Design and Manufacture of a Sustainable Recycled Plastic Shredder

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Abstract. The design of this shredder is part of an ambitious project called "MAREA Plastic" which aims to be a meeting point between the university comunity and society through science and technology by developing its own envi-ronment based on circular economy.

The project's challenge is the creation of portable lab that allows manufacturing new products from recycled plastic waste. To date, this has only materialized in private or temporary environments. A new way of looking at recycling and reuse arises, transferring the whole process to an urban laboratory that counts on the necessary technology to carry out the transformation process in a dynamic and illustrative way.

In this context, the redesign and optimization of specific machinery is needed to make the urban lab possible. The extruder or the injector machines are examples of this. However, prior to using these two machines in the converting process, plastic containers need to be shredded into small shavings.

The purpose of employing affordable and sustainably obtained materials is none other than to promote social awareness on the ecosystem problems and foster the MAREA Plastic project in turning the University of Malaga into a benchmark for cultural change.

Keywords: Circular economy · Recycling · Reusing · Plastic waste · Shredder

1 Introduction

1.1 Object

This paper presents a physical prototype of a plastic shredder for a solid machine design to be used in an urban laboratory as part of the 'MAREA Plastic' project. The development of this machine plays a fundamental role in the continuation and correct performance of this research and social awareness project.

The prototype itself is considered sustainable to a greater extent since it will be composed of different elements and pieces that have at some point been disposed of. These discarded objects were mostly provided by the University of Malaga. By reusing

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them, their useful life is extended giving them a new purpose for which they were not originally intended. In addition, the machine must also transmit inherent values to the project, such as raising awareness and education in environmental sustainability or deep understanding and comprehension of the plastic recycling process in an illustrative way.

The communication between the shredder and the user must be dynamic, without the need for previous knowledge or experience at working with this type of machinery, and also considering it will be shown to a smaller audience. Therefore, even if it is a prototype, it is a priority that it is possible to visualize and understand perfectly what the used plastic is going through the shredder as part of the work chain.

It is therefore of vital importance that the safety of the public and the user is ensured at all times, both in the prototype and in the future shredder. Therefore, understanding and visualizing why the recycled plastic goes through the shredded as part of the work chain even if it is a prototype becomes essential.

All in all, it is of vital importance to ensure the public and user safety at all times, both in the prototype and the future shredder.

1.2 State of Art and Justification

Drastic changes are required in order to protect the planet and its biodiversity and ensure a proper ecosystem for future generations. Plastics, microplastics and their accumulation are one of the main sources of pollution. To fight this, more and more projects are created at an international level so that civilians are involved in improving this situation.

According to the World Wide Fund for Nature (WWF), 95% of all the waste floating in the Mediterranean Sea is plastic in its many different forms. Most of it comes from Turkey and Spain, followed by Italia, Egypt and France. Moreover, each year tourism at these countries increases marine litter by 40% in summer [1].

These figures are devastating and it does not get better when compared to a global level. According to Greenpeace, only 9% of all plastic ever manufactured has been recycled, while 12% was incinerated and 79% ended up in landfills or spread over the ecosystem. In addition, 21–54% of all plastic particles in the world are found in the Mediterranean basin [2].

Plastic pollution in the Mediterranean Sea has been widely documented and studied; however, the impact on biodiversity has not been fully explored. Recent studies contribute to the identification of sensitive and understudied areas where marine species may be threatened in order to find hotspots of special interest [3].

Although in science and technology fields are researching and developing new biodegradable plastics or substitutes, it may be more consistent so far to talk about the sustainability of the material itself, that is to say, plastic waste recycling. At this point is when MAREA Plastic project comes in together with the need for a shredding machine to complete the circular economy chain proposed here.

Many people have already tried to provide solutions to this call, for instance, by redesigning small manual shredders [4, 5]. Among these solutions the proposal by Dave Hakkens outstands. He is the founder of Precious Plastic', a project from which MAREA Plastic draws its inspiration. Hakkens and his team designed the necessary information to build machines able to reuse plastic waste to give shape to new products and released them to the community. Actually, they managed to do it in a very simplified way, making the wholes recycling process much simpler, but also more manual than what the industry allows [6].

2 Methodology

Before referring to the methodology applied to the project, there are two important factors to be considered. The first is that the design presented here starts from a basic shredder model, freely released to the community by Precious Plastic which includes specification data for each piece according to their experience. Secondly, it must be known that the project has been in constant evolution while the prototype design and construction was taking place.

Regarding the first factor, the methodology of Failure Mode and Effects Analysis (FMEA) could be under the spotlight where the quality, reliability and safety of a product or process would be improved during the developing process itself. It analyses where potential failures can occur, their cause and their probability of occurrence.

Some of the features born from this methodology are the following: the use of a Variable Frequency Drive (VFD) to control the shredding speed, a closure to the Hopper in order to avoid the projection of plastic particles, or the incorporation of an intensity sensor to indicate the engine is working properly.

The FMEA methodology allows to focus on the machine and user's safety, being able to foresee the dangers the user will face or whether the machine is not completely safe, either due to mechanical or electronic parts.

Related to the second factor, it should be noted that it is a Design for Manufacture and Assembly (DFMA) oriented methodology that would reduce the number of components to the minimum possible. This method poses four fundamental questions:

- The need for a piece.
- The use of a specific material.
- Movement between components.
- Whether the assembly is hidden between parts.

Thanks to these guidelines, rigid or elastic joints have been used depending on the area and the movement to be carried out. In addition, both standardized elements and pieces of our own design have been employed to make easier the machine's assembly and maintenance.

It has not always been possible to progress in the same path since due to the lack of availability in manufacturing or waiting times for the required components reception. However, at any case, another aspect was developed in parallel meanwhile, such as the mechanical and the structural part, or the safety related operations and the electronic part. Besides, as it consists of a larger project, sharing information and experience between the different machines has played a key role for its development.

There is certain similarity with Concurrent Engineering (CE) by finding this convergence in every process development whenever possible. Not only has it been a matter of time saving but also making a greater effort in the design to reduce costs and improve quality. CE allows to work entire and simultaneously with knowledge, resources and experience employing computerised methods applied to design such as: CAD, CAM, CAE.

3 Background

3.1 Market Study

Currently, there are a diverse large shredder models in the market designed for the industrial environment. These are large machines equipped to be operated by trained technicians thus, not corresponding to the shredder concept MAREA Plastic intends. Furthermore, this kind of shredders do not allow easy transportation due to their high weight of around 250 kg.

They are definitely not aimed at promoting recycling awareness among the public since their industrial character makes them opaque meaning this that the user does not have the chance to see or understand what happens inside them, therefore, preventing the user participation along the shredding process.

Despite starting from the sustainability and circular economy concept there are some similar redesigns to this project that do not take the opportunity to instruct and illustrate the consumer [7].

Since Precious Plastic released the basic model for the shredder machine many individuals have brought themselves to build it for various reasons, whether to contribute the community or to make a profit by selling a product or the machine itself. Not only is the whole machine set considered but many people and small businesses have taken the plunge to sell different parts of the shredder as well. At the Precious Plastic official website there is a 'bazaar' where other users can offer products for the machine construction, and even the complete set [8].

3.2 Study of the Basic Model

The shredder is the backbone of the recycling process (see Fig. 1) since it allows the plastic to be shredded into small flakes that can later be washed and stored, or moved into other workspaces to become new interesting products for its users.

The components of the basic shredder model are:

– Geared motor assembly.
– Shredding box.
– Safety hopper.
– Support structure.

'Precious Plastic' also provides data to the community from its experiences (see Table 1).

From all the above information together with the study of the basic model, several conclusions are obtained and exposed in the following table (see Table 2).

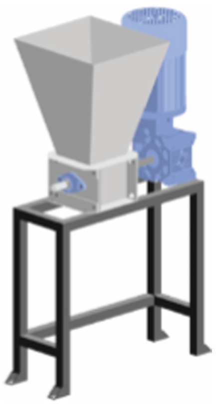

Fig. 1. Conceptual basic shredder developed by 'Precious Plastic'. [4]

Table 1. Values according to the experience with the basic model. [8]

Nominal power	Nominal torque	Output speed
1,5 kW = 2 HP	300 Nm	±70 rpm

Table 2. Pros y cons of the previous basic model. [8]

Pros	Cons
Small and light	Processing load is low
Possibility to granulate small flakes	The granulation process is slow
Relatively inexpensive	High maintenance
Portable	

3.3 Innovation and New Design Requirements

Based on the study previously carried out on the shredder simplest version, and the initial briefing that enabled the collection of material to be given a second life, some improvements and adaptations of the conceptual machine are proposed in order to fulfil the machine's goal in an optimal and safe way.

Improvements are classified by distinguishing three essential parts according to their role in the machine:

- Structure: comprising the support, fastening and transportation of the shredder assembly.

- Mechanics: includes the elements required to transform electrical energy in mechanical energy, able to obtain the torque and output speed of the shredder box shaft.
- Electronics: automation and control of the shredder; electrical power supply is included in this section as it is subject to a microprocessor.

Structural Function

An iron structure is proposed. It is reinforced at the top, where 30 mm thick chipboards are screwed in order to serve as support table for the engine. The lower part must be adapted with another reinforcement that enables the positioning and fixation of the electronic scale used for weighing the shredded plastic.

The wooden board needs to be cut inside with the size of the shredder box lower part so that the plastic shavings can go out the box and through the table into the collecting bucket under the table. This hole shall be protected with a metallic rigid metal mesh that surrounds the edge of the hole covering a depth of around 20–30 cm. This distance depends on the bucket size located under the table to collect the plastic shavings. The mesh holes' size should allow to see the plastic flakes as they pass through and fall in the collection bucket as well as be rigid enough to maintain its shape over time, providing the necessary security to prevent objects or people from coming into contact with the blades.

The same metal mesh shall be employed to cover the mechanical joints of the assembly: the joint between the motor and the reducer, and the joint between the reducer and the shredder box shaft. These critical points of transmission rotate and count on bolted fastenings that could put the user at risk.

The structure must have wheels strong enough to support the load above and allow the movement and transportation of the assembly. The correct mobility of this machine is very important as it is expected to comply not only with its operation environment but also be able to function and be shown to the public in diverse scenarios.

A safety methacrylate-made hopper is designed to enable viewing the box interior while the user can interact with the machine using its hatches.

To avoid vibrations from the motor-gearbox-blades box be transmitted to the whole structure, a sort of "silentblock" type elements shall be used in the base in order to absorb most of the vibrations, crashes and noises. All elements remain fixed to the chipboard table and iron structure by means of screwed joints.

Mechanic Function

It is required to design a part to transmit the movement from the reducer to blades box shaft, as far as possible reusing discarded material.

Electronic Function and Power Supply

A start/stop button shall be located between the three-phase socket and the Variable Frequency Drive (VFD) so that there is no chance for misleading interpretation by the user.

The VFD controls the output speed of the blades box shaft. Consequently, it is the first element needed for the machine automation.

A microprocessor controls the whole machine assembly according to a pre-configuration setup that includes all mechanical and electronic components.

By means of a controller, the connection between the microprocessor and the VFD is ensured.

Locating an end-of-stroke sensor on the side gate of the hopper makes the blades brake and the machines stops directly when the gate is not properly positioned and closed, taking out the risk for the person under use.

An electronic scale is required at the base of the structure so that when the desired weight of shredded plastic is reached, the machine stops.

To prevent further damage in the event of the blades blockage, a rotation inverter between the VFD and the motor is installed so that not only the manual reversal of the shaft rotation is allowed to release the load in the event of failure but the connection between both elements can also be disrupted whether it is for testing and setting up the machine, or in hazardous situations.

A non-invasive current sensor is installed next to the motor, connected to the microprocessor in order to reduce or stop the movement in case the maximum working current is exceeded. This prevents de motor from working beyond its capabilities, thus extending its useful life.

Since ensuring safety is essential, serious consideration has been given to the user environment together with optimizing the machine operation in terms of production and consumption. With all this in mind, considering the innovative elements on the model and the adaptations for its working environment, the solutions and processes carried out for the prototype development are explained below.

4 Solutions and Prototyping Process

A fundamental part of this Project is employing discarded materials that can be re-used for the shredded construction, thus making technology not only an ally to the project motto but also a transmitter and incentive of the recycling philosophy. In this sense, the end product is not the single result of the circular economy process that carries the message, namely, it becomes a part of a continuum where awareness-raising is constant, enhancing the impact on the consumer.

After studying the basic model above, an initial briefing was performed to get an idea of what changes or improvements the prototype needed in general terms. Most materials and components available for reuse were provided by various departments from the University of Malaga (Fig. 2). Among the elements reused, the following are found:

- *Motor:* loaned by the University of Malaga. According to the identification plate, it is a ASEA electric motor with the following specifications:

  – MODEL - MH-90 Lb/4
  – Brand - ASEA
  – Power - 2 HP–1,5 kW
  – Frequency - 50 Hz

Fig. 2. Motor, reducer and shredder box. [Source: Own elaboration]

– Voltage- 2250–380 V
– Speed - 1400 rpm

- *Gearbox/Reducer:* a lower number of RPM output can be obtained without a significant power reduction, increasing the torque in a safe and efficient way. It has a worm gear configuration and was acquired from a gearbox assembly at a scrapyard. Thanks to its modular design it could be ripped apart from the motor that was burnt out and reuse it without problems due to being an entirely mechanical element. Its characteristics are:

– MODEL - SK 1SI63H-IEC90-90L/4
– Reduction ratio (i) - 7,5
– Maximum input speed (n1) - 1800 rpm
– Output speed (n2) - 186 rpm

- *VFD:* It is a second hand component. Improving efficiency and making responsible use of electric consumption are inherent to the project logic that is why only the required amount of electric should be consumed. This is done by meeting the motor speed with that required to perform the process. Thanks to the VFD the motor's energy consumption can be reduced by 20–70% since the VFD is able to adjust the motor's input speed to the real demand.
- *Safety hopper (*Fig. 3*): This* element is similar to a large funnel designed for channelling the plastic material into the shredder box and it is essential in the prototype design. It is a key piece in direct interaction with the user. Its purpose is to allow feeding material to the shredder in a safe and illustrative way. In order to achieve that, it is

decided that the material should not be opaque, this is why methacrylate is selected. The side door is the most important since it allows the controlled feeding process by means of the microprocessor, complying with a safe shredding process. A limit switch device enables the shredder operation only when the side door is close, that is to say, if the side door is open while operation, the shredder would stop immediately.

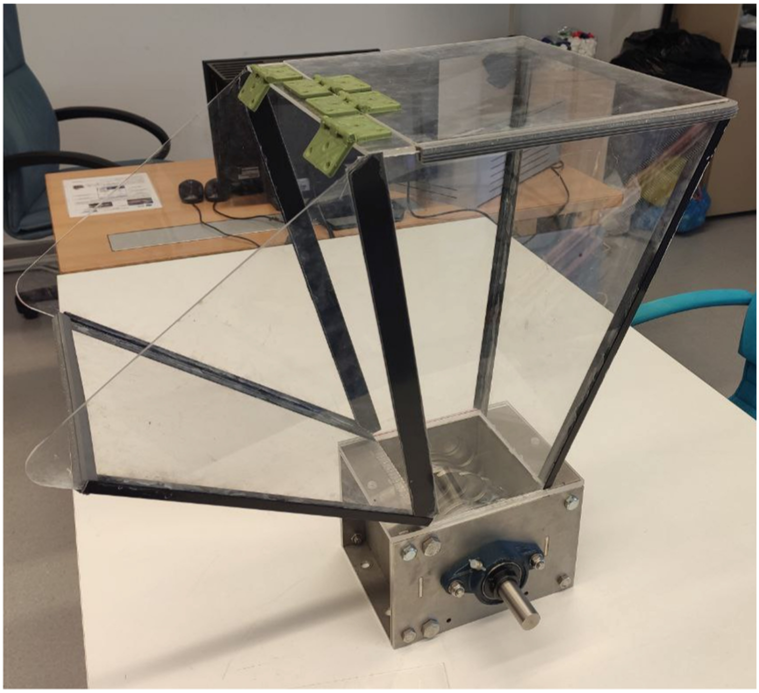

Fig. 3. Safety hopper assembly on top of the blades box [Source: own elaboration]

- *Electronic scale (*Fig. 4*): connected* to the microprocessor through a converter that links to a load cell in charge of weighing the plastic stored in the container. This simple configuration enables the control module to stop the shredder when the pre-settled weight is reached. Thanks to this exhaustive control, the amount of shredded plastic can be quantified any moment.
- *Non-invasive intensity sensor*: it is the most important device in terms of safety of the machine. To simplify the design, manufacture and starting-up, this device is non-invasive as connecting it directly to the wiring implies adding several control elements which would increase the prototype final cost without getting a substantial improvement in current measurement.
- *Microprocessor*: the VFD comprises the first automation step in the machine. Its functions are controlled by a microprocessor that manages the configuration, order transmitted by an operator or by a process unit, and the data provided by various measurements such as speed, current, amount of shredded plastic, etc.

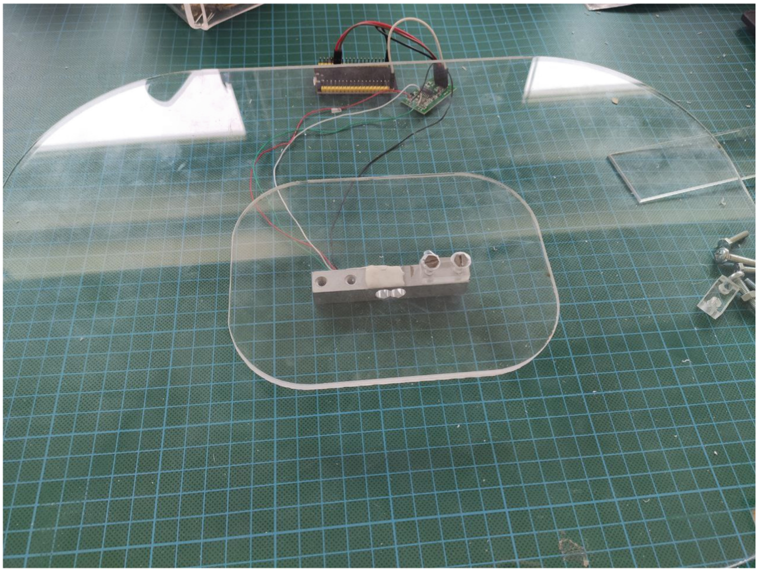

Fig. 4. Electronic scale assembly. [Source: Own elaboration]

5 Prototype Analysis

After performing the corresponding calculations, the following data is obtained according to some the afore mentioned characteristics (see Table 3):

Table 3. Values according to the prototype theoretical approach. [Own elaboration]

Nominal power	Nominal torque	Output speed
1,5 kW = 2 HP	76,6 Nm	±186 rpm

The resulting torque is low and the output speed is high when compared to the results shown above. However, these results can be useful to build the final design of the shredder machine.

5.1 Prototype Experimental Analysis

Two common types of plastic were used to test the prototype: PET, which is present in water bottles as the container itself (but not the cap or ring on the top), and PLA, the most frequent plastic for 3D plastic nowadays.

The procedure consisted in inserting a bottle (without the cap, nor the ring since they are made of a different material, HDPE) into the hopper while the blades are in operation changing the frequency, namely, rearranging the output speed.

Up to a frequency of 30 Hz the blades do not produce enough impact force to tear the plastic. Although reaching 35 Hz the shredding process is able to strip complete bottles, the blades continue to block. From 45 Hz the process begins to be performed properly, with less likelihood of jamming or blocking. Taking the frequency to its maximum, 50 Hz, the output speed is so high that the blades become blocked due to plastic accumulation between the blades strips.

One problem detected along the these testing is that generally, the blades speed is too high and throws the bottle out of the box, making the task more difficult.

The next test was done employing PLA coming from 3D printed pieces. PLA has good mechanical properties compared to standard thermoplastic materials. Its hardness, impact resistance and elasticity are similar to those of PET.

After these tests, it was found that the element density and thickness were key aspects to consider in the process. Shredding at 40 Hz gave the best results in pieces with a low filler percentage. Actually, pieces employed for this test were not very thick, 2–3 mm thick, plate shaped; it was able to shred higher volume pieces but still with a low filler percentage. Besides, those elements that were 5 mm thick with solid filling would block the blades.

6 Conclusions

On the one hand, the FMEA methodology has been fundamental to propose improvements and innovations regarding the basic model. On the other hand, DFMA methodology has further contributed in terms of physically developing the machine, as well as for its assembly and the replacement of different components.

In such a collaborative project as MAREA Plastic is, where diverse machines must work all together for a purpose, a correct information transmission becomes essential, as it occurs in IC.

After studying the analyses carried out and verifying that it is a functional model, significant conclusions can be drawn about the current prototype, as well as the development of the electronics, improvements and other adaptations so that the shredder performance in the project is correct.

Firstly, it is noted that the speed reduction and the torque increase are not enough, so in next developments a higher speed ratio is needed, around 20 or 40 if we use a similar 2 HP motor. The ideal option would be starting from a complete motor-gearbox assembly, since the gearbox is designed to fit the motor, there would be no problem of vibration or internal imbalance.

In addition, a 3HP motor could be used with a lower reduction ratio, that is to say, an output speed greater than 70 rpm may be obtained being able to reduce it by means of the VFD, keeping the torque constant around 300 Nm. This is the reason why the VFD is the best option to initiate the machine's automation, as it opens a wide range of possibilities, being able to play with these parameters without needing a specific motor or gearbox.

It becomes essential to increase the torque to avoid blockages due to accumulation so that the speed does not need to be increased to have enough boost to tear the plastic.

This prototype turns out to be very important in the project development, despite its limited activity, its operation allows elaborating the electronics needed for the future machine. The automation required to control the machine starts with this prototype by creating the individual code for each proposed element for the shredder: limit switch, electronic scale and non-invasive intensity sensor.

The prototype is not especially bulky or excessively heavy, therefore it can be transported quite easily complying with one of the main goals of the Project: instruct, disseminate, encourage and engage the public at MAREA Plastic promotional events. Furthermore, it needs to be said that not a significant amount of the proposed budget needed to be expended on this prototype, which allows to apply the knowledge gained to the following improvements without having reduced the available funds.

7 Future Prototype Improvements

Recently, a new gearbox was acquired with a speed ratio i = 40. Appling the same theoretical calculation mentioned in the previous section, the following data is obtained (Table 4):

Table 4. Future values required according to the prototype theoretical analysis [Own elaboration]

Nominal power	Nominal torque	Output speed
1,5 kW = 2 HP	407 Nm	±35 rpm

Considering the above data, a new experimentation stage needs to be developed employing different materials to verify that the shredder works indeed better under these conditions.

However, going beyond the purely mechanical aspects, there are several features that could pose major advantages over the current prototype. For instance, the user interface could be improved by making possible to access the configuration data and important notifications through a tactile screen directly to the user. Depending on the shredded material, it could also be settled to work efficiently without unnecessary energy waste just by clicking in a button to jump from one configuration to the other.

Thanks to this automation, a record of shredded plastic could be stored. This option was always in mind while designing the codes and selecting the microprocessor, that is why the last one is able to connect via Bluetooth or WiFi. Nevertheless, for the starting versions a local server connected to a computer over a private network is recommended.

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