRENE), ATACTIC	Hummel Polymer Sample Library
3	523	66.96	Poly(styrene:tetramethylene)	HR Nicolet Sampler Library
4	683	66.92	Poly(butadiene:styrene)	HR Nicolet Sampler Library
5	471	66.09	Poly(styrene:methyl methacrylate:acrylonitrile)	HR Nicolet Sampler Library
6	692	66.03	Poly(styrene:a-methylstyrene:acrylonitrile:butadiene)	HR Nicolet Sampler Library
7	47	65.62	POLY(STYRENE:VINYLIDENE CHLORIDE)	Hummel Polymer Sample Library
8	734	65.26	Styrene butadiene block polymer	HR Nicolet Sampler Library
9	614	64.32	Poly(styrene:acrylonitrile:butadiene)	HR Nicolet Sampler Library
10	42	61.77	POLY(STYRENE:ACRYLONITRILE:MMA)	Hummel Polymer Sample Library

Appendix.13 Library search for 1/3 trials for one sample to record PS-match

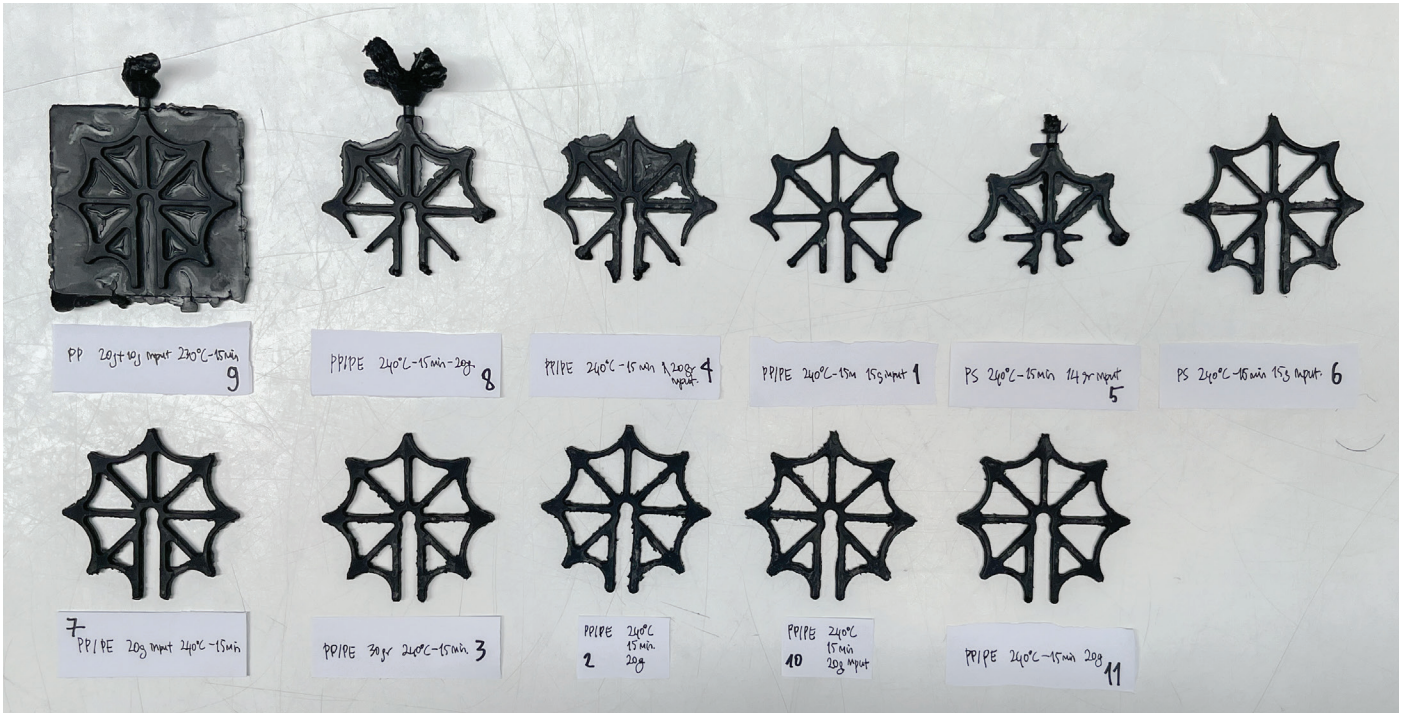
Appendix.14 Weighing each colour cateogory after manual colour sorting before FT-IR identification

Appendix.15 FT-IR identification process after manual colour sorting (1) FT-IR setup, (2) placement of plastic shreds to respective polymer category of SDA-2, (3) placement of plastics shreds of SDA-1

Appendix.16 The samples from manual press experiment setup during/post-processing

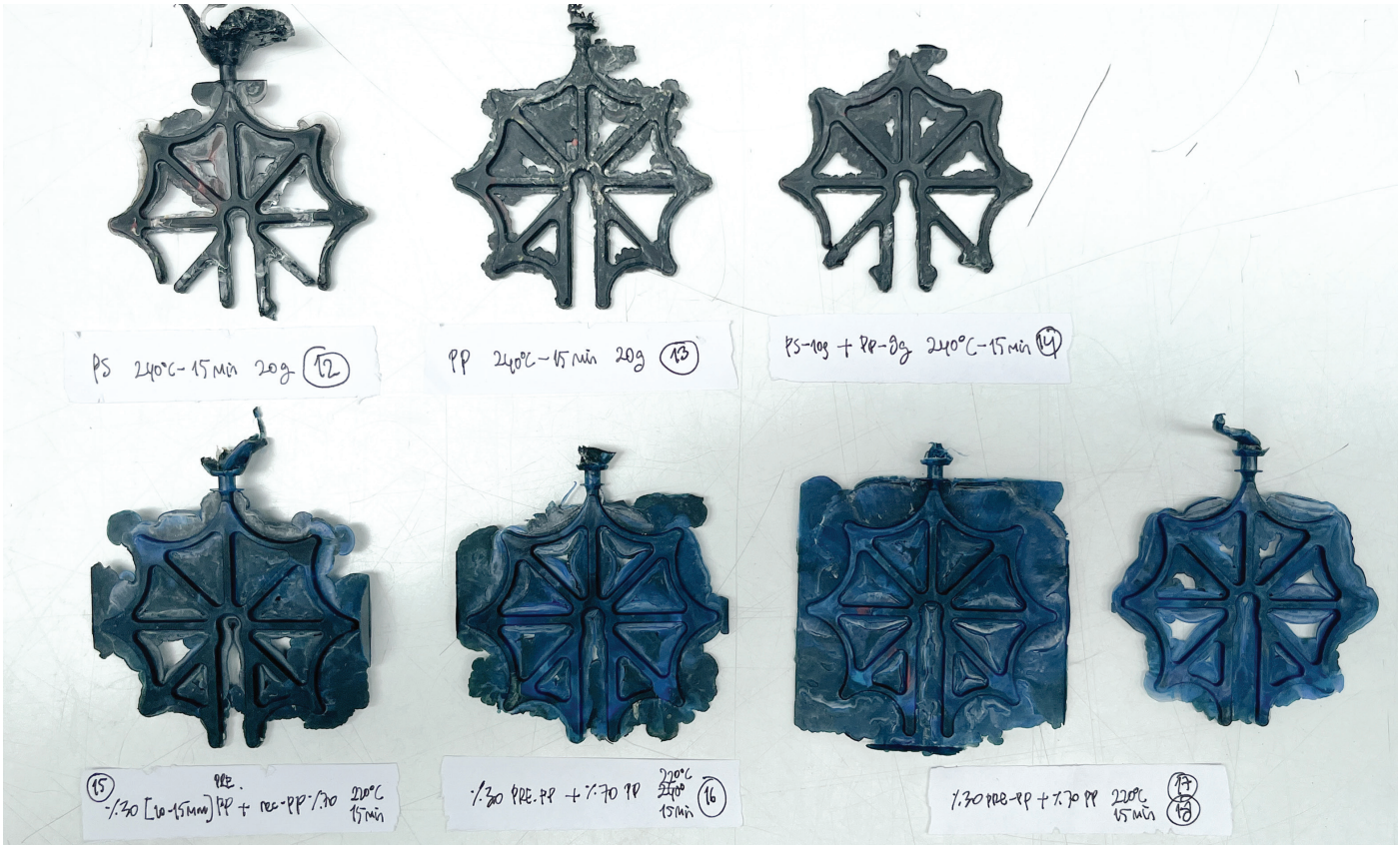


Appendix.17 The samples from pneumatic plunger-type injection molding



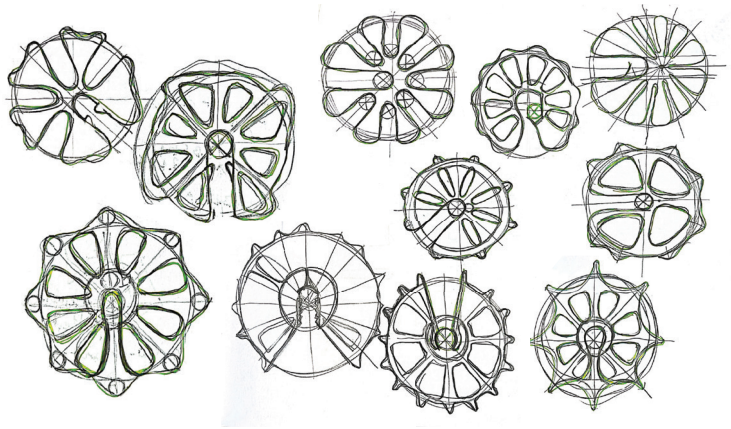
Appendix.18 The samples from the first trials of manual plunger-type injection molding for Spacer 10

Appendix.19 The samples from the second trials with polymer blending for Spacer 10

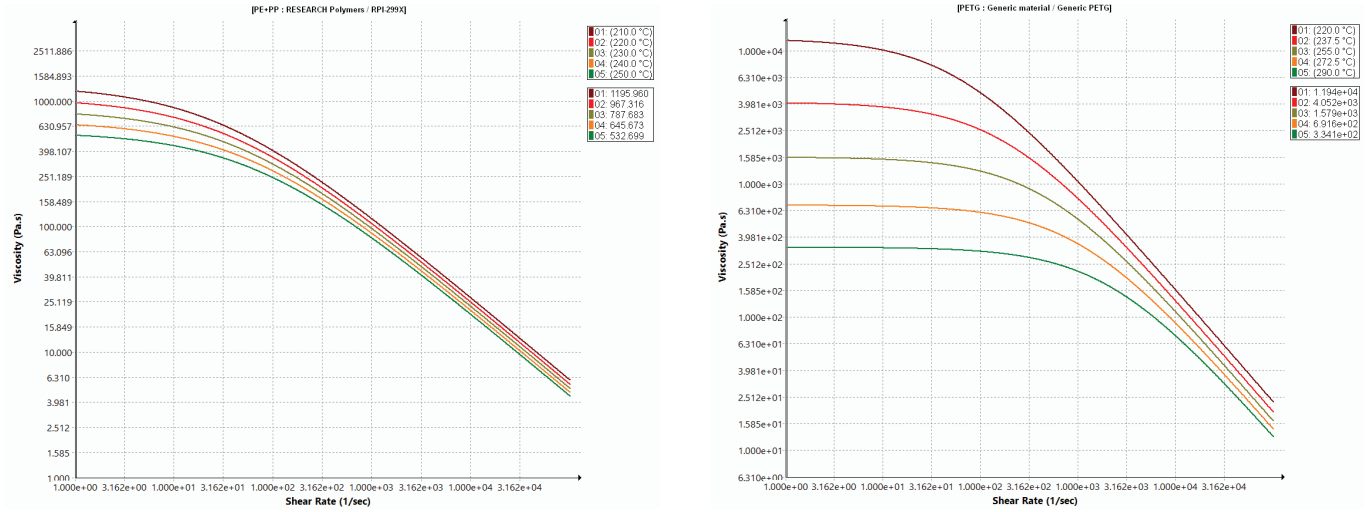


Appendix.20 The samples from the third and fourth trials with polymer blending for Spacer 10

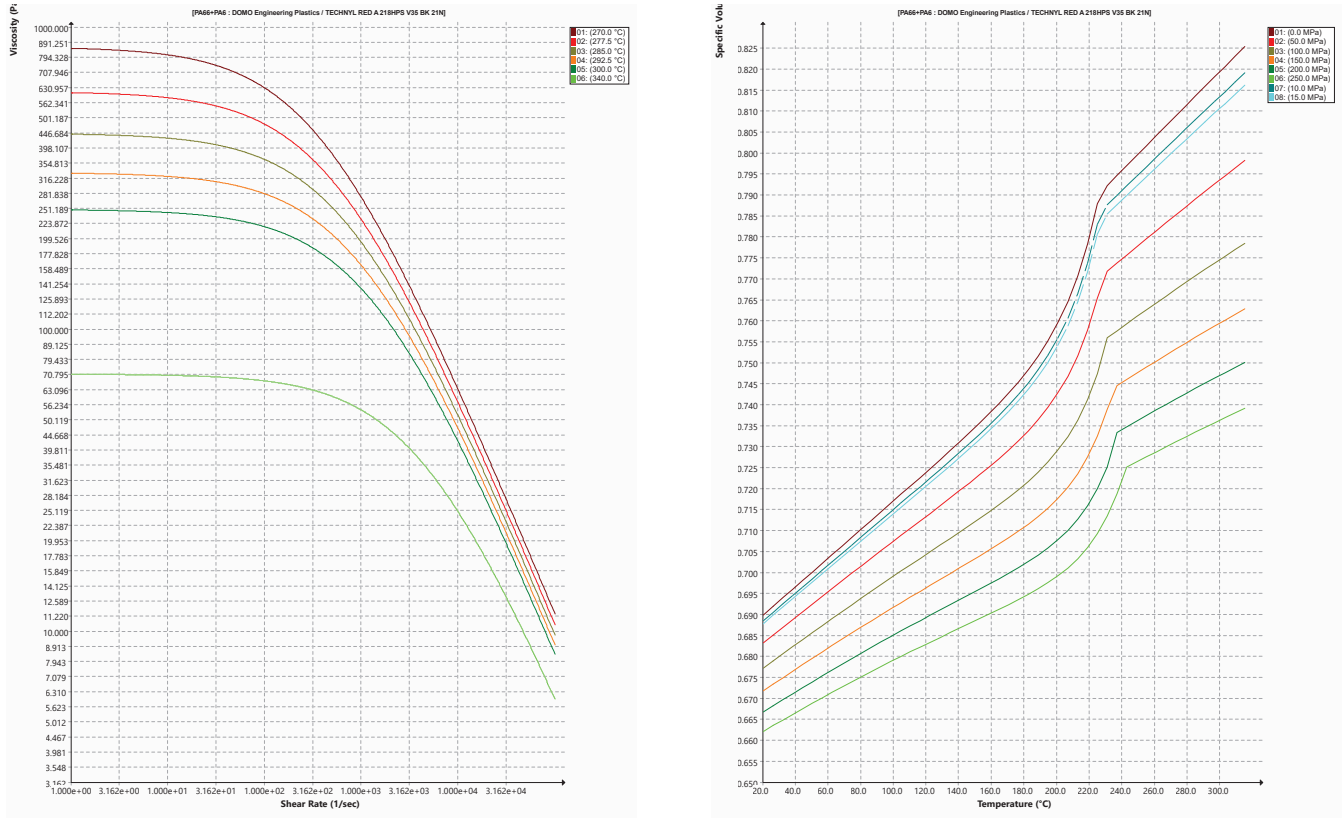
Appendix.21 Collected residues from the injection molding from the failed trials for Spacer 10



Appendix.22 The initial sketches of the wheel spacer designs



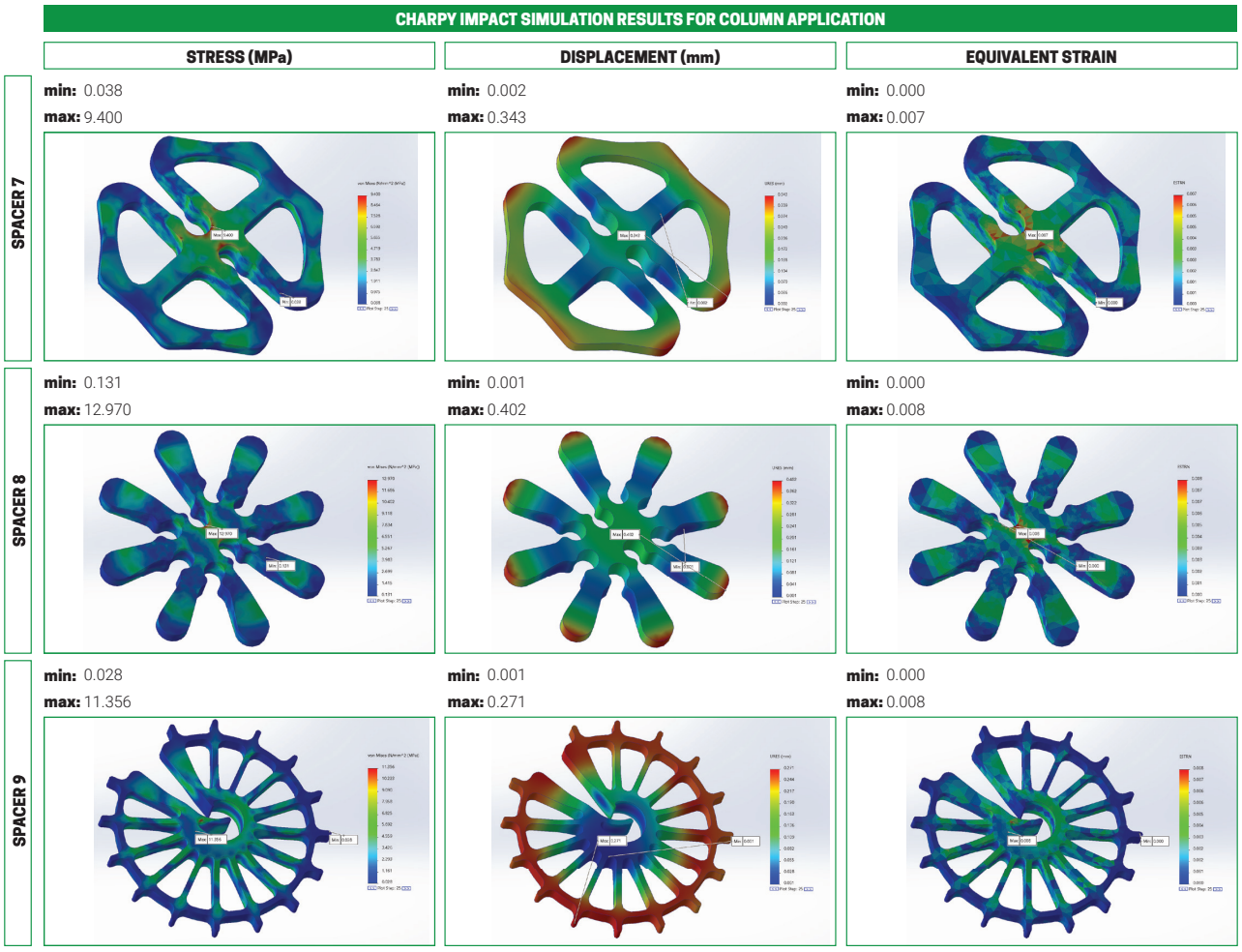
Appendix.23 Shear rate x Viscosity comparison between PP/PE and PET-G (Source: SolidWorks)



Appendix.24 For the first injection flow simulations the collected data on PA6/PA66 blend on (1) Shear rate x Viscosity, (2) Temperature x Specific Heat (Source: SolidWorks)

Design	Parameter	Sub-Parameter	Min/Max Value	Manual Tier Score	Auto Score	Final Score
Spacer 01	Compressive Test Analysis	Stress (MPa)	62.766	10	0	2.50
Spacer 02	Compressive Test Analysis	Stress (MPa)	52.219	7	0	1.75
Spacer 03	Compressive Test Analysis	Stress (MPa)	29.031	7	4	4.75
Spacer 04	Compressive Test Analysis	Stress (MPa)	22.47	7	4	4.75
Spacer 05	Compressive Test Analysis	Stress (MPa)	7.9	4	10	8.50
Spacer 06	Compressive Test Analysis	Stress (MPa)	5.323	4	10	8.50
Spacer 07	Compressive Test Analysis	Stress (MPa)	8.168	4	10	8.50
Spacer 08	Compressive Test Analysis	Stress (MPa)	11.367	7	7	7.00
Spacer 09	Compressive Test Analysis	Stress (MPa)	12.519	7	7	7.00
Spacer 01	Compressive Test Analysis	Displacement (mm)	3.505	7	0	1.75
Spacer 02	Compressive Test Analysis	Displacement (mm)	2.436	0	4	3.00
Spacer 03	Compressive Test Analysis	Displacement (mm)	3.044	7	0	1.75
Spacer 04	Compressive Test Analysis	Displacement (mm)	1.935	4	4	4.00
Spacer 05	Compressive Test Analysis	Displacement (mm)	0.956	7	7	7.00
Spacer 06	Compressive Test Analysis	Displacement (mm)	0.305	4	10	8.50
Spacer 07	Compressive Test Analysis	Displacement (mm)	0.743	7	10	9.25
Spacer 08	Compressive Test Analysis	Displacement (mm)	1.003	7	7	7.00
Spacer 09	Compressive Test Analysis	Displacement (mm)	0.689	10	10	10.00
Spacer 01	Compressive Test Analysis	Equivalent Strain	0.046	7	0	1.75
Spacer 02	Compressive Test Analysis	Equivalent Strain	0.033	4	0	1.00
Spacer 03	Compressive Test Analysis	Equivalent Strain	0.024	7	4	4.75
Spacer 04	Compressive Test Analysis	Equivalent Strain	0.017	7	4	4.75
Spacer 05	Compressive Test Analysis	Equivalent Strain	0.007	7	10	9.25
Spacer 06	Compressive Test Analysis	Equivalent Strain	0.004	4	10	8.50
Spacer 07	Compressive Test Analysis	Equivalent Strain	0.006	4	10	8.50
Spacer 08	Compressive Test Analysis	Equivalent Strain	0.009	7	7	7.00
Spacer 09	Compressive Test Analysis	Equivalent Strain	0.009	7	7	7.00

Appendix.25 The compressive strength analysis parameter table from Design Optimization tool



Appendix.26 Spacer 7-8-9 Charpy Impact simulation results with min/max numeric data

COMPRESSIVE STRENGTH SIMULATION RESULTS FOR COLUMN APPLICATION

	STRESS (MPa)	DISPLACEMENT (mm)	EQUIVALENT STRAIN
SPACER 1	**min:** 0.025 **max:** 62.766	**min:** 0.000 **max:** 3.505	**min:** 0.000 **max:** 0.046
SPACER 2	**min:** 0.002 **max:** 52.219	**min:** 0.000 **max:** 2.436	**min:** 0.000 **max:** 0.033
SPACER 3	**min:** 0.011 **max:** 29.031	**min:** 0.000 **max:** 3.044	**min:** 0.000 **max:** 0.024
SPACER 4	**min:** 0.003 **max:** 22.470	**min:** 0.000 **max:** 1.935	**min:** 0.000 **max:** 0.017
SPACER 5	**min:** 0.000 **max:** 7.900	**min:** 0.000 **max:** 0.956	**min:** 0.000 **max:** 0.007
SPACER 6	**min:** 0.000 **max:** 5.323	**min:** 0.000 **max:** 0.305	**min:** 0.000 **max:** 0.004

Appendix.27 Spacer 1-2-3-4-5-6 Compressive strength simulation results with min/max numeric data

MSc Thesis Report

REC-HERO