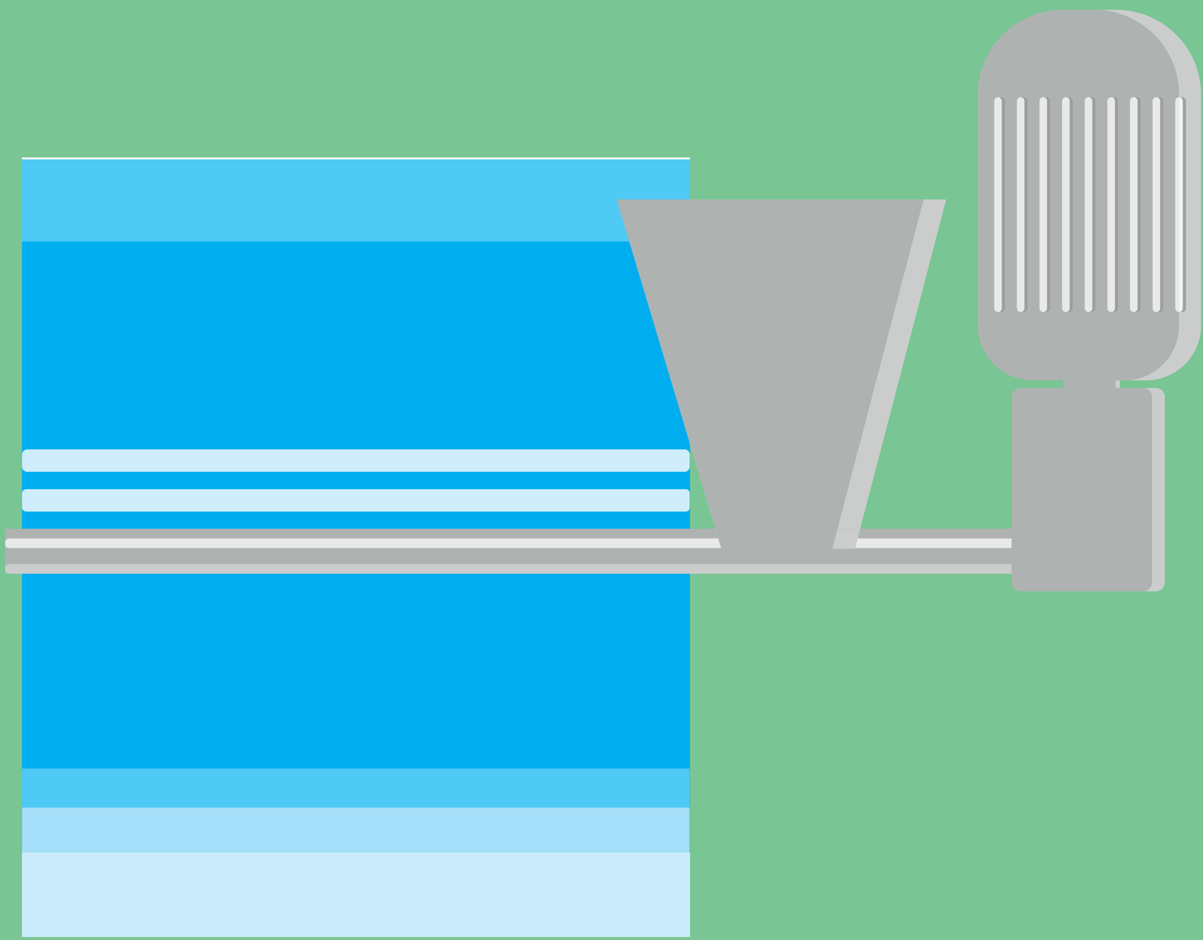
ARCHIMEDE

Research and design of a direct solar heated thermoplastic extruder for Ulundi Local Municipality.



ARCHIMEDE, Research and design of a direct solar heated thermoplastic extruder for Ulundi Local Municipality.

MSc Integrated Product Design
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SUMMARY

As we all know, plastic pollution is a global problem that is constantly growing, with adverse effects on societies, humans, and wildlife.
Many initiatives are focusing on reducing and lowering the effects of plastic pollution. Nevertheless, this phenomenon is growing on a daily basis.

Most of the harmful effects of plastic pollution are found in low and mid-income countries, where waste management is lacking because of the scarcity of infrastructures and recycling facilities. On the other side, since they are located in equatorial zones of the globe, these countries hold a very high potential, the solar heat.

This graduation aims to explore the direct solar heat in the plastic recycling field, to validate its feasibility, and develop a concept for a solar-heated extruder that is feasible, viable and desirable for the Ulundi Local Municipality, the working frame for the graduation project.

The project described in this report consisted of a product-service that can be implemented to allow villages and suburbs to recycle plastic. The main outputs of the project are:

Plastic Extruder:
The solar-heated plastic extruder is the core of the graduation. It allows the entire service to work and has been designed after different iterations, tests and research.

Service and Business Model
The service combined with the business model would allow the extruder to be easily implemented in Ulundi Local Municipality and make an impact desirable from the local communities.

Development Roadmap
Given the project's magnitude and the impossibility of having an implemented design in the graduation timespan, a development roadmap has been designed to guarantee the possibility of implementation of the Product-Service.

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This chapter provides an overview of the project. It explains why the project started, the prior work worth mentioning and the importance of a solution.
Lastly, it explains the methodology approached in this project.

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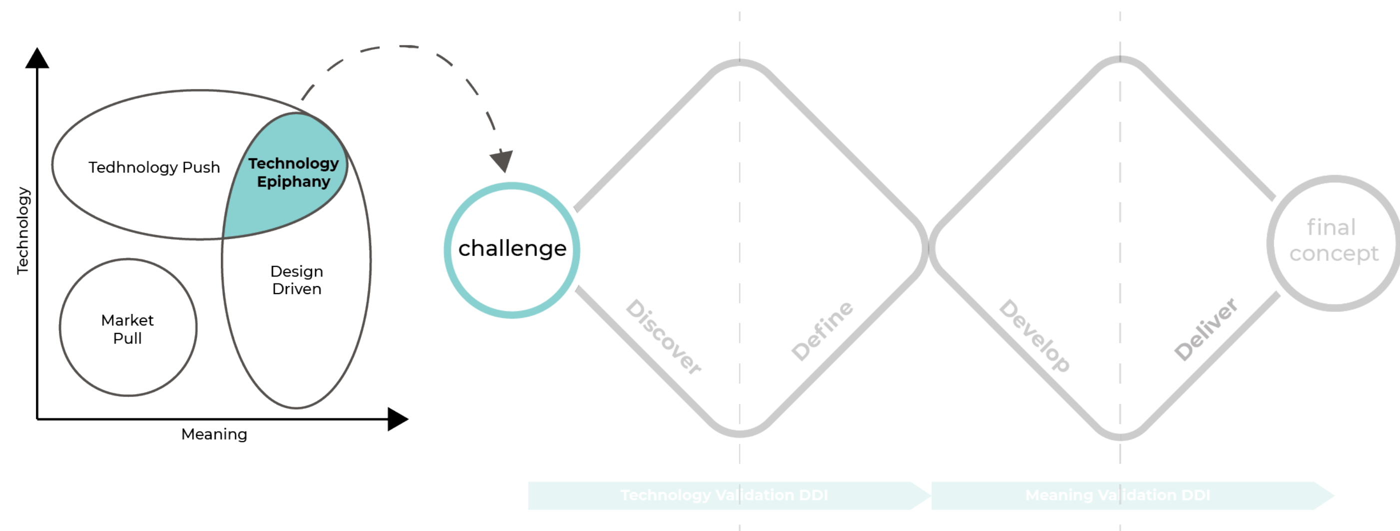
3. Approach



1. Inrtoduction

From its invention and introduction in everyday products, the production of plastic has risen at an exponential rate. Its cumulative production volume doubled, from 3.5 billion tonnes to almost 8 billion tonnes only from 2000 to 2015. (Geyer et al. 2017)
As the following chart shows, retrieved from the same study, the tendency in plastic recycling is growing; however, only a tiny percentage of plastic is being recycled. In 2015, only 19% of the plastic was recycled.

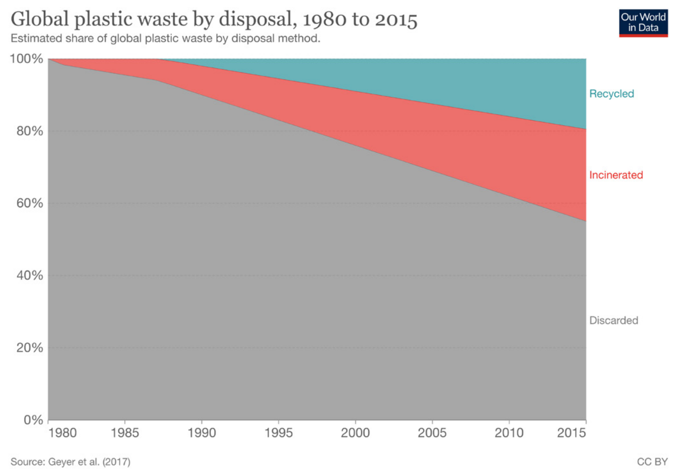


Figure 1: Global plastic waste by disposal

Furthermore, according to research from Jambeck et al. (2015), most of the mismanaged plastic waste is located in Low and Medium Income Countries, as shown in the following image.

However, collection logistics and infrastructure requirements are barriers to recycling in rural areas and developing cities (Guerrero et al., 2013).
When reanalysing the countries mentioned above under an energetic solar point of view, we can easily state that, since they are located in equatorial zones of the world, they hold a high energy potential, as shown in the following map, retrieved from Solargis.com.

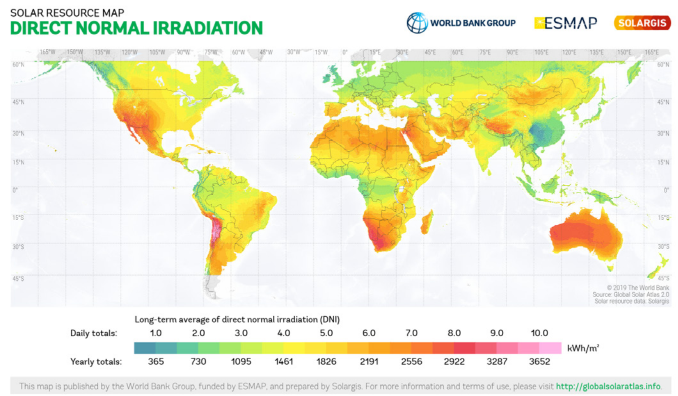


Figure 3: Direct normal irradiation World Map

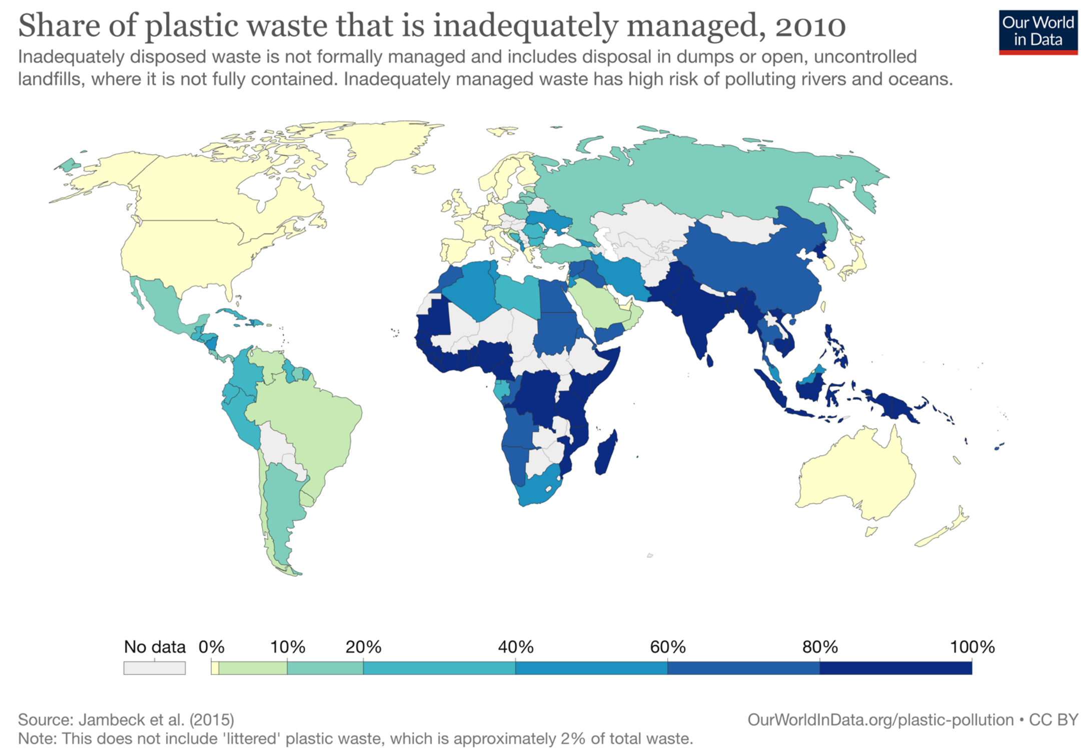


Figure 2: Share of mismanaged plastic

In this specific case, the working frame of the graduation project is Ulundi Local Municipality. A city located in South Africa where the annual 24-hour global solar radiation average is about 220 W/m2, compared with about 150 W/m2 for parts of the USA and about 100 W/m2 for Europe and the United Kingdom. (SA Department of Energy)

The factors mentioned above led to the idea of using solar heat to provide, to Low-Income Countries like South Africa, a technology to recycle plastic.

The principle behind this project is to substitute the electric heating elements in a thermoplastic extruder with a parabolic concentrator that would collect the right amount of solar heat in order to melt the plastic present in the extrusion barrel; which is located in the focus of the parabola. The following image gives a representation of the principle.

Parabolic Mirrors have been chosen over photovoltaic panels for several reasons:

Direct solar heat has a higher efficiency when compared to photovoltaic panels since energy dispersion occurs in every energy conversion. In this specific case, the energy would be converted three times Lightray to electricity - Electricity Accumulated in batteries and Electricity to Heat.

Moreover, concentrating mirrors to collect heat makes the process more sustainable when compared to PV.
One of the sustainability problems nowadays is conceiving it in a compartmentalised way, recycling plastic or consuming less co2 but rarely both at the same time. From a personal point of view, sustainability has to be approached more holistically and systemically.
The given reason led to the decision to use mirrors instead of Photovoltaic Panels and accumulators to avoid complex productions challenging to recycle.

This graduation aims to explore the just mentioned principle, validate its feasibility, and develop a concept for a solar-heated extruder that is feasible viable and desirable for the Ulundi Local Municipality.

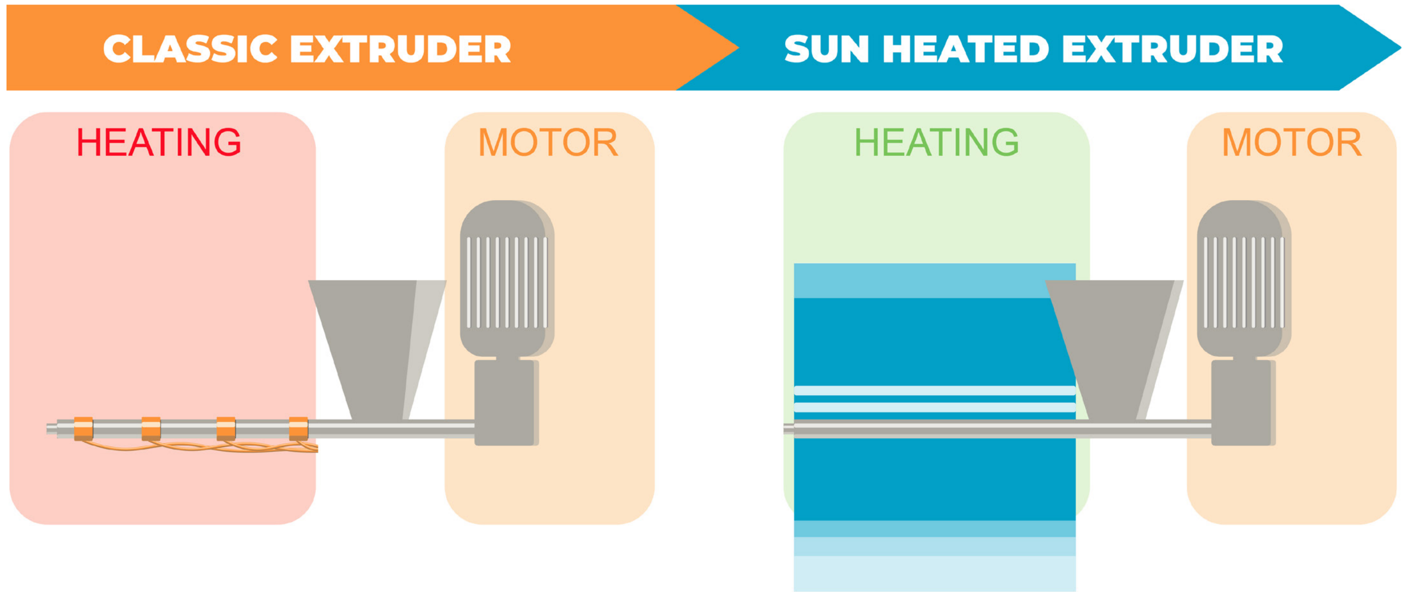


Figure 4: Solar Hated Extruder Concept

2. Prior Work

Before focusing on research it is important to have an understanding of three important case studies that influenced and inspired the project in a prior ideation phase.

2.1 PRECIOUS PLASTIC

Precious-Plastic is a model of an open-source digital commons project based on open hardware plastic recycling. It is based on machinery and tools that grind, melt, and inject used plastic, enabling the small-scale production of new items from recycled plastic. Individual consumers can set up "their own little recycling company" as part of the project. The Precious Plastic Extruder Pro (shown in the following image) has been considered in this specific case. A detailed description of the extruder and its benchmarking is presented in chapter 6 and appendix C.

Figure 5: Precious Plastic Extruder Pro

2.2 PARABOLIC TROUGH PRINCIPLE

The sunlight that reaches earth, even if it appears extremely hot, does not contain sufficient energy in the actual form to generate thermal power. The sunlight from a large area must be concentrated to use its high potential. The parabola has the most potential to concentrate the solar rays for the properties embedded in its shape. As the parabolic reflectance principle explains, every light ray that enters it travelling parallel to the axis of symmetry is reflected toward the focus, as represented in the following illustration.

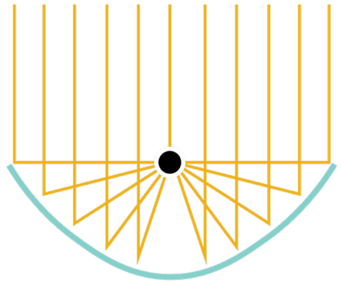


Figure 6: Parabolic Principle

Applications

The process mentioned above is mainly used in the energy production field, but recently it found its applications in a few consumer products.

2.2.1 PARABOLIC TROUGH COLLECTORS, PTC

In the electricity generation field, the energy concentrated by the parabolic reflectors is used to heat a fluid. The hot fluid can be injected into a heat engine, converting the heat energy into mechanical power or electricity. One of the biggest and the most efficient PTC plants is the Mojave solar plant in California, with an energy production of 250Mw per year(energy.gov).
The efficiency of the PTCs is influenced by several environmental factors and also by the construction properties of the system; those elements are further analysed in Appendix B and Chapter 6.

2.2.2 CONSUMER PRODUCTS

Several consumer products have introduced solar trough technology in the last decade. These items are mainly related to the cooking field; the most common are solar ovens produced by Gosun (2021) and solar lighters. These specific kinds of cookers allow independence from electricity moreover avoiding any combustion, as the one shown in the following image.

Figure 8: Gosun Solar Oven

2.3 RESEARCH FROM SWEDEN

Experiments on parabolic trough collectors for polymer melting were performed in 2018 by a group of researchers from Stockholm (Mewes & Sujessy, 2019). The research consisted of designing and testing a parabolic trough collector in two different locations, Sweden and Greek, in order to discover the possibility of recycling plastic via PSC without any specific application.

Figure 7: Parabolic Trough Collectors

3. Approach

The methodology adopted in the graduation project combines DDI, Design Driven Innovation, and a Double Diamond Process. The entire process has been approached following the three HCD, Human Centred Design, milestones: Feasibility, Viability and Desirability.

3.1 DDI

"In conventional product development, companies look for new technologies that will better serve the current needs of their customers. But if they want to create breakthrough products, they should seek to understand how those technologies could be used to address needs that customers may not realise they have."
"Roberto Verganti"

As stated in the previous quote, sometimes the user does not still know what it needs; a classic HCD approach is sometimes not enough to create new meanings. Moreover, as Verganti (2009, p. 4) stated, "people do not buy products but meanings" the creation of meaning is crucial to have a successful implementable innovation.
This approach was the foundation of the earliest stages during the graduation process, before the Project Brief Definition. Indeed, as Verganti describes it (2009 p5 450), Design-Driven Innovation can be considered the very first phase of a design process. Its goal is to open opportunities before thinking about the product or solution to be developed.

Nevertheless, the DDI approach is considered during the entire process, the first diamond aimed to evaluate the meaning on a technological level (Technology Push), the second part focus on the validation of the given idea on a meaning level (Design Driven) in order to reach a Technology Epiphany at the end of the

3.2 DOUBLE DIAMOND

After the project brief definition, the organisation of this project is based on the double diamond process (Design Council 2007). This approach divides the project into four phases, Discover, Define, Develop and Deliver. This methodology allows working on evident results in 100 days. During the 100 days, the main goal has been to research and evaluate the

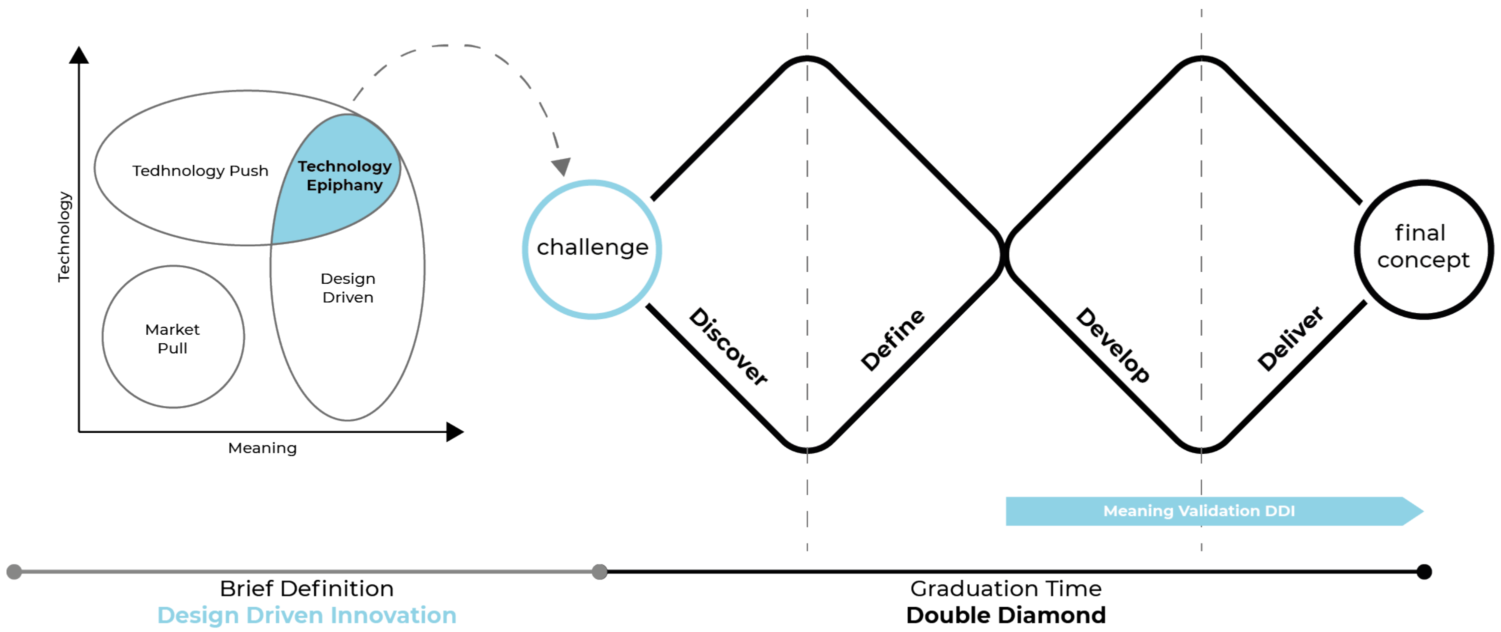


Figure 9: DDI and Double diamond Combination

possibility of using direct solar heating for plastic extrusion to design a feasible, viable, and desirable concept for Ulundi LM.

Discover: This phase includes multiple analyses and researches that dive deeper into the current situations and technologies. This phase's last but most important inputs are preliminary calculation and a test.

Define: All the insights collected in the discovery phase are collected and evaluated in this phase. The given insights transmuted in requirements allowed the design of two concepts, then evaluated and selected.

Develop: The chosen concept is analysed and developed on the three HCD milestones during this step. This step consisted mainly of different expert interviews, a simulation of the system's physical behaviour, and a business model's design.

Deliver: In this last phase, all the improvement and development done in the second diverging phase will be concentrated into a Final Concept and a Product roadmap as a starting point for further developments

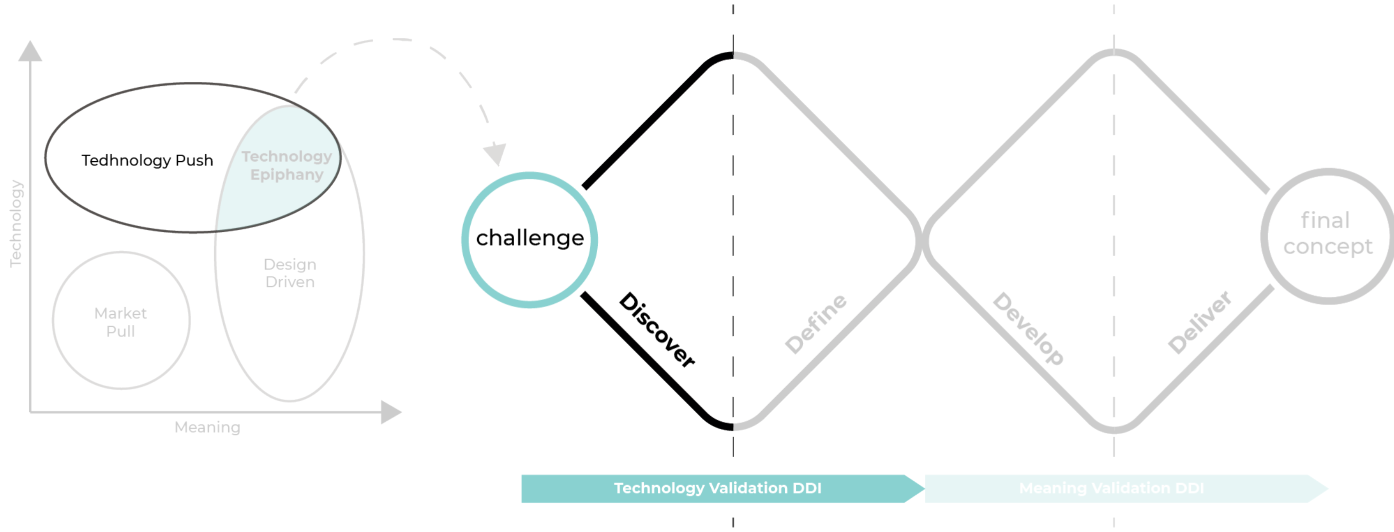
Moreover, through the three HCD principles (feasibility, viability and desirability), the last two phases will focus on the research and defining the meaning founding value of the DDI Method (Verganti, 2009) to verify the natural appeal of this Idea.

As the methodology, the report organisation is conceived by following the same steps.

DISCOVER

This chapter aims to understand the current challenges to face during the project. A first contextual analysis of the working frame is conducted to understand the possibilities and requirements of the user scenario. Then research on the technologies involved in the design will allow having a deep understanding of those and their relative challenges and opportunities.
Moreover, a preliminary physical model has been created to understand the physics involved in this product clearly; some preliminary test has been conducted to verify the physical model and discover other issues and requirements needed in the final design.

In this chapter:



4. Context: Ulundi LM

The following study aims to acquire the required knowledge to understand the project working frame, Ulundi, his relevant waste problem, the stakeholders involved in the waste management and his solar energy potential.

4.1 INTRO

The Ulundi Local Municipality (ULM) is the work frame for the graduation project. Ulundi LM is a town in the Zululand District Municipality, Mahlabathini. Zululand District Municipality comprises five local municipalities, where nearly 50% of their land is also under the jurisdiction of traditional authorities, while the remaining is divided between commercially owned farms and conservation areas.

Figure 10: **Kwa Zulu Natal Region, Encyclopedia Britannica**

4.2 WASTE MANAGEMENT

South African rural communities are among the poorest human settlements in the world, with little access to jobs and educational possibilities(Gopaul 2006). Many of their settlements are impoverished, filthy, and lack modern infrastructure, including telecommunications, water supply, roads, schools, industries, health facilities, and waste management.(Van der Merwe, H.; Steyl, I. 2005)

Waste management is an important issue in the entire ULM but mainly for the inhabitants of rural areas and city suburbs. A significant number demonstrates the severity of the problem: 74 per cent of households outside the city centre do not have access to waste disposal services. (Waste Management Report Ulundi LM 2017).

4.2.1 Plastic Recycling

As stated in the WWF Plastic: Facts and Futures(2020), the current South Africa Plastic Economy is based on a "take-make-waste" approach, also known as linear consumption flow. Almost half of the goods consumed are designed to have a limited lifespan, and the principal waste management techniques are landfilling or open dumping. (WWF 2020)

Nevertheless, plastic recycling is becoming every year a more common practice in South Africa. In 2019, South Africa recycled 352 500 tons of plastics back into raw materials, 14 755 tons were sold to converters outside of South Africa, whereas 337 745 tons were recycled in the country. (Plastic Recycling Survey SA 2019)

The distribution of plastic recycling facilities is concentrated in only a few regions of South Africa. Gauteng has 52% of the recyclers, which recycled 60% of the tonnages in 2019.

The Western Cape has a higher proportion of more prominent recyclers (tons per recycler) than other provinces, accounting for 11% of the total number of recyclers and recycling 14% of total tonnages. (Plastic Recycling Survey SA 2019)

4.2.2 Types of plastic

The most common recycled polymer is LD-PE AND LLD-PE; in 2019, 120 000 tonnes were recycled; moreover, three other common polymers recycled are PET, HD-PE and PP, of which each one in 2019 was recycled an average of 60 000 tons. (Plastic Recycling Survey SA 2019) 70% of the recycled plastic comes from post-consumer usage.

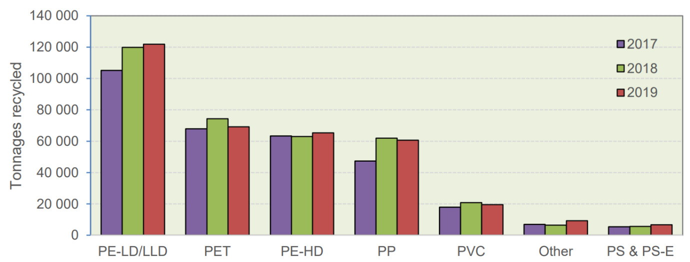


Figure 11: **Plastic recycled in South Africa in 2019, in tonnages**

Furthermore, In the following bar chart, retrieved from the same report, it is better analysed which polymer is present in which kind of disposed of items, as already mentioned before we can notice that most of the volumes are derivative from post-consumer goods.

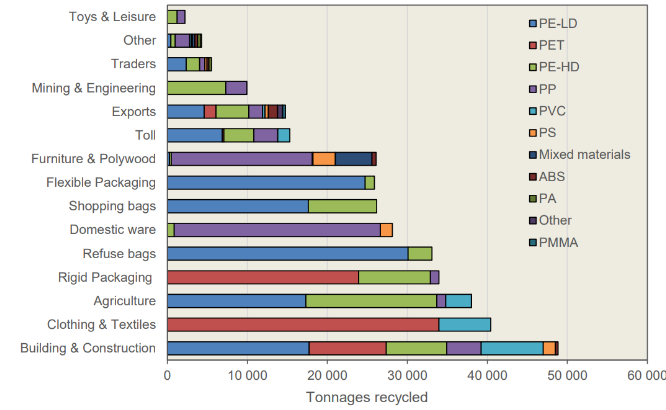


Figure 12: **Plastic waste sources, SA Plastic Recycling Survey**

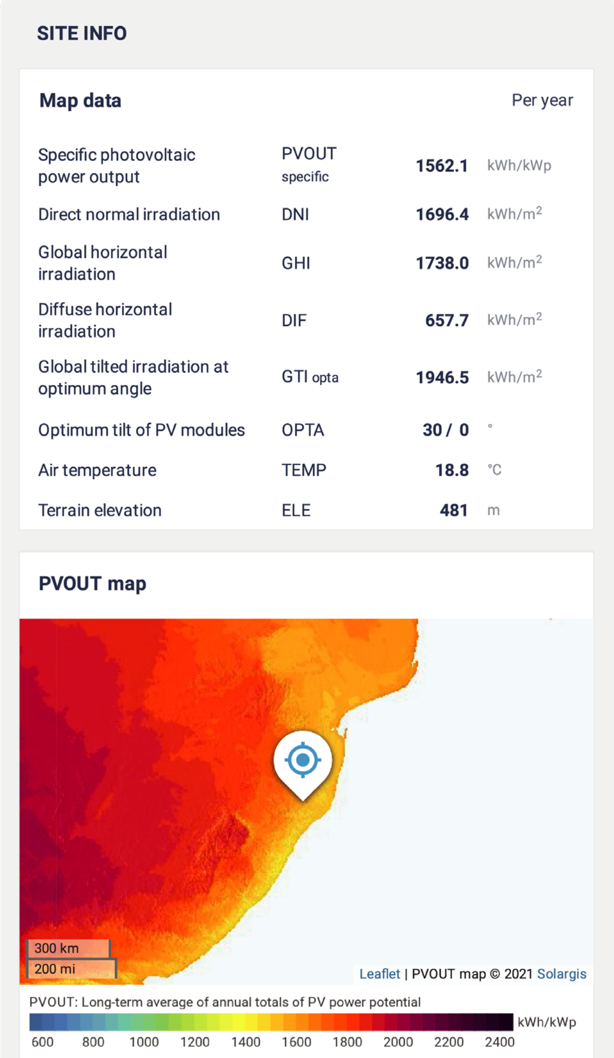
4.2.3 Inhabitants and Recycling

In Ulundi, but common in all South Africa, a phenomenon is informal waste picking. In Ulundi, 49,4% of the population is unemployed (Ulundi Local Municipality - Demographic, n.d.). A study by Dlamini B.R is resulting that for most of the unemployed inhabitants are informal waste pickers, waste picking became then a full-time job for most of them as an instance, in the study group from Dlamini, only 2 people out of 122 are employed, the rest of them are self-employed as a waste picker.
More than 55 per cent of participants earned less than R1000 (USD 75.5), while 32.5 per cent earned between R1 500 (USD 113.3) and R5 000 (USD 377.9). Only a tiny percentage of respondents (1.6%) had an income of at least R5 000, which explains the high incidence of poverty in these places.
Moreover, according to Dlamini et al.(2017) survey on Community Residents Waste Management Perception in KwaZulu Natal District, 98% of respondents affirmed that they were not active in any waste-recovery programs in their communities. However, 51.4% of them were eager to join in such activities when given a chance.

4.3 SOLAR ENERGY

When considering South Africa from an energetic point of view, we can state that it is a very controversial country since it holds a high sustainable energy potential (Pegels 2010) but still relies on unsustainable energy sources. (Department of Energy, Republic of South Africa.) For instance, 77% of South Africa's energy needs are derived from coal. Specifically, 92% of coal consumed on the entire African continent is mined in South Africa; in 2006, 80% of exported South African coal went to Europe.
Furthermore, in all the South African regions, access to energy is the least common in Kwa-Zulu Natal, where only 83,5% of households have access to electricity. (TUDELFT STUDENTS RESEARCH)

Solar power is the most promising among the different sustainable energy sources because of its geographical position. South Africa is among the top three globally, with an average of 2,500 hours of sunshine per year and 4.5 to 6.6 kWh/m2 of radiation level. (Jain & Jain, 2017) Furthermore, the annual 24-hour global solar radiation average is about 220 W/m2 for South Africa, compared with about 150 W/m2 for parts of the USA, and about 100 W/m2 for Europe and the United Kingdom. (SA Department of Energy)
The following chart, retrieved from Global Solar Atlas (2021) , shows the solar energy powers of Ulundi Local Municipality.


SITE INFO

Map data — Per year

Specific photovoltaic power output	PVOUT specific	1562.1	kWh/kWp
Direct normal irradiation	DNI	1696.4	kWh/m²
Global horizontal irradiation	GHI	1738.0	kWh/m²
Diffuse horizontal irradiation	DIF	657.7	kWh/m²
Global tilted irradiation at optimum angle	GTI opta	1946.5	kWh/m²
Optimum tilt of PV modules	OPTA	30 / 0	°
Air temperature	TEMP	18.8	°C
Terrain elevation	ELE	481	m

PVOUT map

Figure 13: **Ulundi LM, Solar Irradiation Data, solargis.com**

5. Analysis: Technologies State of the Art

The following chapter explains the state of the art of the Parabolic trough Collectors (PTC) and the Thermoplastic Extruders, which are the leading technologies influencing the design's success. After preliminary paper research and interviews, a benchmarking between different extruders has been created to define the most suitable case study to take into account for the following development. Deeper research on the technologies can be found in appendix B and C.

5.1 PARABOLIC TROUGH COLLECTORS

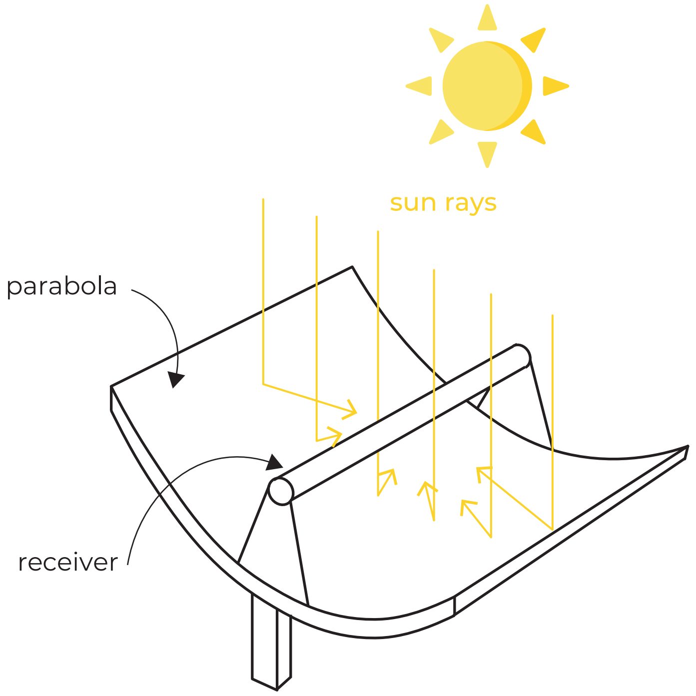


Figure 14: **Parabolic Trough Principle**

When it reaches the earth, solar heat does not contain enough power to be used; in order to do so, the solar heat has to be concentrated. The properties embedded in the parabola allow it to collect all the solar heat. The parabola principle explains that all the rays hitting the parabola perpendicularly to his aperture are concentrated in a unique point called focus, where the receiver is located in PTCs systems. Below are the most critical factors involved in the PTC to consider for this specific project.

5.1.2 Sun Path

Sun path, also known as day arc, is the arc-like path that the sun appears to take across the sky daily and seasonal as the earth rotates and orbits the sun.
The sun's position in the sky can be measured by two angles, Azimuth and Elevation.
Consequently, given the parabola principle and sun path behaviour, the entire system has to be kept constantly aligned.
In the figure below, with the area in yellow, we can notice the yearly sun path range in Ulundi; the range is considered between the longest and shortest day of the year, December and June solstices. (Global Solar Atlas)

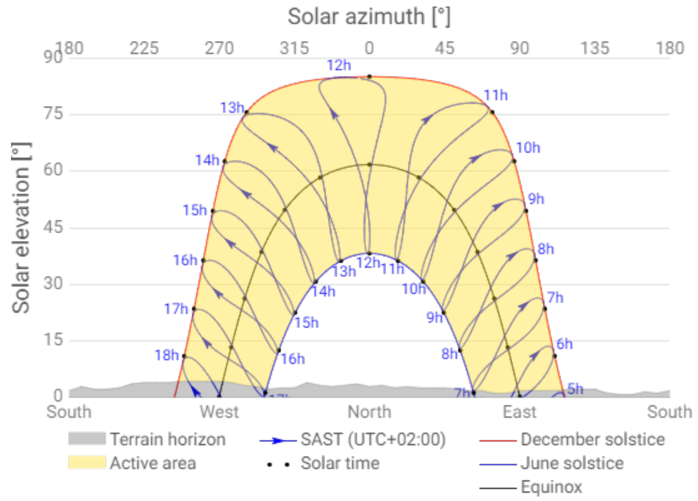


Figure 15: **Ulundi LM Sun Path**

5.1.3 Receiver

In between all the elements of a PTC system, the receiver is one of the most complexes to design since absorption, reflection, and transmission occurs when electromagnetic solar radiation impacts it. (Sauerborn et al., 2012) Most of the receivers are designed as a combination double-layered borosilicate, coated to avoid dispersion Receivers can be classified as Evacuated or Not Evacuated; evacuated pipes are suitable for working temperatures higher than 300° (Lovegrove & Stein, 2012).

5.1.4 Mirror

As mentioned by Jamali H (2019), one of the main factors influencing the reflectance is the material of the mirror and the coating of it. The same study shows that most mirrors reflectance efficiency is between 90% and 99%. A secondary factor influencing mirror reflectivity is the

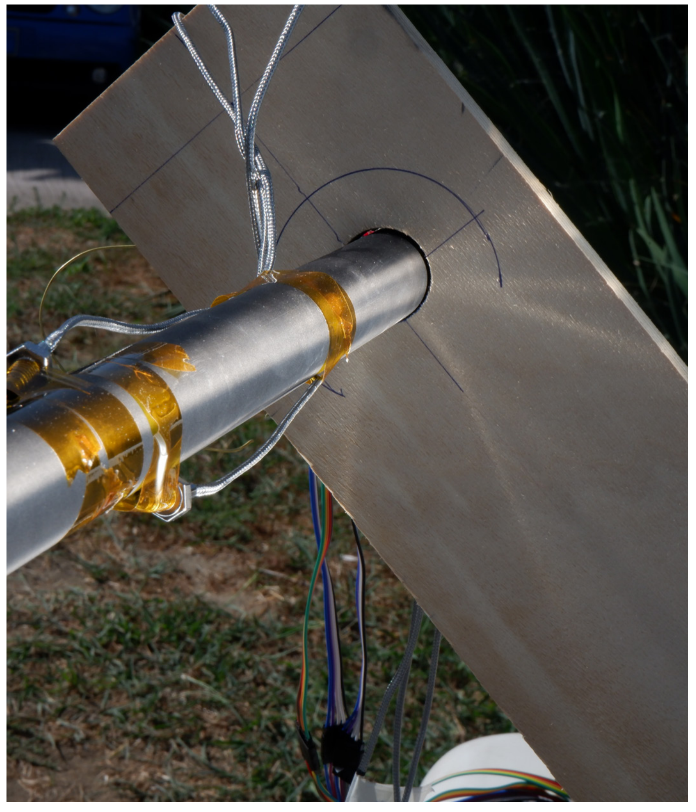


Figure 16: **effect of Local Shape Deviation, Tests.**

Local Shape Deviation (Sauerborn et al., 2012). Minor imperfections and bumps in the parabola can deviate the trajectory of the sun rays from the collector or create zones with different temperatures in the collector. The image above shows how this phenomenon was noticed during the preliminary tests. Specifically, it is noticeable that the light is irradiating the receiver in stripes instead of uniformly.

5.2 THERMOPLASTIC EXTRUDERS

Plastics extrusion is a manufacturing process in which raw plastic is melted and formed into a continuous profile. Extrusion produces pipe/tubing, window frames, plastic films and sheeting, thermoplastic coatings, and wire insulation.
This process starts by feeding plastic material (generally pellets, granules, flakes or powders) from a funnel into the extrusion barrel. The material is gradually melted by the mechanical energy generated by turning screws and the heating bands arranged along the barrel. The molten mass is then forced into a die, which gives shape to the polymer.
Below are listed the most critical factors involved in the plastic extrusion process to consider for this specific project.

5.2.1 Screw

As the illustration at the bottom of the page shows, the extrusion screw is composed of three different zones with different internal diameters. The presence of those zones allows a homogeneous melting and a uniform flow output. Every zone requires a specific temperature. Moreover, by increasing the motor RPMs, the friction created in between screw and barrel causes a heat increase, consequently increasing the plastic output volume. (Personal interview with Pieter de Boer, July 8, 2021).

5.2.2 Temperature Control

Temperature control is the property that unifies the quality of the extrusion.
Temperature tolerances in industrial manufacturing range from 0.1 C° for small sections and highly detailed shapes to a maximum of 0.5 C° for most products; for the project case, the tolerance can be as high as 5 C°. (Personal interview with Pieter de Boer, July 8, 2021).

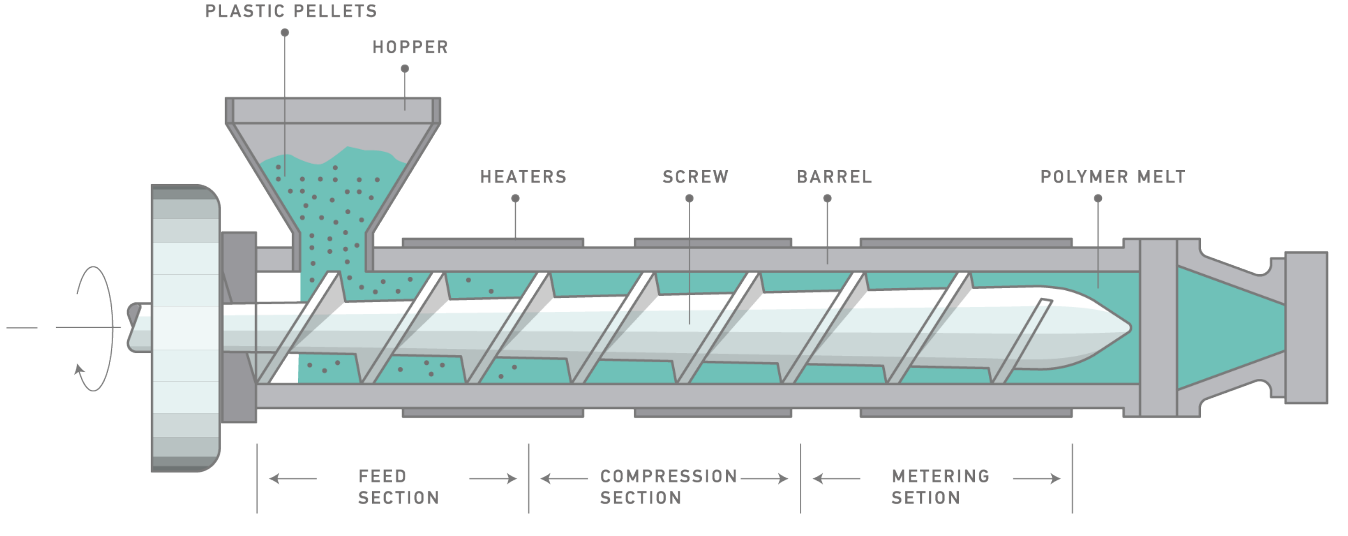


Figure 17: **working principle of a single screw plastic extruder**

5.2.3 Extruder Benchmark

The following chart shows a benchmarking of two completely different types of extruders. The products selected are AMUT EA-30 (Amut), a single screw industrial machinery, and the Precious Plastic Extruder Pro (Precious Plastic), DIY single screw plastic extruder. The aim is to compare their features and evaluate the most critical factors for the process development. The parameters taken into account are mainly related to the dimensions and the energy con-

EXTRUDER	Precious Plastic Extruder Pro	AMUT EA-30
Energy Requirements		
Total Energy Required	5 kw	8KW
Motor Energy	3 KW	4 KW
Heating Energy	2KW	4KW
Design Requirements		
Screw Diameter	30 mm	30 mm
Screw Lenght	790 mm	720 mm
Effective screw Length	600 mm	- - -
Total Length	1500 mm	1600 mm
Total Width	600 mm	500 mm
Total Height	1550 mm	1450 mm
Weight	110 kg	400 kg

Figure 18: **Extruders Benchmarking**

6. Analysis: Calculations

The following chapter addresses the first calculations involved in the project, as the first will be calculated as a comparison between the energy needed to melt LDPE in a classic plastic extruder and the theoretical energy needed to melt LDPE.
The second calculation gives a pre dimensioning of the parabola given the geographic location and all the factors involved.

6.1 ENERGY CALCULATION

The following paragraph presents two models that allow us to calculate the energy required in two different extrusion conditions.
The first model gives us the volume of melted LDPE given a fixed amount of energy, corresponding to the energy that a unitarian parabolic surface can collect. The second model compares the energy required to extrude the same polymer on an industrial level with the energy required to melt it on a theoretical level

6.1.1 Melting Volume

The first model has been considered for Parabola Aperture Surface, an area of 1 square metre $A = 1m^2$ and a Direct Normal Irradiation $DNI = 800W/m^2$.
Moreover, has been assumed an efficiency from the conversion from solar rays to heating of $\eta = 70\%$. Given that the DNI depends on the area, it was possible to multiply the three factors to estimate the energy flux collected on the receiver, $I = A \cdot DNI \cdot \eta$; $I = 560W$.

Knowing this energy has been possible to estimate the amount of plastic recycled in an hour
The energy required to melt one Kg/sec of PE equals $E = 10\ MW/kgsec$.
Consequently, having as Irradiation flux $I = 560W$, the volume of plastic melted in a second is $V = 0.056\ g/s$ that, in an hour is $V = 0.056 * 3600 = 201.6g \cdot h$ for a unitarian surface; $V = 201.6g \cdot h/m^2$

6.1.2 Energy Consumption Comparison

In the second model, we consider the Specific Heat Capacity of LDPE $Cp = 3\ kJ/kg * K$.
By heating up 1 Kg of LDPE to the melting point, we have $Q = m \cdot Cp \cdot \Delta T$; where ΔT is the temperature difference, we have $Q = 1 * 3 * (200° - 20°)$.
Consequently, the energy needed to melt one kg of plastic is $Q = 540kJ/kg$. Converting the result to MegaJoules, we have $Q = 0.54MJ/kg$, that if compared to the energy required for industrial extruder $Qi = 5,79\ MJ/Kg$ we can notice a difference close to one order of magnitude.
This insight shows us how the direct solar extruder has drastically higher efficiency than an industrial level due to many conversions and efficiency gaps.

6.2 PARABOLA DIMENSIONING MODEL

The second model allowed a pre dimension of the parabola given the energy required from the Precious Plastic Extruder Pro (Chapter 6)
Preliminary paper research has been conducted to analyse and define the formulas involved in the system.
A secondary expert interview with Giuseppe Nicotera, Physics double MSc student, University of Pisa, Sorbonne, allowed me to define a proper physical model.
The model is composed of three main parts.

6.2.1 Energy Loss calculation (Q Loss)

This step has to be taken into account first since its result is a fundamental factor influencing the receiver efficiency and consequently the parabola width.
In order to calculate the energy loss from the receiver has been applied the Stefan Boltzmann law of black body radiation.

$$Qloss = A\varepsilon\sigma T^4$$

Where the values are the following :

- T = Temperature of the receiver
- ε = Emissivity of the receiver
- A = External area of the receiver (derived by receiver diameter and length)
- σ = Stefan-Boltzamann constant $(5.6 \cdot 10^{-8})$

6.2.2 Parabola aperture width dimensioning (w)

To calculate the width w, the Solar Radiation Formula $I = W/m^2$; has been inverted obtaining $m^2 = I * W$, imposing W as 2 KW , the maximal energy required by the Precious Plastic Extruder (Chapter 5.2.1)
Knowing that the length of the parabola aperture is a fixed measure, the same length as the Precious Plastic Extruder screw, $l = 60cm$ it has been possible to derivate w, since $m^2 = l \cdot w$; the new formula is $I = \frac{W}{l \cdot w}$.

The $Qloss$ from the first part of the model can be then subtracted to the total Irradiation flux I to have the effective energy absorbed.

The final formula becomes then $I - Qloss = \frac{W}{l*w}$; by inverting this formula it is possible to calculate the width as the only unknown.
The variable involved in the width dimension to consider in the model are:

- I = Irradiation Flux;
- $Qloss$ = Calculated in the first step.

6.2.3 Parabola Creation

Knowing the parabola width has made then easy designing a parabola.The preliminary calculations conducted during the expert interview have been converted and parameterized in Grasshopper (see image on the right), parametric software that allows direct conversion from calculation into geometry.

By parametrising the model, it has been possible to determine different project factors related to the parabola, such as length and weight. All the factors mentioned above can be modified and allow different results; the following chart shows a calculation example.

KNOWN PARAMETERS		RESULT	
Receiver Temperature	180°	Parabola Aperture width	4.15m
Receiver Length (l)	60 cm		
Receiver Radius (r)	1.5 cm		
Receiver Emissivity (ε)	0.95*		
External Area of receiver	r2π*l		
Irradiation Flux (I = DNI)	800 W		

*values assumed.

6.3 CONCLUSIONS

From the first energy calculations, it was noticeable that comparing the energy requirement of a classic plastic extrusion process and the direct heating process shows the magnitude of the two extrusions energy differs by one order.

The second model taught us that, in order to reach the same efficiency as the Precious Plastic Extruder Pro, the parabola width should have a width of 4.15m.
The given dimension would make the final product bulky, challenging to operate and transport. Further research steps are needed to understand which efficiency is reachable with smaller configurations, mainly related to extrusion volumes (chapter 13).

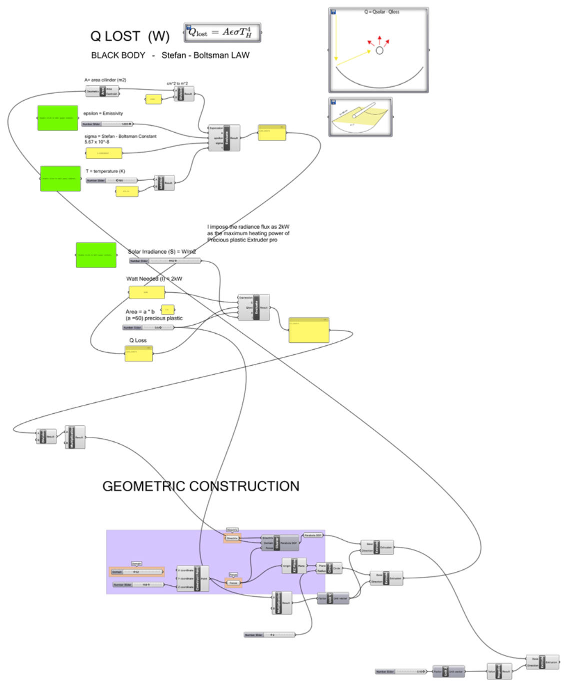


Figure 19: **grasshopper model**

Call with Giuseppe Nicotera, Physics double MSc student, University of Pisa, Sorbonne

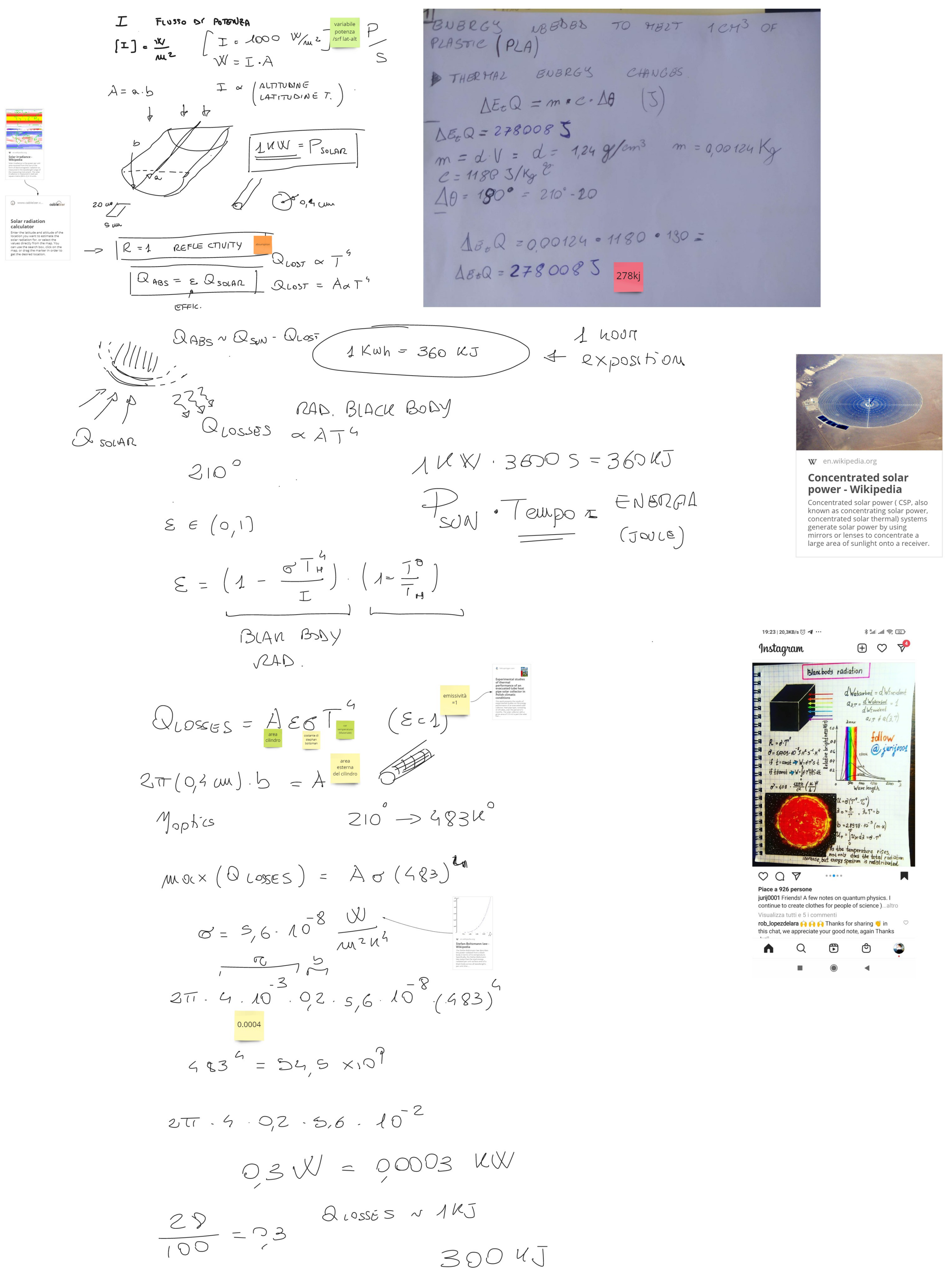


Figure 20: **Parabola Dimensioning Model, First Calculations**

7. Prototype: Test design

The knowledge of solar plastic recycling is based mainly on minimal data; indeed, only one paper has been found related to this topic. Therefore, the research aimed to analyse and explore the behaviour of a solar trough collector for the plastic extruding field.

7.1 INTRODUCTION

Experiments on parabolic trough collectors for polymer melting were performed in 2018 by a group of researchers from Stockholm (Mewes & Sujessy, 2019). Their successful test has generically focused on the possibility of recycling plastic via PSC without any specific application. Consequently, a new test has to be conducted to investigate the PTC's behaviour, specifically for a plastic extrusion scenario.
The test could have been conducted only in this early phase of the project to have the most similar weather conditions as the project context.

7.2 METHOD

7.2.1 Test objective

From the knowledge gained from the plastic extrusion technology (Appendix C), it is known that the working scenario of the temperature has to be kept constant in every zone of the barrel in every weather condition, with a tolerance of 5°(Personal interview to Ruurd Pieter de Boer).

The goal of the test has been to collect data related to the temperature in different zones of a

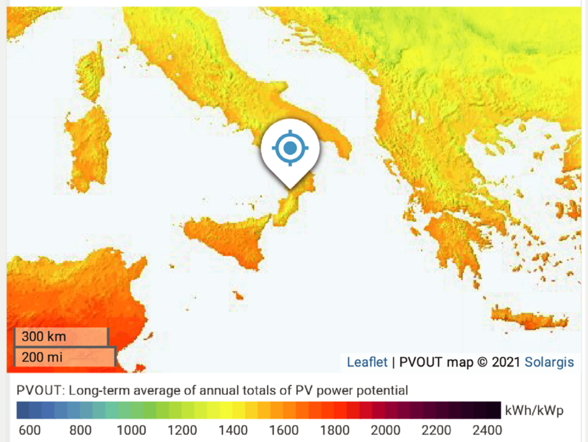
Lamezia Terme

38.957447°,016.316038°
unnamed road, Lamezia Terme, Calabria, Italy
Time zone: UTC+01, Europe/Rome [CET] , Daylight saving time not considered

SITE INFO

Map data			Per year
Specific photovoltaic power output	PVOUT specific	1513.1	kWh/kWp
Direct normal irradiation	DNI	1588.9	kWh/m²
Global horizontal irradiation	GHI	1620.7	kWh/m²
Diffuse horizontal irradiation	DIF	664.1	kWh/m²
Global tilted irradiation at optimum angle	GTI opta	1846.3	kWh/m²
Optimum tilt of PV modules	OPTA	32 / 180	°
Air temperature	TEMP	17.8	°C
Terrain elevation	ELE	146	m

PVOUT map



Ulundi Local Municipality

-28.355151°,031.404419°
unnamed road, Ulundi Local Municipality, KwaZulu-Natal, South Africa
Time zone: UTC+02, Africa/Johannesburg [SAST]

SITE INFO

Map data			Per year
Specific photovoltaic power output	PVOUT specific	1562.1	kWh/kWp
Direct normal irradiation	DNI	1696.4	kWh/m²
Global horizontal irradiation	GHI	1738.0	kWh/m²
Diffuse horizontal irradiation	DIF	657.7	kWh/m²
Global tilted irradiation at optimum angle	GTI opta	1946.5	kWh/m²
Optimum tilt of PV modules	OPTA	30 / 0	°
Air temperature	TEMP	18.8	°C
Terrain elevation	ELE	481	m

PVOUT map

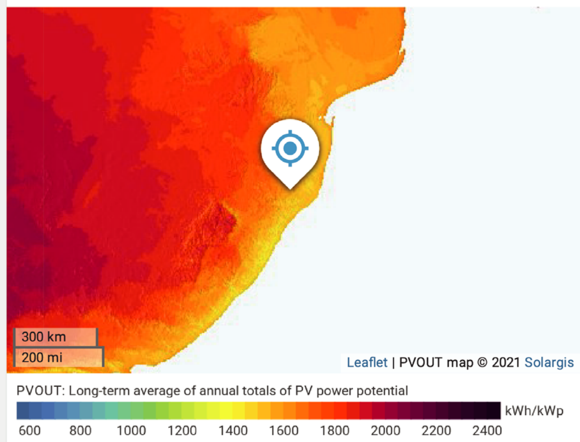


Figure 21: **Solar irradiation data comparison, Lamezia Terme and Ulundi LM**

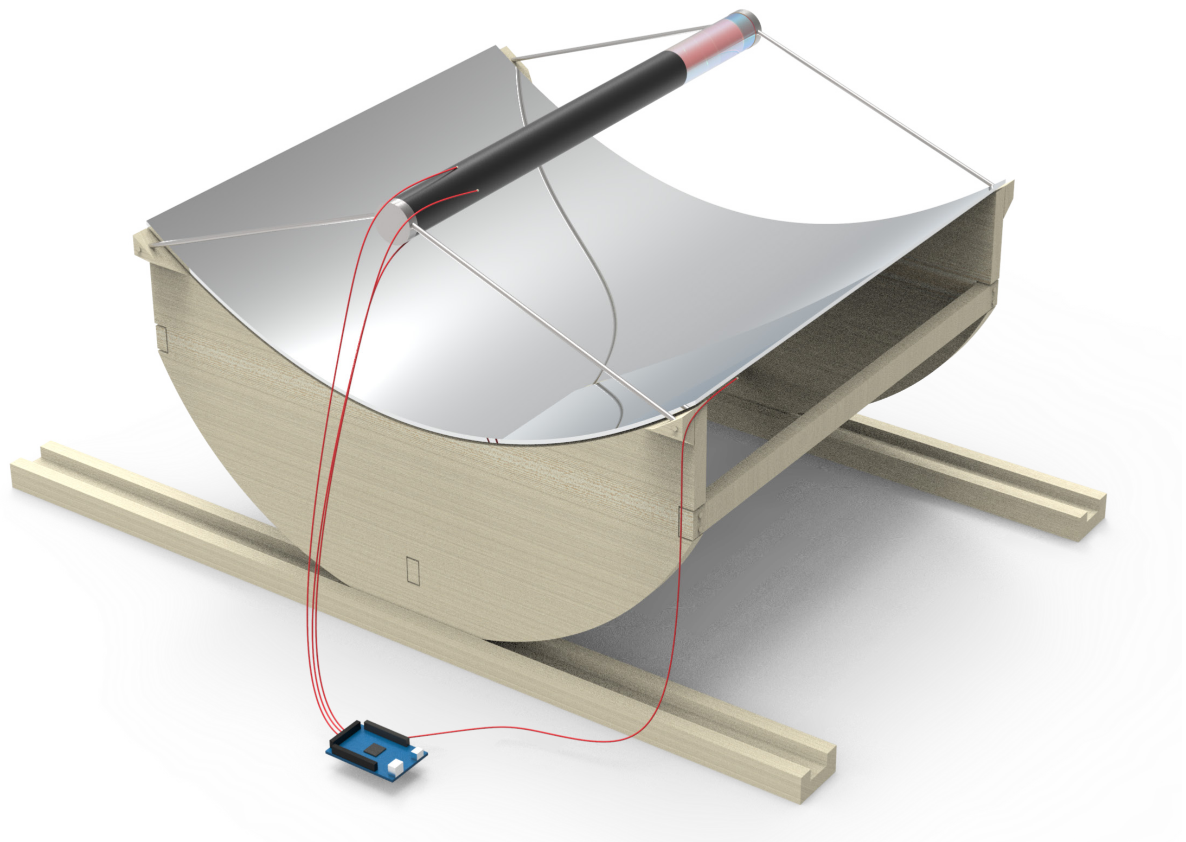


Figure 22: **Preliminary structure visualization**

barrel section in order to understand the behaviour of the solar trough collector in different conditions. The data collected and the observations ensured a conscious design phase.

7.2.2 Location

The tests have been conducted in Lamezia Terme, Italy. The zone has been selected for two main reasons. Firstly for his similar weather features to the final design scenario location. But also for the possibility of working there thanks to a contacts network. In figure 21 is shown the slight differences between the testing zone and the Ulundi Municipality (Global Solar Atlas, 2021)(Appendix E)

7.2.3 Apparatus

In order to answer the research question and understand the PTC behaviour, many decisions have been made. In the following rendering is shown a preliminary apparatus design.

Structure: The structure's shape has been a circular base to allow manual sun tracking; the structure has been thought to be as sturdy as possible to avoid or reduce the Local Shape Deviation (chapter 6). Moreover, the design has been made in plywood to allow easy production via CNC milling.

Thermocouples: Six thermocouples, with an accuracy of ± 0.25°(Max6675), have been disposed at the top, bottom and side of the barrel, relatively three outside and three inside as shown in the following image . This disposition detects eventual differences from the outside to the inside and differences around the barrel section.

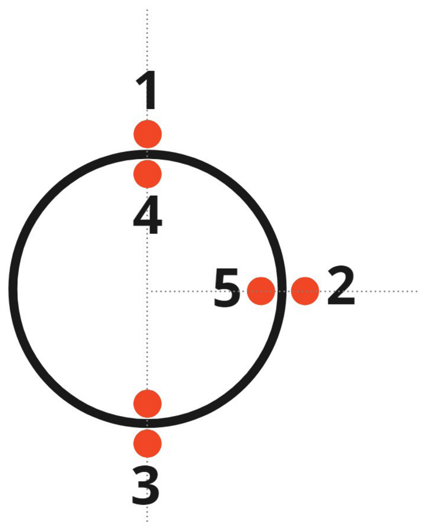


Figure 23: **Thermocouples disposition**

Photoresistor: A photoresistor has been located on the top of the PTC, allowing the detection of light radiations. It permits a comparison with the thermal data to understand better issues related to cloud influence. Moreover, it has been possible to define a working-time scenario by comparing the data collected from it with the sun radiation data retrieved from databases.

Mirrors: Being the project work-frame in a low-income country and having access to fewer materials was also needed to test different mirror materials available in South Africa. Specifically, two materials have been tested, aluminium and steel.

Receiver: Three different receivers have been realised for the test. One of them is a standard 30 mm pipe, and the other two are a system of two concentric pipes with a liquid medium.
The liquid medium is a decision given by the assumption that a liquid medium can better diffuse the temperature by using the physical principle of convection instead of conduction. The inner pipes have a standard dimension of 30 mm as the one from the Precious Plastic Extruder. The external pipes also have standard dimensions, respectively 46 mm and 60mm. As a medium between the pipes was selected the car engine oil 10 W40, as it is one of the most common and suitable for high temperatures. The receivers have then been painted in black to avoid reflection and reduce heat dispersion.

Figure 24: **Test Receivers**

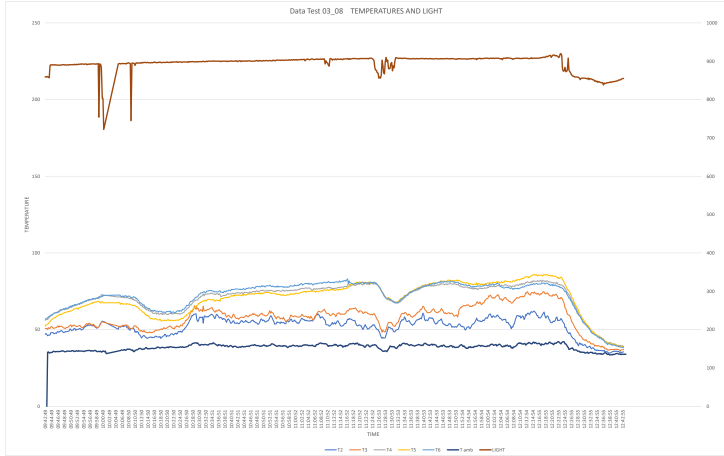
Control: The data collected by an Arduino Mega 2560 board were visualised on a laptop via a virtual monitor. To better detect every small behaviour change, every sensor reads every 15 seconds. .

8. Prototype: Measurements

The following chapter explains the tests setup and how the data were collected. Afterwards, the results are presented and explained.
A test discussion analyses the test results from the project point of view.

8.1 TESTING

The testing sessions took place in the summer of 2021. The decision to conduct the tests over several weeks was made inadvertently; the main goal was to conduct the tests in as similar weather conditions as possible. The original plan called for five days of testing, but due to logistic issues, only four were completed. As a result, the wider receiver has not been tested.
The tests were done in the morning from 9.30 to 13:30. Before the end of every test session, the mirror was covered with a blanket to collect data from the cooling down phase. Moreover, having constant control of the data during the test helped to perform the manual tracking of the PTC

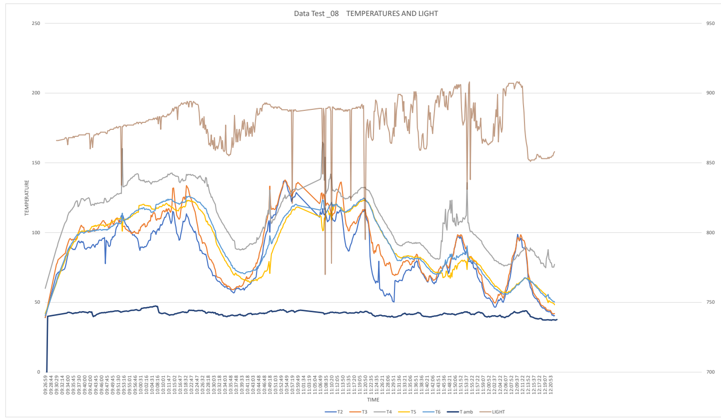


Graph A : 03_08 Test Data

8.2 RESULTS

8.2.1 Heating

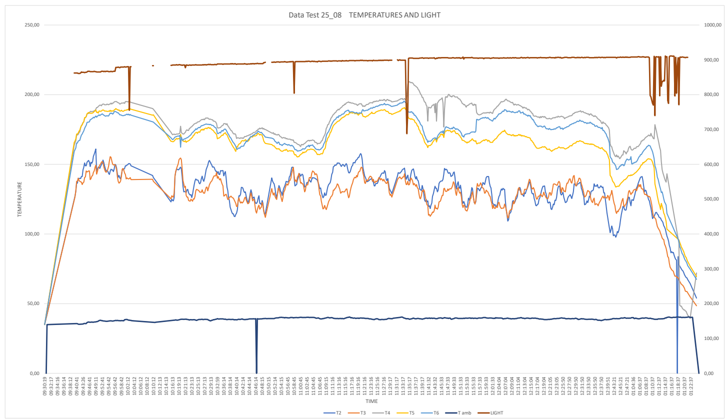
As can be seen in the graphs, the temperature rocketed in the first minutes of the test. After the first peak, a rocky plateau was reached. The given trend can be seen in all the graphs on the side. The result that better illustrates the detected trend is the following graph, in which the internal sensors have a lecture read of 39° at the start of the test, and they reach a read of 195° after the first 25 minutes of sun exposure.



Graph B : 11_08 Test Data

8.2.2 Alignment

As forecasted in the research phase, the alignment is crucial to keep a constant heat flow. During the tests, the apparatus had to be kept constantly aligned, along two revolution axes, the normal to the ground and the receiver axis. An example of this phenomenon can be seen in the graph C, where, after the first peak, we see mistakes in the alignment expressed as small fluctuations in the curve.



Graph C : 25_08 Test Data

8.2.3 Cloud Influence

The influence of a cloud, which is most noticeable in graph B, significantly impacts the system's functioning. For example, a 5% reduction in light results in half of the temperature measured. During the design process, this issue will be of fundamental relevance.

8.2.4 Heat Displacement

In all the graphs can be seen a difference between the sensors at the top of the barrel and those positioned at the bottom, where the temperature was found slightly higher as previously subsumed.

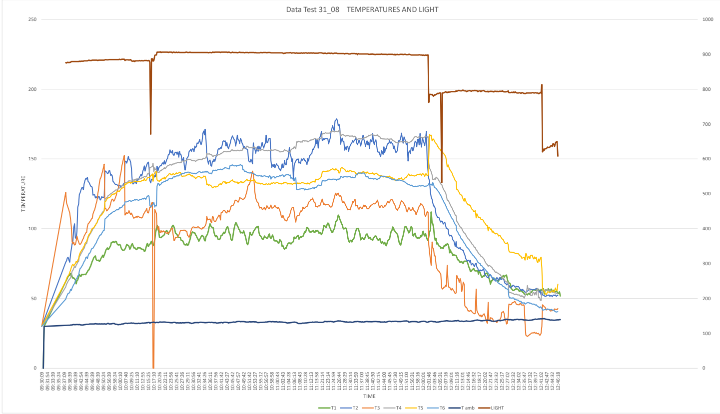
8.2.5 Receivers Differences

The difference in temperature trend can be seen by comparing graph C with D, where the heating time is shorter, and the maximum temperature is also lower in the double pipe receiver (graph D). On the other hand, temperature variations are becoming smaller and less pronounced than with the single pipe receiver. As a result, the temperature is more consistent than a single pipe receiver.

8.2.6 Plastic melting

After reaching the appropriate temperature on the third day of testing, a plastic melting test was performed. Inside the collector, a shredded PE disposable coffee glass was melted. The sample before and after are displayed in the images below. Many experiments were carried out, but only one was successful due to a stroke of luck. Because the PE cup got caught between the sample holder and the barrel, the appropriate pressure was generated, which is another key aspect in extrusion, to melt the sample.

Figure 25: **Pre and Post Melting**

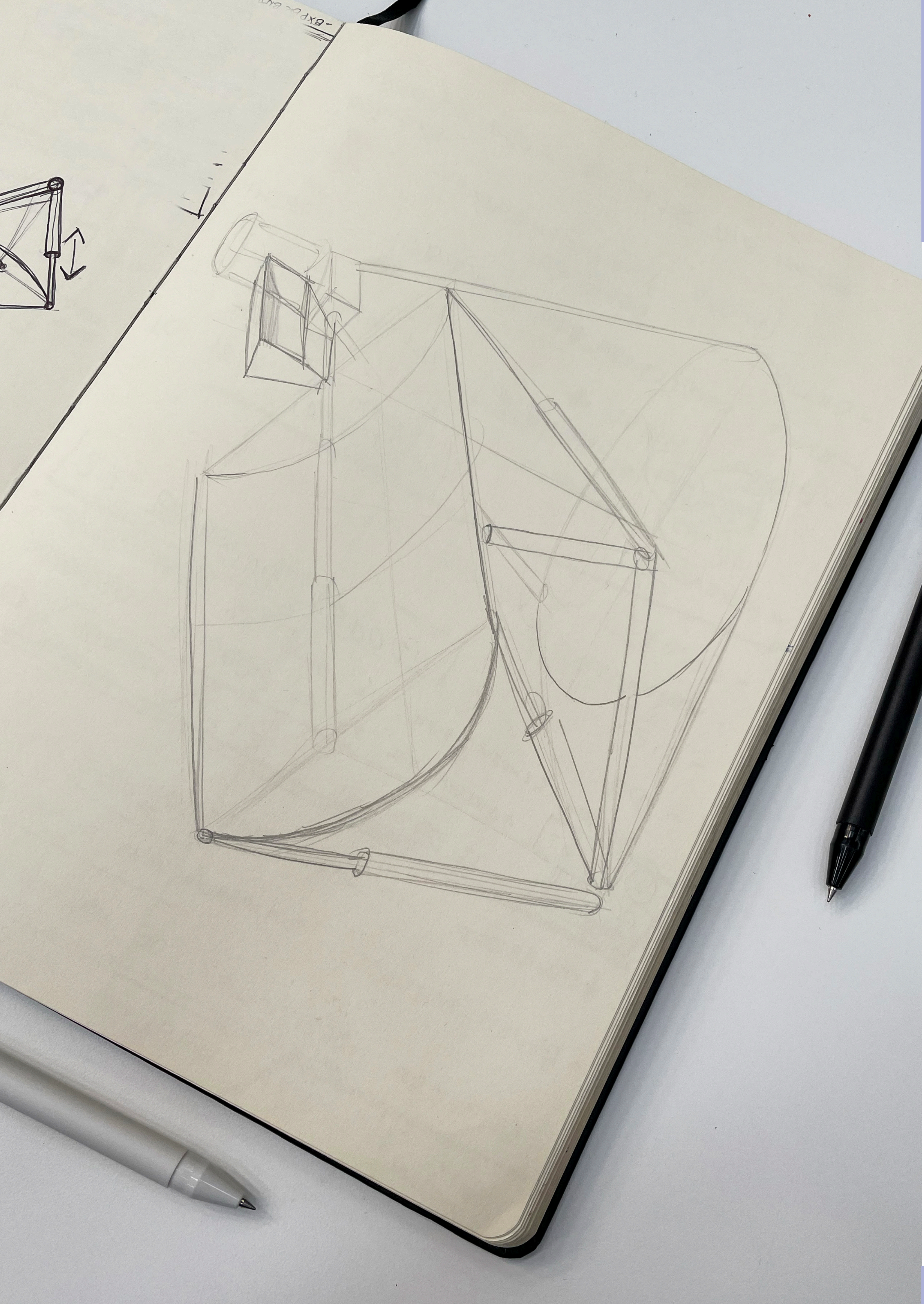


Graph D : **31_08 Test Data**

8.3 CONCLUSIONS

The test can be considered successful, and it confirmed the possibility of implementing the PTC technology in the plastic recycling field for different reasons. Firstly, the melting temperature was reached and kept averagely constant during the test and also, on a small scale, a tiny plastic sample has been successfully melted.
Many aspects and factors involved in the process were not assumed and considered in previous paper research; as an instance factor, the cloud influence has not been considered so problematic beforehand. Moreover, many previously considered problems have been dispelled, such as the heating time that resulted faster than imagined beforehand.
The test and the results are necessary for the project development; in the future steps, all the results present in the previous paragraph will have relatively high importance in the definition and development phases.
On the other side, to scientifically validate the results from the tests, a physical computer simulation has to be conducted (Chapter 13).

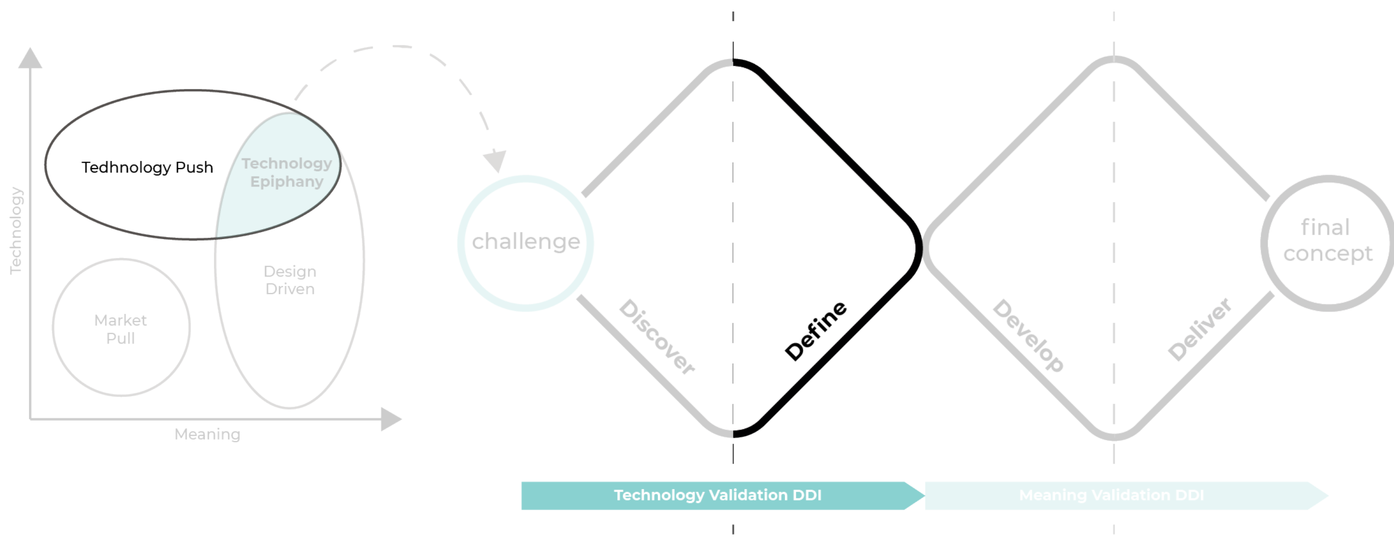
Figure 26: **Prototype building and Tests**



DEFINE

This chapter defines the design concept that has been developed in the next steps. Firstly, a collection of all the insights from the Discover phase allows the creation of Design requirements. A conceptualization phase allows then a creation of two design concepts an evaluation of those allows the selection of a concept to move in the Develop phase.

In this chapter:



9. Insights and Requirements

This chapter starts the second part of the project, the Define Phase. Here below are collected all the insights deriving from the research phase. The insights have been elaborated in a list of project requirements to be the most useful for the project.

9.1 INSIGHTS

The following chapter presents different insights related to the technologies, working frame, and physics involved in the design.

9.1.1 Ulundi Local Municipality

- 74 %of households located outside of the city centre do not have access to waste disposal services.
- South Africa is moving towards a greener future regarding plastic recycling.
- The Ulundi region does not host any recycling facility.
- Most of the recyclable plastic (70%) comes from post-consumer usage.
- The four most common polymers are: LD/LLD-PE, PET, HD-PE, PP.
- 49% of the Population in Unemployed
- A huge phenomenon in Ulundi is informal waste picking, considered as self-employment.
- Ulundi Holds a yearly Direct Normal Radiation Rate of 1696.4 kWh/m2

9.1.2 Thermoplastic Extrusion

- The screw needs to be heated differently in three zones.
- Friction in between screw and barrel given by high RPM can increase the melting rate.
- Temperature Melting Range is giving us the machine temperature tolerances
- The temperature is kept constant by the usage of heating bands and fans controlled by PID controllers.

9.1.3 Solar Trough Technology

- The aperture area of the parabola influences the heating temperature.
- The parabola aperture has to be constantly perpendicular to the sun rays.
- Given the parabola width, we can have an infinite amount of parabolas differing one to each other in perimeter length and reflector height. They can consequently influence the weight and cost of the parabola.
- The reflectivity rate in the material/coating of the parabola influences the reflector's perforV-Standard receivers are evacuated or not evacuated.
- Two-axis sun tracking influences drastically the daily working timespan.

9.2 REQUIREMENTS

Based on the insights collected in the literature and derived from tests and interviews, the final design must meet the following main requirements stated in the following table.

Requirement	Origin
Track the sun along 2 axes	2 axis sun tracking influences the daily working timespan drastically.
The heating barrel needs to deal with 3 different temperature	Extruders screw is composed of three zone (feeding, transition,metering) who needs 3 different temperatures
The temperature has to be kept constant on every part of a barrel section	The temperature has to be kept constant on every part of a barrel section
The temperature has to be kept constant also in presence of a cloud	The influence of a cloud has a significant impact on the system's functioning , a 5% reduction in light results in a half of the temperature measured
Cooling System	In order to keep the temperature constant, in industrial machines fans connected to PID are used for the purpose
The aperture length has to be 60 cm	A commonly used screw, also in the precious plastic extruder, has the given length.
The aperture width has to be 220 cm	To reach the needed energy to have the same properties as the precious plastic extruder that measure was calculated.
Recycle LD-PE	Most common plastic wasted in South Africa and Ulundi

10. Ideation

In the following chapter is present the entire ideation process, as first a morphological chart has been created to address the functions involved in the design. After that, two concepts are designed and selected.

10.1 MORPHOLOGICAL CHART

The technical nature of the project required the use of a morphological chart in order to approach the conceptualisation phase.
This methodology consists of the decomposition of the technology in functions or subproblems; combining different solutions to every function allows to define design concepts. (Boeijen et al., 2014) A crucial step in formulating a morphological chart is the definition of the subproblems, which are derived from the Design Requirements (See chapter 11).

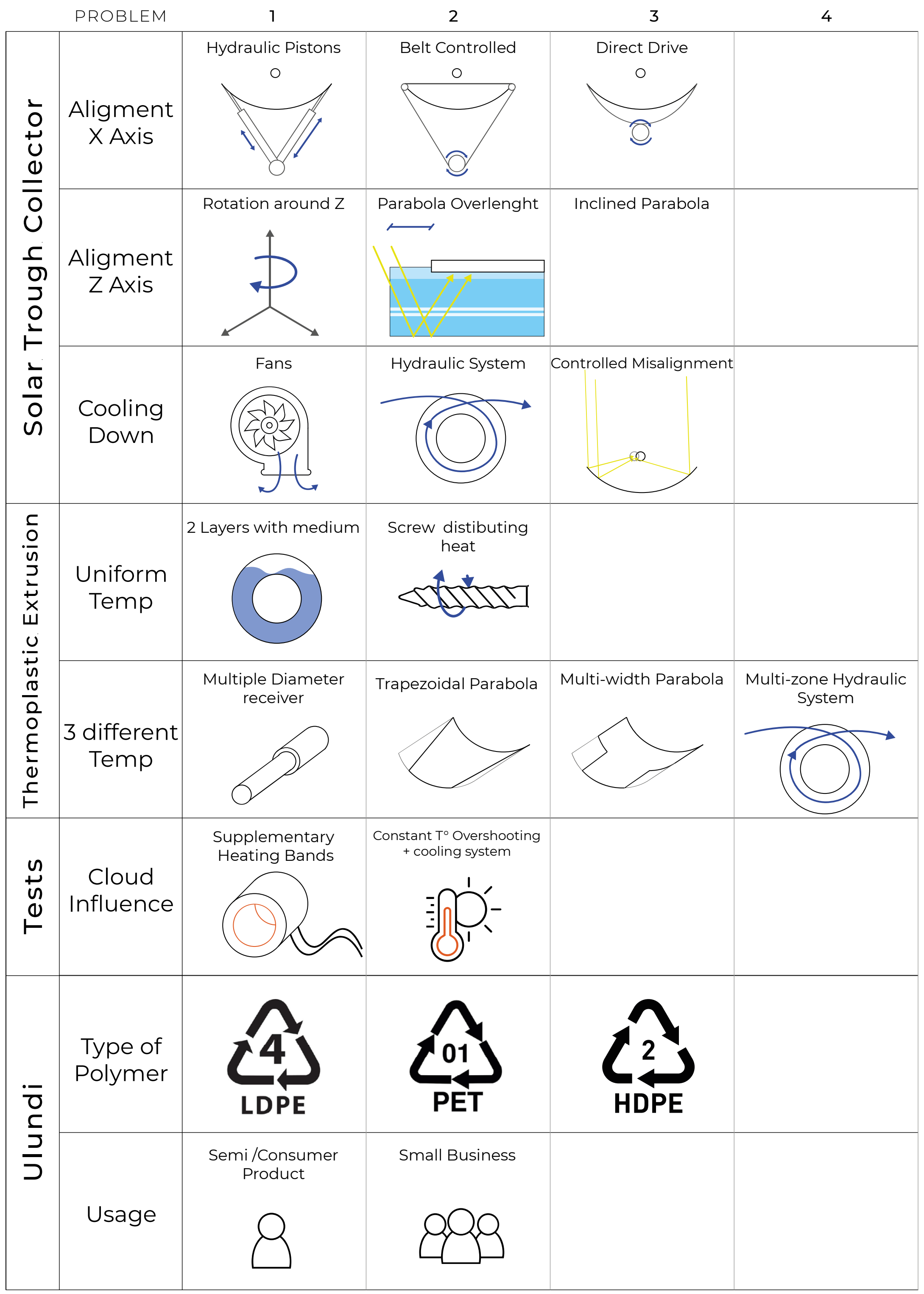


Figure 28: **Morphological Chart**

10.2 CONCEPTS

10.2.1 CONCEPT 1

The first concept has a low technology approach; the sturdy structure will allow a steady position and easy operability. Everything is reduced to the minimum to lower the energy involved in the process. For instance, the alignment of the z-axis is allowed by a parabola overextension, and the moving components are reduced to the minimum to allow a longer lifespan and a lower construction cost.

Below are the solutions from the morphological chart approached for this specific concept; most of the other solutions are used in both concepts, which are explained below after the second concept paragraph.

Alignment Z-axis:
This function is solved with the assumption that extending the parabola over the length of the barrel can balance the alignment of the rays' sun path, specifically covering the elevation angle daily range. (Chapter 6)
As illustrated in the following image, this solution assumes that all the rays hitting the parabola diagonally can still focus on the receiver. The parabola overlength has to be calculated depending on the latitude of the application site and consequently from the elevation angle.

Temperature Fine Tuning
This concept does not present any fine-tuning physical system. The fine-tuning is performed only by slight controlled misalignments of the parabola, actuated by the stepper motors, that guarantee a constant energy flow.

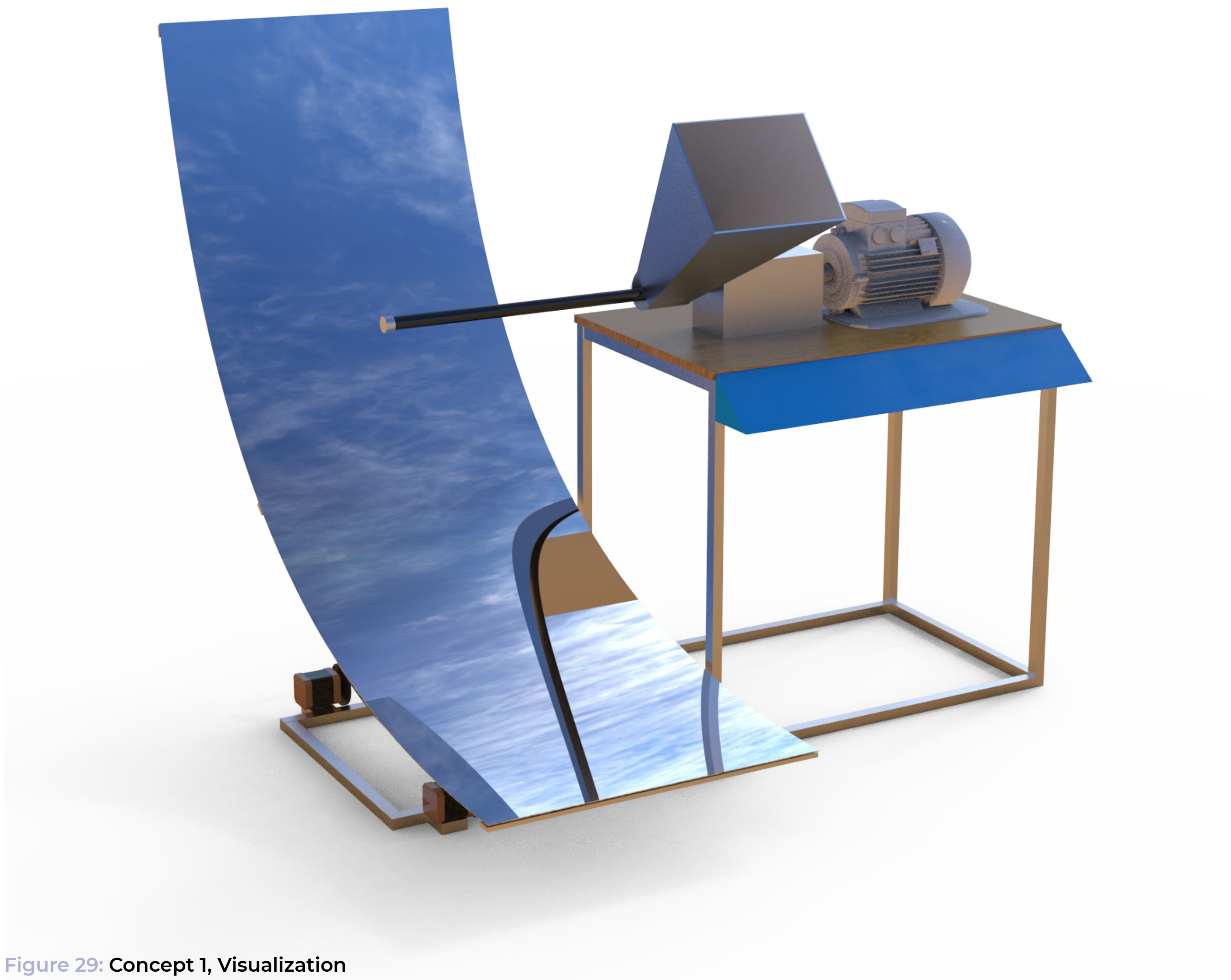


Figure 29: **Concept 1, Visualization**

The following exploded view gives us an indication of the components and materials present in the design.

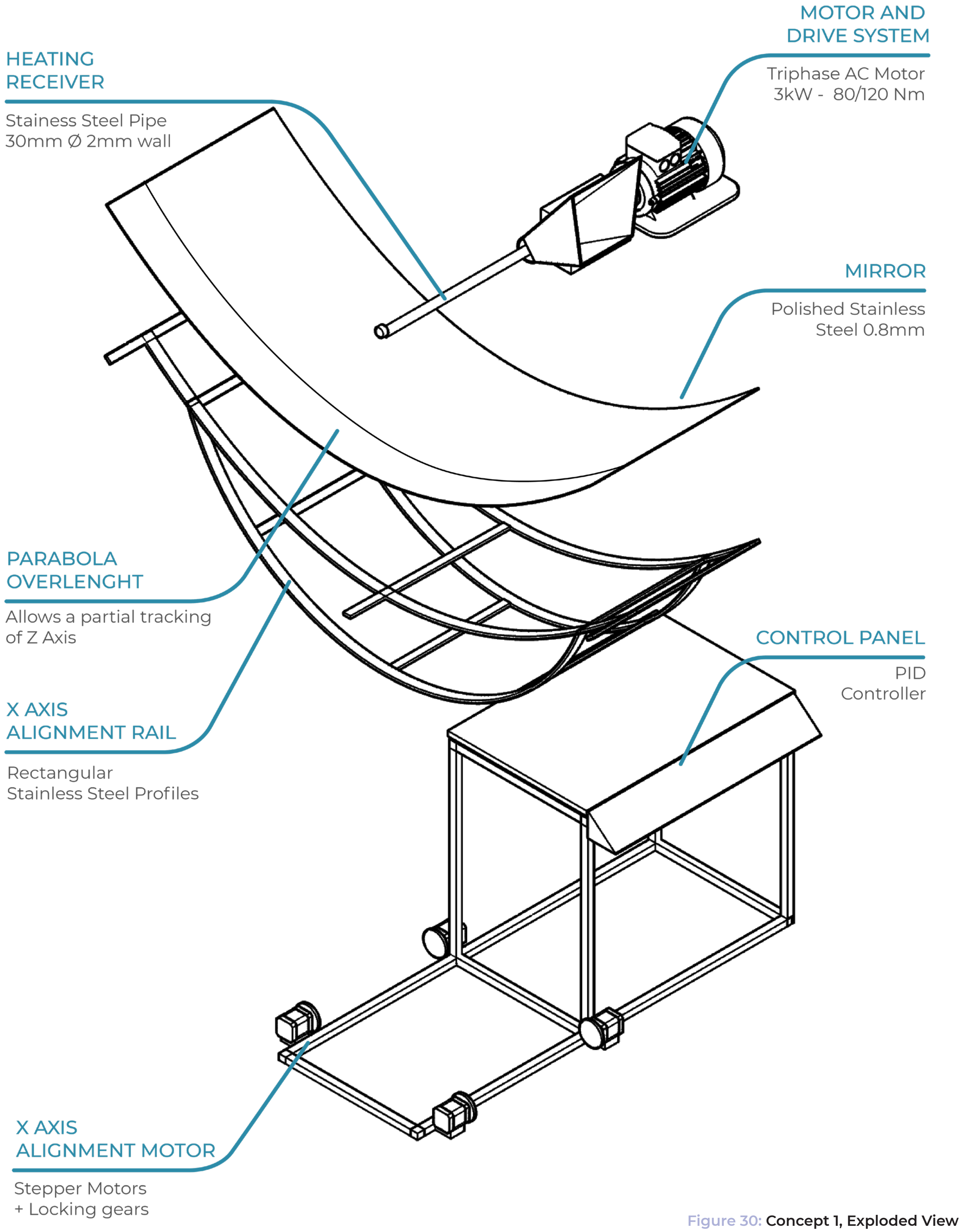


Figure 30: **Concept 1, Exploded View**

10.2.2 CONCEPT 2

The second concept is more advanced but also more performing. The main difference compared to the first concept is the structure; in this case, the structure is more extensive, and two rails systems allow the alignment of the parabola along two axes. This implementation would make the product heavier and consequently slightly more energy-consuming.

Alignment Z-Axis

In the second concept, the alignment task is achieved by a double circular rail system at the machine's base and stepper motors located on the upper circular rail. Photovoltaic sensors send data to a controller who modifies the alignment by controlling the stepper motors.

Temperature Fine Tuning

The fine temperature tuning is allowed by the presence of three fans on the top of the barrel, also managed by a PID controller, who reads the temperatures thanks to the introduction of 3 thermocouples along the barrel; and adjusts the fan speed.

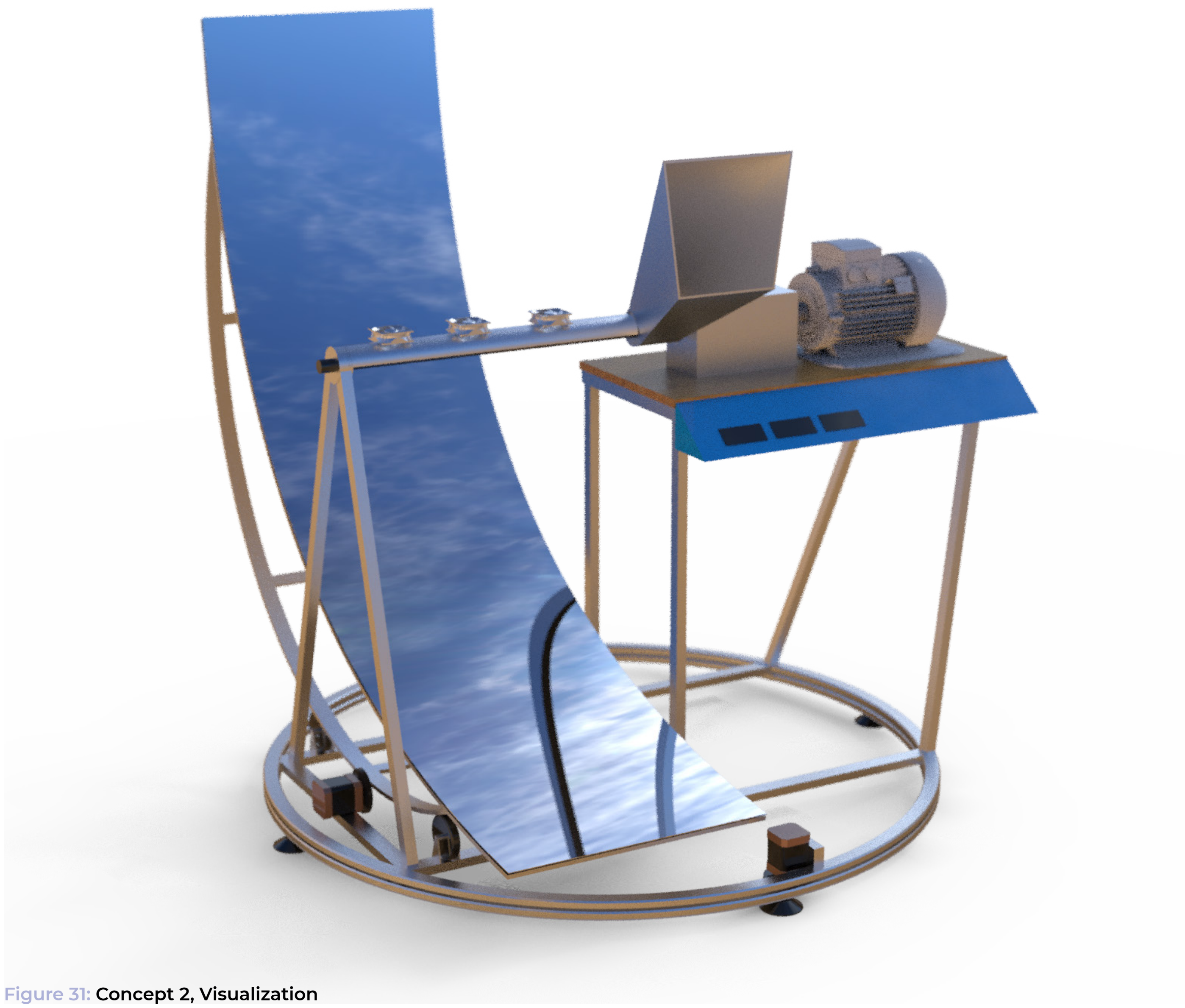


Figure 31: **Concept 2, Visualization**

The following exploded view gives us an indication of the components and materials present in the design.

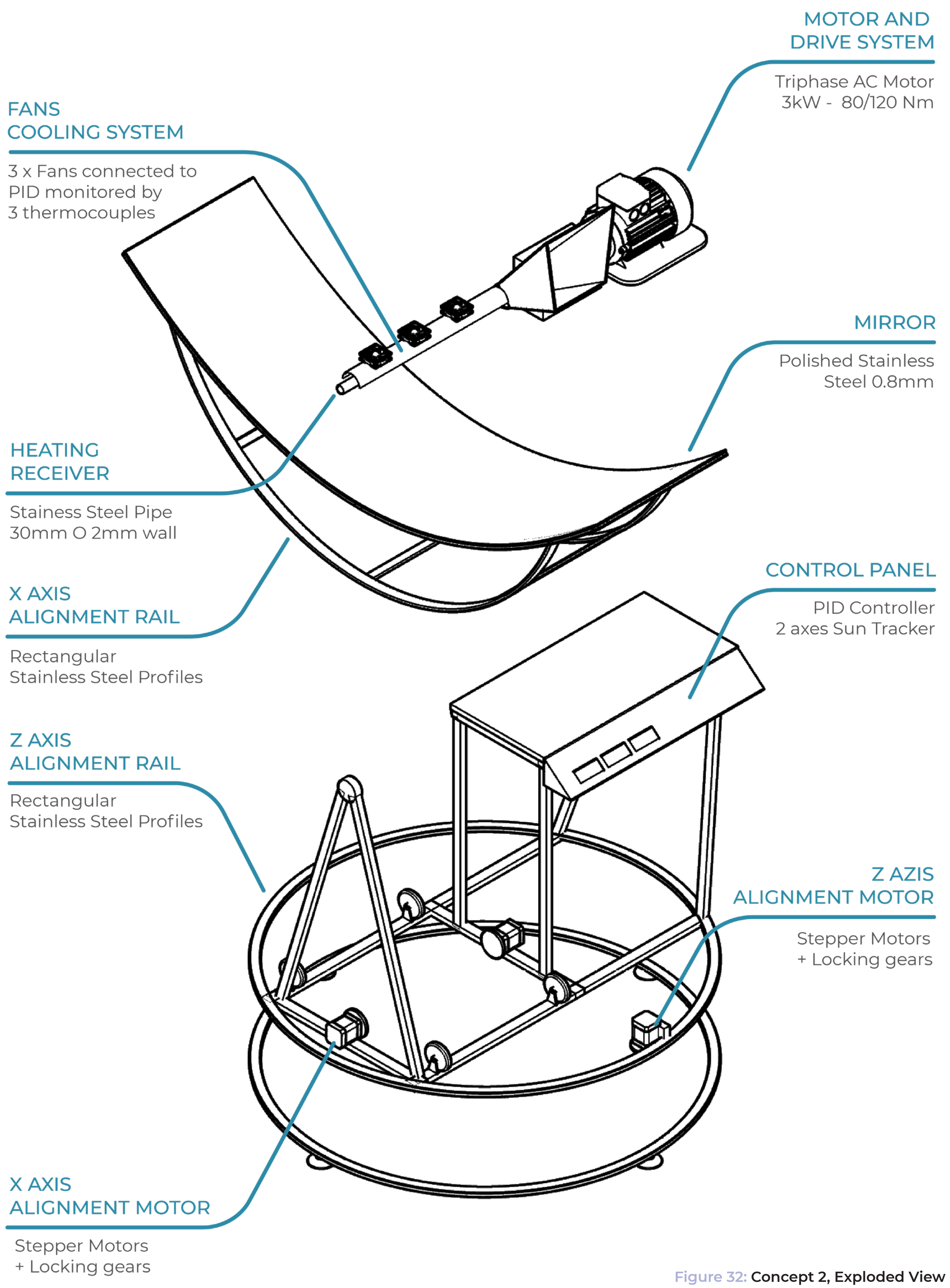


Figure 32: **Concept 2, Exploded View**

COMMON SOLUTIONS

Three Different Temperatures

The barrel needs to have three different temperature zones (Chapter 5). This principle is guaranteed by partially painting the parabola and reducing the width in three zones, as shown in the following image. The parabola is painted instead of cut in order to avoid an overcomplication of the structure and a consequential increase in weight furthermore having a unique width structure can drastically reduce the Local Shape Deviation (Chapter 5)

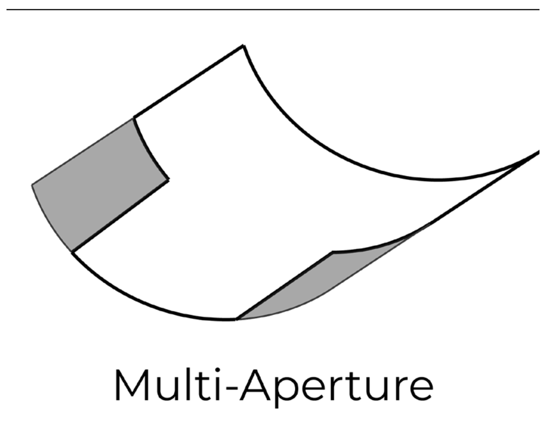


Figure 33: **Multi-aperture Parabola Solution**

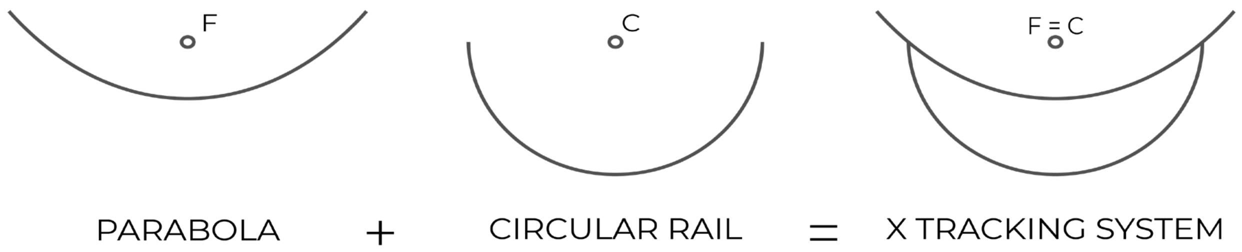


Figure 34: **Parabola Rail System for**

Alignment X-axis

This function is guaranteed by the usage of stepper motors located on rails that allows the rotation of the parabola along the X-axis. A small Photovoltaic Panel used as a sensor sends data to a controller, connected to the stepper motors that adjusts the parabola alignment. All this process is facilitated by the design of the rail/structure system.

Polymer Recycled

The polymer chosen for both concepts is Low-Density Polyethylene for several reasons. At first, LDPE is the most common polymer available and un-recycled in South Africa (Plastic Recycling Survey SA 2019). Second, due to its thermochemical properties, it has one of the broadest temperature melting ranges Tc=170° to 245°. (Tempelman E, et al. 2014).

Parabola Structure / Alignment X-Axis Rail System

In order to keep the heat collector constantly in the parabola's focus, the structure is designed by the overlapping of the parabolic structure to a circular rail with the centre matching the parabola focus, as shown in image 34. Moreover, having a circular ray allows a more straightforward calibration of the alignment controller.

10.3 Concept selection

An analysis of the relative morphological charts by taking into account, as the main factor, the feasibility of the conceived solutions, led to the decision to move Concept 2 to a development phase.
The main reason for this choice is the high uncertainty of the feasibility of the X- Tracking solution conceived for concept 1.
Moreover, elaborating the result from the preliminary tests can be stated that is needed to minimise the energy dispersion. A 2 axis alignment system can better fulfil this requirement.

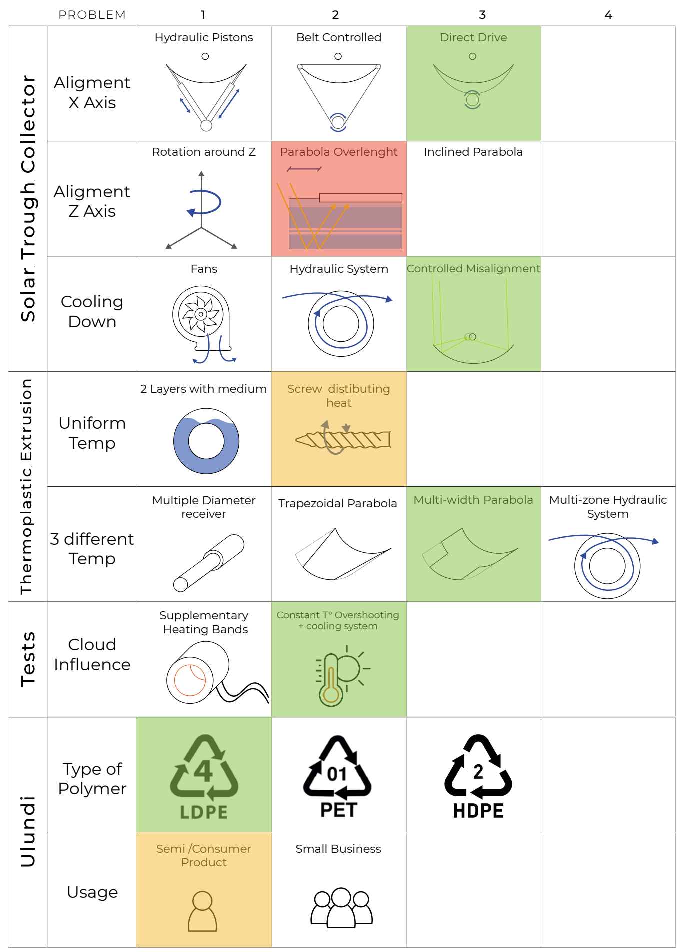


Figure 35: **Morphologic Chart Evaluation Concept 1**

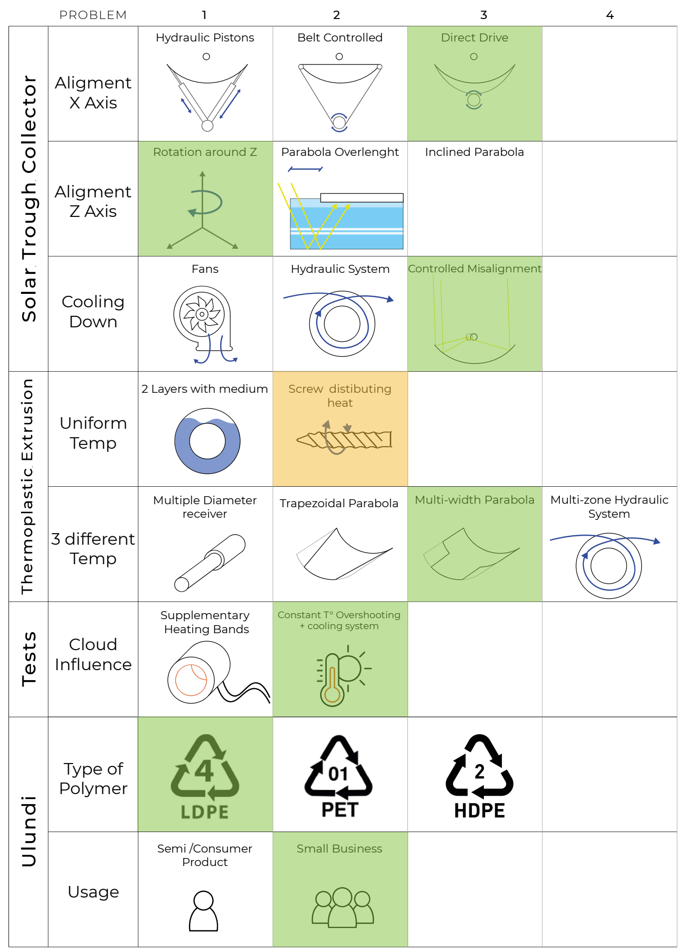
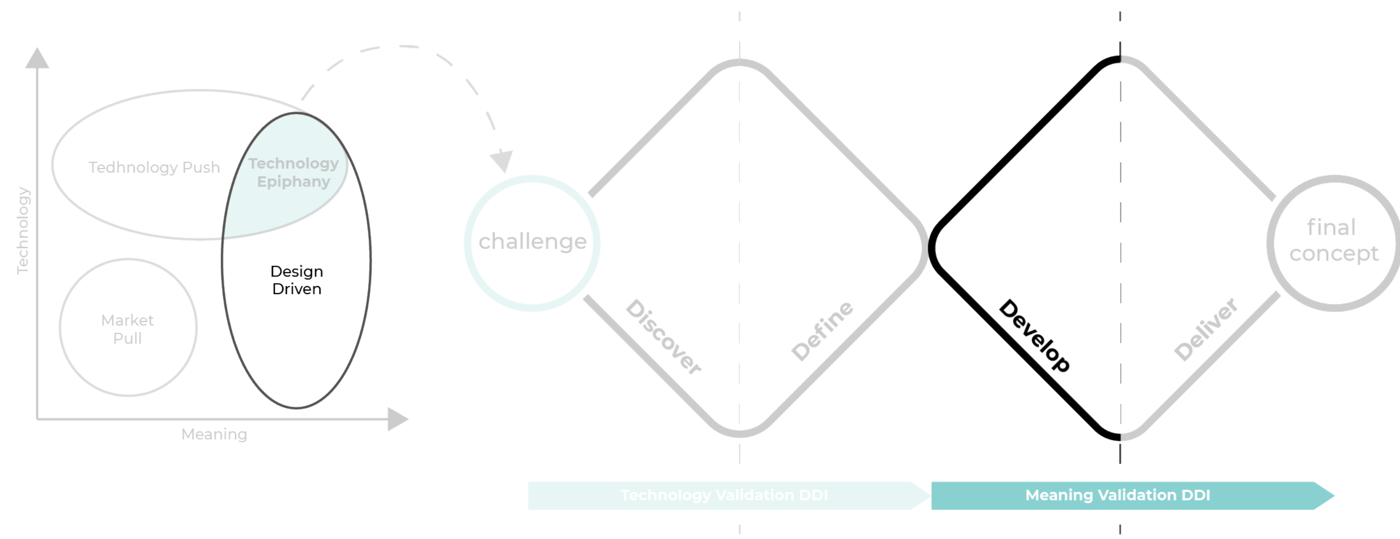


Figure 36: **Morphologic Chart Evaluation Concept 2**

DEVELOP

This chapter aims to find a solution for the current uncertainties present in the chosen concept and fill project-related missing gaps. Expert interviews and paper research allowed the development of different solutions implemented in the final concept.

In this chapter:
- 11. Feasibility
- 12. Desirability
- 13. Viability



11. Feasibility

Different technologies and solutions from the chosen concept need further development. This chapter analyses which elements need priority in the development and aims to evolve the chosen elements.

11.1 MODEL TREE AND TRL ANALYSIS

The TRL map allows a definition of priorities for the development phase. Furthermore, it gives a clear idea of the status of the project in order to design a Product Roadmap (chapter x). The following chart visualises the current TRL per part and the level reached at the end of the graduation project.

The standard parts are visualised as level 9 since the technology is ready and can be bought on the market.
As noticeable in the model tree, the development of the product needs a specific focus on the temperature management system. In which both the subsystems have a TRL 1. Moreover, the entire reflector system has been located in TRL 5 as validated in the relative environment. A physical simulation of the reflector system allows a demonstration of it, allowing a TRL6.

11.2 TEMPERATURE MANAGEMENT SYSTEM

As previously mentioned, this issue has the main priority to guarantee the system's functionality without interruptions.

11.2.1 Cloud Management

The primary solution to balance the loss of heating caused by the cloud influence is by over dimensioning the parabola width.
A controller monitoring temperature and solar irradiations with thermocouples and PV sensors will respectively measure the energy flow and the DNI. The parabola alignment has to adapt consequently.
In the presence of the sun, the parabola has to stay slightly misaligned to convey less energy to the receiver. In case of energy flow reduction caused by a temporary cloud shade, the parabola has to be realigned to rebalance the energy flow.

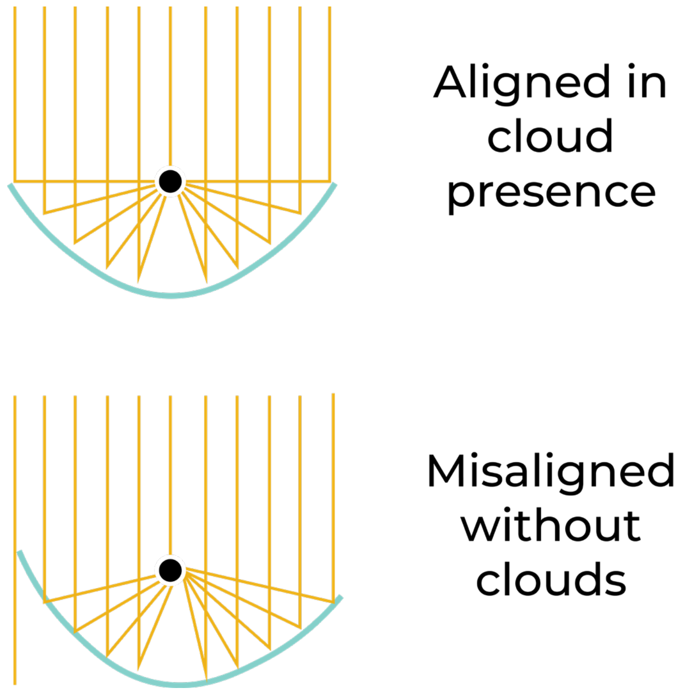


Figure 38: Controlled Misalignment Principle

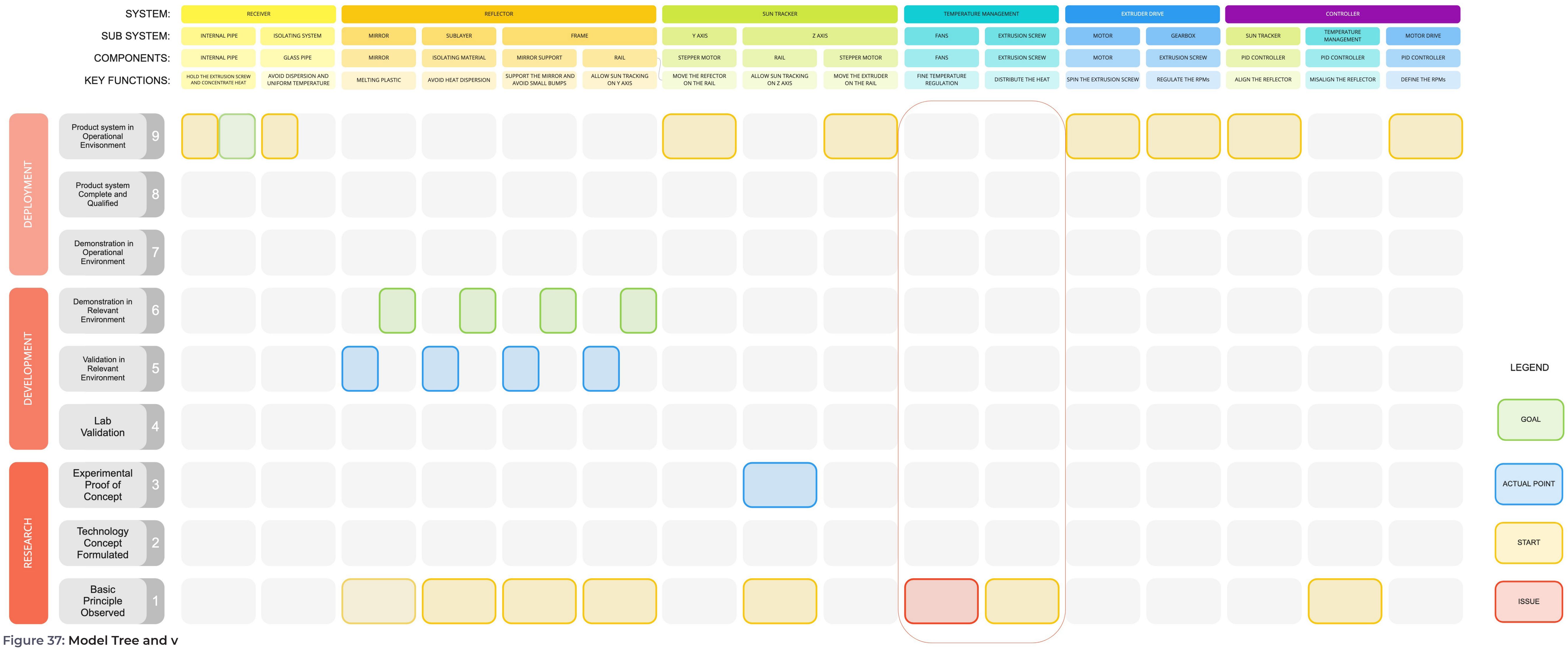


Figure 37: **Model Tree and v**

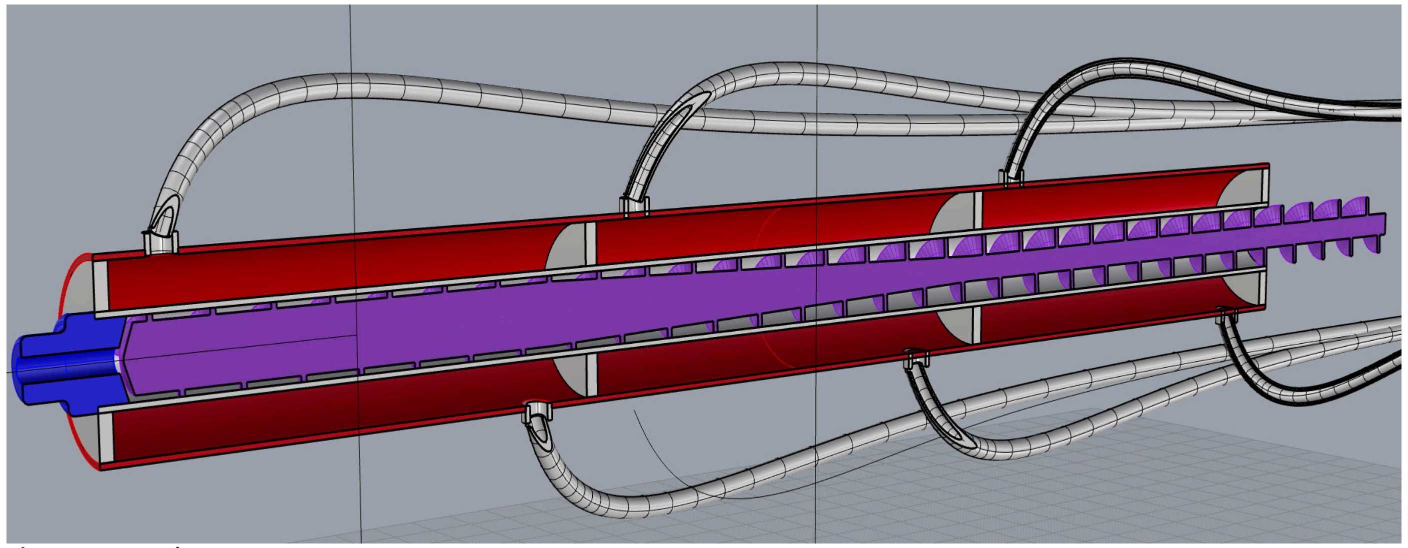


Figure 39: Receiver Concept

11.2.2 RECEIVER DESIGN

The envisioned solution fulfils two requirements and improves different solutions introduced in the Morphological Chart (Chapter 12.1), all interrelated to the Temperature Management System (TRL). The problems taken into account are: fine cooling the receiver, allowing a uniform temperature around the receiver section and reducing the dispersion from the receiver.
The previously designed solution of a Fan Cooling System (chapter 12.2) has been abandoned since the one sided position of the fans would cool only the upper half of the receiver. The previous solution would exponentially increase the issue of heat distribution around the receiver section.

Fine Cooling

The cooling on a fine level is guaranteed in the given solution by implementing an external Borosilicate Glass Pipe, which creates a chamber. Along the barrel are located three different chambers since the screw needs three different temperatures (chapter 6). Every chamber has an inlet and outlet to permit the cooling fluid flow. A medium fluid then performs the fine cooling; a PID controller controls the cooling flow to balance the temperature present in the chamber. A consult about the given solution with Ruurd Pieter de Boer (02/02/22), R&D Manager at Enitor Primo, confirmed the feasibility of the envisioned solution, moreover, this solution has been discussed and theoretically confirmed also with Stephen Gray, Durban Maker Space, (2022) and Peter-Bas Schelling, Philipps - Precious Plastic(2022).

Uniform Temperature Around the receiver section

The friction caused by the rotation of the screw inside the extrusion barrel allows distribution of the temperature. (Martin, 2020)
Since the temperature differs only a few degrees from the top to the bottom of the barrel, as discovered during the testing phase, (chapter 9), the principle mentioned above can be enough to allow a uniform temperature around the screw (Interview with Ruurd Pieter de Boer). Moreover, the presence of a medium fluid would distribute the heat following the principle of convection.

Dispersion

The dispersion factor is reduced drastically with implementing the overlay in Borosilicate Glass, the most common material in Parabolic Trough Collectors Receivers (Chapter 6). The material chemical properties, combined with an anti dispersion coating, would minimise the dispersion reaching an absorption rate that oscillates around 0.96% (Lovegrove & Stein, 2012).

11.3 PHISICAL MODEL

This physical model realised in Altair Activate, allows recreating the tests conducted during summer 2021(Chapter 7,8,9). The goal of the test is firstly to validate the test conducted but more specifically to calculate the energy efficiency and the melting volumes of the parabolic collector in the test conditions and in different scenarios.

The formulas used are the same used in the preliminary calculations (Chapter 6), in this case the Irradiation Data were retrieved from databases (Solargis.com). Specifically, were used the data from the test days in order to be able to compare the two. Unfortunately the data available consists of only one measurement per hour.

The following tab shows the amount of energy collected per every hour of the test. Moreover the amount of LDPE that could have been melted with that energy.

As can be noticed from the tab, the test gives us a working scenario for the plastic extruder that is from 8:00 to 16:00. Moreover, using as a parameter the same parabola width of the test: 150 cm, it would have been possible to melt 59.76 kg of LDPE without taking into account the energy generated by the friction in between the barrel and the extrusion screw.

The test permitted the validation of the test raising the reflector sub-system TRL level from 5 to 6.

TIME	TOTAL ENERGY (J)	PLASTIC TROUGHPUT (cm^3)	Kg of LDPE
8 TO 9	1487824.957	7,461.51	6.86
9 TO 10	1701664.957	8,533.93	7.85
10 TO 11	1837744.957	9,216.37	8.48
11 TO 12	1798864.957	9,021.39	8.30
12 TO 13	1784284.957	8,948.27	8.23
13 TO 14	1759984.957	8,826.40	8.12
14 TO 15	1497544.957	7,510.26	6.91
15 TO 16	1084444.957	5,438.54	5.00
TOTAL	12952359.66	64,956.67	59.76

Figure 40: Model Results

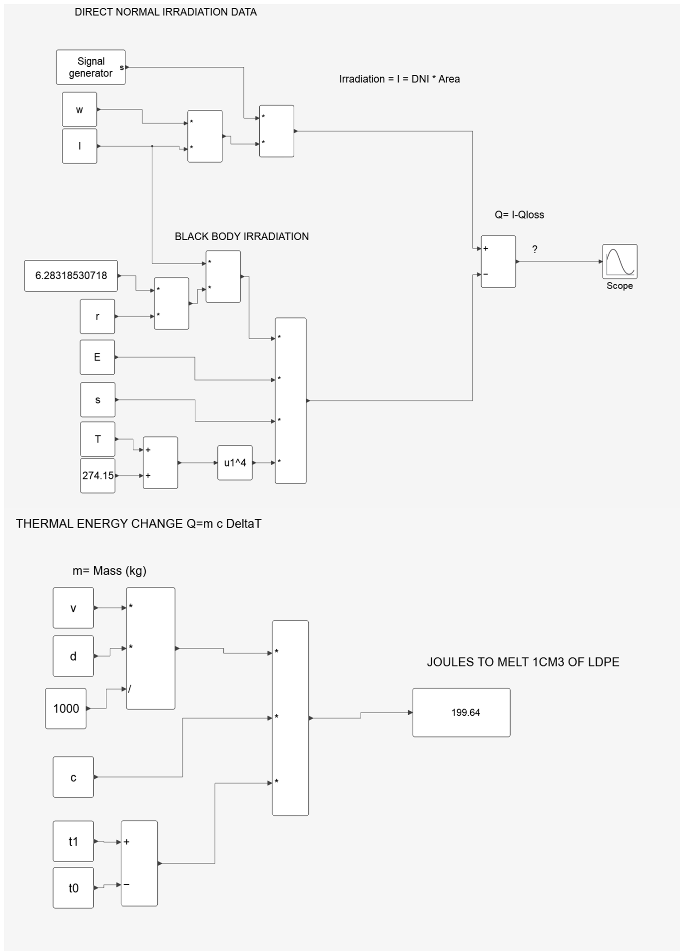


Figure 41: Model in Altair Activate

12. Desirability

One of the goals of this project is to create a societal impact on the Ulundi LM that is acceptable from the local communities.
An expert interview with Stephen Gray from Durban Maker Space (2022) allowed having relevant feedback on the actual user needs and concerns. The following chapter explains the main insights coming from the interview and the envisioned solutions

12.1 WORK PERCEPTION

A classic South African worker is used to feel directly involved in the process. Values such as productivity and knowledge are fundamental for the user; the user feels an active part of the process.
A specific example in the project can be related to the automatisation of the alignment; in this specific case, the alignment can be performed manually.

Furthermore, this solution reduces the electricity consumption of the extruder, which, as explained in the following paragraph, can be a potential blocker.

12.2 ELECTRICITY AUTONOMY

The impossibility to create and managing enough electricity for South Africa causes the need

Static monthly version . This schedule would apply each month. For 30 day month just drop day 31 and for Feb drop days 29 to 31.

Day of the month			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
	00:00	02:30	7								1	2	3	4		6	7	8	5								4	1	2	3		5	6
	02:00	04:30					1	2	3	4	5	6	7	8									4	1	2	3	8	5	6	7			
Province	04:00	06:30	1	2	3	4	5	6	7	8									4	1	2	3	8	5	6	7							
Free State	06:00	08:30	5	6	7	8									4	1	2	3	8	5	6	7									3	4	1
City/Munic	08:00	10:30									4	1	2	3	8	5	6	7									3	4	1	2	7	8	5
Naledi	10:00	12:30					4	1	2	3	8	5	6	7									3	4	1	2	7	8	5	6			
Suburb/Town	12:00	14:30	4	1	2	3	8	5	6	7									3	4	1	2	7	8	5	6							
Wepener	14:00	16:30	8	5	6	7									3	4	1	2	7	8	5	6									2	3	4
	16:00	18:30									3	4	1	2	7	8	5	6									2	3	4	1	6	7	8
	18:00	20:30					3	4	1	2	7	8	5	6									2	3	4	1	6	7	8	5			
	20:00	22:30	3	4	1	2	7	8	5	6									2	3	4	1	6	7	8	5							
	22:00	00:30	7	8	5	6									2	3	4	1	6	7	8	5									1	2	3

Figure 43: **Electricity Shifts SA**

An improvement in the project has been the implementation of alignment sensors that show on the monitoring panel the tasks to perform (see image below).
Consequently, the extruder would be equipped with handles and other manual alignment solutions to allow the tracking.

Figure 42: **Envisioned Control Panel**

to distribute the energy according to time schedules. This phenomenon, called Load Shedding (Eskom 2021), can be a potential blocker for implementing the solar extruder because of the electricity needed to power the extruder motor.

This issue, combined with the possible presence of clouds, could significantly reduce the time usage of the product, or it can cause unexpected stops while in use.
The envisioned solution to implement in the project would be to make the product energy independent by working on the motor optimisation and powering the motor via Photovoltaic panels.

12.3 PRODUCTS

Another consideration to consider to make the product desirable is the machine's output, or more precisely, which product or artefact will the machine create.
A previous thought consisted in creating artefacts as semi-products, beams or bricks since they were considered necessary for the local community.
The insights from the interview with Stephen Gray and the research conducted by himself in the last years show a completely different pattern. A South African citizen is interested in purchasing and owning products with long-lasting properties and especially low priced.

Consequently, it will be necessary to analyse which product can create an added value in order to make the extruder and the process economically sustainable.

Figure 44: **Examples of products**

13. Viability

In the first stage were designed three business models for three different potential customers and with different value propositions. The value propositions were mainly cutting the CO2 footprint or energy saving.
The interview conducted with Stephen Gray and a second iteration permitted the creation of the final business model, with a more compelling value proposition. The preliminary business models can be found on Appendix F.

13.1 VALUE PROPOSITION

The final business model aims to create a product-service system completely independent of energy supply.
This machine feature would allow to create an itinerant service and manage the plastic in the Ulundi LM suburbs. Most of which are not provided by electricity, and the missing presence of infrastructure makes the classic plastic collection impossible.

13.2 KEY ACTIVITIES

In a scenario in which every month the solar extruder is located in a different suburb or village, the service would work following these steps:

Collection Phase
In the months before the recycling phase, Informal Waste Pickers and other citizens (Key Partners) collect, clean and sort the polymers.

Recycling Phase
During this phase, the plastic collected can be shredded and recycled in order to create HouseHold Products, such as Vases, Lamp Shades etc.
Trained operators conduct the recycling phase with citizen support (Key Partners) who would buy the plastic from Informal Waste Pickers and pay eventual Salaries for the support.

Shipping Phase
The product and the process involved in manufacturing the items mentioned above would make the product difficult to sell locally. Moreover, as mentioned in chapter 14, the user from South Africa would not find value in buying such a product but would opt for a cheaper and sturdier product.
Consequently, the Revenue Streams would be generated by selling the product abroad, for instance, in Europe. Further calculation and details are shown in chapter 14.

Collection Phase

The journey restarts in a different Village.

13.3 CONCLUSIONS

The given business model, viable to implement, would modify some characteristics of the Solar Extruder. First, the new concept needs to be electricity independent to be easier to implement. Moreover, to create value, the products must be desirable from a European Customer.

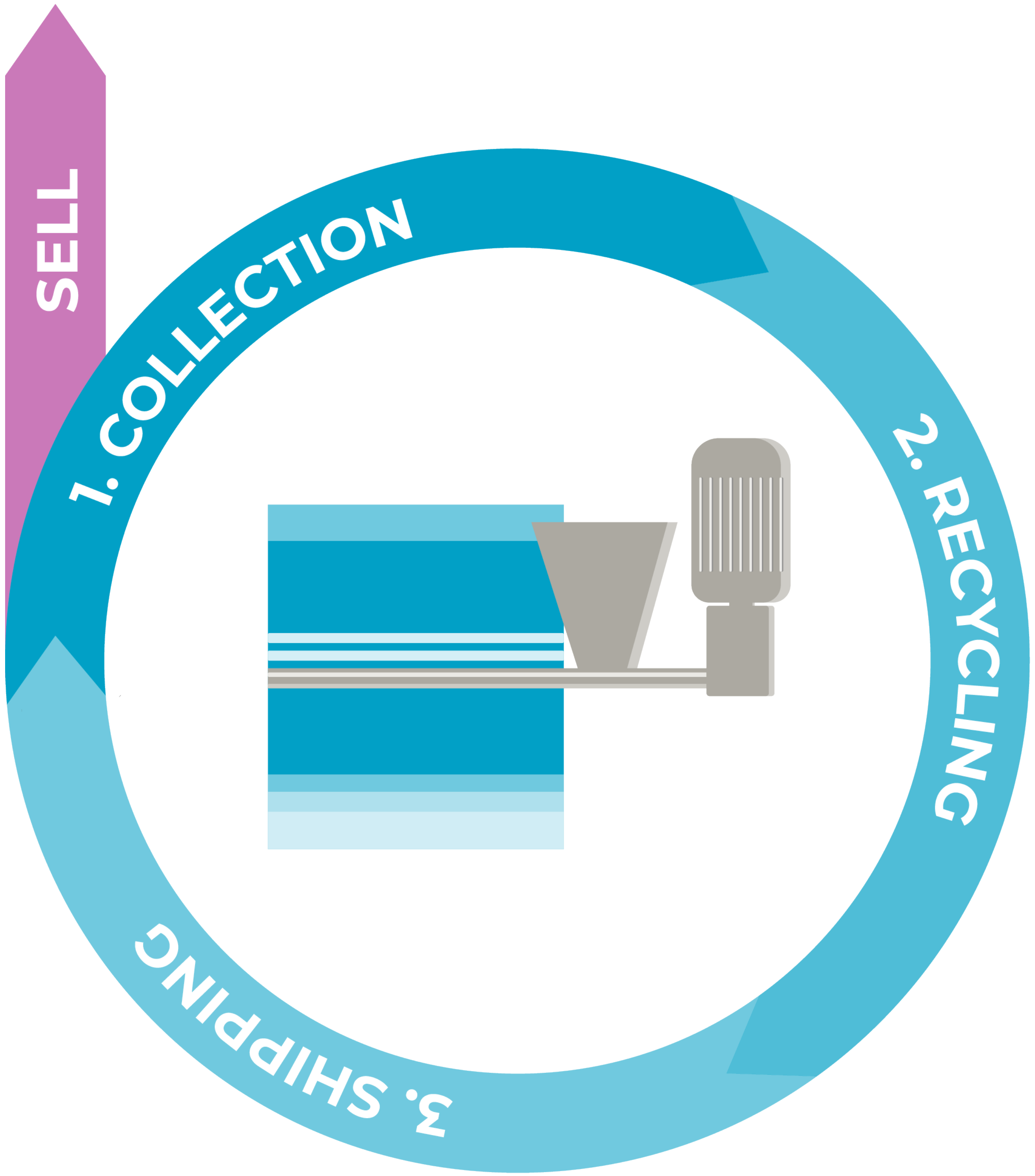
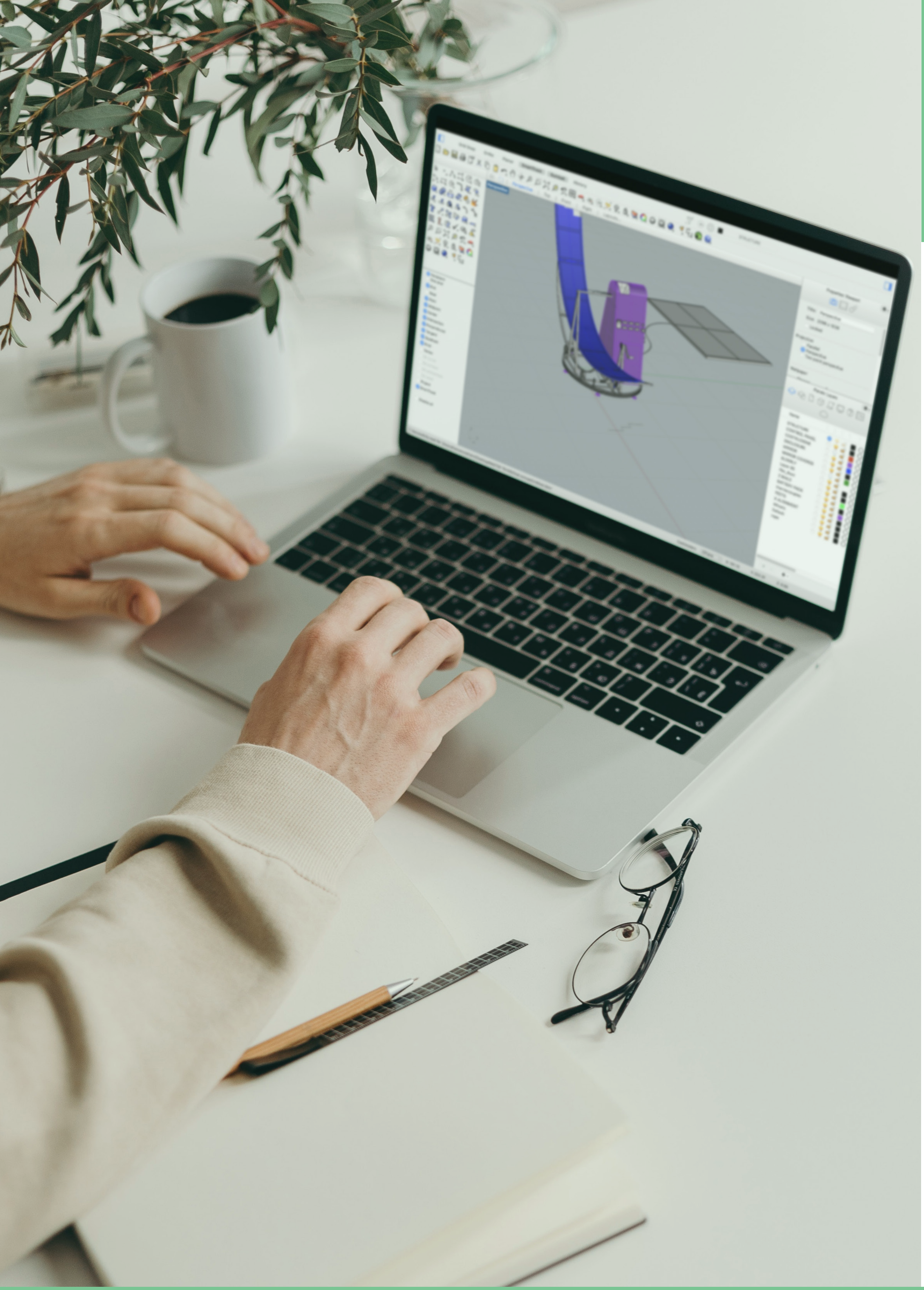


Figure 45: Usage Phases



D E L I V E R

This chapter presents the final design, outcome of the iteration of the concept chosen during the Developing phase

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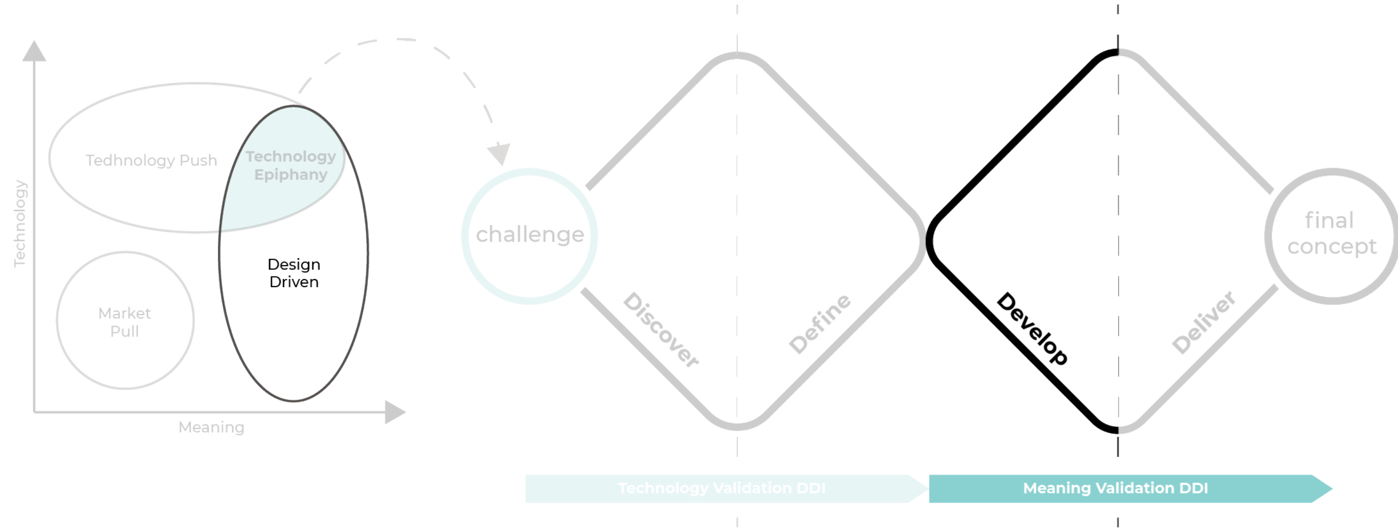

14. Archimede

The following chapter illustrates the final concept and its characteristics. Moreover it explains the service conceived symbiotically to the product and the business model that would allow its implementation.

14.1 INTRO

ARCHIMEDE

Archimede is a solar plastic extruder conceived and designed to be totally electricity independent, its sturdy and handy design allows an easy operability. Being electricity independent it could be operated in a lot more scenarios opening more possibilities and allowing the plastic recycling process in remote areas unserved by infrastructures and recycling facilities.

Figure 46: **Concept Visualization**

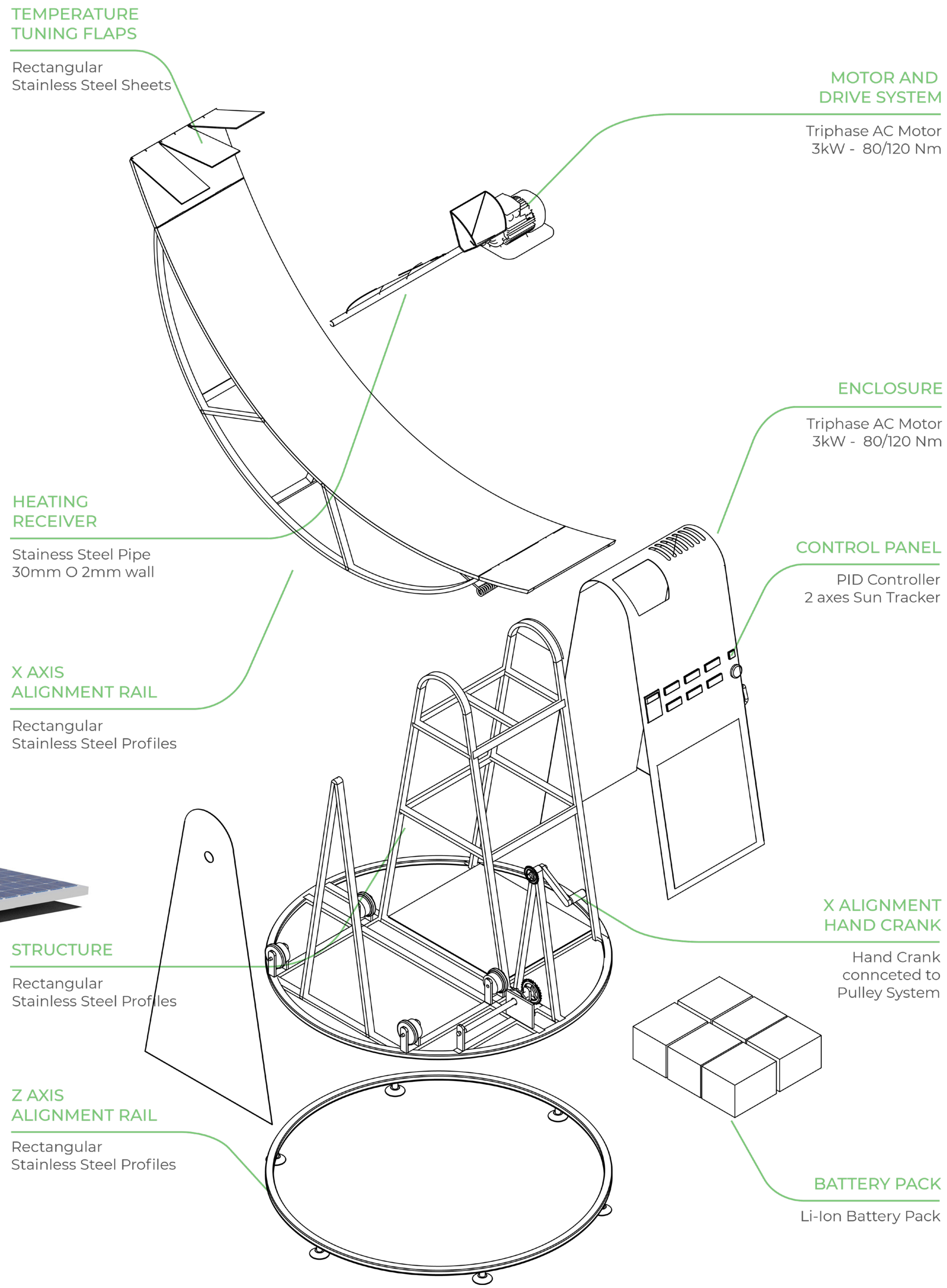

Figure 47: **Concept Exploded View**

14.2 FEATURES

Most of the design specifics are equal to the first concept (Chapter 10), in the following paragraphs are described the new features of the final design.

14.2.1 Parabola Dimensions and Volume Throughput

The second physical model (Chapter 11) permitted the definition of the final parabola width and its relative influence on the polymer throughput (LDPE) . In the table below are present different scenarios, the timespan considered

n	Width (cm)	LDPE Throughput (kg)
1	150	59.75
2	200	87.66
3	300	143.47
4	400	199.28

Figure 48: **Throughput volumes**

for all the cases is 7 hours, from 8:00 to 16:00.
The optimal width to emulate a classic Precious Plastic thermoplastic extruder throughput corresponds to 400 cm. But many other influencing factors such as operability and wind led to the decision to under dimensionate the parabola to a dimension of 200 cm that guarantees a throughput of 87,66 kg per working day.

14.2.2 Manual Tracking

The solar tracking is guaranteed by manual alignment system instead of computer controlled alignment as for the first concept. The decision to move toward a manual alignment comes from the work perception of a South African Worker, who is used to active tasks instead of controlling an automatized process(Chapter 12). Furthermore, a manual system reduces the electricity required in the product.

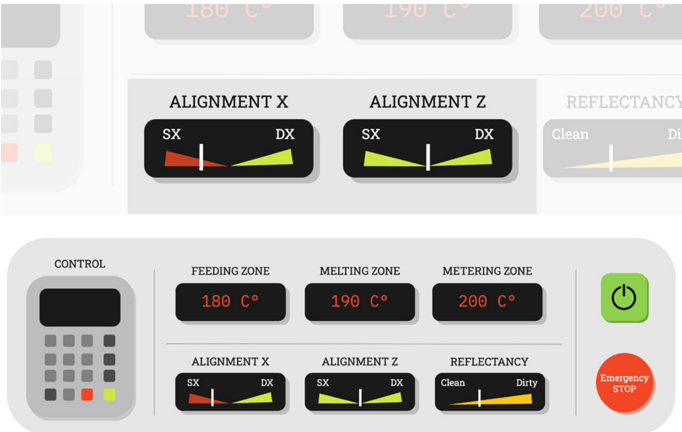

Figure 49: **Control Panel Interface**

The temperature is firstly detected from thermocouples present along the barrel, is then shown on the control panel with indication on how to perform the alignment (eg, rotate dx or sx).
The X Alignment can be actuated by a pulley system controlled by an hand crank, the Z alignment is actuated by the presence of handles who allow to rotate the entire extruder along circular rails as shown in the following images.

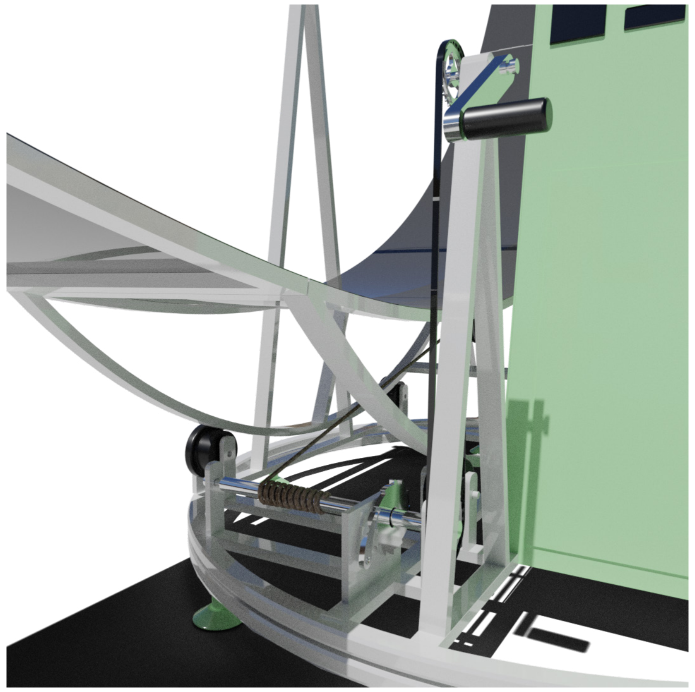

Figure 50: **X Alignment, Pulleys and Handcrank System**

Figure 51: **Z Alignment, Actuation Handles**

14.2.3 Transportability

Due to its big dimensions, the parabola structure has been designed to be foldable and compactable (following image), reducing the width of the parabola from 300cm to 200 cm.

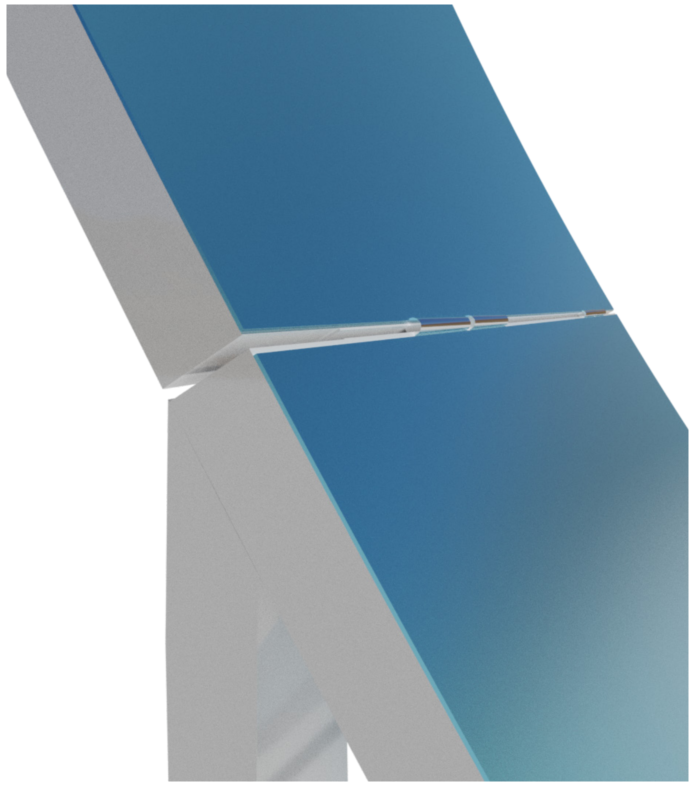

Figure 52: **Hinges for parabola compactability**

14.2.4 Three different temperatures

The implementation of three adjustable flaps permits the manual adjustment of the temperatures along the barrel. As for the tracking system, the temperature control has to be performed manually after reading the temperatures on the control panel.

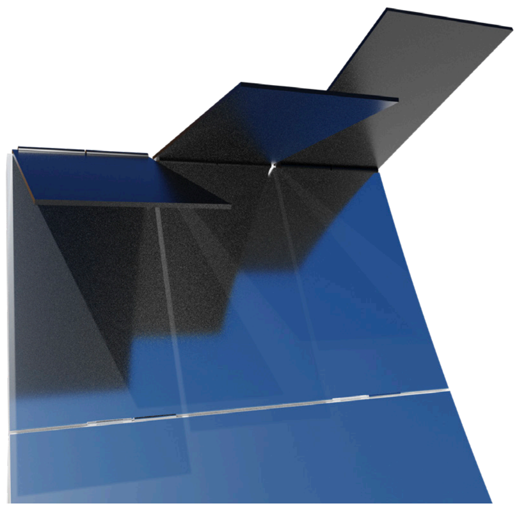

Figure 53: **Flaps**

14.2.5 Electricity Independency

The given feature is crucial for the success of this project and its implementation, as previously mentioned in chapter 12 the scarcity of electricity in most of south African suburbs would make the operability of the extruder almost impossible. Consequently in the final concept has been introduced a system of batteries and photovoltaic panel in order to give power to the motor. In future developments it would be necessary to work on motor optimization and research in sustainable batteries and PV panels.

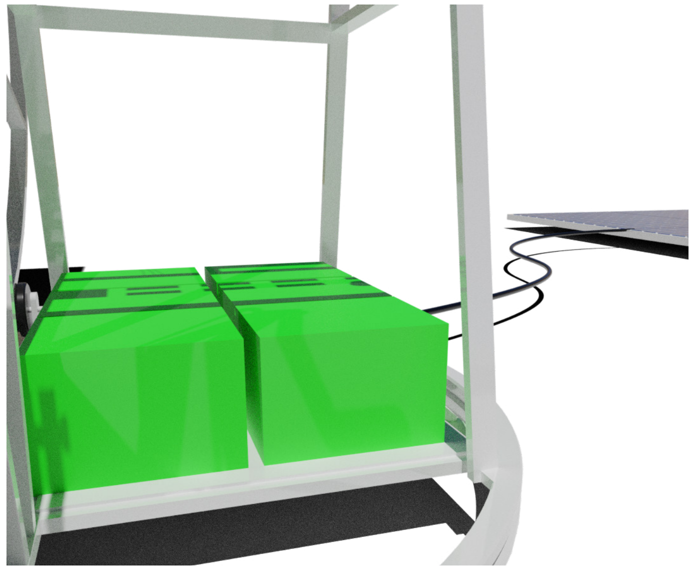

Figure 54: **Batteries Under the enclosure**

14.2.6 Enclosure and Colours

Since the extruder will be used in an outside environment and under the sun, all the metal elements have been designed in light colours as white or light green. Moreover an enclosure will protect the motor, controllers and the batteries from environmental factors.

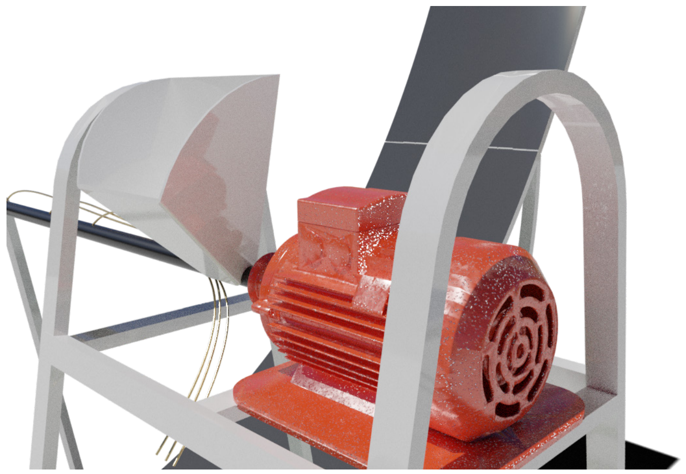

Figure 55: **Motor Under the Enclosure**

14.3 USAGE STORYBOARD

The following images show important steps related to usage storyboard of Archimede, specifically indicating the steps required to permit the alignment of the parabola to the sun.

Figure 56: **Usage Storyboard**

14.4 SERVICE

As previously mentioned in chapter 13 the service conceived aims to create an iterating plastic recycling facility, that by moving from village to village would allow with the time the complete recycling of plastic. The products outcome of the recycling process are then sold in western markets, the profit created would allow the service to sustain itself economically (14.4)
The steps introduced in chapter 13: Collection, Recycling and Shipping are here explored and re analysed, in the envisioned service the stakeholders active during the process are mainly Waste Pickers, Machine Operator, Shipping Company, and final Customer.
The following service blueprint gives an explanation of which stakeholder is involved in every step and which is the task that it is accomplishing during every step.
This service blueprint is conceived for an online shopping scenario and for one single recycling phase, after the machine moves the process will restart from zero.

PHASE	PRE SERVICE START	PLASTIC WASTE PURCHASE	RECYCLING	SHIPPING	DELIVERY
WASTE PICKER	COLLECT THE PLASTIC WASTE AND SORTS IT	SELL THE SORTED PLASTIC TO THE MACHINE OPERATOR			
MACHINE OPERATOR		BUY THE PLASTIC FROM THE WASTE PICKERS AND SHREDDS IT	RECYCLE THE PLASTIC AND COMMUNICATE THE VOLUME AND DETAILS TO THE SHIPPING	HAND IN THE PRODUCTS TO THE SHIPPING COMPANY	
SHIPPING COMPANY			RECEIVE THE ORDER AND PREPARE THE SHIPPING DETAILS	SHIPPING	DELIVERY TO THE USER AND/OR TO STORES
USER		PLACE THE ORDER	RECEIVE INFO ON THE STATE OF HIS/HER PRODUCT	RECEIVES TRACKING INFO	PRODUCT DELIVERED AT HIS/HER PLACE

Figure 57: **Service Blueprint**

14.5 BUSINESS MODEL

The service explained in the chapter above is here explored under a business model point of view in order to make its implementation as effective as possible.
The business model is thought to be a B2B2C, since the direct user of the service is a business as Local Municipality or a private company but the final Customer is a European user who would buy the products and allow a revenue stream.

The business model canvas shown below gives an explanation on how the business model works.

14.5.1 PRODUCT

One of the most important factors in the success of the business model is the outcome of the extruder. The products created through the recycling process should be appetible and valuable from the western markets in order to guarantee a revenue stream that sustains the entire service and creates profit. Moreover, another fundamental requirement of the product is the volume of plastic present in it. An example of a product that can be suitable and can represent a proper case study is a vase or but generally an household product, that can embedd an high volume of plastic

14.5.2 REVENUE STREAM

If assuming an efficiency of 50% caused by weather conditions and operation hypothetical issues the extruder would allow to produce 20 of the above shown vases in a working day. Moreover, assuming that every vase can be sold to the customer at a retail price of 30 € the monthly revenue corresponds to 12 000 €.

	1 day	1 month
Days	1	20
Vases	20	400
Revenue	600 €	12 000 €

Figure 58: Revenue Stream

14.5.3 COST STRUCTURE

Subtracting the cost structure to the total revenue is possible to find the final profit.
By keeping off the scope of the product development, the business model has the following cost involved: salary operators, plastic waste, shipping, marketing and retail cost.
In the following chart is present an estimation of the costs involved in the process on a monthly basis.

	VOICE	COST
1	Salary (2 operators)	3000 €
2	Plastic Waste	500 €
3	Shipping	500 €
4	Marketing	1000 €
5	Retail	1000 €
	Total	6000 €

Figure 60: Assumed Cost Structure

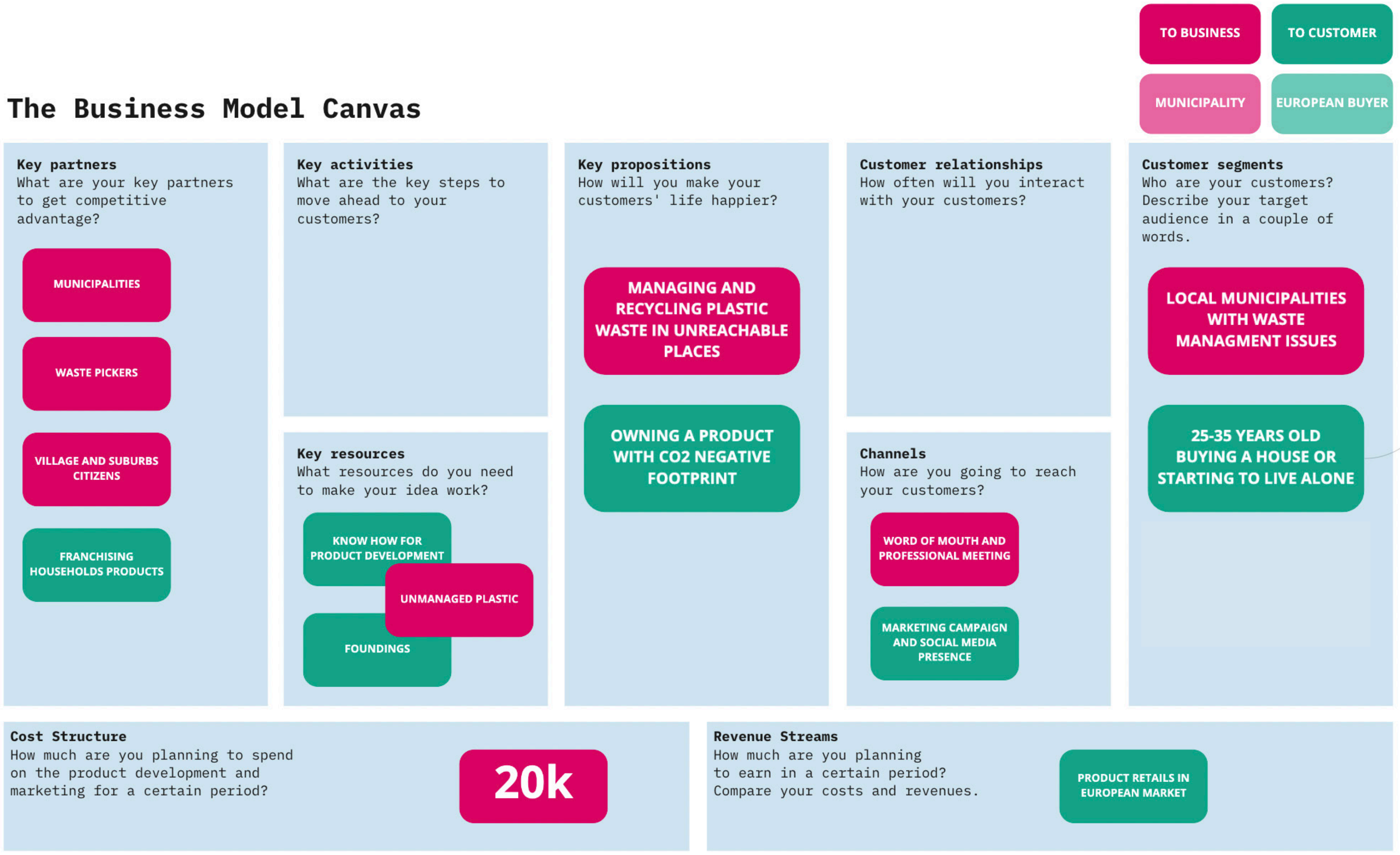

Figure 59: Business Model Canvas

CONCLUDE

This report ends with an evaluation of the work done for this thesis, from the fit with the project goal to the evaluation of the work done. Moreover, a design roadmap shows the recommendation for future development.

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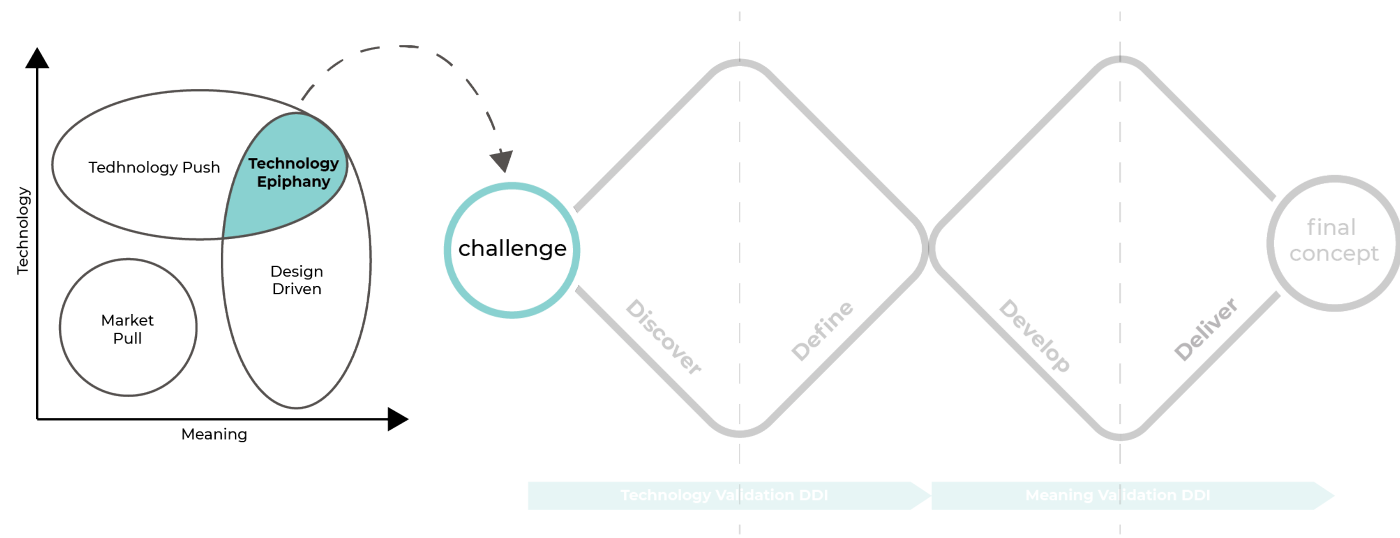

15. Conclusions

This project aimed to explore and design a new plastic recycling method by using direct solar heat instead of classic electricity. The goal of this research is to allow plastic recycling in Ulundi Local Municipality, a municipality that is lacking in waste management and recycling facilities but holds a high solar power potential.

In the first phase, the goal has been to collect and gain knowledge in the Ulundi Local Municipality working frame and in the technologies involved, thermoplastic extrusion and parabolic trough collectors via desk research. The first phase culminated with the execution of tests to understand the behaviour of a parabolic trough collector in a thermoplastic extrusion field. The research conducted and a series of two iterations allowed the development of a feasible viable, and desirable concept that holds the potential to make an impact in Ulundi LM.

It can be concluded that solar heat can be used as a heat source for thermoplastic extrusion processes; many steps still have to be faced with embodying the project and making it implementable (Chapter 15).
The extruder design would not have the same properties and efficiency as a classic one. Still, it gives the possibility to recycle in countries and villages where it is impossible to have such facilities and processes. Moreover, with its small impact, it can contribute to solving the plastic pollution problem. This issue can't be solved with a universal solution but must be tackled from every tiny facet, with their requirements and blockers.

15. Reflections

With this thesis, I propose a new way to recycle plastic by using direct solar heat in the thermoplastic extrusion process. The challenge of this assignment is given by the engineering complexity of the technologies involved in these processes combined with the complex requirements given by the working frame of Ulundi LM.

Although I don't have an engineering background, I decided to undertake this assignment mainly for two reasons.
At first, I wanted to fill my knowledge gaps by approaching a project more technical. Secondly, but most importantly, I wanted to do a meaningful product and invest my time and knowledge in something that can make an impact.

Overall I am satisfied with the results of the graduation, I really liked the fact that I developed something completely mine but moreover, it has been a continuous learning experience.
One of the biggest achievements has been the possibility to work with experts and to be able to manage and involve different stakeholders during the process. The technicality of the project allowed me to gain knowledge in new fields and to

17. Development Roadmap

In the following chapter is presented a Design Roadmap (Simonse et al., 2018) that shows the recommendations in form of a development plan of the final concept and business model in the next few years.

17.1 INTRO

As shown in the image on the next page the Development Roadmap is composed of three horizons, Product Development, Ulundi Implementation and South Africa Expansion. To make the horizons feasible the roadmap has been created on four different layers, Product Service, Market, Resources and Stakeholders, and Technology. The Market layer has been divided in Europe and South Africa since they need different actions.

17.2 PRODUCT DEVELOPMENT

To reach the first horizon the product needs some development on the Cooling and Alignment system in order to design and build a working prototype. After this first phase, if obtaining grants through the TuDelft Impact Contest , TuDelft Grants or private Investors, the prototype would be built in South Africa with the collaboration of the Durban Maker Space.

Once tested in loco the prototype would have reached a TRL 7 in all its subsystems, afterwards through the AED Industrial Design's exam the product would be embodied and reach the TRL 9 since ready for full scale deployment.

17.3 ULUNDI IMPLEMENTATION

Once reached the trl 9 before implementing the product few steps are still necessary, firstly on the Technology layer, the products need to be patented and produced.
Moreover on a Market layer it would be necessary the creation of strong relations and partnerships with local stakeholders but most importantly it would be needed to create a Retail Network in Europe.
Having the retail in Europe gives the advantage to apply for European Union's grant both for Startup but also for Developing Countries Partnerships.

After achieving the above mentioned goals the first pilot can officially start. During the pilot, all the insights are collected in order to improve the product-service and start with the real Ulundi implementation for July 2024
From this point on, the revenue flow is actively starting.
In the meanwhile on a market level, would be conducted a market research in order to start the expansion in South Africa.

17.4 EXPANSION IN SOUTH AFRICA

After tested the first product-service and researched new market the extruder would need some updates and a parametrization in order to be suitable for a different communities or a relatively different weather (e.g. Northern Cape has a drastically higher solar irradiation).
From this moment on, research on batteries and motor optimization would be conducted on a technology level.

17.5 OTHER COUNTRIES EXPANSION

The final horizon of the project roadmap aims to have an implementation of Archimede in other countries. This last step is taken into account now but still not developed since it requires a high market knowledge and major investments.

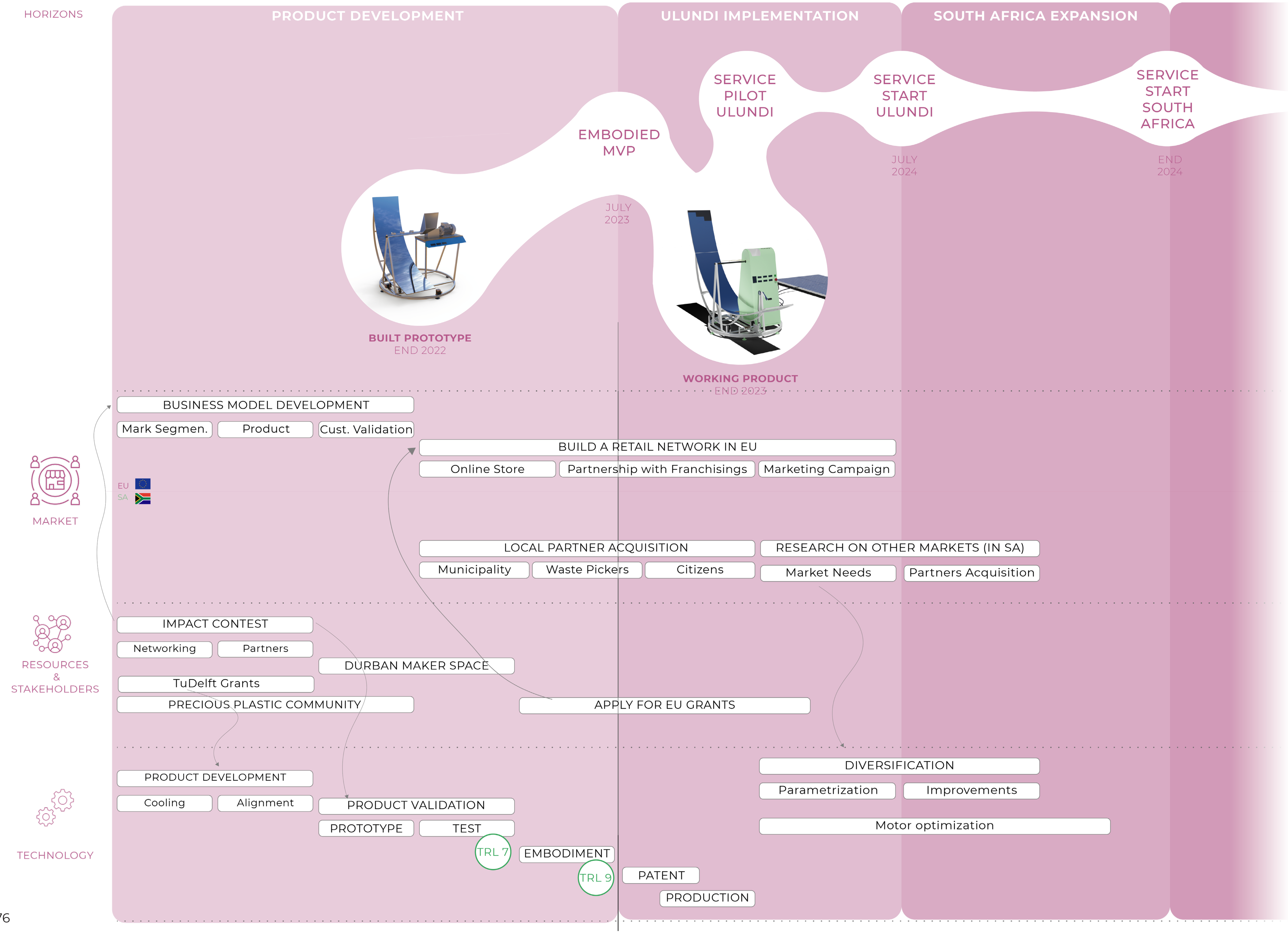

Figure 61: **Development Roadmap**

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