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Desenvolvimento de Equipamento Lúdico de Processamento de Plástico Reciclado

Development of Recreational Equipment for Processing Recycled Plastic

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Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Engenharia Mecânica, realizada sob a orientação científica do Doutor Victor Fernando Santos Neto, Professor Auxiliar do Departamento de Engenharia Mecânica da Universidade de Aveiro, e do Doutor António Manuel de Bastos Pereira, Professor Associado c/ Agregação do Departamento de Mecânica da Universidade de Aveiro.

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palavras-chave

Plástico, Máquina de Reciclagem, Reciclagem, Sustentabilidade, Precious Plastic, Gestão de Produção

resumo

O presente projeto visa contribuir para o aumento da literacia relacionada com a reciclagem de plásticos, dos processos tecnológicos associados e da criação de novos produtos feitos com esta matéria-prima, de uma forma lúdica. Os materiais plásticos apresentam e contribuem para um muito baixo impacto ambiental ao longo do seu ciclo de vida, exceto no final de vida, pois se descartados para o meio ambiente serão fonte de contaminação por milhares de anos. Importa, pois, por um lado desenvolver processos de reciclagem e incorporação desta matéria-prima em novos produtos e por outro lado criar aceitação destes produtos feitos com matéria-prima reciclada na sociedade. É neste contexto que o presente projeto tem a sua génese, inspirado no projeto *Precious Plastics*, um projeto de desenvolvimento de equipamento de reciclagem de plástico aberto ("*open source*"), assente num conjunto de máquina e ferramentas que trituram, fundem e injetam plástico reciclado, permitindo a criação de novos produtos a partir de plástico reciclado em pequena escala. O projeto *Precious Plastics* iniciado em 2013 por Dave Hakkens (Países Baixos) tem vindo a ser replicado em vários pontos do mundo, tendo a Universidade de Aveiro, em parceria com a Design Factory Aveiro, apoiados pelo projeto "INTEGRA@TEC –Transferência de competências integradas e geradoras de inovação empresarial na Região Centro", desenvolvido, em 2019, um conjunto de equipamentos de processamento de plásticos reciclados que integraram o *Smart Plastic Lab*, que dispõe de um polo no Departamento de Engenharia Mecânica da Universidade de Aveiro e um segundo polo na Design Factory Aveiro do Parque Ciência e Inovação. Os equipamentos serviram já diversas ações de disseminação e exploração cientifico-tecnológica, nomeadamente atividades da Academia de Verão da Universidade de Aveiro, hackathons do projeto OceanWise diversos trabalhos de mestrado. Serão agora enquadrados também no projeto *Precious Plastics* Aveiro, um projeto a ser desenvolvido pela Universidade de Aveiro. Este é financiado pelo Instituto Português do Desporto e Juventude por via do Orçamento Participativo Jovem Portugal, que juntará novos equipamentos, adaptados para uma maior transportabilidade, de modo a serem levados às escolas do ensino básico e secundário. O projeto *Precious Plastics* Aveiro tem como objetivo a criação de uma unidade de reciclagem criativa, com atividades deslocalizadas desenvolvidas pela Fábrica Centro de Ciência Viva, e atividades nos Departamentos de Engenharia Mecânica e de Ambiente e Ordenamento, assim como na Design Factory Aveiro.

keywords

Plastic, Recycle Machine, Recycling, Sustainability, Precious Plastic, Project Management.

abstract

This project aims to increase literacy related to plastics recycling, associated technological processes and the creation of new products made with this raw material. Plastic materials present and contribute to a shallow environmental impact throughout their life cycle, except at the end of life. If discarded into the environment, they will be a source of contamination for thousands of years. It is therefore essential, on one hand, to develop recycling processes and incorporate this raw material in new products and, on the other hand, to create acceptance of these products made with recycled raw material in society. The circular economy is an alternative to the current linear, make, use, dispose of, economy model, to keep resources in use for as long as possible, extract the most value from them while in use, and recover and regenerate products and materials at the end of their service life. The Precious Plastics project was started in 2013 by Dave Hakkens (Netherlands) and replicated in several locations worldwide. The University of Aveiro, in collaboration with Design Factory Aveiro and with the support of the project "INTEGRA@TEC -Transfer of integrated skills and generating business innovation in the Central Region". It developed a set of recycled plastics processing equipment in 2019, which integrated the Smart Plastic Lab, which has a pole in the Department of Mechanical Engineering. Students have already used the equipment, professors and researchers for several scientific-technological dissemination and exploration actions, namely activities of the Summer Academy of the University of Aveiro, hackathons of the OceanWisee project and several masters' works. They will now also be in Precious Plastics Aveiro, a project to be developed by the University of Aveiro. This project was funded by the Portuguese Institute for Sports and Youth through the Youth Participatory Budget Portugal, which will bring together new equipment adapted for better transportability to be taken to presentations. The project Precious Plastics Aveiro aims to create a creative recycling unit, with offsite activities developed by the Living Science Centre Factory and activities in the Departments of Mechanical Engineering and Environment and Planning, as well as in the Design Factory Aveiro.

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Abbreviations

- **2D** – Two Dimensions
- **3D** – Three Dimensions
- **CE** – Circular Economy
- **PVC** – Polyvinyl Chloride
- **LDPE** – Low-Density Polyethene
- **HDPE** – High-Density Polyethene
- **PP** – Polypropylene
- **PEs** – Polysulfones
- **PS** – Polystyrene
- **PET** – Polyethylene Terephthalate
- **PCS** – Plastic Collective System
- **PID** – Proportional Integral Derivative
- **PVT** – Phase Volume Temperature
- **SSR** – Solid State Relay
- **CAD** – Computer-Aided Design

1 Introduction

The first chapter of this assignment will discuss the background of the assignment as well as the purpose and motivation for the assignment. Following that will be a discussion of polymer science, which is at the core of the entire recycling concept itself. Furthermore, it will discuss some of the most pertinent case studies that will make a real impact on the world towards sustainability in the future.

The Precious Plastic Aveiro project, a project of the University of Aveiro for education and awareness of the correct use of plastic materials, has as one of its objectives the provision of equipment, in a logic of "marketspace", which allows the transformation of plastics used in new products. From this perspective, students from past years designed a set of four easily portable equipment to allow shredding and moulding by injection, extrusion, and compression of plastics of current use. This thesis proposes the analysis of these projects, their materialisation, and testing to allow this equipment to be shown to other people, children, and students to create awareness and motivate people to build a better world. For exhibitions, the goal is for the objects and machines to appeal to and catch the watchers' interest.

The main issue with plastic is its non-biodegradability. Even though the world's production of plastics is from finite, non-renewable resources, there are concerns that plastics could cause due to their chemically active precursors. The current usage pattern is unsustainable as they are known to cause pollution and other ill effects, creating global waste management problems [1]. Thus, proper plastic waste management is a serious issue that must be tackled globally through policy and adequate waste management.

These effects can put humans and the environment in danger. Also, making new ones can waste resources if plastic is not managed correctly. Thus, it is reasonable to reuse and reprocess the plastic to avoid waste in an instructed manner [2].

Over the years, some communities have already been challenged with how to dispose of plastic waste. In recent years, with a new large waste of plastic from the protective equipment that the world population uses to protect against the Covid-19 virus, it is essential to know how to control this waste to think of a solution using its recycling. Garbage dumps are increasingly overloaded, and the oceans are also beginning to feel that weight [2].

1.1 Aim

This project aims to create plastic processing equipment that promotes creativity by using reprocessed plastics to produce new products, creating awareness of the opportunities and difficulties in plastic recycling but, simultaneously, turning recycling processes more accessible and practical, acknowledging a Circular Economy.

The starting point of the current master project is the already available equipment developed and projected that it is available at the PCI Science Park and at the Mechanical Department, placing as one of the aims of the master project the development of new machines with improvements having in mind the characteristics of the older ones that didn’t work or are not as viable for the end wanted. Also, if there’s time, solve the problems with the existing ones that appeared with the use over time.

A very important aim of the machines developed is to go to a creative space linked to the university, which will then travel around to various places to perform plastic processing demonstrations, and ease of mobility is required. Each machine should be tested before being delivered to the factory so that possible improvements of the machines or new ones made by the same basic designs can be analysed.

In short, the goals set at the beginning of this project is to build the 4 pieces of equipment that I will talk about that are present in precious plastic's workspace but with some changes such as ease of mobility. That is, the equipment should be smaller or even dismountable to make it easier to transport. This is because these equipments are expected to make some trips between schools to make demonstrations and thus promote creativity and sensitize the audience about the importance of recycling.

1.2 Motivation

Engineering can be the art of doing something complex effortlessly. It is about the process of taking something that seems complicated and making it simple and easy to do. Engineering happens when you take a complex situation, explore it in depth, and then find a way to simplify it so that others can benefit from what has been learned. It's a process of discovery and creativity that yields a useful result. It's about making things easier so people can do more. As such, while engineering is a distinct industry, it is helpful to see it as a subset of many other industries where knowledge of science and technology is advantageous.

During the design process, engineers investigate the methods others have used to solve similar problems. It is also when the environment where the solution will be implemented is directly studied to ensure the awareness of all possible restrictions [3].

The goal of this thesis is to improve the aesthetics of ludic equipment without compromising its usability. As someone does a presentation with a specific audience, the speaker tries to captivate the attention as well as possible. Another aspect to be concerned comparing to the other challenges is the mobility of the machines to be developed and being aware of the materials used. One must consider the use of wheels, ergonomic trays or any other form to assist the machine's mobility.

Also, a big motivation for choosing this thesis was the concerns regarding the environment and the desire for an improved world for better future living.

It is essential to acknowledge that this equipment is intended to be able to reutilise plastic and contribute to a circular economy. Therefore, knowing how to separate and work with each kind of plastic for each desired creative end is necessary.

The knowledge needed for separating the plastics is related to the polymer science that will be aborded in the following subchapter to understand better the polymer processes and their different types and characteristics.

1.3 Polymers

This subchapter will introduce polymer science and technology, which is essential because it is a multidisciplinary field that involves synthetic polymers, biopolymers, polymer characterisation, designing, and fabrication of new innovative products related to a safer, sustainable environment. Continued development of new polymeric materials is crucial to sustaining and expanding the growing interest in polymer technology. Modern polymer science is highly proficient in tailoring polymers to specific mechanical and thermal stability aims. [4]

In polymer processing, viscosity is experienced under various states of deformation. For example, the polymer melt is subjected to significant shear stresses and strains in injection moulding. Therefore, shear viscosity is of concern. [5]

Polymer melts are processed under different processing conditions. The rate of shearing applied to the melt depends on the process used, as outlined in Table 1. Polymer melts exhibit a wide range of viscosities (10^2 – 10^6 Pa.s), mainly depending on the polymer type, shear rate and melt temperature. Polymers behave like Newtonian liquids at low shears, but their behaviour becomes pseudoplastic at high shear rates. [5]

Table 1 Shear rate depending on the process [6].

Process	Shear rate, s^{-1}
Compression Moulding	1-10
Calendaring	10-100
Extrusion	100-1000
Injection Moulding	10^3-10^4

Before covering processes, it might be helpful to include a few essential characteristics of some common thermoplastics:

- Polyethylenes
- Polypropylene
- Polystyrene
- Polyamides/nylons
- Polyvinyl chloride (PVC)
- etc

Polyethylenes come in many well-known grades, depending on their density as influenced by the degree of micro-structural crystallinity. Low-density polyethene (LPDE) is flexible and strong, used for the less expensive end of the commodity market, such as bowls, buckets, and bottles. It burns slowly, softens at approximately 50ºC, and does not resist boiling water. It usually is optically translucent. High-density polyethene (HDPE) is used where more rigidity is required. It softens at approximately 80ºC. Optically it is less clear than LDPE. There are several other grades of polyethene. [5]

Polypropylene (PP) is similar to PEs but more versatile and sturdier. Polyolefins (a generic name for aliphatic polymers such as PEs and PPs) offer a range of plastics, increasing softening points, rigidity, gloss, and chemical resistance. Therefore, polypropylene is not used for more applications usually associated with LDPE. The cost may become a factor because of flexibility requirements and market circumstances. [5]

Polyvinylchloride (PVC) is one of the few plastics to which plasticisers can be added. Thus, it exists as a rigid and flexible material. Unplasticised PVC (uPVC) is rigid, brittle (not as crispy as polystyrene) and resistant to many solvents (soluble in ketones, esters, and chlorinated hydrocarbons). Furthermore, it is one of the few polymers with good inherent resistance to catching/spreading flame, offers excellent electrical insulation, and softens at about 80-100ºC [5].

Polystyrene (PS), readily identified by the metallic noise when dropped onto a hard surface, essential PS is colourless, transparent, complex, and brittle, softens at 85-95ºC, resists aliphatic H/Cs, but is soluble in aromatic (e.g., benzene) and like ordinary PEs, is not expensive. The lightweight PS (structural foam PS or expanded PS (EPS)) is an excellent heat insulator. Still, since PS dissolves in aromatic solvents as display/insulation panels, it should only be painted with emulsion [5].

Making something out of thermoplastic differs from metal, glass, ceramic, or wood. Not only are the methods constrained (or perhaps liberated) by the plastic processing methods involved, but there are often many other constraints, many of which seem to contradict each other [7].

The molecules of thermoplastics do not cross-link on heating and can be maintained in a softened state while being made to flow under pressure into a new shape. There are forming methods designed for thermoplastics and others for thermosets, although the barriers between these methods are becoming somewhat blurred. The processes/forming procedures that are generally associated with thermoplastics include: [5]

- Injection moulding – the principle is shown in Figure 2
- The extrusion – the principle is shown in Figure 3
- Thermoforming/vacuum forming
- Rotational moulding
- Coating
- Dispensing foam
- Machining/joining of plastics

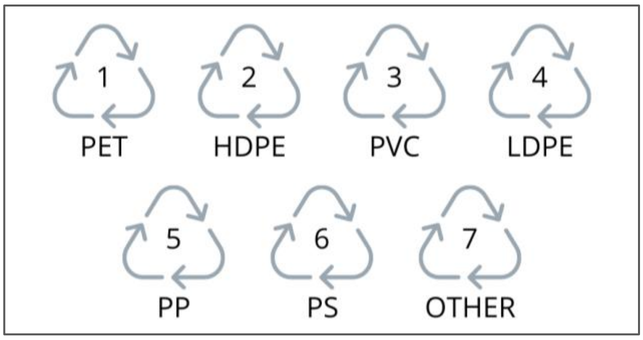


Figure 1 Plastic Labels.

As Figure 1 shows, these seven different designations generally come at the bottom of the plastic recipients of our daily lives. Typical uses of the other plastics [8]:

- PET - Soft drink, water bottles, salad domes, biscuit trays, food containers.
- HDPE - Shopping bags, freezer bags, milk bottles, juice bottles, ice-cream containers, shampoo, crates.
- PVC - Cosmetic containers, electrical conduit, plumbing pipes, blister packs, roof sheeting, garden hose.
- LPDE - Cling wrap, garbage bags, squeeze bottles, refuse bags, mulch film.
- PP - Bottles, ice-cream tubes, straws, flower- pots, dishes, garden furniture, and food containers.
- PS - CD cases, plastic cutlery, imitation glass, foamed meat trays, and brittle toys.
- OTHER - PC (CDs & DVDs…), PLA (bioplastics), ABS (3D-printing filament, toys, electronic products…), PMMA (acrylic glass)

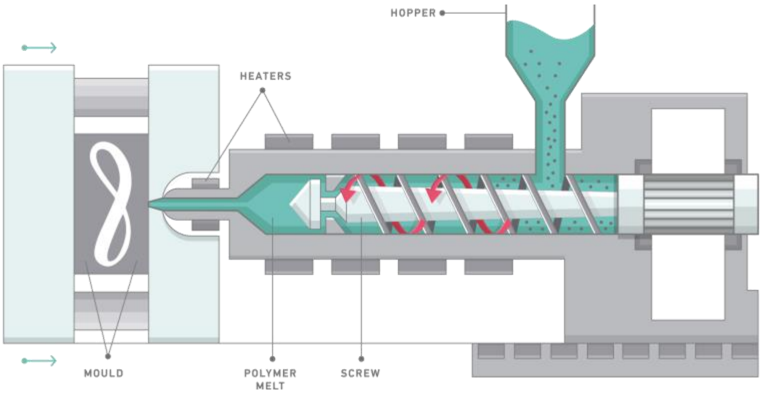


Figure 2 Injection Moulding [9].

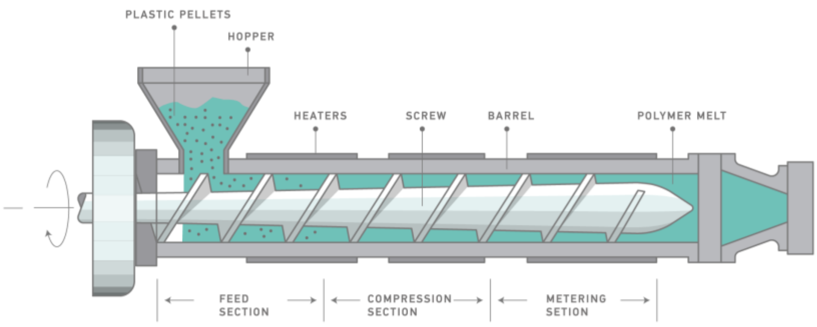


Figure 3 Single-screw Extruder [10].

1.4 Sustainability and Environmental Concerns

As plastic is a global issue, international cooperation is needed to coordinate actions to have an efficient decision-making in order to tackle this major environmental problem. A number of initiatives and activities exist aiming at addressing the plastic waste problem and eliminating plastic litter entering the oceans. A historical turn was reached at the fifth UN Environment Assembly (UNEA-5.2) in February 2022 as countries agreed to establish an International Negotiating Committee (INC), to develop an international legally binding instrument on plastic pollution by the end of 2024. The resolution specifies that the instrument could include both binding and voluntary approaches, based on a comprehensive approach that addresses the full lifecycle of plastic [11].

Plastics are one of the world's greatest industrial innovations. However, the sheer scale of their production and poor disposal practices result in growing adverse effects on human health and the environment, including climate change, marine pollution, biodiversity, and chemical contamination, which require urgent action. Plastics exist in many sectors, including packaging, construction, automotive manufacturing, furniture, toys, shoes, household appliances, electrical and electronic goods, and agriculture. This wide demand has caused plastic production to explode globally, outgrowing most manufactured materials [12]. Plastic production increased more than twenty-fold between 1964 and 2015, with annual output reaching 322 million metric tonnes (Mt) [13]. A second analysis indicates that global yearly plastics production rose from 2 Mt to 380 Mt between 1950 and 2015 [14]. Future plastics production will double by 2035 and almost quadruple by 2050 [15].

Historically, plastics were produced primarily in Europe and the United States. However, this has recently shifted to Asia. China is now the leading producer with 28% of global production in 2015, while the rest of Asia, including Japan, produces 21% (Figure 4), i.e. nearly half the worldwide production of 2015 [16].

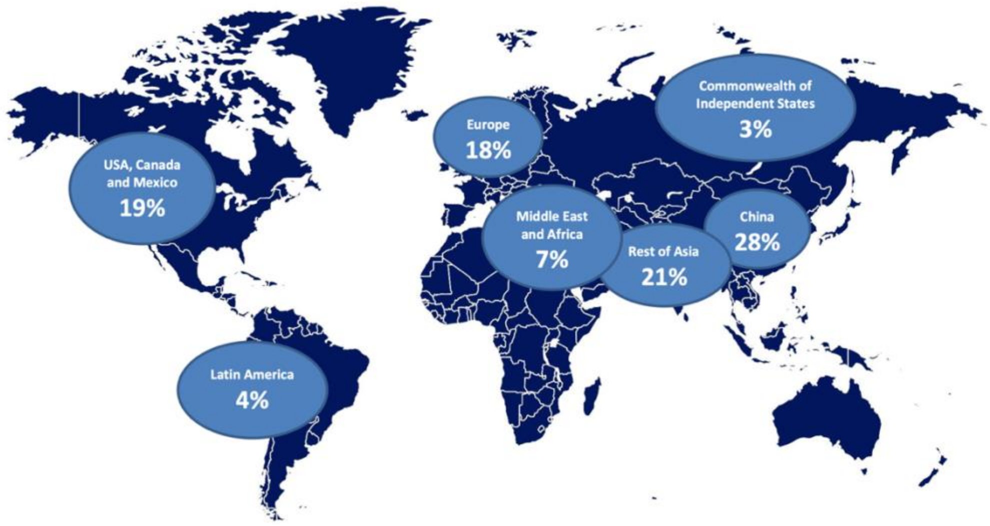


Figure 4 Global distribution of plastics production [16].

Plastics contribute to economic growth, but their current production and use pattern, on a linear model of 'take, make, use, and dispose', is a primary driver of natural resource depletion, waste, and environmental degradation. Climate change has adverse human health effects. Globally, it is estimated that only 9% of the 6300 Mt of plastic waste generated between 1950 and 2015 was recycled [17]. India has probably the highest plastic recycling rate, with 47 to 60% estimates. In the EU, only approximately 30% of 25 Mt of post-consumer plastic waste was recycled in 2014; China had a recycling rate of 22% in 2013 [18], while only 9.5% of plastics entering the US municipal solid waste stream were recycled in 2014. Recycling rates are also low in Latin America and the Caribbean. [9]

Conventional plastic production is highly dependent on virgin fossil feedstocks (mainly natural gas and oil) and other resources, including water – it takes about 185 litres of water to make a kilogram of plastic. Plastic production uses up to 6% of global oil production. This oil production is expected to increase to 20% by 2050, when plastic-related greenhouse gas emissions may represent 15% of the global annual carbon budget.

Some plastics contain toxic chemical additives, including persistent organic pollutants (POPs), linked to health issues such as cancer and mental, reproductive, and developmental diseases. It is challenging to recycle some plastics without perpetuating these chemicals.

Plastics stay in the environment for a long time; some take up to 500 years to break down; this causes damage, harms biodiversity, and depletes the ecosystem services needed to support life. Plastics are broken down into tiny pieces (microplastics) in the marine environment, threatening marine biodiversity. Furthermore, microplastics can end up in the food chain with potentially damaging effects because they may accumulate high concentrations of POPs and other toxic chemicals.

Microplastics are an emerging source of soil and freshwater pollution. The contamination of tap and bottled water by microplastics is already widespread, and the World Health Organization assesses the possible effects on human health.

1.5 Circular Economy of Plastics

The circular economy is an alternative to the linear economy: make, use, dispose of, economy model, which aims to keep resources in use for as long as possible, extract the maximum value from them whilst in use, and recover and regenerate products and materials at the end of their service life [19]. The circular economy [20] promotes a production and consumption model that is restorative and regenerative by design [21]. It is designed to ensure that products, materials, and resources are maintained in the economy at the highest utility and value for as long as possible while minimising waste generation by designing [22] waste and hazardous materials. The circular economy applies to both biological and technical materials. It embraces systems thinking and innovation to ensure the continuous flow of materials through 'the value circle' [23], with manufacturers, consumers, businesses, and government playing a significant role [24].

The circular economy is a production and consumption model involving sharing, leasing, reusing, repairing, refurbishing, and recycling existing materials and products for as long as possible. In this way, the life cycle of products is extended [25]. There are main targets by application areas, as shown in Figure 5 [16].

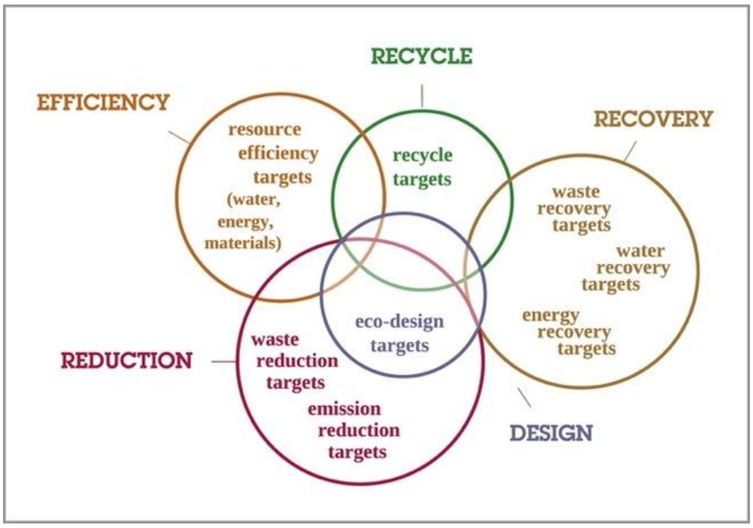


Figure 5 Main existing Circular Economy targets by application areas [25].

The plastics circular economy is a model for a closed system that promotes the reuse of plastic products, generates value from waste and avoids sending recoverable plastics to landfills. Plastic waste is a valuable resource that can produce new plastic raw materials, manufacture plastic parts and products, or generate energy when recycling is not viable.

Currently, the plastics industry is researching alternatives to replace fossil sources with renewable resources and carbon dioxide (CO_2). New thinking all along the value chain – from product design to recycling – focuses on converting more waste into recycles, maximising resource efficiency and reducing greenhouse gas emissions. [26]

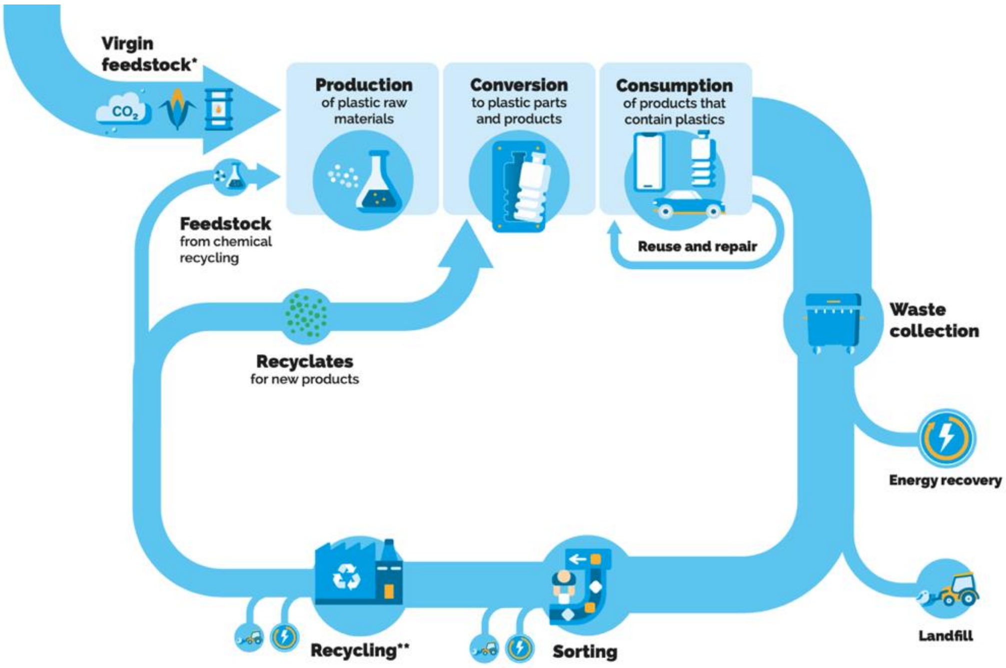


Figure 6 Plastic circular economy - Virgin feedstock originates from fossil fuels, CO2, or renewable feedstock - Recycling includes mechanical, chemical, and dissolution. [27]

Plastics are used to produce products (e.g. a bottle, a pipe, a chair, etc.) or to produce parts for more oversized products (components and parts in vehicles and planes, insulation for houses, shoe soles, etc.). The former is called "plastic products", and the latter is called "products containing plastics".

The use phase of plastic products or plastics production depends on their application, ranging from approximately less than one year to fifty years (e.g. beverage bottles, phones, car parts, insulation for homes and buildings). This explains why waste volumes for a given year (here, 2018) are considerably smaller than the total manufactured plastic products and parts put on the market for the same year. Their longevity (use phase) makes plastics attractive in delivering more value, sustainability and resource efficiency.

Today, plastic waste that cannot be recycled mechanically, such as composite materials, is recovered to produce heat and electrical energy. However, new chemical recycling developments show that this type of waste will soon be recycled more often.

Innovations such as chemical recycling and solvent dissolution provide the potential for complementary recycling methods to mechanical recycling. The combinations of these recycling methods have the potential to reshape waste management.

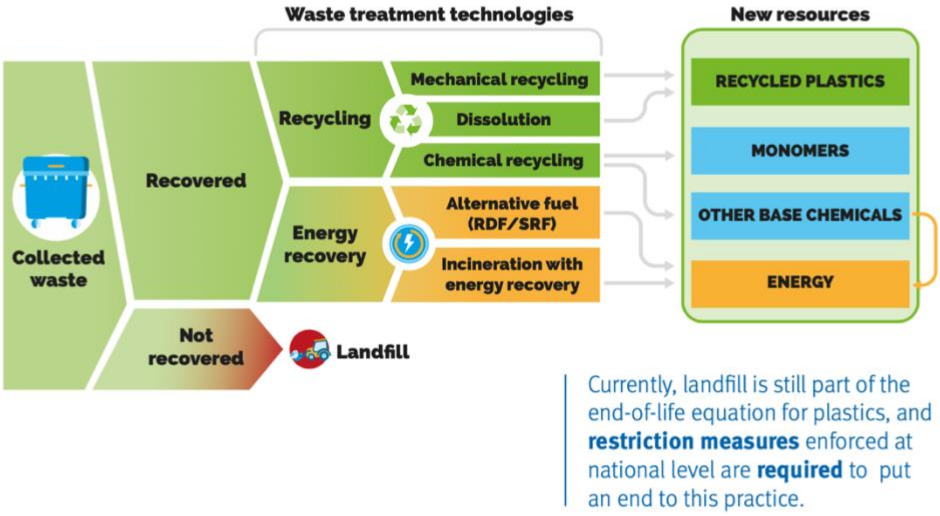


Figure 7 Reshape of waste management. [27]

Plastic is good support in our modern lifestyles. Due to their attributes, plastics are essential in promoting sustainability as part of a circular economy. This concept promotes a sustainable way of life, where resources are used efficiently and retain the economy for as long as possible.

Considering all aspects of the plastic and plastic waste system and processes that go beyond end-of-cycle solutions, sustainable management requires an integrated solid waste management strategy with a renewed emphasis on the design of plastic waste. [27]

1.6 Resource and Waste Management

Only 4% of the world's oil reserves are used in the manufacture of polymers is sometimes used as an argument that they do not contribute much to the degradation of the environment, but 4% still represents a valuable resource. Furthermore, there are other issues to consider, such as the generation of solid waste and pollution associated with polymeric materials and products. Hence addressing the problem of polymers in the environment remains an important goal. However efficiently we use resources, the laws of thermodynamics teach us that some waste will always be generated. The waste management hierarchy follows the options of reduction, reuse, recycling, incineration and landfill by this order.

The most desirable option in this hierarchy is the reduction of resources, which also leads to a reduction in waste. The following two options aim to turn waste back into resources through reusing and recycling materials, conserving natural resources and reducing other environmental damage. Thus, adopting a 'more with less' approach maximises benefits from products and services, uses the minimum amount of resources and rejects the least amount of waste or emissions to the environment. In essence, barren production is seen as a demonstration of the inefficient management of resources. This is in harmony with the laws of Nature, where there is no such thing as waste. All biological systems are interconnected; what is a waste for one system is a valuable resource for another.

The last two options in the hierarchy are incineration (without energy recovery) and landfill. Because they both waste valuable resources, with incineration also contributing to air pollution, they are not considered sustainable options. However, it should be borne in mind that, even with the first three options fully implemented, some waste is still unavoidable and has to be disposed of by either incineration or landfill. [28]

1.6.1 Mechanical Recycling

Mechanical recycling uses physical and automated means, such as grinding, heating and extruding, to process waste plastics into new products. It requires clean and homogeneous waste, which means that plastics have to be sorted by type and separated before they can be incorporated into virgin polymers of the same kind or used on their own. The availability of homogeneous waste streams of known characteristics is thus a key criterion for successful recycling. [28]

1.6.2 Chemical Recycling

This is another material recycling form particularly well suited to mixed plastics waste. It uses chemical processes to break the polymers into their chemical constituents and convert them into valuable products, such as basic chemicals and/or monomers for new plastics or fuels. As in mechanical recycling, some pretreatment of plastic waste is required to meet the specification of the recycling process. [28]

1.6.3 Energy Recovery

If material recycling is not viable or after certain products have been removed from the waste stream for mechanical recycling, the high calorific value of plastic waste can be recovered as energy20. Waste polymers can be used directly in production processes to substitute other fuels (such as cement kilns) or for power generation. Energy recovery can be made through direct incineration, such as municipal waste incinerators, to generate heat and electricity.

Currently, most post-consumer waste is recycled as energy, followed by mechanical and chemical recycling at much lower rates. The recycling rates differ in different countries but are still deficient overall. In Western Europe, only 30 % of polymer waste is recycled, and the rest goes to landfills. However, there is an indication that the recycling rates may be increasing. For example, according to some estimates, mechanical recycling in Western Europe could double in 1995–2006 from 1.2 million tonnes to 2.7 million tonnes20. [29]

Choosing the best recycling option is difficult because each case is different, and many factors must be considered. These include the suitability of the material for each waste management option, location, transport, infrastructure, technological developments, economic viability, and end markets. It is also essential to ensure that the resources used in the overall recycling operations do not exceed the environmental benefits of recycling. [28]

1.7 Case Studies

Now it is presented some case studies that are associated with the project report.

1.7.1 Plastic Collective

Plastic Collective uses the Plastic Collective System (PCS) to deliver projects to communities. It provides communities with tools, knowledge, and processes to establish plastic resource recovery operations, eliminate waste and prevent pollution.

PCS includes plastic recycling facilities that can process discarded plastic into valuable products such as recycled plastic, manufactured products, and plastic credits.

PLASTIC COLLECTIVE

The PCS provides four critical components for establishing a successful resource recovery and recycling program to enable communities and businesses to mitigate their plastic impact and create value from plastics as a resource: Hardware infrastructure and equipment; Digital software for monitoring and compliance; Education and training programs; Marketplace and supply chain network Infrastructure and equipment hardware.

1. Infrastructure and equipment hardware

Provides communities with an innovative package of technologies, machinery, training, and support that enables them to establish a profitable plastic recycling micro-enterprise.

Onsite recycling hardware can include shredders, granulators, balers, extruders, compression moulders, and generators Figure 8.

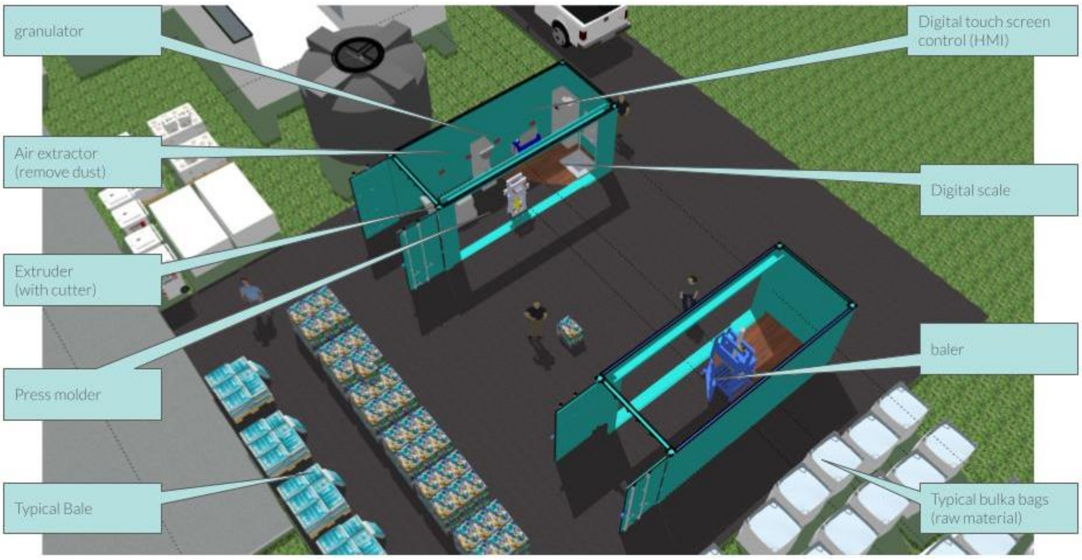


Figure 8 Basic Floorplan [30].

2. Digital software for monitoring and compliance

This allows communities to connect with verifiable supply chains through local and global markets and provides end-to-end solutions for brand partners to track plastic material right through the value chain. The software includes provenance tracking and certified ethical and environmental compliance within the programs by forming community partnerships. The digital infrastructure includes:

- Integrated Software
- Tailored technologies
- Ethical and Environmental monitoring and compliance data
- Value chain tracking

3. Issuance of Plastic Credit Certificates

For projects that are validated to sell plastic credits, Plastic Credit compliance is verified for materials recovered and recycled through the system with a certification.

Plastic Collective has developed three main modules covering Plastic Education, Project Essentials, and Operational Training [31]

Plastic Education
M1 – Plastic Collective System
M2 – Global Plastic Crisis
M3 – Local Community
M4 – Materials Knowledge

Project Essentials
M5a – Project Preparation
M5b – Enterprise Essentials

Operational Training
M6 – Recovery Operations
M7 – Concentration Operations
M8 – Recycling Operations

1.7.2 The New Raw

The New Raw crafts plastic waste with robots is a research and design studio based in Rotterdam (Netherlands) founded in 2015 by architects Panos Sakkas and Foteini Setaki with the ambition to give new life to discarded materials through design, robots, and craftsmanship.

The New Raw develops its own (digital) craftsmanship techniques through a formal and technical language highlighting the texture and the layer-by-layer character of its in-house robotic manufacturing process. Exploring the possibilities that the automated methods provide transforms plastic waste into beautiful and meaningful products that are 100% circular. [32]

Figure 9 Robots and Design Examples [32].

1.7.3 The Plastic Flamingo

Founders Francois & Charlotte were mesmerised by Nature showing itself at its best and at the same time being confronted with how mass consumerism and the production of cheap plastic have led to the enormous plastic waste pollution we all know today.

This led to the creation of The Plaf, also known as The Plastic Flamingo, a social initiative based in the Philippines that collects and transforms plastic waste into a range of sustainable construction materials. These materials can be used to build new schools, housing, and shelters to help make this country more resilient against the many natural hazards the country faces yearly.

It begins by separating household plastic waste and partnering with companies so that we can ensure that plastic waste does not end up in landfills, river streams, or even oceans. About 10% of the waste management network are public delivery points where individuals can leave their plastic waste clean to help support our mission.

The recycling warehouse segregates both post-consumer plastic waste and post-industrial plastic waste. When separating, the types of plastics are categorised before recycling them.

Once cleaned and dried, the remaining plastics are crushed into flakes, the main ingredient for recycled products. The Research & Development team is constantly testing different formulations, optimising and expanding the product line – trying to incorporate plastic resins that are known to be quite difficult to recycle.

The flakes are mixed in a unique formulation that undergoes an extrusion process and is moulded into different shapes. The transformation is now complete, transforming plastic waste into eco-durable woods. They currently have two sizes and two colours available on the market, ready to be purchased and used for drawings. [33]

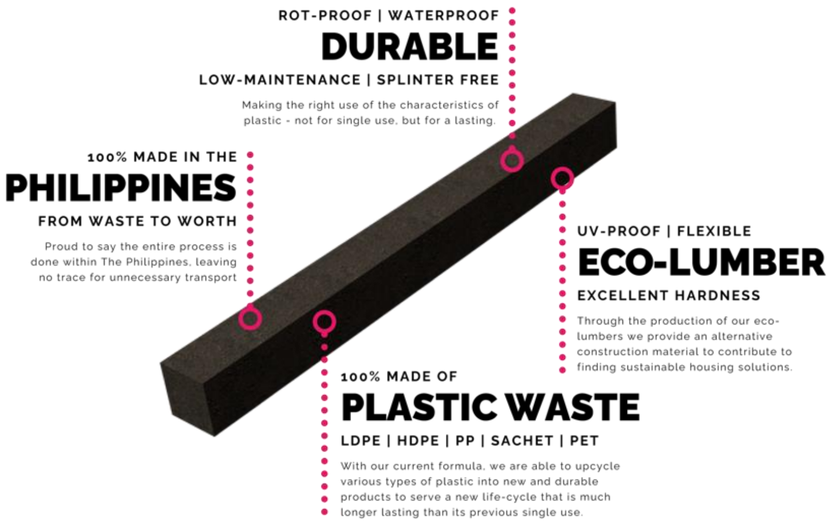


Figure 10 Construction Part Obtained [34].

1.7.4 Back to Nature – Andrea Mangone

Back to Nature is a set of 3 products made of recycled plastic containers and bags to be used not by humans but by wildlife and plants.

Project background: Back to Nature was born as a personal exploration of how to close the plastics loop. The project aims to raise awareness of the excessive production of disposable plastic products and make urban locations more welcoming to animals and insects. [35]

This project makes beehives, flowerpots, and bird feeders (Figure 12) from recycled plastic using a circular economy, as shown in Figure 11.

Figure 11 Circular Economy from Back to Nature [35].

Figure 12 Birdfeeder and beehive examples [35].

1.7.5 Precious Plastics

This is the project on which this thesis is based.

Born in the Netherlands, Precious Plastic is an open-source project. Precious Plastic approaches count on people to bring about the necessary change. It combines people, machines, platforms, and knowledge to create an alternative global recycling system to develop new products on a small scale [36].

A Precious Plastic **Workspace** is where plastic gets transformed from waste into valuable raw materials or products. There are five workspaces: Shredder, Extrusion, Compression, Injection, and Mix.

Collection Points gather plastic from neighbours, organisations, and businesses to be processed by local Shredder Workspaces.

Community Points connect and grow the local recycling network. They are strengthening the existing community while involving more and more people.

Machine Shops produce and build parts, machines, and moulds for others in the local recycling network.

Precious Plastic **Members** are the ones who fuel the recycling network by helping with plastic collection, spreading the word, purchasing recycled plastic products, and supporting in other ways.

Shedder

The Shredder is the backbone of Precious Plastic. It allows the worker to shred plastic into small flakes - it can easily wash and store shredded plastic and transport it to other Precious Plastic workspaces to make valuable products. [37]

Extrusion

Extrusion is a continuous process where shredded plastic enters the hopper, is heated, and pressed with a screw through a long barrel. The output is a steady line of plastic. This machine creates filament (challenging but doable) and granulates, or the user can get creative and spin this continuous line around a mould; and is excellent for educational purposes as the process is straightforward to understand. Plastic is extruded nicely, blends different colours and produces a clean, homogenous colour. [37]

Injection

The injection machine has a quick production output with high precision, but it takes a little bit more effort at the beginning to design and make a mould. Shredded plastic enters the hopper and is heated and pressed through a long barrel into the chosen mould. The output colour is often unpredictable when mixing colours in the barrel, allowing different patterns to add to one-of-a-kind products. [37]

Compression

The compression machine is an electric kitchen oven to heat the plastic and a compression mechanism (a carjack) to apply pressure to your mould. The process is slower than the other Precious Plastic machines, allowing larger moulds to be used. It can be used to create raw material, like sheets or shapes, that can be further worked on to make new products and gives a specific flake-like look to the plastic. [37]

1.8 Summary

The motivation for developing user-friendly processing equipment is presented in the current introduction chapter, along with developing plastic processing equipment that fosters creativity by using recycled plastics to create new products and raise awareness of basic polymer science. In this scope, an introduction to different polymers and processing equipment, resources and waste management, and a brief description of similar projects have been done.

The next chapter will address state of the art concerning mechanical design; sustainability and environmental concerns; the circular economy of plastics; and the initial state of the project, this is, the use, as a starting point, of the solutions presented in the Precious Plastic platform and examples developed at the University of Aveiro. Following the presentation of methodology and project solutions, the presentation of the solutions' materialisation and discussion follows. The report is then ended with the conclusion chapter.

2 Theoretical Contextualisation and Literature Review

The introduction chapter has highlighted the leading plastics typically encountered in the home waste environment, namely PET, HDPE, LPDE, PP, and PS, the leading processing technologies for production and recycling, and many ludic solutions. With the analysis of the case studies, it becomes clear that with some of these, it is possible to make new objects and stock materials that can be useful to our daily life and avoid an extreme amount of pollution. This chapter intends to address the state of art concerning mechanical design, sustainability and environmental concerns; the circular economy of plastics; and the initial state of the project.

Initial State of the Project

The starting point of the present work was the solutions presented in the Precious Plastic platform and a set of previously developed machines at the University of Aveiro. Some of these machines presented problems, and others did not work. The proposed aim was to develop four new devices that could be transported easily and avoid some of the mistakes done in the projects done previously.

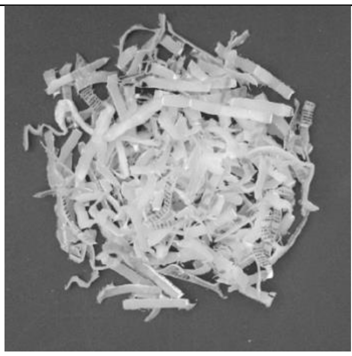
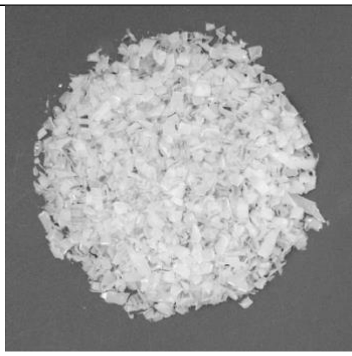
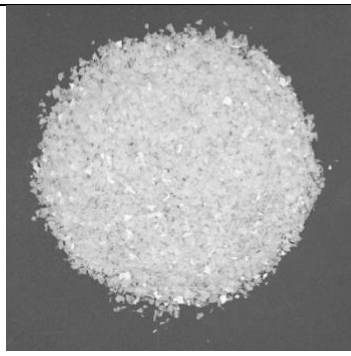
2.1 Shredder Review

Figure 13 shows the Shredder, maybe the most crucial machine in the workspace. This machine shreds plastic into small flakes. The previously cleaned plastic is inserted into the hopper and then shredded by the blades in the shredding box. After this, it goes through a net that filters the bigger flakes, only letting through the ones that can be used in the following stages. If the final stage flakes are too large, the plastic can go through the same process until the desired size for each result, as in Table 2.

Figure 13 Shredder Pro.

The machine in the proposed project thesis does not use a motor. It aspires to be able to shred the plastic with a handle attached to a gear system and be able to use only human force to shred any type of plastic already used in the original Shredder.

Table 2 Flake Sizes.

0 – 30 mm	0 – 10 mm	0 – 7 mm
		
• Sheetpress	• Sheetpress • Injection • Compression	• Sheetpress • Injection • Compression • Extrusion

In the Shredder that already exists, there were some problems with the net because it deformed after some usage. The fact that the plastic could not drop into the blades on its own and that moving the machine was challenging were additional issues.

Rotating blades constitute the cutting system in the form shown in Figure 14. The existence of only one momentum may be one of the problems that lead to the plastic's inability to go through the blades on its own. When applied to manual equipment, as this thesis suggests, the answer identified in some literary examples is represented by Figure 15 and not only benefits in momentum but also might be capable of minimizing the force applied to the handle, making rotation easier.

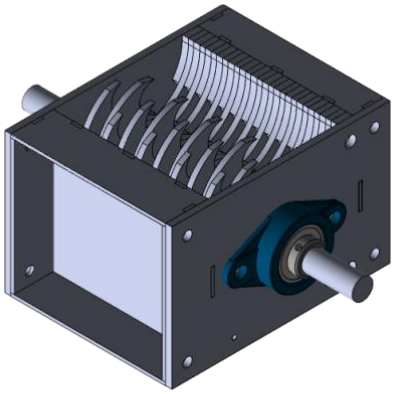


Figure 14 Original shred project.

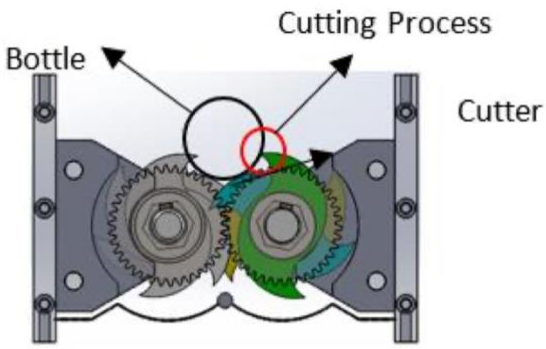


Figure 15 Possible shred solution.[38]

Aware of the project's easy mobility goal, a solution without a motor may be a good proposition because the weight of a simple motor can significantly influence that aspect. We can also look at the manual option as an economic electricity saving that the project can achieve. Large-scale shredders use a considerable amount of electricity for such applications in industries.

Figure 16 Manual shredder possibility. [38]

Now looking from a different point of view, it is essential to analyse industrial shredders.

The following evaluation aspect is how the shredding mechanism influences the plastic output. For example, it presented four different shredders from the same company, but the shred system is built, as shown in Figure 17.

Figure 17 Four different shred mechanisms.

The first machine (Figure 18) utilises a system with two-shaft primary reducers, commonly employed in volume reduction or pre-shredding applications with a wide range of commingled materials, including unsorted waste, ideal for the primary liberation of materials. Compared with the second machine (Figure 19) is constructed with a line of two-shaft shredders and is commonly employed in volume reduction, product destruction or primary shredding applications. These low-speed, high-torque industrial shredders are ideal for processing compressible materials such as rubber, metals and many plastics that need to be “cut” to be reduced. [39]

Figure 18 Primary Reducer.

Figure 19 Two-Shaft Shredder.

The mechanism presented in Figure 20 comprises four-shaft shredders that process a wide range of material streams to a consistently small size in a single pass. This form is ideal for commingled materials without overly thick metals, and their large "throat" opening allows even large, bulky items to be processed. The last machine (Figure 21) is formed with one-shaft shredders ideal for size reduction of consistent materials such as paper, plastic, foil, foam, textiles, aluminium, tire chips and more. These shredders can work as stand-alone machines in some applications or as secondary machines that reduce the output from primary shredders after removing metals. [39]

Figure 20 Four-Shaft Shredder.

Figure 21 One-Shaft Shredder & Grinder.

Overall, the analysis of this *SSI Shredding Systems* makes clear the variety of possibilities of output material by varying the blade system this can be helpful to any future improvements in the project in sight.

2.2 Extrusion Review

The Extrusion (Figure 22) is a process machine that works with a motor. The plastic is introduced in the hopper. As the band heater starts working, the plastic is heated until a specific melting temperature depends on the material. When the plastic reaches the desired temperature, we can finally turn on the motor to start turning the screw inside the barrel, making the melted plastic move until the end of the tube, forming a continuous steady line of plastic.

Figure 22 Extrusion.

One of the problems found in the existing was the confusion of the initiation of the machine because the two buttons were placed in a very close place. If someone turns on the motor before the resistance, the screw will break due to forces made by the solid plastic (something that eventually occurred). The temperature of the plastic needs to be very thorough to guarantee the quality of the final product. Also, transportation was an issue despite the wheels at the machine's base that had to be removed for stability reasons.

A precisely regulated output volumetric flow can indicate a high extrusion product quality. It can be accomplished by controlling the screw revolution speed, melt pressure, and melt temperature within narrow variations. Among all these process variables, melt pressure and melt temperature are the key variables. [40]

Previous studies focused on extrusion process control were limited. Some researchers attempted to use theoretical models to control melt pressure [41]–[43]. The effect, however, was not that obvious.

A traditional proportional integral derivative (PID) controller has been applied to control the melt pressure. For barrel temperature control, conventional on–off and self-tuning PID controllers are most widely used. [44] These controllers provide good robustness but at the cost of poor transient performance, usually with overshoots during the start-up period and oscillations at a steady state. On the other hand, model predictive control is more applicable for processes with slow dynamics and large dead-time [45]. [46]

The plastic extrusion equipment found on companies' and initiatives' websites has many great solutions. For example, *eFACTOR3* is a turn-key supplier and can also supply systems integration and installation. The solution found on their website was the following "MAS 24 Laboratory Extruder" (Figure 23) that used a co-rotating parallel twin screw extruder.

Figure 23 MAS 24 Laboratory Extruder.

Technical Highlights:

- Compact design; Small footprint
- Conical, co-rotational twin screw system
- Superior homogenisation
- Large infeed opening
- Low melt temperatures
- Reduced energy consumption

This equipment displays the heating zone temperature with preset values, extruder screw speed, melt temperature and pressure. However, the most original part of this device is the twin screw system which integrates a significant intake volume.[47]

Also worth noting are the wheels at the bottom of the machine for mobility reasons.

2.3 Injection Review

The Injection machine (Figure 24) is a tall machine that uses human force and with a little help of gravity injects plastic into a mould. The shredded plastic is inserted into the hopper and heated in the pipe by the band heater. As the operator pushes the handle when the plastic is at the desired temperature, the mould is meant to be screwed into the pipe's end and receive the plastic to create a new object.

By applying pressure to a piston that pushes the plastic mass towards a mould with an inner chamber that has the geometry of the object to be obtained, plastic can be vertically injected into a mould. A vertical injection (as represented in the picture above) allows gravity to come into play and assist the process.

This equipment had many problems, like the strength needed to put down the handle was too much for just one person. Because the thermocouple is inside the tube rather than at the end, it could not precisely monitor the plastic's temperature, as shown in Figure 25. This makes it impossible to know the right plastic temperature and, therefore, the moment when the plastic will start to melt and give time for the operator to screw the mould avoiding any waste.

Figure 24 Injection.

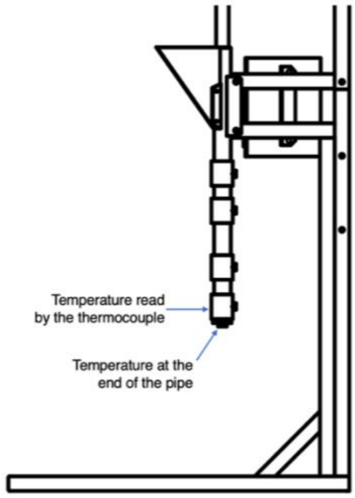


Figure 25 Temperatures at the Injection Pipe.

This is the most challenging equipment to work with among the four being more advantageous for a person accustomed to operating in this industry or finding solutions for easier handling.

It is crucial to notice that the existence of this type of machine in the industry working manually is rare, and the literature is reduced.

The injection moulding process incurs considerable changes in the rheological (field of science that studies the deformation and flow of matter - viscosity is the best-known rheological property and the only one that characterises Newtonian fluids) and thermomechanical properties of polymeric materials and their composites due to varying stresses at various points of the process, materials processing at melt temperatures, and high cooling rates of the final product. It is imperative to state that the properties of injection moulded materials play a crucial role in obtaining the net shape of a final product. A material endures large amounts of shear stresses during injection moulding, and rheological properties can be quantified to understand the stability of feedstock during moulding. Many researchers studied rheological properties consisting of variations in viscosity with shear rates. [48]–[53]

PVT (Phase Volume Temperature) diagrams for different materials are available in the literature [51], [52], [54]–[56]; as an example, Figure 26 shows the PVT diagram of polystyrene for specific volume versus temperature at different pressures.

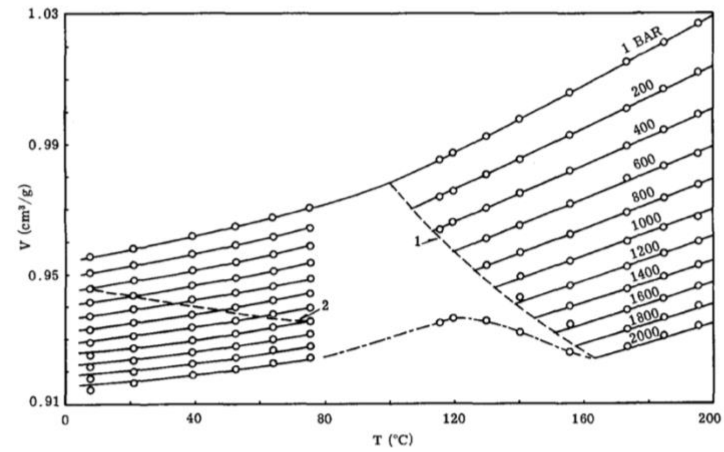


Figure 26 PVT Diagram.

Given the above, various factors affecting injection moulding must be analysed thoroughly before deciding the feasibility of producing a product with the desired quality and intricacy. Such factors can be classified into three categories as follows [57]:

1. Machine parameters (independent variables): Barrel temperature, nozzle temperature, coolant temperature, packing pressure, holding pressure, back pressure, injection pressure, sequence and motion, switch-over point, injection speed, screw speed, shot volume, cushion, etc.
2. Process parameters (dependent variables): Mould temperature, melt temperature, cooling temperature, melt pressure, melt-front advancement, shear stress, injection time, filling time, packing time, holding time, cooling time, mould open time, injection rate, material flow rate, rate of heat dissipation and cooling, pressure switch-over, etc.
3. Quality indices (final responses): Part dimension, shrinkage, warpage, sink marks, appearance and strength at weld lines, and other aesthetic defects such as burn marks, gate blushes, surface texture, etc.

The machine parameters can be controlled using effective sensors or upgrading various machine components. The parameters depend on process conditions, material properties, and mould design. On the other hand, the quality indexes are the target variables, which are to be precision controlled for obtaining the desired net shape and intricacy. However, the degree to which each machine and process parameter affects the outcomes may not be the same or connected. Further, the machine and process parameters can form multiple input sets, resulting in different output responses. However, a considerable hindrance occurs in identifying the significant input parameters, their inter-dependency on each other, and their relationships with output responses. [58]

Desktop the mini injection machine (Figure 27) is the latest model from *FANCY INJECTION TECHNOLOGY CO., LTD,* suitable for lab item invention plastic moulding process and lightweight, small-volume plastic injection moulds. The cycle time can reach 10s for each shot, and very easy to run with 220V power. It can be used as one computer to print plastic moulds fast and trivial. [59]

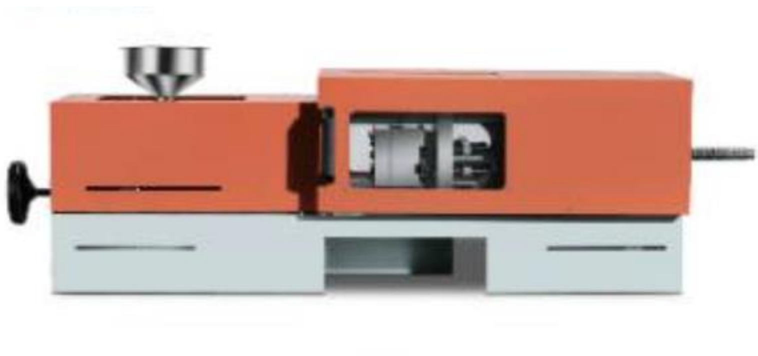


Figure 27 Mini Injection moulding machine.

The main reason for the importance of this injection machine is the transportability of the equipment as well as the use of the PID controller, which is one of the key features for the evaluation of this experiment.

2.4 Compression Review

Last but not least, the Compression machine is presented in Figure 28. This machine is a kitchen oven turned to the side 90º in the X0Y plane and drilled in the base to create a system of compression using a car jack and a metal plate to apply pressure into a mould. It is the slowest of the processes, but it makes larger moulds than injection.

Figure 28 Compression.

There was an issue we found, which was that the oven door was hard to open and close, since it had a spring that all ovens usually have for security reasons, making it hard to open and close. When these were removed, it was impossible to keep the door open without the help of someone who held it, which made it difficult to have the door open when needed as well as independent work by a solo worker. Another issue was the lack of stability of the car jack because the rod had to pass through a hole made in the oven that was big enough to pass freely but not small enough to create stability for the tray inside the oven, the tray that holds the selected mould or the press plates in case of wanting to make sheets.

The new version of the compression machine of the precious plastic website is an excellent alternative for the stability problem because the base structure would look like the Figure 29.

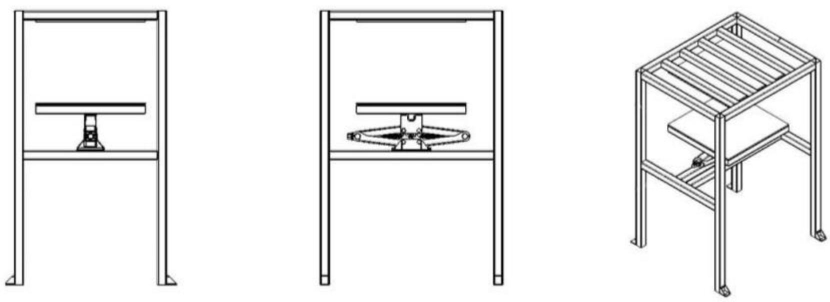


Figure 29 New form of structure.

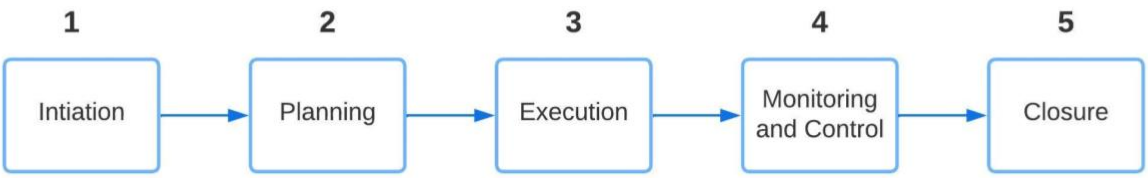
The metal mould material, aluminium, which has a thermal conductivity of about 237 W m^{-1} K^{-1}, as opposed to, for instance, polystyrene, which has a thermal conductivity of only 0.06 W m^{-1} K^{-1}, retains the heat for a long time. To take the desired shape, after the plastic is melted inside the oven, it will need to be compressed outside in order for the plastic to take its desired shape while both the mould and the plastic itself become cold as the mould cooling process takes place.

3 Execution Methodology

The project's present objective is for the four machines projected by former students based on the Precious Plastics initiative to be materialized. The base of project management has the following considerations:

- Cost and Budget
- Team size
- Ability to take risks
- Safety of machines
- Flexibility
- Timeline
- Client/stakeholder collaboration

Project management involves steering a project from the start through its lifecycle. The main objective of project management is to complete a project within the established time, budget, and quality goals. The project must go through five phases, as seen in the following diagram.



Starting the project, it is necessary to discuss each mechanism’s functionality with each of the teams involved with the project.[60]

In terms of scheduling, the following Table 3 shows the approximated calendarisation of the project:

Table 3 Calendarisation.

	March	April	May	June	July
Writing the bill of material					
Acquisition of materials and components					
Machine construction					
Changes and tests					
Creation of activities of plastic processing					

3.1 Safety of machinery

Equipment built and marketed in the EEC must comply with EU directives and must meet the standards in force EN ISO 13849-1:2015, with the aim of:

- Build safer machinery
- Increasing machine safety
- Avoid equipment stoppages with production losses
- Reduce non-availability time of types of equipment
- Reduce the number of breakdowns
- Increase equipment lifetime
- Reduce equipment failures

The current Directive has as its primary goal to build safer machinery, using as a concept (Safe Design), reducing the risk of accidents during the design phase. This Directive also allows the building of safer and more reliable machines/equipment, using the necessary safety equipment according to the level of risk that could occur during the equipment operation. [61]

During the design phase of a piece of equipment, the risk assessment should be used to identify the risks associated with the equipment. In the case of built equipment, the risks should be analysed.

- Temperature (Burns) → Risk reduction → Placement of protections
- Mechanical Risk → Crushing → Use of protections
- Electrical Risk → Electrocution (insulation failure of heating resistances, defective electrical motors) → Need to use differential switches, motor circuit breakers, earthing the electrical panel and the equipment housing, etc.

The risk assessment of equipment also resorts to calculating the risk estimate (HRN - Hazard Rating Number), identifying the risks and identifying the risks according to the hazard, which is necessary to provide complementary measures for risk reduction. [62]

It is not always possible to reduce certain risks of equipment, making it necessary to signalise the hazards with appropriate symbols.

The equipment must comply with the EU directives depending on the type of equipment:

- Type A standards: fundamental standards to be applied to all types of machinery
- Type B standards:
    - Type B1 standards
    - Type B2 standards
- Type C standards

All equipment must have associated technical documentation (user manual, risk assessment, electrical diagrams, and mechanical design—Declaration of conformity (CE Declaration). [61]

Depending on the final risk level of the equipment, it is necessary to use the emergency control circuit: Category 1, 2, 3, and 4) and use the necessary safety equipment: Emergency stops, Immaterial Barriers, etc. [62]

In the Injection, Compression and Extrusion it will be necessary to be aware of the melting temperatures of the plastics in use like shown in Figure 30.

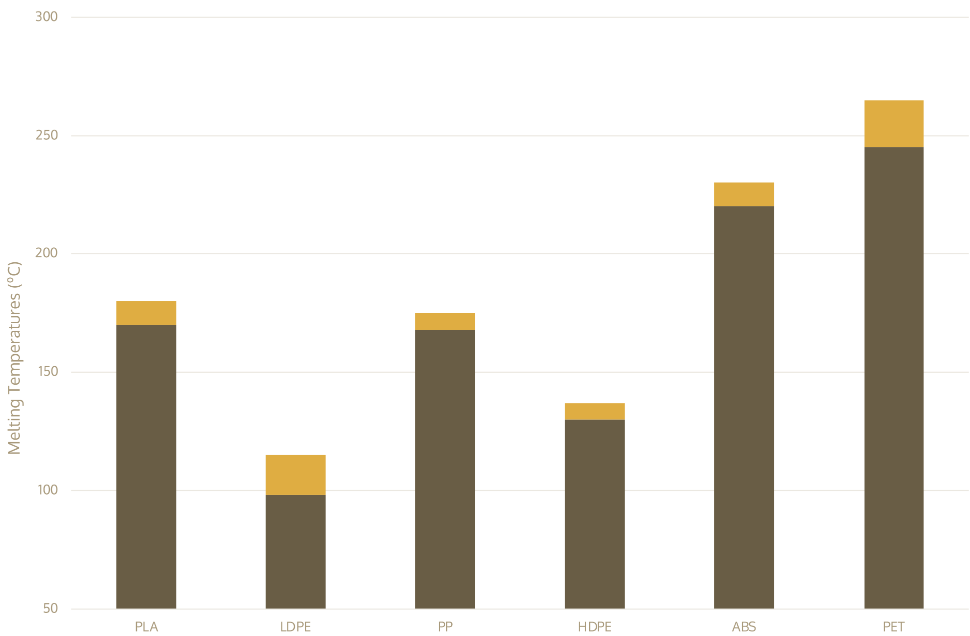


Figure 30 Reaction of different polymers at varying temperatures.

3.2 Shredder planning

To begin this project, the first machine to be developed was the manual Shredder which consists of five elements: shredding system, structural support, output storage, input storage and energy system, as the chart demonstrates in Annexe A – Shredder Documentation.

The project suggests a portable and manual machine that requires special attention to forces made on shredding plastic and moving the machine itself for the purpose of making exhibitions of the equipment's work outside the factory where it will end up in.

At the very beginning of the project, the team was presented with a proposal developed in SolidWorks by the students from the year before (Figure 31) which already came with the list of materials and already with the construction equipment mostly bought.

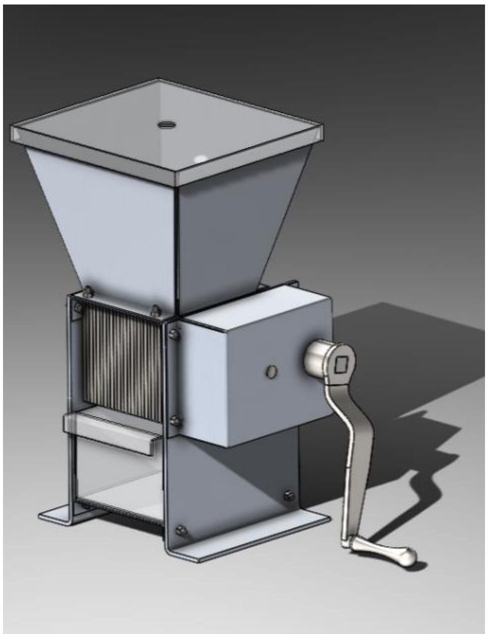


Figure 31 CAD of the initial project of the Shredder.

The main shaft is a hexagonal profile, and this profile was chosen because its surfaces guarantee contact tensions by creating normal forces and the greater the number of surfaces the greater the number of different blade positions and thus a better distribution of forces along the shaft, and better the cut made (better contribution of all the blades), which would be impossible with the circular profile.

The smaller shaft (of the pinion) has a square profile to ensure that it fits and works with the crank, creating torque and rotation.

Starting by evaluating forces, the analysis of the 'Blades + Fixed Blades' forces is one to consider. Given the need for an increase in power, using the gears and the crank, an analysis of the blades' efforts is necessary to certify the structure's integrity.

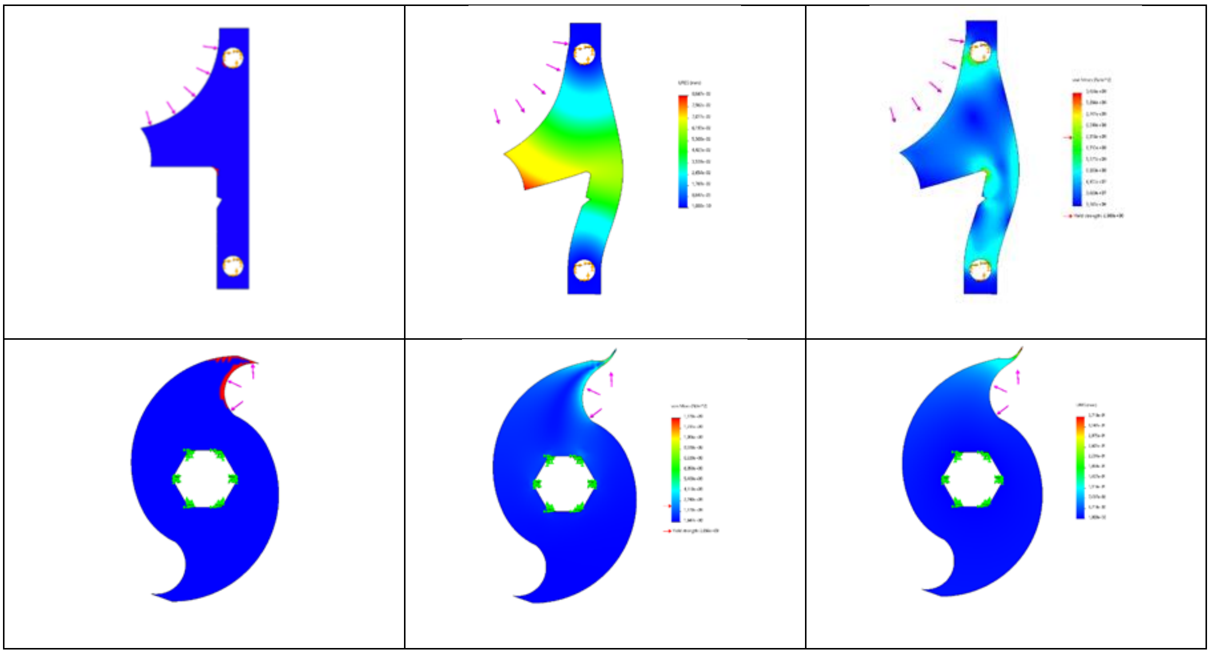
Considering a force of 225 N at the crank handle, about 23 kgf, actuated by the manipulator when standing (upper force limit recommended for pulling and pushing) and considering a value of 180 Nm obtained at the main shaft.

$$M = F * \frac{rM_1}{M_2} = \frac{Z_1}{Z_2}$$

M - Moment (N.m); **F -** Force (N); **r** - distance (m); **Z -** number of teeth

The following analysis in Table 4 was made assuming a maximum force of 7.2kN on the blades (force at a distance of 25mm from the main shaft):

Table 4 Images of the studies of stresses in the blades (fixed blades on the top, moving blades on the bottom).



- Fixed Blades: Maximum Stress - 343 MPa; Maximum Displacement - 88 µm; Critical Points - top fixing hole and bottom inside corner
- Moving Blades: Maximum Stress - 1 370 MPa; Maximum Displacement - 372 µm ; Critical Points - outer and inner side of blade tip

The power transmission between the shafts and the gears works using keys since maintenance is safer and more accessible.

In this way, the fixed blade system was manufactured using laser cutting, presenting two types of blades according to their position relative to the shaft—a fixed blade used with a cutting blade and another type used with a cutting spacer.

Analysing the elements' bearings and gears for smooth grinding with few interruptions, a system was envisioned to increase the user's torque using gears and a crank. When incorporating the gears, keys were chosen instead of welding the gears directly onto the shaft simply because of the safer and more accessible maintenance.

To obtain the maximum possible torque, a max recommended transmission ratio for straight gears was used, i.e. a ratio of 4. Thus, the machine had 60-tooth (wheel) and 15-tooth (pinion) gears. The gear material is steel, and the gear module is 2.

The crank, being the part where the force of the mini-granulator operator will be exerted, needed to be of a reasonable size in order to be able to withstand that force.

To prevent overloading the blades and maintain a steady plastic intake, a conical nozzle was chosen, so the inclination and the existence of roughness on the walls contribute to the smoothness of the fall. Scientifically speaking, this means increasing the frictional force, the force against the movement, since the closer the angle is to 90º, the lower the normal force on the surface.

$$\sin\frac{\pi}{2} = 1 > \sin\frac{\pi}{3} = 0.866$$

To make it easier to handle the sheet, we adapted the conic shape to a rectangular pyramid with only flat faces. A pyramid height of 20 cm was also chosen to protect the user from possible plastic particles that might be expelled, which was later complemented with an acrylic cover.

3.3 Extrusion machine planning

The following machine to be developed was the Extruder which is the most complex machine among the four only because of the electric part and because the use of the motor.

The project starts with the CAD project shown in Figure 32.

Figure 32 Initial State of Design of Extruder.

Unlike the last machine, this one has an electrical part, and it was necessary to order the elements missing from the lab not only from that part but also from de mechanical one.

In order to ensure portability, it was decided that the machine would consist of modules: the table with the electric motor and reducer, the extruder tube, the material collector and associated drill; and then a box with the electrical part separated. All of these will be relatively quick to assemble, and it should also be noted that the table has been designed to have folding legs. (Technical drawings available in 8.2.1 of the Annexe B – Extrusion Machine Documentation)

The module of the material collector and auger (support) consists of the structural core of the extrusion machine because this is where the process marks its beginning. The dimensioning of its elements was based on the characteristics of the wood drills available on the market. In previous extrusion machines, the drill was the most challenging element to acquire, and the motor's capacity was intended to be used to achieve portability.

According to the chosen drill (D=20mm), the available inside diameter most appropriate for the good functioning of the collection and distribution process of the crushed plastic was ¾''. Its materialisation consists of:

1. Cutting the circular profile pipe (plumbing pipe) to a length of 166 mm
2. Marking the distance between the side edges and the centre of the circular outline, then the size of the slot that best suits the lower opening of the tank
3. Cutting the slot using an angle grinder
4. Polishing the pipe surface manually or using an appropriate device so that the surface is smooth and ensures a good joint with the other parts, as well as a better aesthetic finish

Analysing now the electric scheme in the Annexe B – Extrusion Machine Documentation in the Technical Information section by making a scheme of principle. (Figure 33)

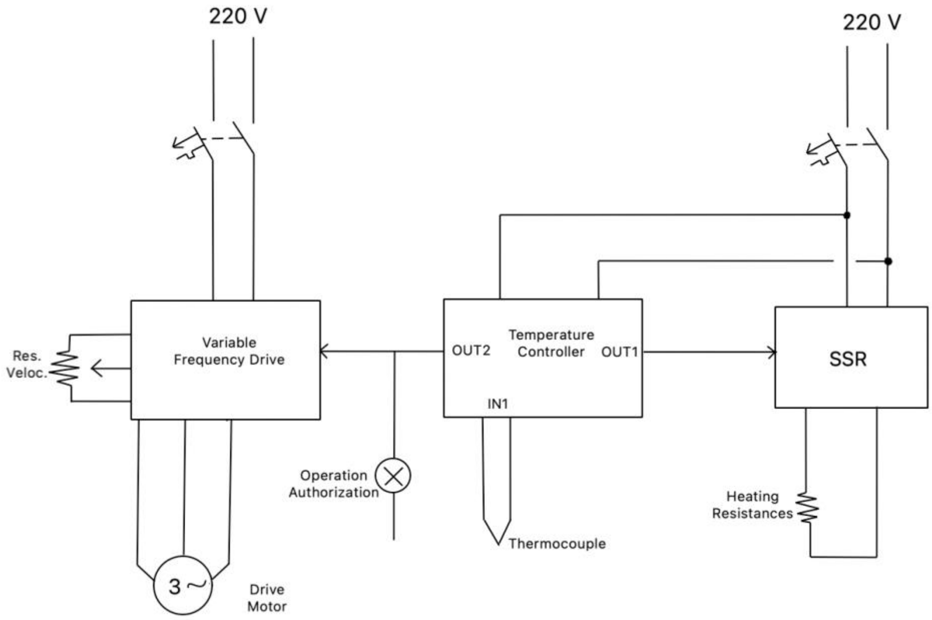


Figure 33 Scheme of Principle for Extruder Machine.

PID controller

In the figure named Temperature Controller, this element is considered the machine's brain, where the user can set the desired temperatures. It will send power to the heaters until PV (point variable) matches SV (set value). It does these using readings from the thermocouple and the SSR (Solid-State Relay - electronic 'switch' that opens and closes depending on the signal it receives from the PID).

This component was programmed to, as the user chooses a temperature limit, only let the resistances heat until that temperature, and once it gets there it sends a signal to authorize the motor to run, ensuring that the plastic has already melted and won't damage the machine. The authorization for the motor's execution will be manually activated by the operator and ideally be able to choose the drill to have a clockwise rotation or a contraclockwise rotation, the first one to expel the material as normal and the second one as an alternative if some material gets stuck for some reason inside the extrusion tube.

The motor is protected by a thermal-magnetic circuit breaker, protecting the motor against short circuits and overloads.

3.4 Injection moulding machine planning

The following machine to be developed was the Injection which is a complex machine because of the electric part and because of the constrains normally found when working with this type of manual machine already mentioned in the Annexe C – Injection Machine Documentation section of this project report.

The injection machine planned is presented in the CAD in Figure 34.

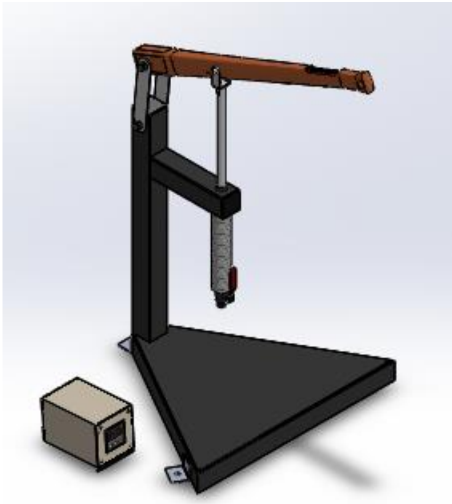


Figure 34 Initial State of Design of Injection.

Starting by describing the elements of the equipment, it was used an axe handle not only because it is more ergonomic, but also gives the machine a more rustic look. The rod allows the connection to the handle/lever of the machine. The handle also contains a horizontal segment of the same profile with a hole to house the plastic heating chamber. Returning to the base, some sheet metal was used to create an even surface underneath the injection tube. (Another option: the base could consist of the profiles alone, leaving the centre open, or wood could be used as in the Precious Plastic model to match the axe handle). After finishing the machine, a fix could be created to bolt the base to the table if a structural imbalance is discovered.

The lever is where the necessary force is exerted so that the heated plastic in a pasty state enters the mould. An axe handle was used not only because it is more ergonomic but also gives a more rustic look to the machine. The escape from the idea of a conventional "lifeless" machine allows a more appealing design, especially for children, who are the target public of this project.

To implement the axe handle in the machine, it is necessary to drill it at two points whose distance depends on the working angle we want to leave. Remember that the greater the distance between the tip of the axe (where force is exerted) and the piston, the greater the momentum created, and the less effort will be needed to force the plastic into the mould. This topic is relevant because if we are talking about a machine that is expected to be used by a solo worker if it is necessary to exert too much force, that would be impossible.

Connected to the lever, there must be a piston, which forces the plastic into the mould. The piston must have the same profile as the heating chamber (injection tube), in this case, circular. The clearance between the piston and the injection tube should not be too high, as this could mean a heat leak by convection that delays the heating of the plastic and an escape of the plastic itself that may come out of the tube when pressure is applied. Likewise, the gap cannot be too small as this can create a suction effect when the lever is raised (air cannot escape from the heating chamber). Assuming that the plastic in contact with the tip of the piston is not entirely liquid after the heating process, the risk of leakage is lower compared to the others and therefore, clearances of 1 mm or 2 mm relative to the inner diameter of the injection tube and piston diameter are reasonable.

Focusing now on the dimensioning the piston, it must not be so short that the whole lever is lowered and the piston is not able to force the mass of plastic sufficient to fill the mould, nor must it be so big that when you want to remove the piston from the tube, it does not come out (difficult to happen, but it takes attention).

The piston still needs an additional element to connect the piston to the cable later. The approach might be to take some sheet metal and weld it together to form a structure that will hold the piston in the injection tube even if the axe handles to move. However, there are binding elements similar to this that can be purchased.

The bottom end of the injection tube will need to be threaded to connect to the valve. Machining makes this threading possible and must be done outside the pipe. Therefore, the thickness of the pipe must also not be too small to allow this work on the part. The threading must be completed after the valve attached to the pipe has been installed. In this way, errors are minimised, making it possible to make a correct sizing of the thread.

It was decided to use a ball valve to control the plastic flow between the injection machine and the mould. Valve selection became challenging because the plastic working temperature will be between 180ºC and 200ºC. A ¾" stainless steel ball valve was chosen. Its most relevant characteristics are the working temperature between -25ºC and 180ºC and the maximum pressure of 140 bar.

The valve also has another advantage: it allows a threaded connection to the mould, which avoids more complex and space-consuming clamping systems, such as a pressure clamping jack.

In addition, it was drawn a simple scheme of principles (Figure 35) to give an illustration of the electric part organizing and simplifying the components of the complete scheme presented in Annexe C – Injection Machine Documentation in the Technical Information section (8.3.1).

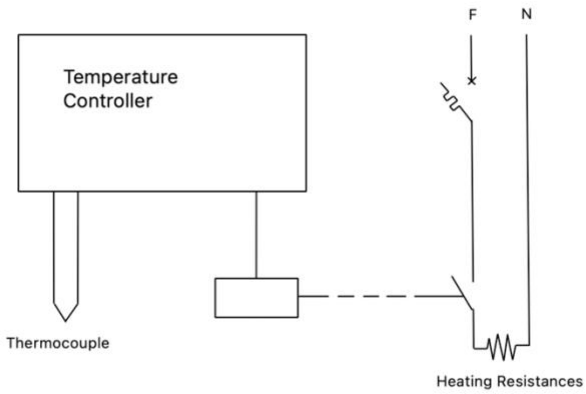


Figure 35 Scheme of Principle for Injection Machine.

With this scheme in mind, it is important to analyse the whole electric part starting with the main component of this group, that is the PID Controller or Temperature Controller in this case. This element allows the temperature of the heaters to be modified to heat the plastic and monitor this temperature.

The resistors heat the surface temperature of the injection tube, and the conduction phenomenon heats the plastic. In this project, between 1 and 4 resistors can be implemented, depending on their dimensions.

The thermocouple enables the determination and transmission to the PID of the temperature on the injection tube's wall surface. According to one of the guiding professors, the thermocouple can be made at the university, but most PID kits already include the thermocouple.

A relay that can be found online under the SSR is also necessary to make some connections. This is also included in the PID kits.

Finally, we have other components, such as electrical cables, fuses, and sockets, to connect to 220V.

3.5 Compression moulding machine planning

After analysing the solutions in the The main reason for the importance of this injection machine is the transportability of the equipment as well as the use of the PID controller, which is one of the key features for the evaluation of this experiment.

Compression Review subchapter, it was decided to follow the solution where the mould is compressed outside the oven. This is better because it avoids heat losses through the hole that would have been done in the base of the oven and increases the plates' stability during the compression.

The compression machine consists of 4 main components: the metal structure, an oven (not represented in the CAD), a ratchet jack and a mould. (Figure 36)

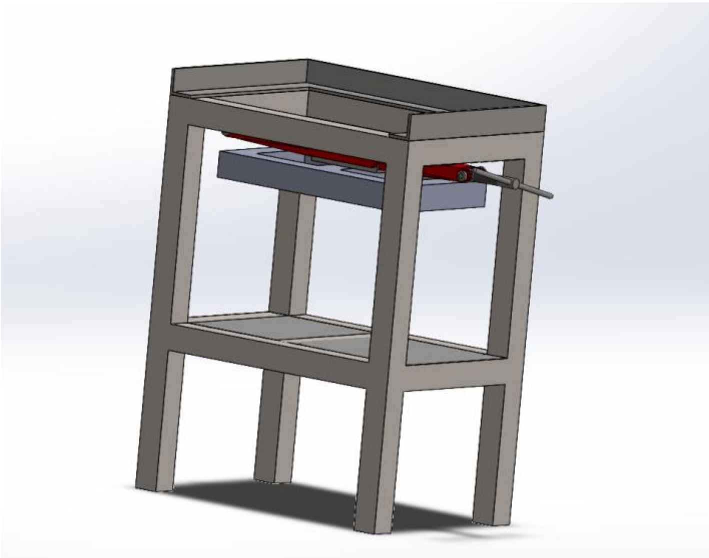


Figure 36 Initial State of Design of Compression.

The oven is intended to be a separate device from the rest of the metal structure in order to make the structure more practical to move and use but the ideal way to build this would be to creat some kind of docking system to offer some stability to the oven while running. To operate the machine, the oven should be placed at the top of the structure, plugged into an ordinary socket and the timer and temperature knobs adjusted to melt the plastic chosen for the purpose.

As far as the actual compression is concerned, first remove the container very carefully from inside of the oven - with tweezers or proper gloves - and place it on the base in the middle of the structure. Next, close the mould with the upper part and apply pressure with the diamond mallet, which should be screwed to the lower part of the top of the metal frame so that it extends and slowly presses downwards, bearing in mind that mouldability may vary throughout the compression process.

After cooling and subsequent solidification of the piece, it is also advisable to unscrew the jack, remove it, and deburr any resulting imperfections with a chisel.

The jack base will be attached to the top plate of the structure, as shown in Figure 37.

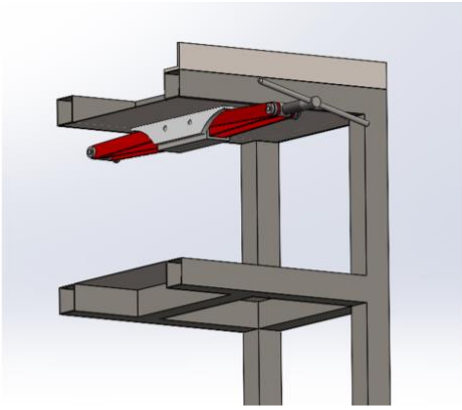


Figure 37 Attachment of jack.

The mould support will be fixed to the upper plate of the jack (Figure 38), utilising screws that will go through the support entirely and screw into the upper mould, thus ensuring the connection of these two parts.

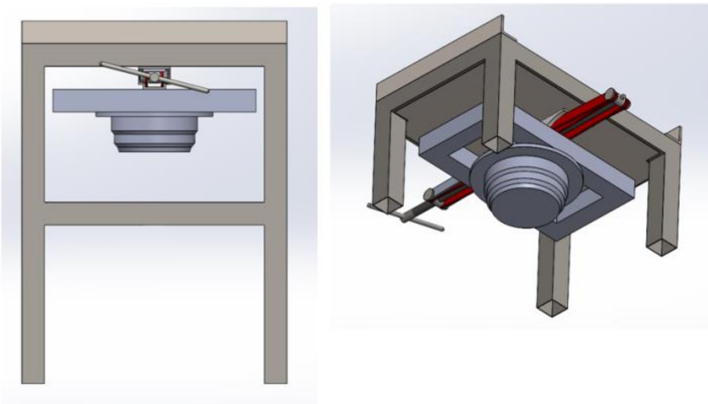


Figure 38 Attachment of the top part of the mould.

The mould will be fixed on the bottom plate using bolts and nuts (Figure 39). In this stage it can also be placed two plates of aluminium and applied the pressure in a secondary manner, meaning that the jack pushes the plate and, consequently, the plates apply force evenly in the mould.

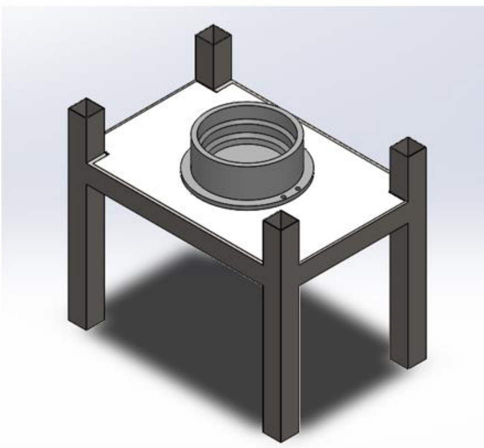


Figure 39 Attachment of the bottom part of the mould.

4 Execution

Given the methodology described in the chapter above, this next chapter will approach the execution following approximately that methods, and calendar and overcome some challenges that came up during the practical work.

4.1 Shredder

4.1.1 Construction of Shredder

Reusing some materials and pieces from other projects/machines was essential to making the project even more sustainable, but inevitably, it was necessary to use new components listed in the bill of materials.

In order to develop the machine, the first step is to construct the shredding system: the main shaft has a circular profile with two parallel slots going all the way from top to bottom in the largest diameter section of the shaft. It was necessary to allocate two parallel keys to the respective slots of the energy system in order for the keys to be subjected to a smaller amount of shear stresses as a result of the energy system (Figure 40).

Figure 40 Assembly of the main shaft and grinding teeth.

Due to the lack of tolerances in the SolidWorks technical drawing illustrated in Figure 43 as well as an error in the review of the material dimensioning when the material order was made, the compliance of the main shaft was smaller than anticipated in CAD, so the spacers and the blades hit exactly the point of the end of the key, and this makes de blades rotate with a lot of friction.

The final teeth (on each side of the shaft in contact with the side plates) were left with only half the width in contact with the attached key, taking advantage of the existing material and avoiding the production of a new spear or changing to new products in the middle of the project. The blades and spacers had already been produced by laser cutting and presented a lot of burr around the whole surface, especially in the cutting edges and in the inner slots. So, when assembling them on the shaft, it was verified that most of the elements did not pass through the shaft keys. Consequently, it was necessary to remove the burr. The burr was removed with the help of straight files, and the blades were fixed on the lathes in order to make a parallel filing in the case of burr removal from the slots. (Figure 41)

Figure 41 Grinding and spacers and teeth.

The cutting blades have two cutting edges oriented in the same direction, so their resistance to deformation is better. The blades have a round geometry with a slot corresponding to the shaft, affecting the torque transmission and easing up the grab of plastic that is left down on the net that is still too big to come through (Figure 42).

Figure 42 Assembled the main shaft.

The cutter spacers have two inner slots to rotate synchronously. The purpose of the spacers is to leave a gap between the cutting blades so that the raw material shreds more efficiently and sequentially.

Since the shaft was small because the tolerances of the shaft with the teeth and spacers were not considered, it tightened the mechanism's structure, interfering with its mobile part. In this way, squeezing the two side plates of the machine caused the cutting blades housed at the ends of the main shaft to be in direct contact with the side plates. On the one hand, this contact, due to friction between metals, made the rotation movement more complicated, and, on the other hand, in the long term, this contact would lead to the ruin of the side plates. The solution involved producing two spacers which fit into the holes in the plates dedicated to housing the bearings.

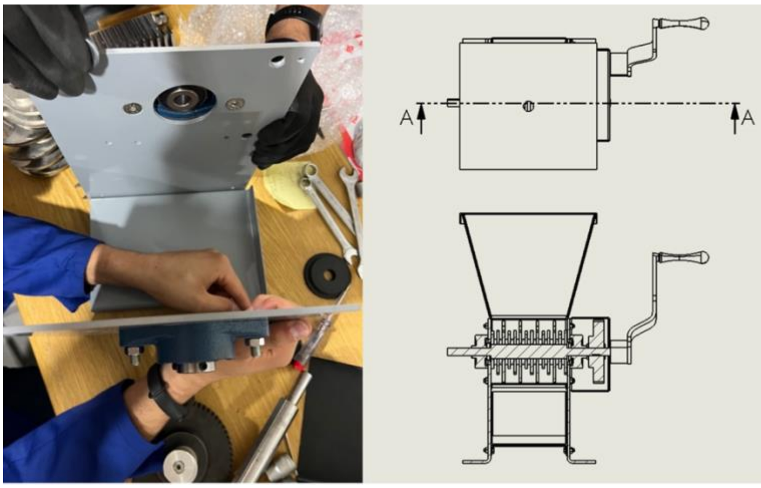


Figure 43 Side plate assembly and Technical drawing of the inside of Shredder.

The next stage was to allocate the shredding system between the plates despite the deficiency of the tolerances. The solution was to increase the distance in the machine's width using rings, polystyrene dusters, and a solid metal block (aluminium), as shown in Figure 44.

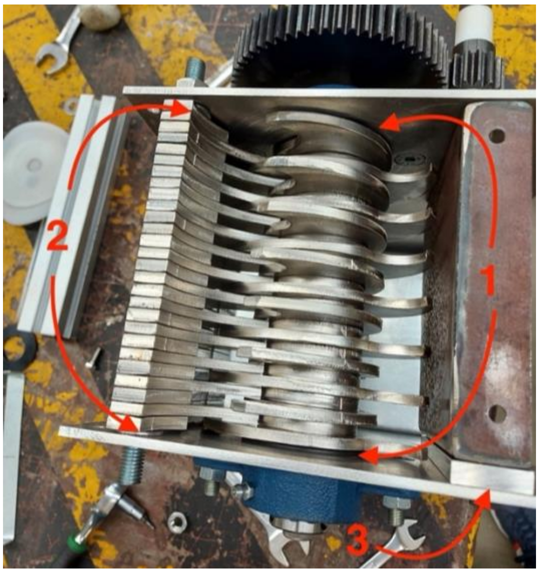


Figure 44 Points of increased distance.

The net allocated in the place shown in Figure 45 has the purpose of letting the small pieces of plastic go through the drawer turned out crooked and did not fit between the two plates, so it was necessary to create a new one with the correct dimensions.

The transmission system presented in Figure 46 is a pinion and a wheel, which will be driven by a crank so that the grinding will be manually smoothed and with few interruptions.

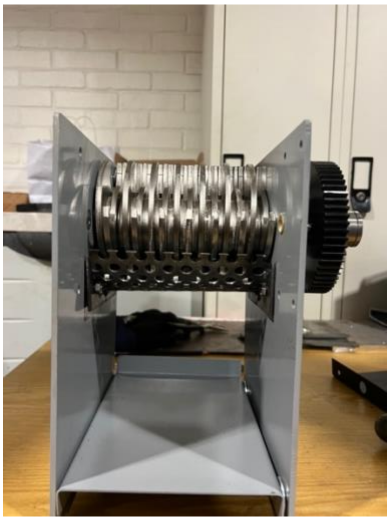


Figure 45 Shredding system completed.

Figure 46 Transmission System.

Finally, after painting the visible parts we obtained the manual Shredder like so (Figure 47).

Figure 47 Finished Shredder.

Consult 8.1.2 (Annexe A) for the User Manual for a simple explanation of how to work with the Shredder Machine.

4.1.2 Testing of Shredder

For testing this equipment, the first type of plastic tested was a water bottle made of PET and a cap made of PP.

In the PET part of the bottle, the most challenging part to shred was the very top part represented in Figure 48.

Figure 48 Water bottle.

With this testing, it was concluded that the resistance of the blades is still very challenging for manual shredding. The PP part of the bottle was easier to shred, and less strength was necessary to destroy it.

Another type of plastic was tested: 3D printing PLA that would go to waste. For this new shred, we needed to clean the machine, and in this first step, we had to carefully turn the machine upside down to ensure that we did not have the rest of another plastic mixing the PLA (Figure 49). This way of cleaning is not the easiest, or even the most secure for the end wanted. And this happens because the gap between the teeth and the wall is too big, letting pieces that are too large to go through the net but small enough to fall between the teeth and the plate as shown in the Figure 51.

Figure 49 Cleaning of the rests of plastics.

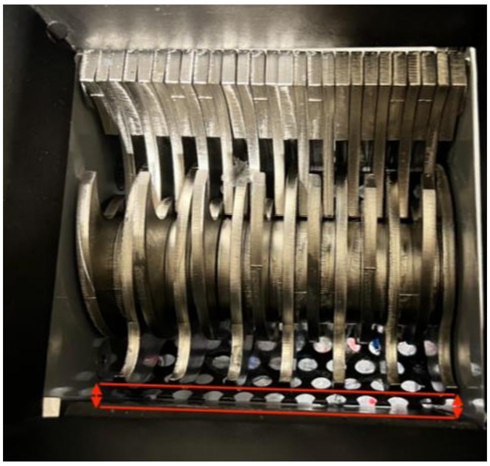


Figure 50 Gap between teeths and plate.

4.2 Extruder

4.2.1 Construction of Extruder

Some components were available as a variable speed drive, single-phase motor, and reducer. Again, with reusing components from other equipments it is always a step closer to a more sustainable project.

The montage started to come together, and some issues were coming up. The variable speed drive only worked with three-phase input, so one of the possibilities was to buy a new one with a monophase input.

Then a three-phase motor became available to be used with a three-phase variable speed drive with a single-phase power supply. The first problem found in this motor was heavier than the previous one, making the final product's mobility another problem to solve.

The project received two circuit breakers in the initial order of materials: one of 2 A and one of 4 A. One was supposed to be able to bear the three resistors of 150W, and the other was the motor and the variable speed drive. However, for this last one, the system needed at least 6.6 A (the variable speed drives current) plus 1.9 A (the peak motor current), which none of the circuit breakers could bear, so we decided to exchange the one 2 A for one of 10 A for the system to work correctly and safely.

Now, the structure that holds all the electric equipment is a folding table with a thin wooden top and thin steel detachable legs to be easier to carry. The wood available to be used was too narrow for the accumulated weight of the machine itself, so we decided to switch that plank for a thicker plate of timber which had more resistance and did not bend so easily. After some adjustments and polishing, we obtained the table in Figure 51, which had folding legs that folded when pressed a trigger under the top.

However, these adjustments increase the final product's weight, and two people must carry this part, if necessary, with the final assembled extruder, as shown in Figure 52.

Figure 51 Table of support for the extruder.

Figure 52 Extruding system.

In order to reduce thermal losses in the extrusion tube, thermal insulation covering the tube and the thermal resistances were introduced.

For the electric panel, the desired system was that we could choose the plastic melting temperature, and the resistances would warm up to that and stop. When the plastic reaches the desired temperature, the motor rotates, and the drill starts bringing the plastic out of the extruder.

As we developed the circuit, it became a big box, so the next issue to be addressed would be the mobility of the electric panel (Figure 53).

Figure 53 Inside of electrical panel (Extrusion).

As shown in

Figure 54, the orange light is on until the temperature is 40ºC. This light is on means that the resistances are on. As the temperature difference is <5ºC, it is possible to turn on the motor with the first black switch that allows us to choose the direction of the drill too. The grey stick that can be seen is the potentiometer. With this, the user can control the velocity of the bur, making the plastic outing faster or slower, as the user desires.

Figure 54 Visible part of the electric panel (Extrusion).

For mobility reasons, we added plug connectors (Figure 56 and Figure 57) to separate the resistors from the electric box and a three-phase plug to separate the motor too (Figure 58). For this, we needed some structure to hold and transport the panel. So it was decided to go with the solution in Figure 55.

Figure 55 Wheel structure to move the electric box.

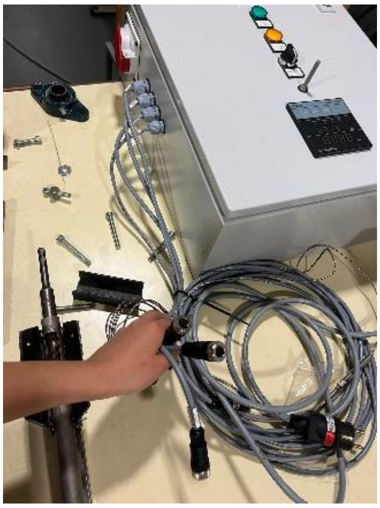


Figure 56 Plug-in connectors.

Figure 57 Plug-in connectors in place.

Figure 58 Motor plug-in

Finally, the machine obtained was the one in Figure 59.

Figure 59 Final Extruder.

Consult 8.2.2 (Annexe B) for the User Manual for a simple explanation of how to work with the Extruder Machine.

4.2.2 Testing of Extruder

Passing now to the testing of the extruder, the main issue is the difficulty in maintaining the constant diameter and speed of the material leaving the extruder opening (Figure 60).

Figure 60 Output of HDPE in Extruder.

Another thing to notice but not exactly a big issue was that the plastic accumulates itself in one part of the nozzle because of the drill movement it shows (Figure 61). This can originate small heat losses. In the future, it could be analysed possible to change the size of the nozzle to a smaller one.

Figure 61 Material (HDPE) in the nozzle.

Now passing to the testing of PLA (Figure 62). This material appeared to be less sticky but faster to melt and not as breakable. Although to make objects in which the plastic must glue itself, it doesn't work as well as HDPE.

Figure 62 Testing of PLA in Extruder.

4.3 Injection

4.3.1 Construction of Injection

The next machine to be finished was the injection machine. After making the base structure shown in Figure 63 and thinking of ways to assemble the rest of the components, some issues with the initial project should have been noticed before welding the element.

Figure 63 Initial Structure of Injector.

Before making further progress with the actual machine, a prototype was made in wood to see the options for the solution, as seen in Figure 64.

The main problem was the through-hole through which the shaft passes, preventing the post from passing correctly and making it impossible to inject into the mould this way.

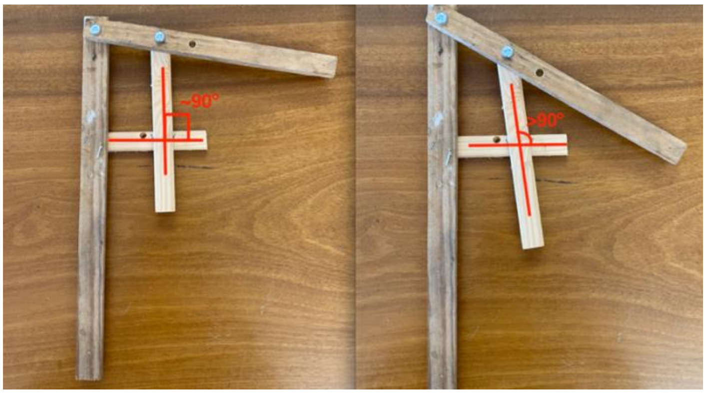


Figure 64 Prototype of the issue.

The system works correctly if the shaft-holder angle is 90º, but following the project until this step, that did not happen. If, in the future, we need to drive the shaft in the through-hole into the hopper, it will bend it, so this technique is no longer practical.

The solution found was a piece shaped like a ‘Y’ that connected the axe and the piston in a way that let it move at a different angle like it is shown in Figure 65, as the left part of the metal support has also been lengthened to increase the height of the base.

Figure 65 Joining piece.

After coming up with these solutions, the machine was built with no other significant problems. In Figure 66 it can be observed that the almost finished prototype was missing only the electrical connections.

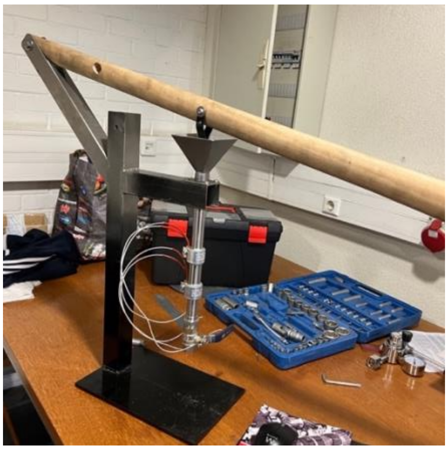


Figure 66 Injection machine without electrical box.

Taking advantage of an old computer's electrical box, a slot was made for the PID and the circuit breaker, and inside the electrical was assembled following the sheet in Annexe C – Injection Machine Documentation was made as shown in the pictures (Figure 67 and Figure 68).

Figure 67 Visible part of the electric panel (Injection).

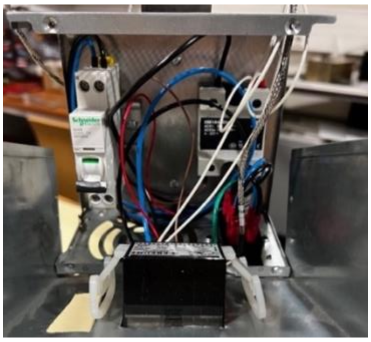


Figure 68 Inside of electrical panel (Injection).

After the electrical installation, the PID controller was programmed following the parameters in Annexe C – Injection Machine Documentation, the insulation was put around the resistors along the pipe, and it was obtained the final machine prototype (Figure 69).

Figure 69 Final Injection Machine.

Consult 8.3.2 (Annexe C) for the User Manual for a simple explanation of how to work with of the Injection Machine.

4.3.2 Testing of Injection

This machine was only tested with plastic once with PLA. The plastic took ~40 minutes to melt (Figure 70), which is a lot and then wouldn't come out even with extra pressure made in the handle (Figure 71). A possibility for this could be that at the outing of the injector, the plastic starts to cool down and hardens, forming a plug.

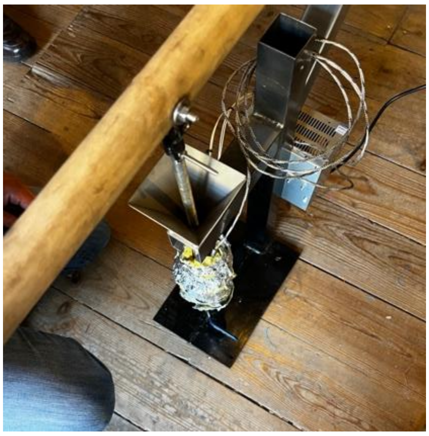


Figure 70 Waiting for the plastic to melt.

Figure 71 Pressuring the handle to make plastic fall.

With the help of a metal rod whose length is longer than the injection tube, it was possible to remove the plug from the outlet and it came out in the form shown in the Figure 72.

Figure 72 Result of PLA in the injection machine.

4.4 Compression

4.4.1 Construction of Compression

Finally, the Compression machine is a structure with a carjack underneath the top surface that holds a plate for compressing the moulds.

The metal structure was the first thing to be built following the drawing shown in Annexe D – Compression Machine Documentation. The problem was that the baking oven was still not ordered, so the measurements were off when first positioned, and the measurements in the top section of the base structure were too small (Figure 73 and Figure 74).

Figure 73 Compressor structure (right side).

Figure 74 Compressor structure (front).

It was necessary to rebuild the top part of the metal structure or remove the restricting areas of the sides so that the oven could fit (Figure 75). Furthermore, after painting, the carjack was put into its position (Figure 75 and Figure 76).

Figure 75 Welding of carjacking in base and correction of measurements in the top part.

Figure 76 Final base structure with the arranged top part.

For shifting reasons, a set of 4 wheels were added to the bottom of the legs. The next step was to install the mould and secure the oven.

It was decided that the oven would be separated from the base because it would be easier to transport from place to place if the top part of the machine only rested on the structure with no welding.

This is only possible because the electrical part of the machine is separated from the mould when it is forming the peace. This happens because the heat that the mould material can keep in itself is enough to make the compression outside the oven without making any modifications and turning the machine detachable into two different pieces plus the mould.

Finally, we obtained the final product (Figure 77).

Figure 77 Final Compressor Machine.

Consult 8.4.2 (Annexe B) for the User Manual for a simple explanation of how to work with the Compressor Machine.

4.4.2 Testing of Compression

As we finished and delivered this machine, the mould was not ready so we tested using aluminium plaques as can be seen in Figure 78 and Figure 79. This allows to achieve a sheet of plastic after the compression like the one in Figure 81.

Figure 78 Heating the plaques.

Figure 79 Making compression.

Figure 80 Sheet of recycled plastic.

5 Discussion of Results

5.1 Shredder

The first machine to be concluded and tested was a success in terms of the timing of construction. The primary issue was that the force needed to shred some plastic in the system was more significant than expected but not impossible. A possible solution to this problem could be a change in the transmission system to decrease the force applied to the handle. Moreover, this might be enhanced by extending the handle's arm, which is the distance indicated in Figure 81 by an 'x'. By augmenting the distance to 'x+n', the force applied will be less and, therefore, easier to shred the plastic.

Figure 81 Handle measure.

Although the project did not present a base structure, it could be a good idea to stabilize it as much as possible while grinding plastic because trembling is inevitable in any shredding system. With the change of the size of the handle, the base is essential because the increase of 'x' will make it challenging to work with the system if not positioned at the edge of a table, which is not feasible.

The portability is possible and relatability easy but can be optimized by maybe allocating some handholds on the bottom like a tray, so the transportation of the machine is safer than the current state.

A problem testing this machine was the fact that there was a gap between the teeth and the black plate above the drawer, which allowed the flakes not yet in the desired size to fall to the net and not be destroyed. With this problem, another one was discovered: there is no easy way to clean the net from the plastic that won't come through it because of the first problem.

The technical drawing execution part is a crucial part of any machine development. When a measurement tolerance is misplaced or not considered, the purchase of materials and assembly is compromised. In this case, the development of the machine needed to suffer some alterations because of this type of miscalculation and because of the changes made during the assembly process (the rings, polystyrene dusters, and a solid metal block). With time passing, the nuts can originate slacks and jeopardize the system's stability. This instability is likely to occur because the side plates were misaligned due to the heat treatment and the mobility transportation, and the nuts were purposefully left a little loose so the drawer would fit.

With the tests made it is possible to see that the manual shredding system is achievable with a simple machine like this one however there is room for future improvements.

5.2 Extruder

The next machine to be concluded was the most challenging one to build. The existence of an electrical part is more complex than a manual machine montage. Attention to small technical details is essential to a successful project.

The mobility is a little tricky because it involves many wires connecting and disconnecting, and the user needs to know the connections beforehand for the extrusion process to work. Although the legs of the table can be folded, it is not that simple to do so because the motor and the extrusion system that follows it are screwed to the tabletop, which makes it difficult to reach the bottom of the table or even turn it upside down. With this, the table must be transported as shown in Figure 82, and therefore it is not so simple to move it because, given the weight of the system, two people are needed to move it. If, as the initial project shows, the tabletop had wheels on the left side like represented and a handle on the other, it could be easier to transport. But this could only be possible if the legs of the table were easy to fold.

Figure 82 Mobility add-ins.

The electrical box is easy to move, so the portability issue in this section of the machine succeeded well. Additionally, the panel outside the box is simple and intuitive.

The fact that this extruder can increase or decrease the velocity of the motor is advantageous because this way, the user can control the output of the plastic, making the filament come out quicker or slower as a result requires. The possibility of rotating the drill in different directions is a different story. If the operator has any issue regarding the bur being stuck with some plastic inside, it is possible to rotate the drill the other way to make it easier to solve the problem.

The output result of the extruder can be enhanced. The extruder's nozzle was built broader than expected, making the filament's diameter bigger. The elasticity of the plastic used in the testing (HDPE) made it possible to stretch the filament at the outing with a tweezer while it was still warm and mouldable. This could be seen as an added value because, having in mind the title of this thesis, these machines are made to challenge our creativity, and therefore this could be seen has an increase of possibilities to create new things and not as an obstacle.

A machine like this one gives the sustainable world a lot of possibilities. Although it is an improved version of older ones built there is still a possibility to build a better one.

5.3 Injection

This next machine also includes an electrical part, but this one is more basic than the extrusion machine and smaller. The structural result and the electrical part work, but this machine is probably the most challenging to work with because it relies heavily on gravity.

This is a tiny version of an injection machine, smaller than the one that already exists in PCI and this way, it can be said that an arrangement like this is easier to move around than one with double the height (and weight). As thought in the beginning, the addition of small wheels to the bottom is not viable because this equipment's weight does not justify that it always works on top of a table. Although, some kind of handle in the rectangle base can be added and carried in the two points marked in Figure 83.

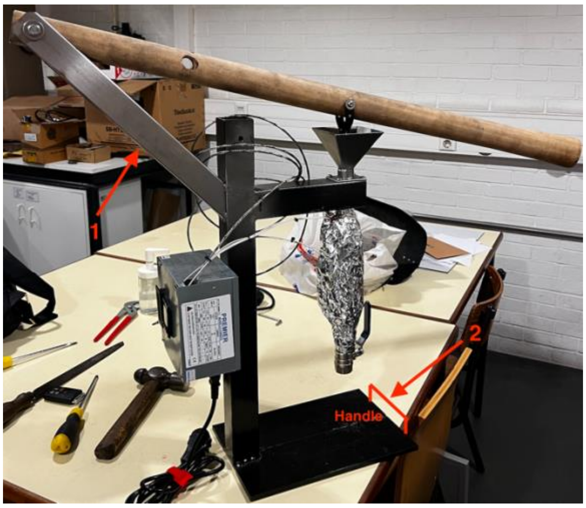


Figure 83 Where to grab injection machine for easy mobility.

The electrical box was screwed to the machine itself because the number of electrical elements was adequate for a small solution like this.

A tap mechanism is beneficial so that any plastic is wasted during the process. The PID controller shows the user the approximated temperature of the tube and, therefore the plastic inside. This way, there is time to screw the mould to its place and open the tap, making it more efficient. Another objective for the PID is setting the limit of the temperature of the resistors around the tube.

Also, opting for a wooden handle is a more comfortable grab for the operator and lighter than the metal one on the original projects of the precious plastic website and even the existing PCI. This wood still requires some type of treatment for its material for long-lasting purposes. This could be wood polish or wax just for the material's surface to be protected, causing the whole axe handle to be stiffer.

Another key point problem found in the testing of this machine was the lack of good insulation that could be causing the plastic to form a plug at the tap end. Another possibility is that the resistances are too far apart or too far from the outing, letting the plastic get cold and solidify before desired. It could be studied the possibility to add another resistance in the tube to spread the heat better as well as increase the insolation.

The base itself (the rectangle plate in the bottom stabilizing the machine) revealed itself to not be ample enough to hold the vertical force especially if the user grips the end of the stick and the equipment is positioned on a table. The tests were made with the machine placed on the ground with the foot of the user on top of the base.

The good and bad thing about an injection machine is that the possibilities for every object imaginable are endless as the positive aspect, but the necessity of making a new mould every time needed is a negative one. Despite this, there's still a wide variety of creative activities to develop with this machine.

5.4 Compression

The electrical part in this machine is solely sourced from the existing oven, so during the production of this machine, this was not something to worry about.

The mobility problem in this machine becomes only between floor levels because it has considerable weight. Although moving around on the same floor is easy because of the addition of the four wheels indicated in Figure 84. An easier way to move would have to be by adding a handle on one or each side of the top of the metal structure (as shown in the picture) to avoid moving the machine by grabbing the legs or the oven.

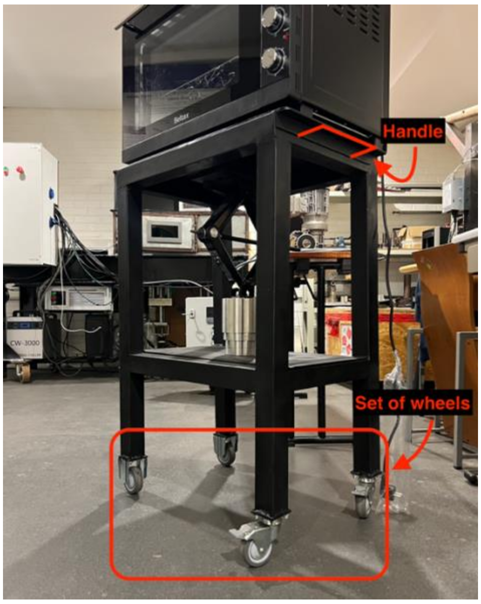


Figure 84 Moving Technology.

A problem with this result is that the oven is just resting on the steel base. Consideration should be given to constructing a docking mechanism to secure the oven not only during transport but also when using the machine itself for safety and stability reasons. A metal angled bracket is already placed in the back of the oven, making the back support better. Still, there is none on the sides and the front, and it is essential because when opening the oven door, there are some forces to be exerted forward and it may not be safe. Therefore, considering that the exact mechanism used at the back of the oven cannot be used because it would prevent it from opening, one could opt for a fitting from below the oven or even a screwed option only on the sides.

Like the injection machine, the favourable aspect is that everything imaginable may be made in infinite ways; the drawback is that a new mould is required each time. Unlike the injection machine, this one allows to produce a sheet of recycled plastic mixing a lot of colors and patterns if desired. With this in mind, there are still a lot of creative activities that can be developed with this equipment.

6 Conclusions and Future Work

The Precious Plastic Aveiro project primarily aims to educate and spread awareness of the correct use of plastic materials after use. One of its objectives is the provision of equipment, as discussed in this project report. This thesis concluded by analysing these projects, their materialisation, and testing to allow this equipment to be shown to other researchers, children, and students to show possibilities and motivate people to build a better world.

The initiative platform's solutions and a group of previously created machines at the University of Aveiro served as the foundation for the development of this thesis. Some of these devices had issues, while others were not functional. The suggested goal was to create four new transportable devices while avoiding some of the errors made in earlier initiatives. The purpose of the thesis was well succeeded.

Some of the tasks passed the timeline projected at the beginning of the project giving that this project allowed to work a lot regarding the project management part of the engineering. Everything was finished, but it still needs to go through some more testing, especially with injection and shredder machines to improve some of the details highlighted in the discussion chapter. Moreover, this gives the opportunity to learn more about time management, budgeting, and teamwork, all of which found to be both challenging and rewarding at the same time.

Recycling is a crucial subject in the day-to-day lives of the whole world, and this is a small project that can show awareness regarding the circular economy of plastic and what we can do to make some change. Plastic cannot be an enemy because nowadays we need it to make the life we know. As students, researchers, and professors, we must find ways to turn plastic into an advantage and see what we can do with it from a positive point of view and try to build new alternatives easy and attainable in the present world.

With that being said, it is then relevant to the proximity of recycled plastic processing equipment near us and is easy to use. To this end, it is necessary to continue raising society's awareness of the problem and educate about the differentiation of the types of plastics, starting with those that are effectively possible to recycle and those that are not and how to do it in our lives.

For the future of this project, the discussion summarises some small changes that can be added just to improve the mobility of the equipment, for example, the addition of the handles in the 4 machines, the docking system for the compression machine, the wheels in the extruder, the possible addition of a table base type for the shredder to stabilize it and a bigger handle to decrease the force applied. The path of this theme is a long and challenging one with many possibilities.

As a possible future work, with the type of extrusion machine that was developed, it is to pair it with the development of filament of recycled plastic for 3D printing (with some improvements in the nozzle system), which is something that requires much testing and studying but is very valuable in the circular economy of plastics and, therefore, sustainability.

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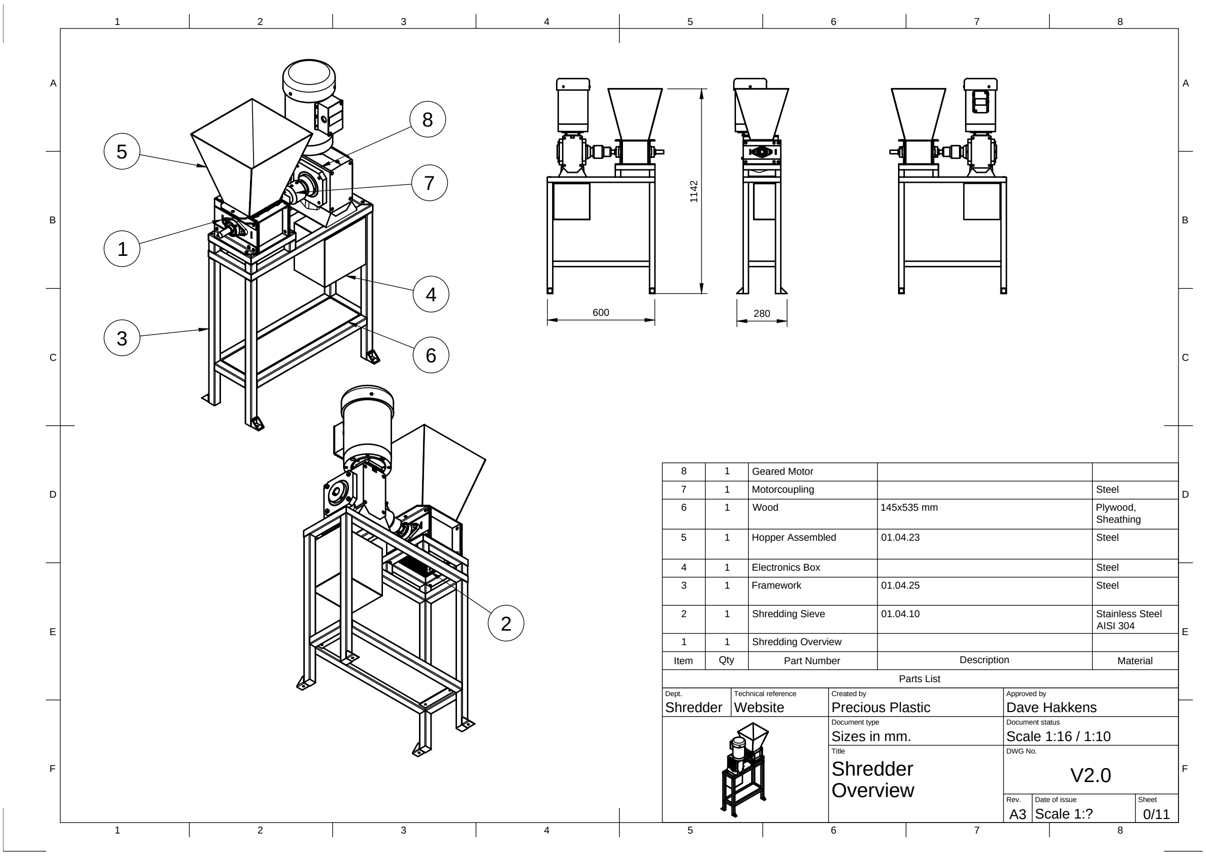
8 Annexes

8.1 Annexe A – Shredder Documentation

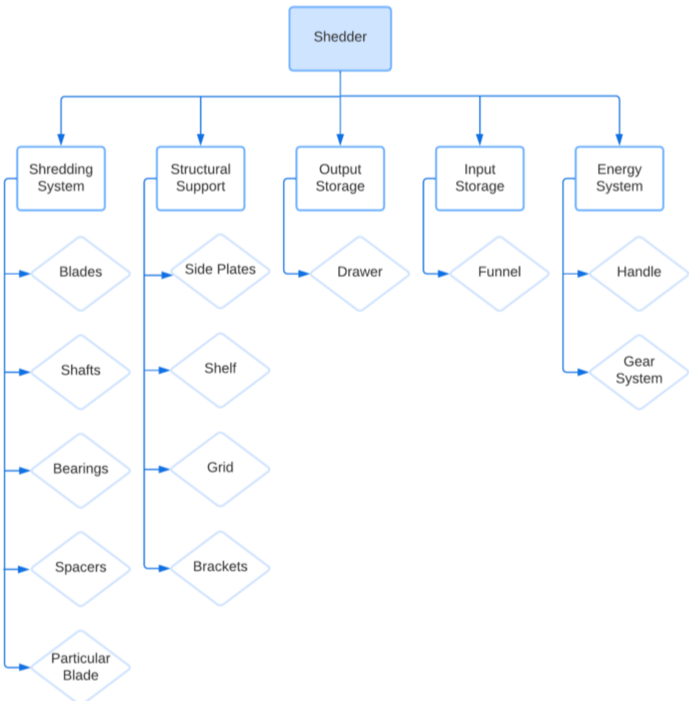
8.1.1 Technical Information



Item	Qty	Part Number	Description	Material
8	1	Geared Motor		
7	1	Motorcoupling		Steel
6	1	Wood	145x535 mm	Plywood, Sheathing
5	1	Hopper Assembled	01.04.23	Steel
4	1	Electronics Box		Steel
3	1	Framework	01.04.25	Steel
2	1	Shredding Sieve	01.04.10	Stainless Steel AISI 304
1	1	Shredding Overview		

Parts List

Dept.	Technical reference	Created by	Approved by
Shredder	Website	Precious Plastic	Dave Hakkens
		Document type: Sizes in mm.	Document status: Scale 1:16 / 1:10
		Title: Shredder Overview	DWG No.: V2.0
			Rev.: A3 · Date of issue: Scale 1:? · Sheet: 0/11



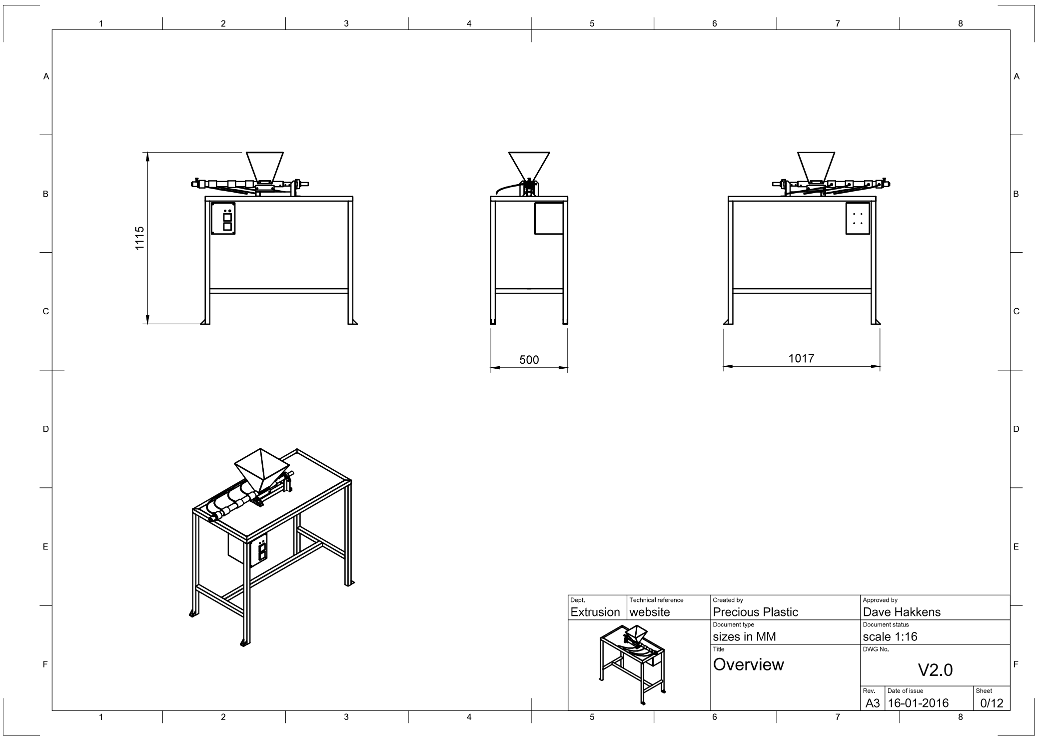
8.1.2 User Manual

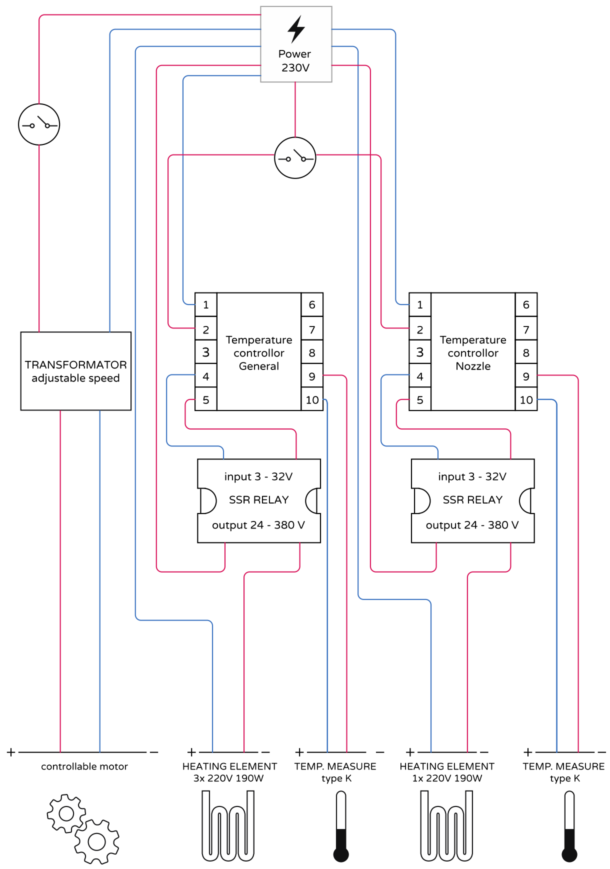
Shredder

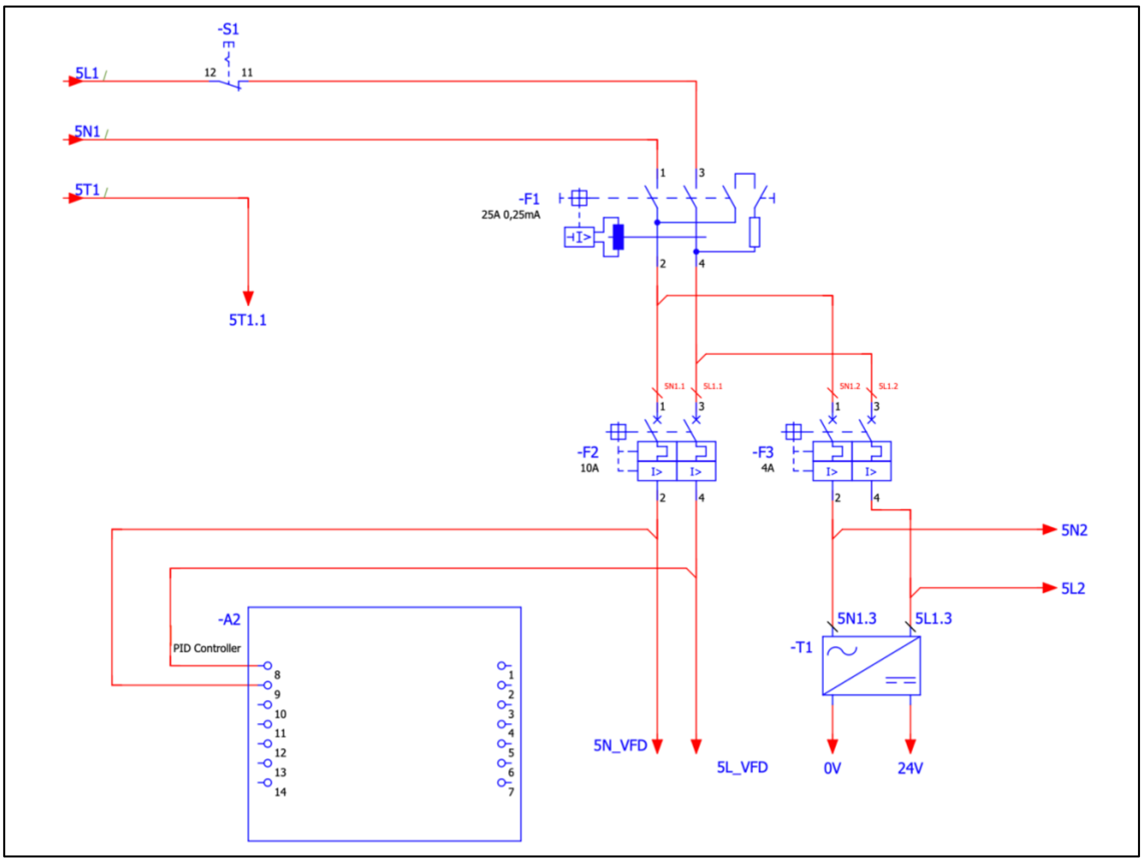
This machine is quite simple because it works manually. It is only necessary to take special care with the rotating teeth and always put the polycarbonate cap because it is possible to jump pieces of plastic when grinding. In any case, the use of goggles when handling the machine is advised.
After separating the plastic, place in the funnel what you want to grind, place the plastic cover and then turn the crank counterclockwise.
Note that this machine is difficult to clean at 100% if the net is not removed under the teeth.

8.2 Annexe B – Extrusion Machine Documentation

8.2.1 Technical Information




Power
230V
TRANSFORMATOR
adjustable speed
Temperature
controllor
General
Temperature
controllor
Nozzle
input 3 - 32V
SSR RELAY
output 24 - 380 V
input 3 - 32V
SSR RELAY
output 24 - 380 V
controllable motor
HEATING ELEMENT
3x 220V 190W
TEMP. MEASURE
type K
HEATING ELEMENT
1x 220V 190W
TEMP. MEASURE
type K


-S1
5L1
5N1
5T1
5T1.1
-F1
25A 0,25mA
-F2
10A
-F3
4A
5N2
5L2
-A2
PID Controller
5N1.3
5L1.3
-T1
5N_VFD
5L_VFD
0V
24V

Extruder

First steps

- MAKING CONNECTOR CONNECTIONS:

Mesa		**Quadro**
10B1	→	10WB1
20R1	→	20WR1
20R2	→	20WR2
20R3	→	20WR3

- Start the engine to the electric box (20M1)
- Check that the switch on the left side of the frame is at 0
- Connect the machine to the power
- Turn switch to 1

Resistors turn on automatically.

To set a temperature limit for the resistors:

Click the 'set' button for ~3s and when it starts flashing click the arrows to the desired temperature.

Wait for the temperature to be reached (red value that appears at the top)

Resistances in this example will heat up to 245ºC

Then the green LED gives permission to start engine.

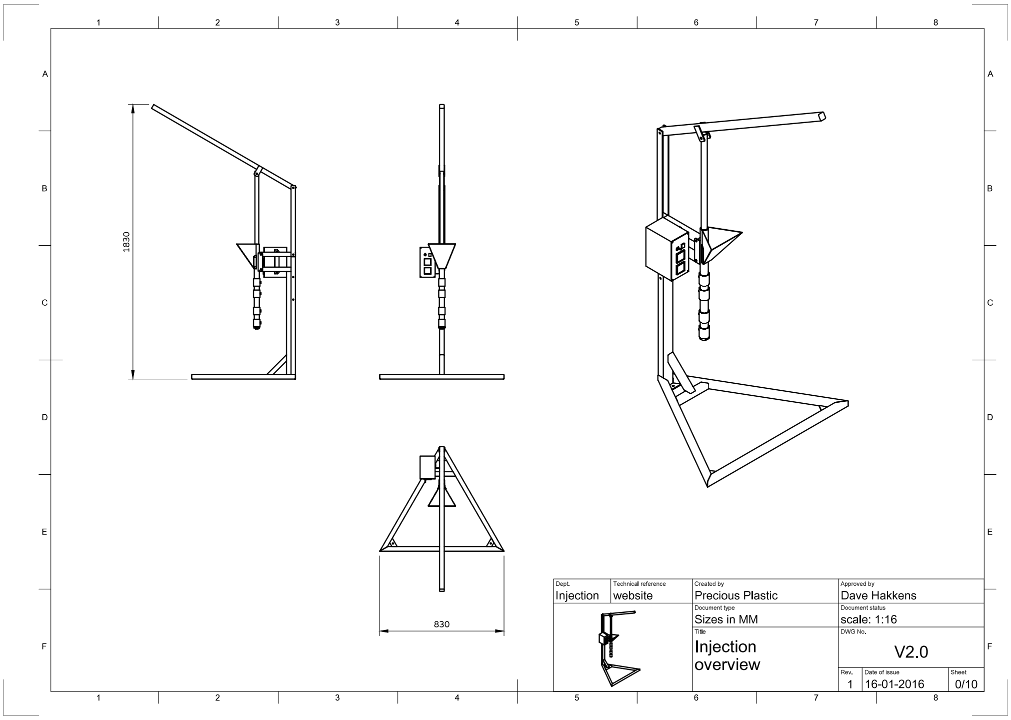
The green LED indicates that it is safe to turn the black switch for the engine to start running.

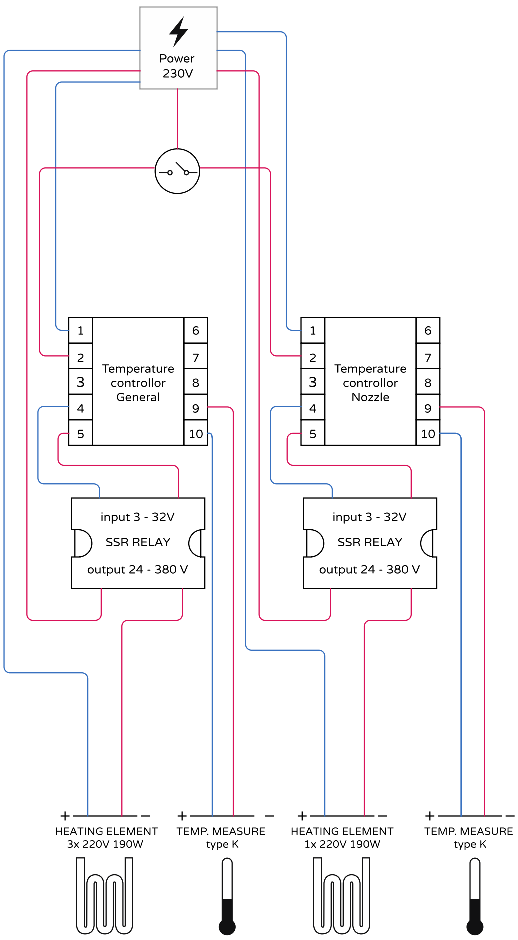
Motor rotates to the **right** to work normally to expel the material and to the left if there is any problem and get some material stuck in the tube and is necessary.

The first element of the frame allows you to increase or decrease the engine speed so that the output of the material is faster or slower as desired.

8.3 Annexe C – Injection Machine Documentation

8.3.1 Technical Information





PARAMETERS DESCRIPTION

INDICATION SCREEN

PV **SP**	**Temperature indication screen**. The upper (red) display shows the value of the measured variable (**PV**) temperature. The lower display (green) shows the control setpoint value (**SP**), which is the desired value for the process temperature.
SPA1	Alarm SP. Value that defines the alarm actuation point. For **Differential** type functions, this parameter specifies error (*).

TUNING CYCLE

Atun	**AUTO-TUNE**. Enables the automatic tuning of the PID parameters (**Pb, Ir, dt**). See **PID Parameters Definition** chapter. **oFF** Auto-tune off. **FASt** Perform tuning in fast mode. **FULL** Perform tuning in precise mode.
Pb	Proportional Band. Value of the term **P** of the control mode PID, in percentage of the maximum span of the input type. Adjustable between 0 and 500.0 %. **When set to zero (0), control action is ON/OFF.**
Ir	Integral Rate. Value of the term **I** of the PID algorithm, in repetitions per minute (Reset). Adjustable between 0 and 24.00. Displayed only if proportional band ≠ 0.
dt	Derivative Time. Value of the term **D** of the control mode PID, in seconds. Adjustable between 0 and 250 seconds. Displayed only if proportional band ≠ 0.
Ct	Cycle time. Pulse Width Modulation (PWM) period in seconds. Adjustable between 0.5 and 100.0 seconds. Displayed only if proportional band ≠ 0.
HYSt	Control hysteresis. Hysteresis value in degrees for ON/OFF control. Adjustable between 0 and the measurement range width of the selected input type.
ACt	Action control: **rE** Control with **Reverse Action**. Appropriate for **heating**. Turns control output on when PV is below SP. **dIr** Control with **Direct Action**. Appropriate for **cooling**. Turns control output on when PV is above SP.
Out1 **Out2**	Operation mode of OUT1 and OUT2 outputs: **oFF** Not used. **A1** Alarm output. **CtrL** Control output.

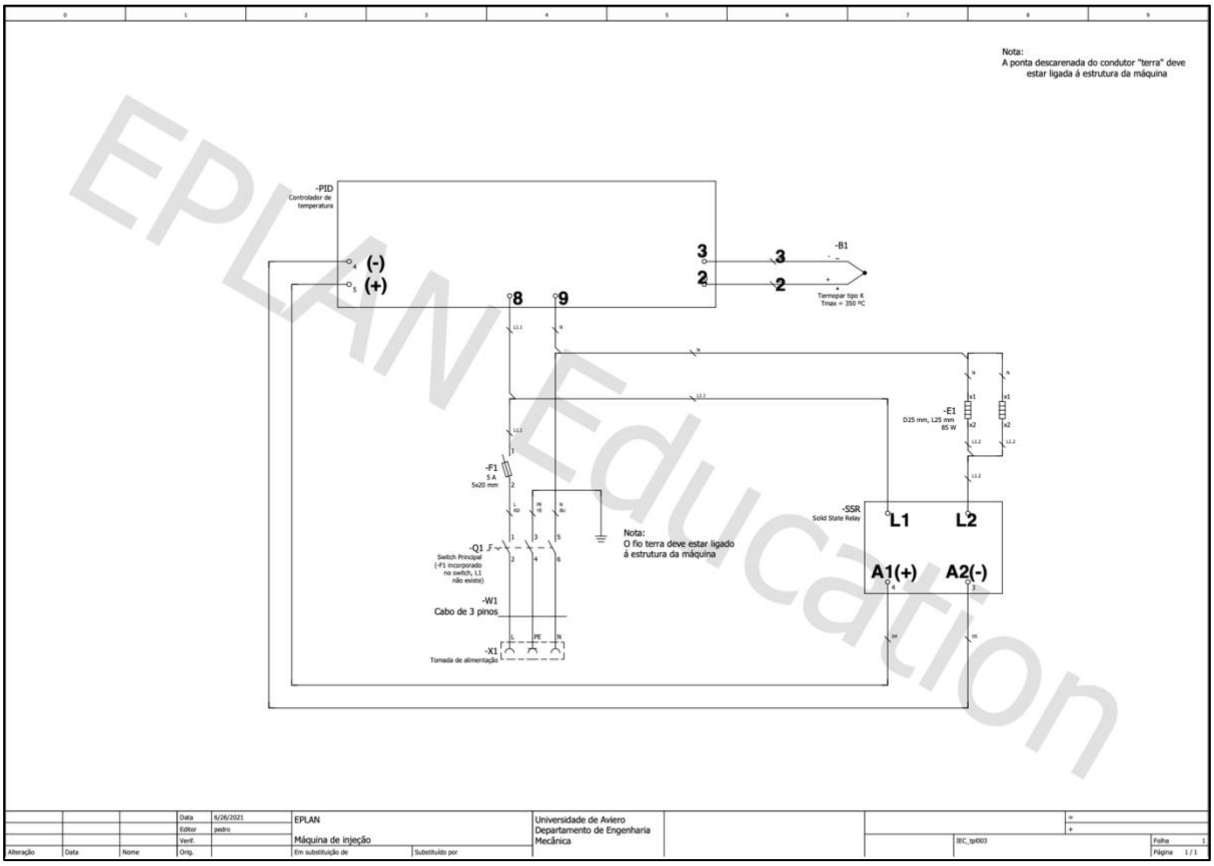
CALIBRATION CYCLE

All input types are calibrated at the factory. If a recalibration is necessary, it must be performed by a specialized professional. If this cycle is accessed accidentally, do not promote changes in its parameters.

PASS	Password. This parameter is shown before the protected cycles. See **Configuration Protection** chapter.
CAL	Calibration. Allows you to enable the function to calibrate the controller. When the function is not enabled, the calibration of the related parameters will remain hidden.
InLC	Input Low Calibration. Allows you to enter the value corresponding to the low scale signal applied to the analog input.
InHC	Input High Calibration. Allows you to enter the value corresponding to the full-scale signal applied to the analog input.
rStr	Restore. Allows you to reset the input factory calibrations, disregarding all changes made.
PAS.C	Password Change. Allows you to set a new access password, always different from zero.
Prot	Protection. Allows you to define the protection cycle. See **Table 03**.

INPUT CYCLE

tYPE	Input type. Sets the input type used by the controller. Refer to **Table 01**.
dP.Po	Decimal point. Sets the presentation mode of the decimal point.
unit	Sets the temperature unit to be used: **C** Indication in Celsius. **F** Indication in Fahrenheit.
OFFS	Offset. Parameter that allows you to make corrections to the indicated PV value.
SPLL **SPHL**	SP Low/High Limit. Sets the lower/upper limits for adjustments to the control SP value. Does not limit the setting of the Alarm SP value.
FuA1	Alarm functions. Sets the alarm functions from the options in **Table 02**.
SP.A1	Alarm SP. Sets the alarm actuation point. For **Differential** type functions, this parameter defines the error (*).
bLA1	Blocking Alarm. This function blocks the alarms (*). **YES** Enables initial blocking. **no** Inhibits initial blocking.
HYA1	Alarm hysteresis. Sets the difference between the PV value at which the alarm is turned on and the value at which it is turned off (*).
SP1E	Allows to display **SP.A1** parameter in the controller Operation Cycle (*) (**). **YES** Displays **SP.A1** parameter in the Operation Cycle. **no** Does not display **SP.A1** parameter in the Operation Cycle.


Nota:
A ponta descarenada do condutor "terra" deve estar ligada á estrutura da máquina
-PID
Controlador de temperatura
(-)
(+)
8
9
3
2
-B1
Termopar tipo K
Tmax = 350 ºC
-E1
D25 mm, L25 mm
85 W
-F1
5 A
5x20 mm
-SSR
Solid State Relay
L1
L2
A1(+)
A2(-)
-Q1
Switch Principal
(-F1 incorporado no switch, L1 não existe)
Nota:
O fio terra deve estar ligado á estrutura da máquina
-W1
Cabo de 3 pinos
-X1
Tomada de alimentação
EPLAN Education
Data 6/26/2021
Editor pedro
Verif.
Orig.
Alteração
Data
Nome
EPLAN
Máquina de injeção
Em substituição de
Substituído por
Universidade de Aviero
Departamento de Engenharia Mecânica
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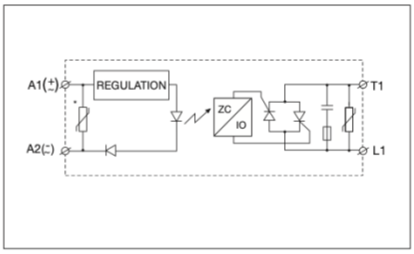
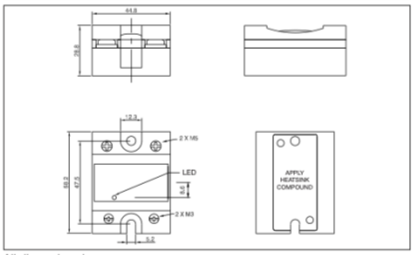
Functional Diagram



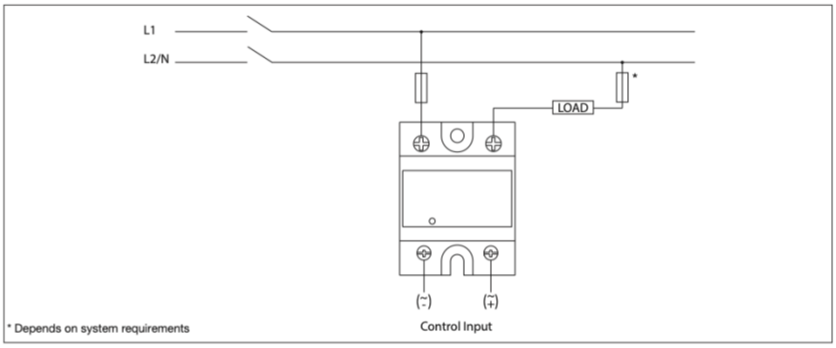
* Varistor across input applies to AC control versions only.

Dimensions



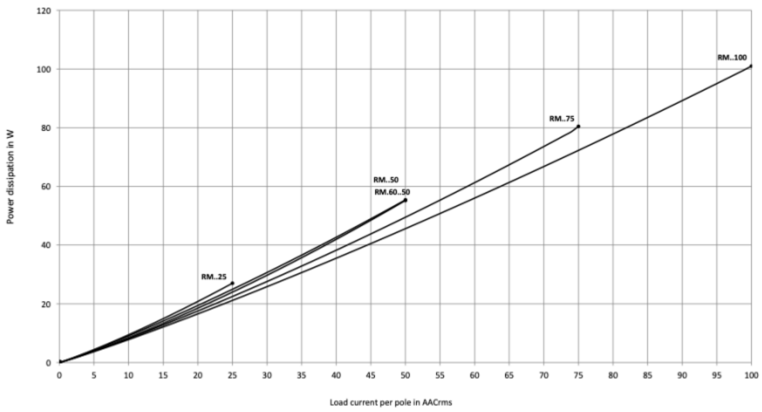
All dimensions in mm

Connection Diagram



* Depends on system requirements

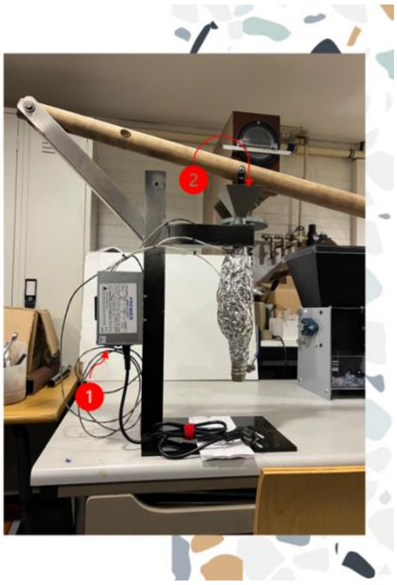
Output Power Dissipation



8.3.2 User Manual

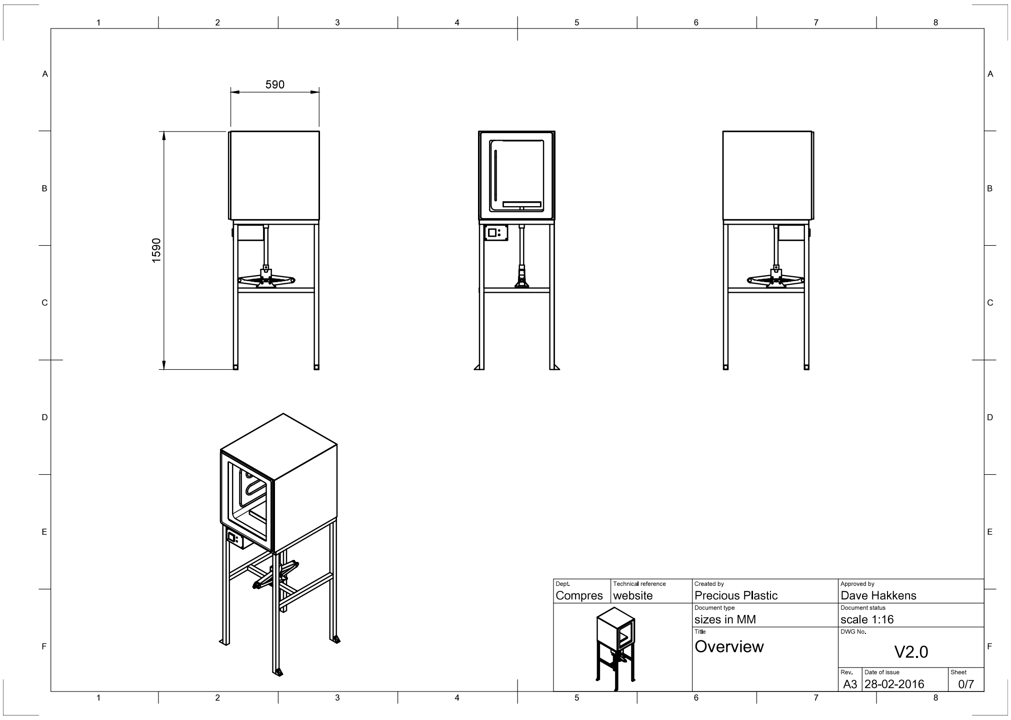
Injection Machine

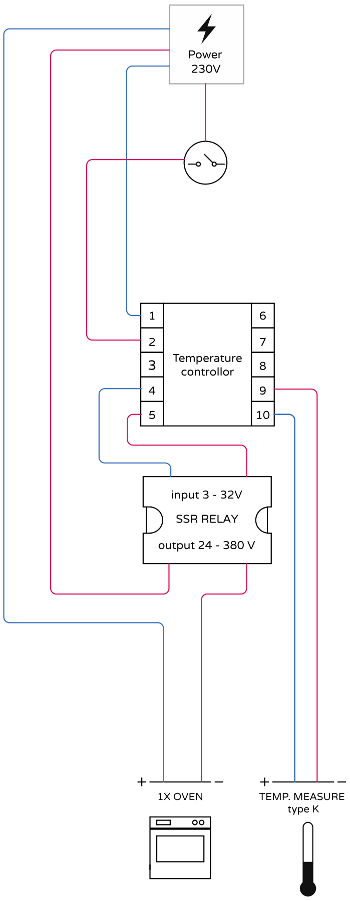
1. Connect power plug
2. Connect switch that is under the metal box (shown in no. 1)
3. Check that the tap is closed
4. Put up the rod
5. Putting plastic in the funnel (no. 2)
6. Choose the heating temperature of the resistances in the PID using the arrows ▲ ▼ and wait until the system says it has reached the desired temperature
7. Place mold
8. Open the faucet and lower rod.



8.4 Annexe D – Compression Machine Documentation

8.4.1 Technical Information





8.4.2 User Manual

Compressor

This machine is quite simple because the electrical part is just an electric oven that we are used to using in our daily life.
Put the crushed plastic inside a mold, place the mold inside the oven in order to melt the plastic and then place the mold on the tray as shown in the figure and rotate the jack to press until the mold cools.