



ING. MECATRÓNICA

**Thesis submitted prior to obtaining the degree of
Mechatronics Engineer.**

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Diseño y construcción de una trituradora para soportes de impresión 3D (PLA y PETG).

Design and construction of a crusher for 3D printing supports (PLA and PETG).

Quito-2026

Aprobación del Tutor del Trabajo de Integración Curricular

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Dedicatoria

A mis padres, por ser el cimiento de mis sueños y el motor de mi constancia, por su sacrificio y amor incondicional, todo lo que soy y lo que he logrado en esta etapa se lo debo a su fe inquebrantable en mí. Este título es tan suyo como mío. A mi hermana, por ser mi refugio en los días grises y por recordarme siempre que no hay meta inalcanzable. Y a Silvia y Leonardo por ser el aire fresco cuando el mundo de la universidad se sentía sofocante. Gracias por cada café, cada risa y por ayudarme a desconectar para poder volver a empezar con más fuerza.

Agradecimiento

En primer lugar, quiero agradecer a la Universidad Internacional del Ecuador por brindarme las herramientas necesarias para mi formación profesional. Un agradecimiento especial al Ing. Marcelo Moya, director de la facultad, por su apertura para resolver mis dudas, y al Ing. Guillermo Mosquera, director de la carrera, por su gran ayuda y valiosas correcciones en la redacción de este documento. A mi tutor, el Ing. Vladimir Bonilla, por su guía y por compartir conmigo su visión crítica durante el desarrollo de este proyecto. También agradezco a mi examinadora, la Ing. Cristina Oscullo, por su excelente disposición para responder a mis preguntas y por las revisiones que enriquecieron mucho la calidad técnica de esta tesis. Finalmente, a mis compañeros y amigos de Mecatrónica, con quienes compartí interminables jornadas de estudio, proyectos y tazas de café. Gracias por ser el apoyo necesario en los momentos de mayor exigencia y por hacer de esta etapa universitaria una experiencia inolvidable.

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Resumen

Este trabajo presenta el diseño y construcción del Crusher, una trituradora de doble eje de cizalla a escala de escritorio, desarrollada para la reducción volumétrica de soportes de impresión 3D fabricados en PLA y PETG mediante el proceso de deposición fundida (FDM). En el laboratorio de Ingeniería Mecatrónica de la Universidad Internacional del Ecuador (UIDE), los soportes retirados de cada impresión se acumulan como residuo general al no existir una solución de reducción de tamaño in situ, lo que implica tanto un costo de disposición recurrente como la pérdida de un recurso recuperable de valor económico significativo. El sistema fue desarrollado bajo la metodología V-Model (VDI 2206), a través de dos iteraciones de prototipo. El Prototipo 1, accionado por un motor limpiaparabrisas de 12 V, evidenció torque insuficiente para lotes superiores a 15 g, con una tasa de atasco irrecuperable del 8,6 % que requirió intervención manual en tres de los diez ensayos realizados. El Prototipo 2 incorporó un motor a pasos NEMA 23 con caja reductora planetaria 20:1, logrando un margen de torque de 1,77 sobre el requisito de diseño (con factor de seguridad $S_F = 2$) y eliminando por completo las intervenciones manuales en los 16 ensayos de caracterización. Las pruebas de trituración con lotes de 10 a 25 g arrojaron rendimientos medios de tamiz de 94,5 % para PLA y 91,9 % para PETG, con partículas en el rango objetivo de 2 a 4 mm aptas para la re-extrusión de filamento.

Palabras clave: Reciclaje de plásticos, economía circular, detección de atascos.

Abstract

This work presents the design and construction of the Crusher, a desktop-scale twin-shaft rotary shear shredder developed for the volumetric reduction of FDM 3D-printing support waste made from PLA and PETG. At the Mechatronics Engineering laboratory of the Universidad Internacional del Ecuador (UIDE), support structures removed from each print batch accumulate as general waste due to the absence of an on-site size-reduction facility, representing both a recurring disposal cost and a recoverable polymer resource of significant economic value. The system was developed under the V-Model systems engineering framework (VDI 2206) across two prototype iterations. Prototype 1, driven by an automotive wiper motor, exhibited insufficient torque for batches above 15 g, with an unrecoverable jam rate of 8.6 % that required manual intervention in three of ten tests. Prototype 2 incorporated a NEMA 23 stepper motor with a 20:1 planetary gearbox, achieving a torque margin of 1.77 over the design requirement ($S_F = 2$) and eliminating all manual interventions across 16 characterisation tests. Static Structural simulation confirmed a maximum von Mises stress of 178.5 MPa on the A36 cutting blades under the 240 N design load, against a material yield strength of 250 MPa. Shredding tests with 10 to 25 g batches yielded mean sieve yields of 94.5 % for PLA and 91.9 % for PETG, with output particles in the 2 to 4 mm target range suitable for filament re-extrusion.

Keywords: FDM plastic recycling, circular economy, jam detection.

TABLE 1
ABET Criteria/Final Report Cross Reference Table

ABET Criterion Outcome	Target Level of Mastery	Best Examples with Section Numbers
1. An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics.	<i>Analyze</i>	Sec. 2.3; Sec. 2.4; Sec. 3.1 ; Sec. 3.2
2. An ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors.	<i>Create</i>	Sec. 2.1; Sec. 2.2; Sec. 3.7;
3. An ability to communicate effectively with a range of audiences.	<i>Apply</i>	Sec. 2.6; Sec. 3.3 and 3.4; Appendix A ;
4. An ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts.	<i>Evaluate</i>	Sec. 1 ; Sec. 2.3 ; Sec. 3.7 ;
5. An ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives.	<i>Apply</i>	Sec. 2.1; Sec. 2.4 ;
6. An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions.	<i>Evaluate</i>	Sec. 2.7 ; Sec. 3.3 ; Sec. 3.4 ; Sec. 3.5
7. An ability to acquire and apply new knowledge as needed, using appropriate learning strategies.	<i>Apply</i>	Sec. 2.5 ; Sec. 2.6 ; Sec. 2.3;

Chapter I

Introduction

The rapid expansion of additive manufacturing, particularly fused deposition modeling (FDM), has solidified 3D printing as a fundamental technology in academic fabrication laboratories for prototyping. The global 3D printing plastics market was valued at approximately USD 1.5 billion in 2024 and is projected to grow at a compound annual growth rate of 19.4 % through 2033 [2], a trajectory driven largely by the widespread adoption of FDM in educational and research environments. The downside to this growth is the environmental impact. It is estimated that 33% of all FDM prints end up as waste [3, 4]. Most of this comes from failed prints, supports, and calibration tests made of PLA or PETG. Throwing these plastics in the trash worsens microplastic pollution, as these plastics can remain in the environment for hundreds of years [5]. At the Universidad Internacional del Ecuador (UIDE), the Mechatronics Engineering laboratory operates multiple FDM printers for classes and student projects. Currently, leftover support structures pile up in regular trash bins because there is no local way to break them down. Considering that PLA and PETG filament typically costs between 15 and 40 dollars per kilogram [6], discarding this material every semester represents a real economic loss. Allowing this to continue means incurring unnecessary laboratory costs and generating avoidable plastic waste, which directly conflicts with the environmental principles of the ISO 14001:2015 standard [7].

FDM recycling has been studied since the mid-2010s. The process generally consists of shredding the plastic and re-extruding it to obtain new filament. In 2013, Baechler et al. (ref. 10) demonstrated that plastic from desktop printers could be shredded and re-extruded using inexpensive parts. The problem was that their single-shaft shredder produced particles of varying sizes, which compromised the quality of the subsequent extrusion. Zhong and Pearce [8] went a step further by connecting a shredder to a RepRap extruder. They found that dual-shaft rotary shredders create much more uniform particles than single-shaft ones, although their prototype was not desktop-sized.

Also, according to Hidalgo-Carvajal et al. [9], keeping the particle size between 2 and 4 mm helps preserve the flowability and strength of the melted plastic. Their tests showed that 74% of properly shredded plastic reached the target range.

When Sánchez et al. [4] reviewed 68 studies on 3D printing recycling, they observed three main obstacles. First, there are not many small, affordable shredders for laboratories. Second, the industry lacks standardized methods for analyzing recycled plastic. Third, the shredding, extruding, and quality control steps are not well integrated. Because of this, there is a clear need for a desktop system.

As long as particle size and temperature are controlled, PLA and PETG retain approximately 90% of their tensile strength after two recycling cycles, according to Vidakis et al. [10]. They also determined the shear strength of PETG to be roughly 30 MPa. This exact value is taken as a reference to calculate the shear forces of the design. Mikula et al. [3] reached similar conclusions, pointing out that common FDM plastics can be safely re-extruded 2 to 3 times before the material degrades.

When analyzing all these previous studies from the perspective of the UIDE laboratory, three main limitations stand out. First, most existing shredders are large-volume machines that require more space than a workstation offers. Furthermore, none feature automatic jam detection, which means the machine must always be supervised. Finally, the component lists for these reviewed designs include parts that cannot be purchased in Ecuador. Relying on imports raises costs and causes delays due to international shipping.

The development of the Crusher is justified on three complementary grounds. From an environmental perspective, closing the polymer material loop at the point of generation directly reduces the volume of thermoplastic waste entering the general waste stream, aligning with the circular economy principles of the Ellen MacArthur Foundation [11] and with the waste-minimisation objectives of ISO 14001:2015 [7]. From an economic perspective, recovering PLA and PETG support waste as re-extrudable feedstock eliminates recurring filament purchase costs; at market prices of USD 15–40 per kilogram [6], even modest recovery volumes generate measurable savings over an academic year. From an academic and technical perspective, the project demonstrates the complete mechatronic design cycle requirements analysis, analytical sizing, structural simulation, prototype construction, and experimental characterisation applied to a real problem in the UIDE laboratory environment, with an open-design approach and exclusive use of locally available components that makes the system directly replicable by other Ecuadorian educational institutions.

In light of the justification above, this project proposes the design and construction of a desktop-scale twin-shaft rotary shear shredder for PLA and PETG FDM support-structure

waste.

The general objective is to design, build, and experimentally validate a desktop-scale twin-shaft shredder that reduces PLA and PETG support waste into particles of 2 to 4 mm suitable for filament re-extrusion, using materials and components available in Ecuador.

The specific objectives are the following:

1. To select and analytically size the mechanical sub-systems of the shredder, applying shear-stress and machine-design theory to establish the parameters that ensure the required cutting capacity.
2. To verify the structural integrity of the cutting blades under the design shear load through static structural simulation, validating the design prior to fabrication.
3. To design and implement an electronic control unit with automatic jam detection, motor control, and a multi-mode operator interface.
4. To evaluate the shredding performance of both prototype iterations through variable-mass tests with PLA and PETG, measuring sieve yield, jam frequency, and processing time to confirm compliance with the 4 mm particle-size requirement.

Chapter II

Methodology and Design

This chapter describes the methodology applied during the design and construction of the 3D printing support shredder. The V-Model was adopted to structure each phase of the project, from defining the requirements to validating the prototype. The following sections detail how it was applied, the criteria used for component selection, the analytical calculations for each design decision, the iterative revisions of the prototype, and the control system developed for the shredder.

V-Model Systems Engineering Framework

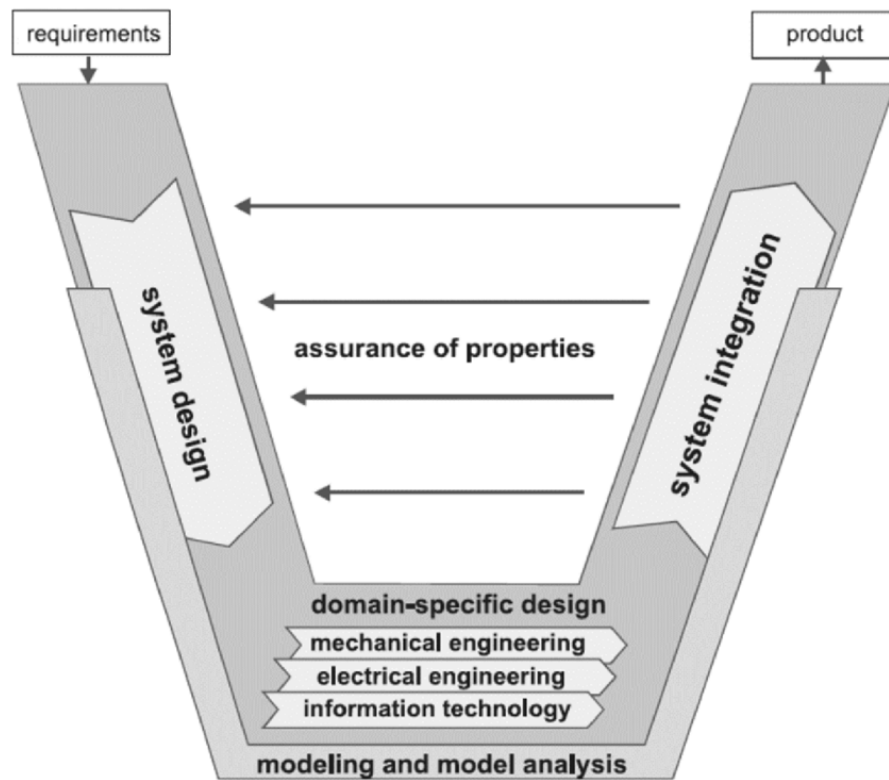


Fig. 1. V-Model applied to the 3D-print support shredder project [1].

In the left branch (decomposition), three levels of definition were executed sequentially. At the system level, the needs of the stakeholders at the UIDE mechatronics laboratory were translated into five functional requirements (FR-01-FR-05), three non-functional requirements (NFR-01-NFR-03), and five constraints (CON-01-CON-05), establishing the acceptance criteria by which the final prototype is evaluated. At the subsystem level, the crushing topology was selected from three options, the transmission architecture was defined, and the dimensions of

the chamber and sieve were fixed. At the component level, each part cutting blades, hexagonal shafts, spacers, motor, gears, and control electronics was analytically dimensioned and documented with explicit traceability to the previous requirements.

The manufacturing and assembly phase of the V-shaped model was carried out in two prototype iterations. Prototype 1 was responsible for assembling the base design, while Prototype 2 incorporated revisions and changes to address the issues identified in the initial tests.

On the right side of the verification section, each level has a corresponding validation activity. At the component level, the A36 metal cutting blades were verified through static structural simulation using materials simulation software (Section 3.2), confirming that the von Mises stresses remained below the yield strength under the 240N design load. The control logic was tested with 26 consecutive cycles (Section 3.7). At the system level, variable-mass shredding tests with PLA and PETG (Sections 3.4–3.5) validated compliance with the particle size requirement (NFR-01) and the jamming functional requirement (FR-03).

The quantitative performance data from Prototype 1 provided the evidence that drove the two design changes, implemented in Prototype 2, demonstrating how the feedback loops of Model V are fundamental to design decisions.

Requirements Definition

Functional Requirements

- **FR-01:** The system shall shred PLA and PETG support generated by 3D printers.
- **FR-02:** The operator shall be able to select a shredding cycle through a control interface.
- **FR-03:** The system shall detect motor stalls and automatically reverse rotation.
- **FR-04:** The sieving subsystem shall operate simultaneously with shredding and continue operating for 5 seconds after shredding ends.
- **FR-05:** The control system shall record motor current data for each shredding cycle.

Non-Functional Requirements

- **NFR-01:** Output particle size shall not exceed 4 mm.
- **NFR-02:** The shredding chamber shall be fully enclosed to prevent particle ejection during operation.
- **NFR-03:** The system shall operate safely without exposing the operator to moving cutting elements.

A reduced-aperture feed cover with a transparent hatch is installed above the cutting chamber, allowing support structures to be dropped into the shredding zone while physically preventing

the operator from inserting a hand. Figure 2 shows the implemented cover.

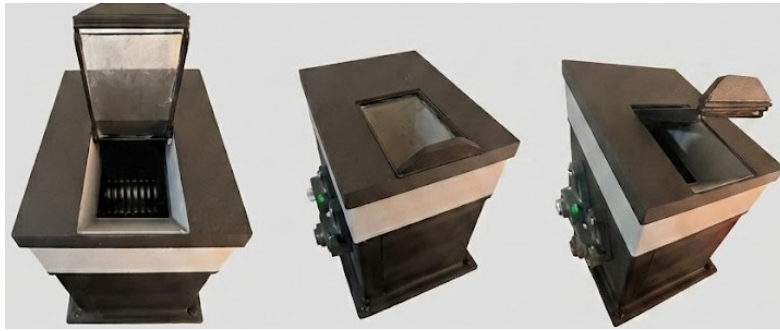


Fig. 2. Reduced-aperture feed cover.

Constraints

- **CON-01:** The machine shall operate from a 12 V DC power supply.
- **CON-02:** Mechanical components shall be manufactured from ASTM A36 plate and SAE 1018 bar stock.
- **CON-03:** Materials and components shall be commercially available in Ecuador.
- **CON-04:** The shredding chamber dimensions shall be fixed at 77 mm × 144 mm.
- **CON-05:** Particle classification shall be performed using a 4 mm sieve.

Input Material Characterisation

The two target materials determine the worst-case mechanical loads on the cutting system. PLA (polylactic acid) is a semi-crystalline biopolymer with a tensile strength of 50–70 MPa and relatively brittle fracture behaviour [9]. PETG has a tensile strength of approximately 50 MPa but have a greater ductility and toughness [10]. Both materials become viable for re-extrusion when reduced to a particle size of 2 to 4 mm by Hidalgo-Carvajal et al. [9], who report that particles in this range produce consistent melt-flow behaviour in subsequent extrusion.

System-Level Design

Shredder Concept Selection

Before selecting the shredding mechanism, three designs were evaluated. The first was a single-shaft hammer mill. Although mechanically simple, it was discarded because it produces irregular particle sizes [8].

The second option was a single-shaft granulator. While it controls particle size well, it requires extremely precise spacing between the moving and stationary blades.

Ultimately, a twin-shaft rotary shear shredder was chosen. This design uses two counter-

rotating shafts with interlocking blades to shear the plastic [8]. It was selected because it distributes the workload evenly across multiple blades, produces a much more uniform particle size, and shreds effectively even with slight variations in blade alignment.

Chamber and Sieve Definition

The shredding chamber has internal dimensions of 77 mm x 144 mm (CON-04). This size fits the largest support structures printed by desktop FDM machines, eliminating the need to cut the plastic beforehand.

Below the blades, a sieve with a 4 mm mesh (CON-05) sits on a tilted rail. A 12V DC motor (CON-01), controlled by an HL-52S relay, uses a crank-slider mechanism to shake the sieve back and forth. This vibration, combined with the tilt, helps particles smaller than 4 mm fall through the mesh. Larger pieces slide down the rail to be cut again, fulfilling requirements FR-04 and CON-05.

Under the sieve, a two-drawer system sorts the shredded plastic by size. The top drawer catches everything that passes through the 4 mm sieve. The bottom of this drawer features a 2 mm mesh that traps particles between 2 and 4 mm. According to Hidalgo-Carvajal et al. [9], this is the ideal size for re-extruding filament. Any dust or particles smaller than 2 mm fall into the bottom drawer to be discarded eliminating the need for manual sorting (supporting NFR-01).

To meet FR-04, the sieve motor runs for an extra 5 seconds after the shredder stops. This clears out any remaining plastic on the mesh before the machine shuts down entirely.

Transmission Architecture

The transmission system had three stages.. First, a sprocket mounted on the output shaft of the motor transmits torque via a roller chain to a sprocket fixed to the primary hexagonal shaft, providing a speed reduction ratio of $i_{\text{chain}} = 3.0$. Second, each hexagonal shaft carries a module-4 spur gear of equal tooth count with 16 teeth that meshes directly with the gear on the opposite shaft, enforcing a 1:1 counter-rotation between the two cutting shafts with no additional speed change. This architecture decouples the speed-reduction function the chain stage from the synchronisation function. A roller chain was selected for the primary transmission stage in preference to a direct gear or belt drive because it accommodates the centre distance between the motor shaft and the cutting shaft without precise alignment, absorbs torsional vibration during jam events. [12].

System Block Diagram

Figure 3 presents the system-level block diagram of the Crusher, showing the five principal subsystems and their signal and power interactions. The system with 12V DC laboratory supply stepper driver, the sieve motor, and the electronics. The sensing subsystem acquires the motor current via the ACS712 Hall-effect and feeds the analogue signal to the microcontroller. The subsystem, centred on the ESP32 microcontroller, executes the operating-mode logic, the jam-detection algorithm, and the data logging. The actuation subsystem have the TB6600-driven NEMA 23 stepper motor with 20:1 planetary gearbox for the cutting shafts and the relay-switched 12V DC motor for the sieve. The human-machine interface provides mode selection via a encoder with button and status feedback via the LCD 20×2 display.

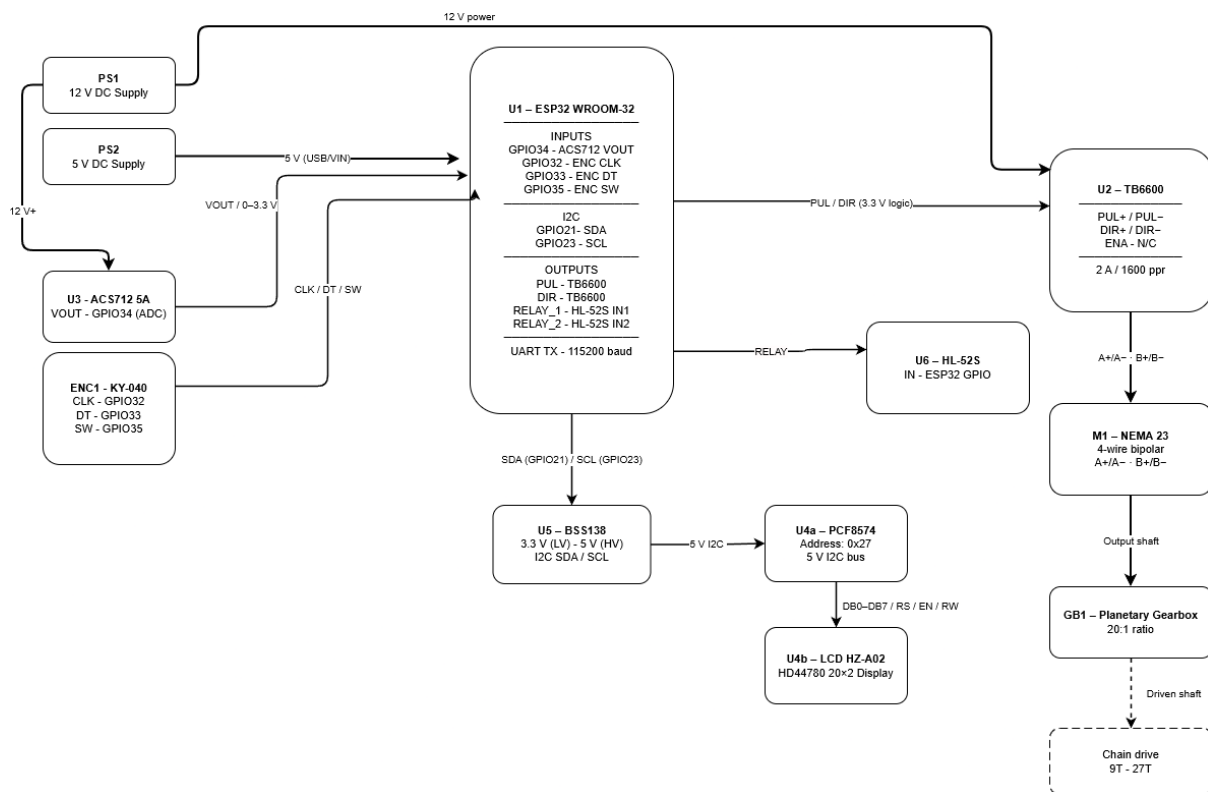


Fig. 3. System-level block diagram of the Crusher

Conceptual Design Evolution and Prototype Iterations

The development of the crusher did not follow a single linear path from concept to final prototype. In accordance with the iterative feedback loops of the V-Model, alternative mechanical configurations and drive systems were evaluated, built, and tested before arriving at the validated design described in the following sections. This section documents the major design decisions that were reviewed and the engineering rationale that guided each review.

Basic configuration of prototype 1

The first physical prototype was constructed to validate the twin-shaft concept and establish baseline performance benchmarks. Its principal specifications are summarised in Table 2.

TABLE 2
Principal specifications of Prototype 1.

Parameter	Value
Shafts	3/4 in hexagonal, SAE 1018
Blades per shaft	8 x 4 mm A36 steel
Spacer thickness	4 mm A36 steel (equal to blade thickness)
Drive motor	12 V DC automotive wiper motor, approx. 60 RPM
Motor driver	L298N dual H-bridge
Transmission	Roller chain, $i_{\text{chain}} = 3.0$
Shaft speed	approx. 20 RPM

As can be seen in figure 4, this was a preliminary version of the project where the critical elements were located to test the cycles, jams and the behavior of the windshield wiper motor

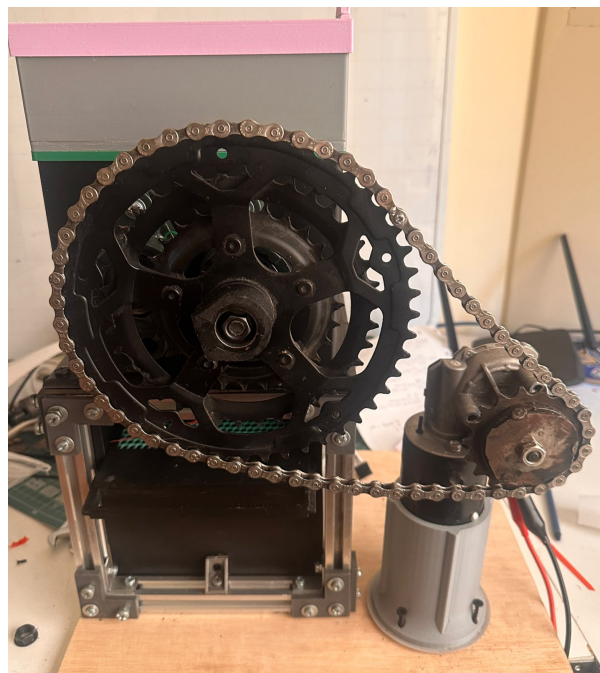


Fig. 4. Prototype 1 assembly showing the wiper motor

During the testing campaign described in Section 2.7, two systematic deficiencies were identified in Prototype 1.

The first issue was blade interference. Because the blades and spacers were both exactly 4 mm thick, there was no gap between them. The spacers were laser-cut from the same 4 mm ASTM A36 steel plate as the blades simply because it was the most practical option within the project's constraints. Without a built-in clearance gap, the blades scraped against each other, creating excess friction that caused the motor to stall.

The second issue was a lack of motor torque. While the wiper motor was strong enough for thin, light support structures, it frequently stalled when trying to cut thicker or multi-layered pieces. The automatic anti-jam feature (Section 2.6.3) helped reduce these stalls, but it couldn't eliminate them. In severe cases, the automatic reverse function wasn't enough to clear the jam, and the machine had to be unclogged by hand. This showed that the motor simply wasn't powerful enough to handle the toughest materials.

Design Revisions Leading to Prototype 2

The two deficiencies detected in prototype 1 helped to make revisions to the design of the spacer and the drive system before the assembly of the second prototype.

Spacer Geometry and Material Revision. To prevent the blades from rubbing together, the spacer thickness was increased from 4 mm to 4.4 mm, adding a 0.4 mm clearance gap on each side of every blade. At the same time, the spacer material was switched from ASTM A36 steel to 3D printed PETG.

This material change for two reasons. First, the spacers do not endure any actual cutting forces, they only need to withstand the pressure of being squeezed together on the shaft. Second, 3D printing allowed the exact 4.4 mm thickness to be set in the software, freeing the design from relying on whatever commercial sheet metal sizes were available.

PETG was chosen over PLA because it holds its shape better under the mild heat generated by friction inside the shredder [10]. Before assembly, the thickness of five spacers per shaft was checked with digital calipers to ensure they were accurate to within 0.05 mm.



Fig. 5. Axial stack cross-section

Drive Motor Replacement. The wiper motor was replaced by a NEMA 23 stepper motor equipped with an integrated 20:1 planetary gearbox. This selection was motivated by three factors. First, the nominal output torque of the NEMA 23 stepper multiplied by the 20:1 gearbox ratio yields a shaft output torque that substantially exceeds the design torque requirement of 8.7 N m at the drive sprocket (Equation 2.9). Second, the stepper-motor architecture provides controlled step resolution (1600 pulses/rev with 1/8 microstepping via the TB6600 driver), enabling the firmware to execute precise reversal sequences during jam recovery and to report displacement data over the serial bus. Third, the stepper draws a defined phase current even at stall, providing predictable current signatures that improve the reliability of the ACS712-based jam-detection algorithm compared to the less-predictable stall behaviour of the wiper motor.

The roller-chain transmission and the sprocket ratio ($i_{\text{chain}} = 3.0$) were retained unchanged. The combined mechanical reduction from the stepper shaft to the cutting shafts is

therefore:

$$i_{\text{total}} = i_{\text{gearbox}} \times i_{\text{chain}} = 20 \times 3.0 = 60 \quad (2.1)$$

Table 3 summarises the specification changes between the two prototypes.

TABLE 3
Comparison of Prototype 1 and Prototype 2 principal specifications.

Parameter	Prototype 1	Prototype 2
Spacer thickness	4 mm A36 steel	4.4 mm PETG (FFF)
Drive motor	12 V wiper motor	NEMA 23 + 20:1 planetary gearbox
Motor driver	L298N H-bridge	TB6600 stepper driver
Total reduction ratio	3.0	60
Shaft speed	approx. 20 RPM	approx. 15 RPM (adjustable)

Detailed Component Design and Selection

Cutting Blades

Sixteen cutting blades were designed for the two shafts (eight per shaft), laser-cut from 4 mm ASTM A36 hot-rolled steel plate (CON-02). A36 was selected because its yield strength of 250 MPa provides an adequate safety margin against the computed shear stresses, its machinability is well documented, and it is widely available in local markets (CON-03) [13]. Each blade has a mass of 89 g.

Shear-Force Analysis. The shear force required to cut PETG, being the main material, was estimated using the fundamental shear stress relationship. [13]:

$$\tau = \frac{F}{A} \quad (2.2)$$

where τ is the material shear strength (Pa), F is the cutting force (N), and A is the shear area (m^2). For PETG the ultimate shear strength is conservatively taken as $\tau = 30 \text{ MPa}$ [10]. The shear area is defined by the contact patch between adjacent blades:

$$A = t_{\text{blade}} \times l_{\text{contact}} = 4 \text{ mm} \times 2 \text{ mm} = 8 \text{ mm}^2 \quad (2.3)$$

Substituting into Equation 2.2:

$$F = \tau \cdot A = 30 \times 10^6 \text{ Pa} \times 8 \times 10^{-6} \text{ m}^2 = 240 \text{ N} \quad (2.4)$$

Operating conditions allow a maximum of two blade pairs to be simultaneously in contact with material, giving a peak cutting force of $F_{\text{total}} = 2 \times 240 \text{ N} = 480 \text{ N}$.

Spacers

Prototype 1. The spacers for Prototype 1 were laser-cut from the same 4 mm ASTM A36 hot-rolled steel plate used for the blades. This was simply because sourcing a separate steel plate with a slightly different thickness didn't fit the local availability. As a result, the blades and spacers were exactly the same thickness, meaning the gap between opposing blades relied entirely on manufacturing tolerances. Each spacer weighs 25 g, making the fully assembled shaft (which holds 8 blades and 8 spacers) weigh 460 g.

Prototype 2. For Prototype 2, the spacers were redesigned and 3D printed in PETG with a thickness of 4.4 mm. This simple change fixed the blade rubbing issue and bypassed the sheet metal limitations, since 3D printing allowed for direct control over the dimensions. Because the spacers don't endure any actual cutting forces, the lower strength of PETG compared to steel is not a problem. They were printed with 100% infill to ensure they stay rigid when compressed on the shaft.

Hexagonal Shafts

Both shafts are machined from standard SAE 1018 steel hex bars (CON-02) measuring 3/4 inch (19.05 mm) across. SAE 1018 is selected for light-to-medium-duty shafts because it is easy to machine and has a solid yield strength of 370 MPa [13]. The hexagonal shape naturally locks the blades and spacers in place to transmit torque, eliminating the need for keyways and spreading the load.

Each end of the shaft is held by a wall-mounted pillow-block bearing (UCF204 flanged type) bolted to the side plates of the shredder. These bearings hold the shafts firmly in place, allowing them to spin smoothly while preventing them from bending sideways under load. This physical setup perfectly matches the boundary conditions used in the static structural simulation (Section 3.2), where the blade bore was modeled as a fixed support, verifying that the simulation accurately. Furthermore, the pillow-block constraint directly addresses the axial blade alignment challenge identified during Prototype 1 integration (Section 3.1.1): by eliminating

shaft runout at the bearing seats, the bearings ensure that the 0.4 mm axial clearance established by the PETG spacers in Prototype 2 is maintained uniformly across the full blade stack under operational load. The shaft mass is 460 g per shaft.

Torque Calculation. The torque required at each shaft is determined by the cutting force and the pitch radius of the 27-tooth driven sprocket [12]:

$$r = \frac{z \cdot p}{2\pi} \quad (2.5)$$

where $z = 27$ is the number of teeth and $p = 12.7$ mm is the chain pitch. Therefore:

$$r = \frac{27 \times 12.7 \text{ mm}}{2\pi} \approx 54.6 \text{ mm} \quad (2.6)$$

The torque per shaft is:

$$T_{\text{shaft}} = F \times r = 240 \text{ N} \times 0.0546 \text{ m} \approx 13.1 \text{ N m} \quad (2.7)$$

A safety factor $S_F = 2$ is applied in accordance with design guidelines for machinery with uncertain load profiles [13], yielding the design torque:

$$T_{\text{design}} = S_F \times T_{\text{shaft}} = 2 \times 13.1 \text{ N m} \approx 26.2 \text{ N m} \quad (2.8)$$

The required torque at the motor output is reduced by the chain-stage ratio:

$$T_{\text{motor}} = \frac{T_{\text{design}}}{i_{\text{chain}}} = \frac{26.2 \text{ N m}}{3.0} \approx 8.7 \text{ N m} \quad (2.9)$$

Drive Motor for the prototype 1

An automotive 12 V DC wiper motor was selected as the prime mover for the first prototype. Wiper motors are widely used in low-cost shredder and recycler prototypes because they deliver high torque at low speed, incorporate an integrated gearbox, are mechanically robust, and are readily available at low cost [14]. The motor operates at approximately 60 RPM at the output shaft under no-load conditions. After the chain-stage reduction ($i_{\text{chain}} = 3.0$), the hexagonal cutting shafts rotate at:

$$n_{\text{shaft,P1}} = \frac{n_{\text{motor}}}{i_{\text{chain}}} = \frac{60 \text{ RPM}}{3.0} = 20 \text{ RPM} \quad (2.10)$$

Testing results (Section 3.4) demonstrated that the wiper motor torque was insufficient for worst-case material conditions, motivating its replacement in Prototype 2 as described in Section 2.4.2.

Drive Motor for the prototype 2

The NEMA 23 stepper motor with 20:1 planetary gearbox is driven by a TB6600 microstepping driver configured at 2 A phase current and 1/8 microstepping (1600 pulses/rev). The combined mechanical reduction ratio is $i_{\text{total}} = 60$ (Equation 2.1). At a nominal operating pulse rate of 1200 pulses/s, the motor input shaft rotates at 45 RPM and the cutting shafts rotate at:

$$n_{\text{shaft,P2}} = \frac{45 \text{ RPM}}{i_{\text{chain}}} = \frac{45}{3.0} = 15 \text{ RPM} \quad (2.11)$$

This speed is intentionally conservative; it can be increased by adjusting the pulse rate in firmware without any mechanical modification.

Power transmission of the chain and sprockets

The power transmitted by the chain drive is calculated from the required motor torque and angular velocity [12]:

$$\omega_{\text{motor}} = \frac{2\pi \cdot n_{\text{motor}}}{60} = \frac{2\pi \times 60}{60} = 2\pi \text{ rad/s} \approx 6.28 \text{ rad/s} \quad (2.12)$$

$$P = T_{\text{motor}} \cdot \omega_{\text{motor}} = 8.7 \text{ N m} \times 6.28 \text{ rad/s} \approx 54.6 \text{ W} \quad (2.13)$$

The transmission ratio between the 9-tooth driver sprocket and the 27-tooth driven sprocket confirms the design ratio:

$$i_{\text{chain}} = \frac{z_{\text{driven}}}{z_{\text{driver}}} = \frac{27}{9} = 3.0 \quad (2.14)$$

The centre distance between the two shaft axes is 64 mm, which also defines the centre distance of the inter-shaft spur-gear mesh that enforces the 1:1 counter-rotation between cutting shafts.

Stress Simulation of Cutting Blades

To confirm that the A36 steel blades can handle the cutting forces without bending or breaking, a static structural simulation was run [15]. The blade was modeled using its standard

dimensions, including its 4 mm thickness. The material was set to ASTM A36 steel, which has a yield strength of 250 MPa.

A cutting force of 240 N per blade (Equation 2.4) was applied evenly across the cutting edge, and the center hole (bore) was locked in place to simulate the shaft holding it rigid. The von Mises stress criterion was used to evaluate the risk of the material yielding under pressure [13].

As detailed in Chapter 3, the simulation results show that the maximum stress on the blade reaches 178.5 MPa. Since this is well below the steel's yield strength, it proves that the blade's design and material are strong enough to handle the loads.

Electronic Control System

System Architecture

The electronic control system detailed in this section is the final setup used in Prototype 2. Prototype 1 used a nearly identical architecture, differing only in the motor driver an L298N H-bridge instead of the TB660 and lacking specific stepper controls. The system is centered around an ESP32 microcontroller [16] programmed in the Arduino IDE. This board was chosen simply because it has enough input/output pins to connect all the machine's sensors and actuators without needing any extra expansion modules. The main hardware components are:

- **ESP32 microcontroller [16]:** Used as the central processing unit to run the control algorithm, read sensors, and manage the motors and display.
- **ACS712 current sensor [17]:** Used to measure the motor's power draw to detect mechanical jams (FR-03).
- **TB6600 stepper driver (Prototype 2) [18]:** Used to control and drive the NEMA 23 shredding motor.
- **HL-52S relay module:** Used to turn the 12V DC sieve motor on and off.
- **LCD 20x2 with I2C interface [19]:** Used alongside four push-buttons as the main control panel to select operating modes and display the machine's status (FR-02).
- **12V / 10A DC power supply:** Used to provide power to the stepper driver, the sieve motor, and the relay module (CON-01).

Operating Modes

Three shredding modes are available for selection via the LCD interface:

- **Rapid mode:** the shredder operates for a fixed duration of 15 s. Intended for small support volumes.

- **Extended mode:** the shredder operates for a fixed duration of 30 s. Intended for medium support volumes.
- **Continuous mode:** the shredder operates indefinitely until the operator presses the stop button. Intended for large or irregular batches and used exclusively during the characterisation tests.

In all modes, the sieve motor is activated simultaneously with the shredder and remains active for an additional 5 s after the shredding cycle ends to ensure complete evacuation of reduced-size particles from the chamber (FR-04).

Control Algorithm

The firmware implements the following control sequence, illustrated in Figure 6:

1. The operator selects the desired mode using the LCD push-buttons.
2. Upon confirmation, the ESP32 sends step and direction pulses to the TB6600 in the forward direction and activates the relay to start the sieve motor. The cycle timer begins.
3. The ACS712 sensor is sampled continuously at 100 Hz. If the measured current exceeds the jam-detection threshold, the ESP32 immediately reverses the step direction to apply reverse rotation to the motor for a defined interval, attempting to free the obstruction (FR-03).
4. If the current drops below the threshold after the reversal interval, forward rotation resumes and the cycle continues.
5. If the current remains above the threshold after the reversal interval, the ESP32 disables the TB6600 output enable line and the relay, halting all motion and displaying a fault message on the LCD.
6. At the end of the shredding cycle the stepper output is disabled. The relay remains active for an additional 5 s before being de-energised, completing the sieve evacuation sequence (FR-04).
7. Upon completion of each cycle, the ESP32 transmits a structured data frame over UART containing current statistics and jam event data for that cycle (FR-05).

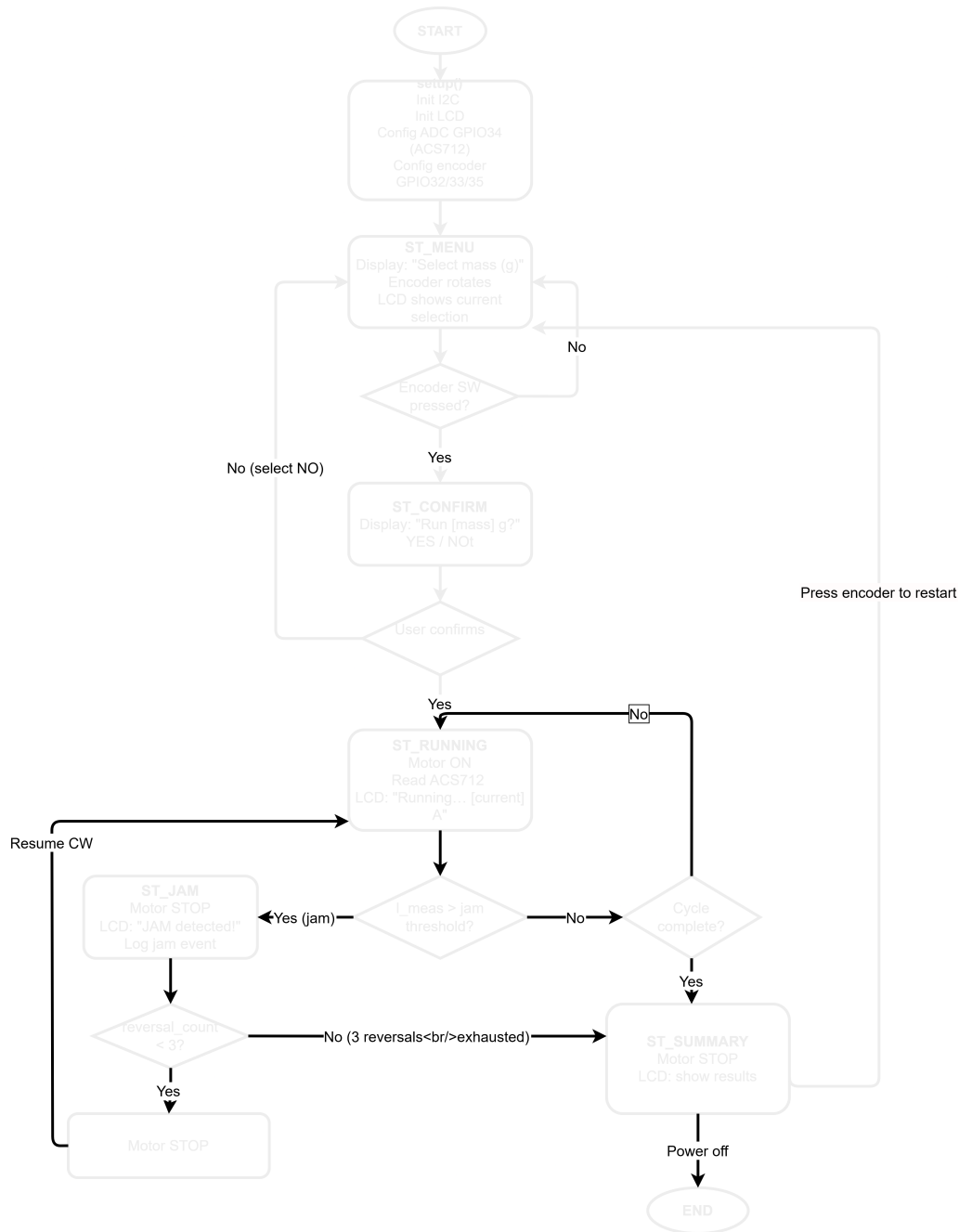


Fig. 6. Control algorithm flowchart for the ESP32 shredder control system main loop.

Data Acquisition Protocol

To satisfy FR-05 and to characterise the performance of both prototypes under controlled conditions, a structured data-acquisition protocol was established. Current measurements from the ACS712 sensor are logged on a cycle-by-cycle basis, providing objective evidence of motor loading, jam events, and recovery sequences.

Test Configuration

Each test uses a single batch of PLA or PETG support structures. Prototype 1 was tested with five different weights: 10 g, 15 g, 20 g, 25 g, and 30 g. Prototype 2 was tested with four weights: 10 g, 15 g, 20 g, and 25 g. Every test was repeated twice for each material. Testing different weights helps determine how well each motor setup handles various loads.

Prototype 1 was tested only with PLA because the material is brittle and breaks cleanly, making it easy to tell the difference between normal shredding and a jam in the data logs. Prototype 2 was tested with both PLA and PETG to confirm it meets requirement FR-01. All tests were run in Continuous mode so the machine would run until all the plastic was cleared, rather than stopping on a timer.

A cycle is defined as one complete pass of the plastic through the shredder. Any pieces that do not fit through the 4 mm sieve on the first try are collected from the tray, inspected, and fed back into the machine for another cycle. A test ends when either all the material has passed through the sieve, or the leftover pieces are so small that further shredding is useless (defined as having less than 0.5 g of plastic left after three cycles in a row).

Instrumentation and Data Logging

The ESP32 reads power data from the ACS712 current sensor 100 times per second (100 Hz). At the end of each cycle, the system sends this data over a serial connection at 115200 baud, fulfilling requirement FR-05. The data is formatted as follows:

```
CYCLE,,<duration_s>,<I_mean_A>,<I_max_A>,<I_min_A>,<jam_count> <jam_duration_s>
```

Here, jam_count is the total number of jams detected during the cycle, and jam_duration_s is the total time spent automatically clearing those jams. A Python script running on a connected laptop receives this data, saves it to a CSV file named shredder_log_YYYYMMDD.csv, and prints a live summary on the screen.

Jam-Detection Threshold

The jam-detection threshold was established empirically during a preliminary calibration run without material in the chamber. For Prototype 1 (wiper motor), the no-load current was measured at $I_{\text{no-load}} = 1.8 \text{ A}$; the jam threshold was therefore set at $I_{\text{jam}} = 4.5 \text{ A}$, corresponding to 2.5 times the no-load value. For Prototype 2 (NEMA 23 stepper), the no-load current was 2.0 A at the supply rail; the jam threshold was set at $I_{\text{jam}} = 5.0 \text{ A}$. Both thresholds were verified not to trigger false positives during normal shredding under representative loading conditions.

before the characterisation tests began.

Frame and Chamber

The shredder frame and chamber walls were fabricated from ASTM A36 steel plate (CON-02) using conventional cutting and welding processes. The chamber interior dimensions (77 mm x 144 mm) were maintained within a tolerance of 0.5 mm to ensure correct blade-to-blade clearance. Pillow-block bearing housings were bolted to the chamber side walls to support the hexagonal shaft ends.

Blades and Spacers

The 16 cutting blades (8 per shaft) were laser-cut from 4 mm A36 plate for both prototypes. The hexagonal bore in each blade was produced by wire electrical discharge machining (EDM) to guarantee a slip fit onto the shaft without play. For Prototype 1, the 16 spacers were also laser-cut from the same 4 mm A36 plate. For Prototype 2, the spacers were replaced with FFF-printed PETG parts at 4.4 mm, as described in Section 2.4.2.

Shaft Machining

Both hexagonal shafts were turned to final length and chamfered on a conventional lathe. The shaft ends were machined to receive the pillow-block inner races and the sprocket and gear hub bores. Surface finish on bearing seats was maintained at R_a 1.6 μm .

Additive Manufacturing of Enclosure and Spacer Components

Non-structural enclosure and guiding components were produced by FFF using PLA on a desktop printer, consistent with the design-for-manufacturability approach outlined for low-volume production [14, 20]. The Prototype 2 spacers were produced by FFF using PETG as detailed in Section 2.4.2. The feed cover described under NFR-03 was also produced by FFF in PLA, with a transparent PETG window bonded to the hatch aperture.

Assembly Sequence

Assembly followed the sequence: (1) blade and spacer stacks onto the hexagonal shafts, (2) shaft insertion into pillow-block bearings, (3) inter-shaft spur-gear alignment and mesh verification, (4) chain-drive installation between motor and primary shaft, (5) sieve and crank-slider mechanism installation, (6) feed cover installation above the cutting chamber, (7) electronic control panel wiring and enclosure closure. Torque specifications for all fasteners were applied in accordance with [12].

Chapter III

Results

This chapter presents the experimental results obtained during the validation phase of the V-Model. Section 3.1 documents the system integration process, describing the assembly of both prototypes, the challenges encountered, and the engineering decisions taken to resolve them. Section 3.2 reports the structural FEA of the cutting blades. Section 3.3 presents the analytical justification for the drive-motor change between prototypes. Sections 3.4 and 3.5 report the shredding test campaigns for Prototype 1 and Prototype 2, respectively. Section 3.6 analyses particle-size compliance. Section 3.7 validates the electronic control system and the safety enclosure, and Section 3.8 summarises the implementation cost.

System Integration

System integration encompassed the physical assembly of all mechanical, electronic, and software subsystems into two successive prototype configurations. This section documents the assembly sequence, the challenges encountered during integration, and the engineering decisions taken to resolve them constituting the physical verification step on the right branch of the V-Model.

Integration and Challenges of prototype 1

Prototype 1 was assembled following the sequence described in Section 2.8: blade and spacer stacks onto the hexagonal shafts, shaft insertion into pillow-block bearings, spur-gear alignment, chain-drive installation, sieve and crank-slider fitting, and electronic panel wiring. Two integration challenges were identified during this phase.

The first problem was aligning the blades. Because all the pieces were cut from the same 4mm steel plate, small defects in the material accumulated as they were stacked. This caused the blades on one shaft to not fit properly with those on the other. This was mitigated during assembly by selectively orienting individual blades to minimise runout, but the underlying cause, the absence of deliberate axial clearance was identified as a systematic design limitation requiring revision in Prototype 2.

The second challenge was chain-drive tensioning. The centre distance between the motor shaft and the primary cutting shaft (64 mm) left minimal adjustment range for the roller chain. A fixed-position motor mount was replaced with a slotted mount that allows 8 mm of

longitudinal adjustment, resolving the tensioning issue without modifying the sprocket selection.

Integration and Challenges of prototype 2

Prototype 2 incorporated the spacer revision (4.4 mm PETG-printed parts) and the motor replacement (NEMA 23 with 20:1 planetary gearbox). Two new integration challenges arose during this build.

The first challenge was gearbox-to-chain alignment. The NEMA 23 gearbox output shaft has a different diameter and key-way specification than the wiper motor shaft it replaced, requiring a custom hub adapter to mount the 9-tooth driver sprocket. The adapter was machined from SAE 1018 bar stock at the UIDE workshop and produced a total indicated runout of less than 0.1 mm at the sprocket pitch circle.

The second challenge was EMI coupling between the TB6600 stepper driver and the ACS712 current sensor. During initial power-up, the step-pulse signal radiated by the TB6600 induced noise in the ACS712 analogue output line, causing spurious jam-detection events at idle. The issue was resolved by adding a 100 nF ceramic decoupling capacitor at the ACS712 supply pins and routing the sensor signal wire away from the stepper driver power leads, reducing noise amplitude below the detection threshold.

Final Integrated System

Following the resolution of the challenges described above, Prototype 2 was operated through a 10-cycle burn-in sequence with a representative 15 g PLA batch before the characterisation campaign began. No mechanical or electronic faults were observed during burn-in. The feed cover (NFR-03), electronic enclosure, and LCD interface were fitted last and verified for mechanical clearance and operator accessibility before testing commenced. Figure 7 shows the final assembled system.

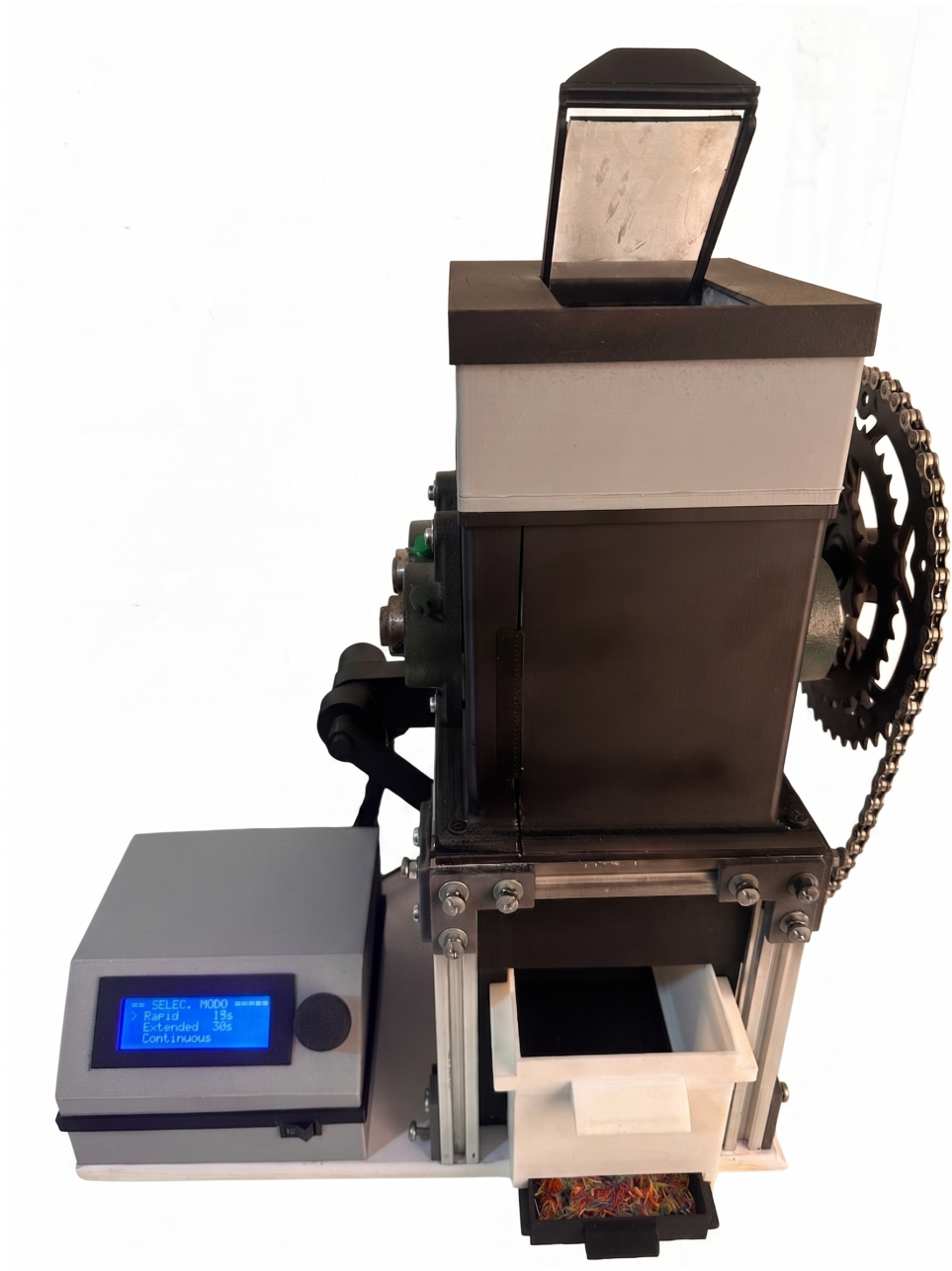


Fig. 7. Prototype 2 fully assembled system.

Structural validation with finite element analysis of cutting blades

The Static Structural simulation performed in Simulation verified that the ASTM A36 cutting blades withstand the design cutting force of 240 N per blade without yielding. Figure 8 presents the von Mises stress distribution, and Figure 9 the corresponding resultant displacement map.

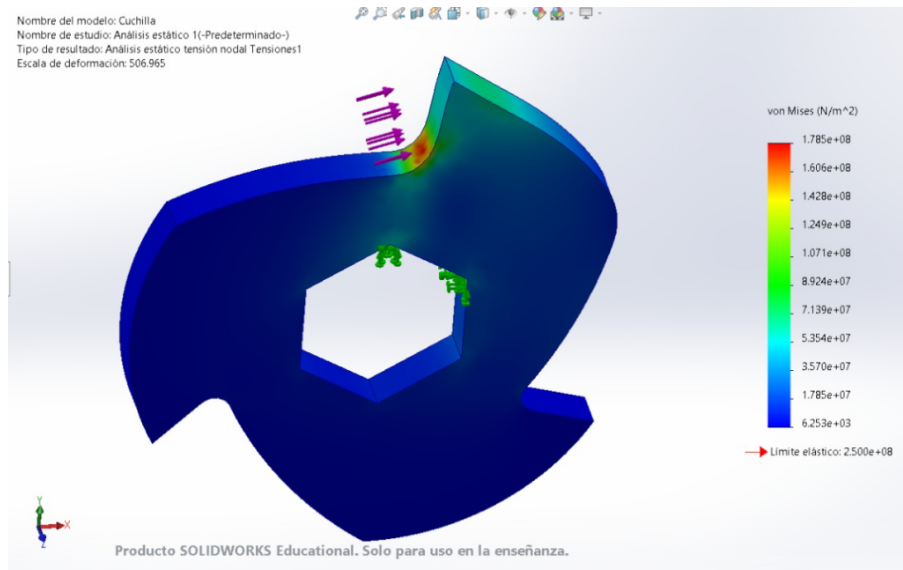


Fig. 8. Von Mises stress distribution on the A36 cutting blade under a 240 N shear load.

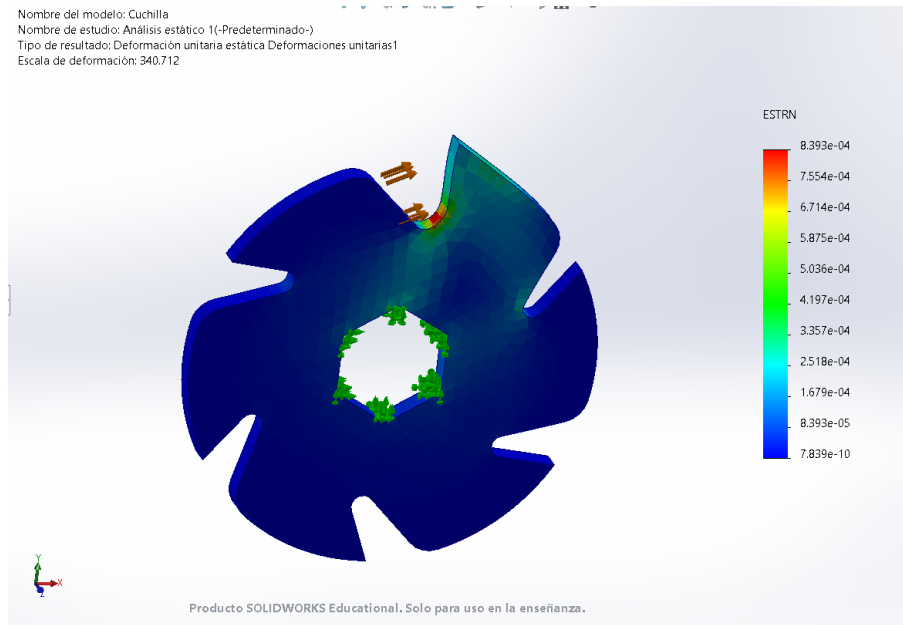


Fig. 9. Resultant displacement (URES) of the A36 cutting blade under a 240 N shear load.

The maximum von Mises stress obtained from the simulation is 178.5 MPa, localised at the blade cutting edge where the 240 N shear load is applied, as indicated by the red zone in Figure 8. This value is below the yield strength of ASTM A36 ($\sigma_y = 250$ MPa), giving a simulation-derived stress safety factor of:

$$S_{F,FEA} = \frac{\sigma_y}{\sigma_{\max,FEA}} = \frac{250 \text{ MPa}}{178.5 \text{ MPa}} = 1.40 \quad (3.1)$$

This result is consistent with the analytical design safety factor of $S_F = 2$ applied to the

torque calculations: the FEA value of 1.40 reflects a stress concentration at the blade tip that the analytical model, which assumes uniform shear across the full contact area does not capture. In both cases the blade remains in the elastic range under the design load, confirming that the A36 geometry and material selection are structurally adequate. The maximum resultant displacement is 0.026 mm, representing 6.4 % of the designed blade-to-blade clearance of 0.4 mm and therefore having no measurable effect on the cutting gap geometry during operation.

Drive-Motor Torque Analysis and Justification

Wiper Motor Torque Budget for prototype 1

Automotive wiper motors of the 12 V class typically deliver a stall torque of 3.0–3.5 N m at the output shaft [14]. Taking the upper bound and applying the chain reduction ($i = 3.0$):

$$T_{\text{shaft,P1}} = 3.5 \text{ N m} \times 3.0 = 10.5 \text{ N m} \quad (3.2)$$

The minimum required torque without safety factor is $T_{\text{shaft}} = 13.1 \text{ N m}$ (Equation 2.7), giving a margin of:

$$\text{Margin}_{\text{P1}} = \frac{10.5}{13.1} = 0.80 \quad (3.3)$$

This margin below unity indicates that the motor cannot deliver the minimum required torque even before accounting for three additional loss mechanisms observed experimentally. First, DC motors experience dynamic torque reduction at working speed due to back-EMF, typically 60–70 % of stall torque [13], reducing the effective shaft torque to approximately 6.3 to 7.4 N m. Second, identical-thickness spacers (Prototype 1) caused intermittent blade-to-blade contact, generating parasitic friction torque not included in the original calculation. Third, irregular fragment geometries produce impact loads that momentarily exceed the quasi-static shear-force estimate, particularly when multiple thick fragments engage the blades simultaneously. These three factors collectively explain why the wiper motor functioned acceptably with small batches (10–15 g) but stalled progressively more often as input mass increased.

NEMA 23 Torque Budget for prototype 2

The NEMA 23 stepper motor (23HS22-2804S-HG20) has a holding torque of 1.03 N m at 2.8 A phase current. The integrated HG-series planetary gearbox provides a 20:1 reduction at a rated efficiency of 75 % [12]. The torque at the gearbox output shaft is:

$$T_{\text{gearbox}} = 1.03 \times 20 \times 0.75 = 15.45 \text{ N m} \quad (3.4)$$

After the chain stage ($i_{\text{chain}} = 3.0$):

$$T_{\text{shaft,P2}} = 15.45 \times 3.0 = 46.35 \text{ N m} \quad (3.5)$$

The margin over the design torque ($S_F = 2$, $T_{\text{design}} = 26.2 \text{ N m}$):

$$\text{Margin}_{\text{P2}} = \frac{46.35}{26.2} = 1.77 \quad (3.6)$$

TABLE 4
Torque budget comparison between Prototype 1 and Prototype 2.

Parameter	Prototype 1	Prototype 2
Motor torque (nominal)	3.5 N m (stall)	1.03 N m (holding)
Total reduction ratio	3.0	60 (20 x 3.0)
Gearbox efficiency	—	75 %
Torque at cutting shaft	10.5 N m	46.35 N m
Design torque ($S_F = 2$)	26.2 N m	26.2 N m
Margin	0.80 (below 1)	1.77 (above 1)

Variable-Mass Shredding Tests for prototype 1

To characterise the operating envelope of the wiper-motor configuration and to identify the batch mass at which performance degrades unacceptably, ten shredding tests were performed with PLA support-structure fragments at five input masses: 10 g, 15 g, 20 g, 25 g, and 30 g, with two repetitions per mass level. Table 5 summarises the results. Tests marked with (M) required manual intervention to clear a persistent jam that the automatic reversal sequence was unable to resolve.

TABLE 5
Prototype 1 shredding test results of PLA batches

Test	Mass	Cycles	Time	Jams	I _{mean}	I _{max}	Yield
	(g)		(s)		(A)	(A)	(%)
T-01	10	2	52	0	2.6	3.4	97
T-02	10	2	56	0	2.7	3.5	96
T-03	15	3	87	1	3.0	4.6	93
T-04	15	3	92	1	3.1	4.7	92
T-05	20	5	164	3	3.4	4.9	87
T-06	20	6	198	4	3.6	5.0	84
T-07	25	7	267	5	3.8	5.1	80
T-08 (M)	25	8	312	6	3.9	5.2	78
T-09 (M)	30	9	358	7	4.0	5.2	75
T-10 (M)	30	10	402	8	4.1	5.3	73
Results	—	5.5	199	3.5	3.32	4.59	85.5

The results show that the machine's performance drops as the input weight increases. At 10 g, both tests finished in just two cycles with no jams and a yield over 96%. This confirms that the wiper motor has enough torque for small, thin pieces.

The machine really starts to struggle between 20 g and 25 g. At this weight, it took 5 to 8 cycles to clear the material, jammed 3 to 6 times, and the yield dropped below 87%. At 30 g, the machine took 9 to 10 cycles and jammed 7 to 8 times per test. Three of these heavier tests even required the operator to step in and clear the jams by hand, and the final yield fell to just 73 to 75%. The progressive increase in I_{mean} from 2.6 A at 10 g to 4.1 A at 30 g is consistent with the torque analysis in Section 3.3, which established that the wiper motor delivers only 80 % of the minimum required torque before accounting for dynamic losses and parasitic friction.

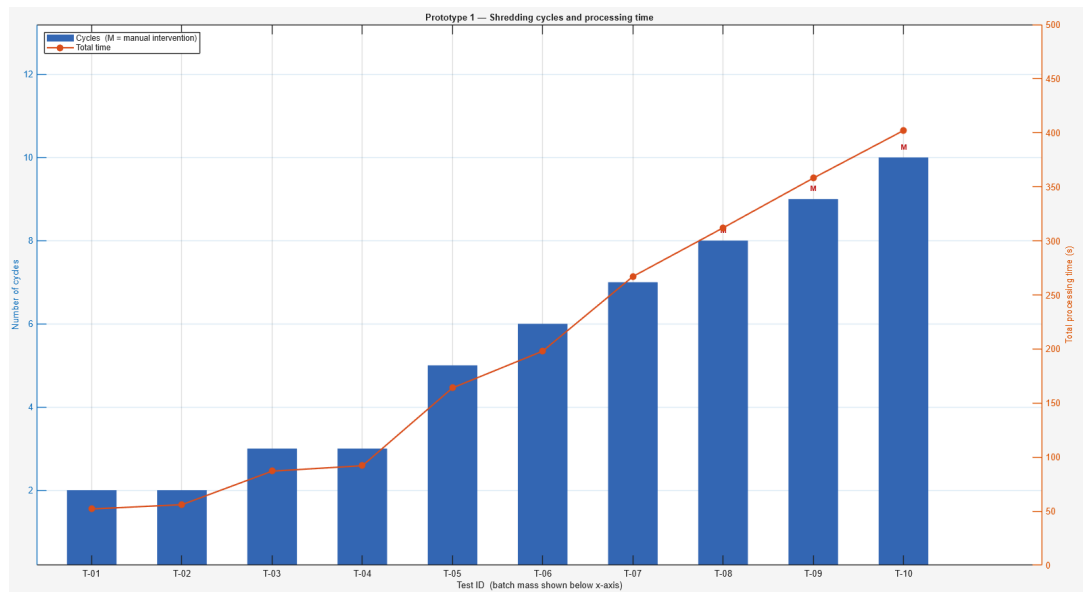


Fig. 10. Prototype 1: number of cycles (bars, left axis) and total processing time (line, right axis) for each test. Batch mass is labelled below each test identifier.

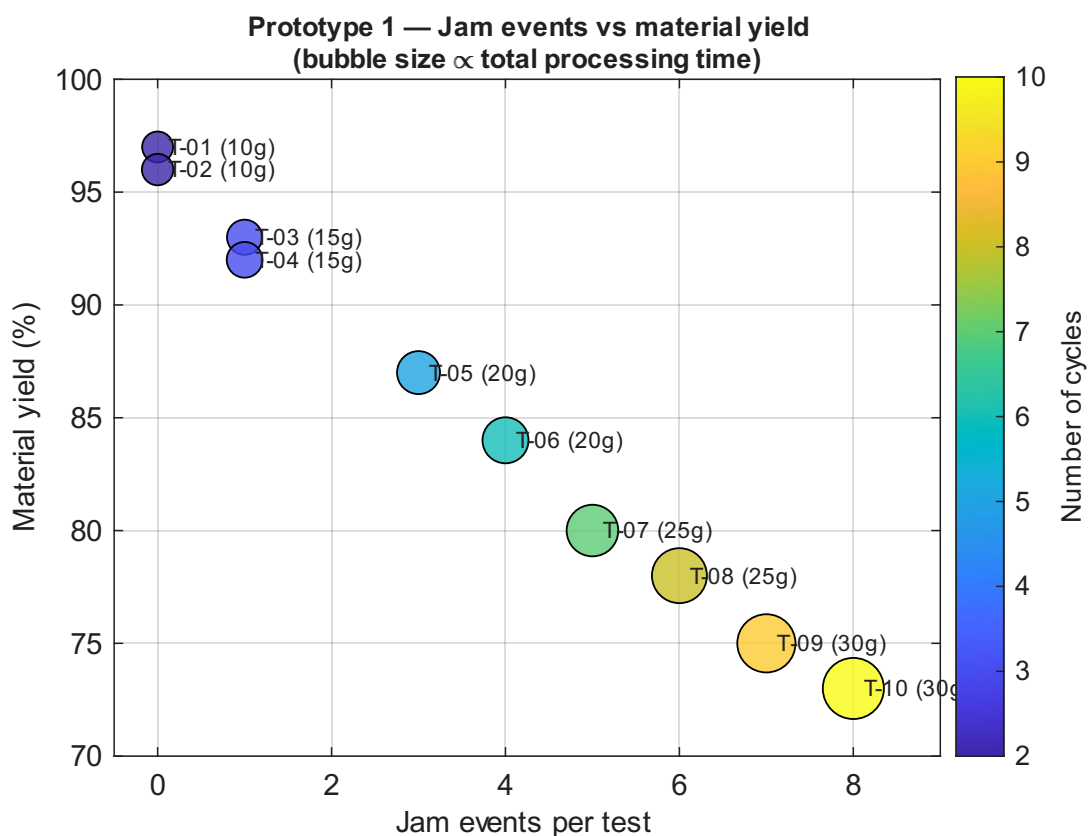


Fig. 11. Prototype 1: jam events per test versus material yield. Bubble size is proportional to total processing time; colour encodes cycle count.

Performance and Particle Size Tests for prototype 2

Following the drive system and spacer revisions described in Chapter 2, a characterisation campaign of 16 tests was conducted with Prototype 2 to evaluate shredding performance

and particle-size compliance with both target materials (FR-01). Tests were performed at four input masses (10 g, 15 g, 20 g, and 25 g) with two repetitions per condition per material, giving 8 PLA tests and 8 PETG tests. The jam-detection threshold was set at 5.0 A, calibrated for the no-load current of 2.0 A measured at the supply rail. The particle-size yield is defined as the percentage of input mass that passed through the 4 mm sieve aperture (NFR-01); the retained mass (oversized fragments) is reported separately.

PLA Shredding Results

TABLE 6

Prototype 2 shredding test results PLA batches. Pass: mass through 4 mm sieve; Ret.: retained mass.

Test	Mass	Cyc.	Time	Jams	I_{mean}	I_{max}	Pass	Ret.	Yield
	(g)		(s)		(A)	(A)	(g)	(g)	(%)
P-01	10	2	38	0	2.4	3.1	9.7	0.3	97.0
P-02	10	2	44	0	2.6	3.4	9.5	0.5	95.0
P-03	15	2	55	0	2.7	3.5	14.5	0.5	96.7
P-04	15	3	71	1	2.9	4.1	13.9	1.1	92.7
P-05	20	3	76	0	2.8	3.8	19.2	0.8	96.0
P-06	20	3	83	1	3.0	4.3	18.6	1.4	93.0
P-07	25	3	94	1	3.2	4.4	23.5	1.5	94.0
P-08	25	4	112	2	3.4	4.6	22.8	2.2	91.2
Results	—	2.75	72	0.63	2.88	3.90	—	—	94.5

All PLA tests completed without manual intervention. Five jam events were recorded in total, none at 10 g or in P-05, and a maximum of two in P-08 (25 g), all resolved automatically within a single reversal attempt. The mean yield of 94.5 % is within 0.5 percentage points of the 95 % design target; this marginal shortfall is attributable to natural variability in fragment size and orientation within each batch rather than to a systematic deficiency in the cutting mechanism [10]. Peak currents remained well below the 5.0 A threshold at all mass levels.

PETG Shredding Results

PETG is more ductile than PLA and tends to deform plastically before fracturing under shear loading, requiring greater mechanical work per unit mass and producing less uniform fragment geometries [10]. This behaviour is reflected in the results presented in Table 7.

TABLE 7
Prototype 2 shredding test results PETG batches. Pass: mass through 4 mm sieve; Ret.: retained mass.

Test	Mass	Cyc.	Time	Jams	I_{mean}	I_{max}	Pass	Ret.	Yield
	(g)		(s)		(A)	(A)	(g)	(g)	(%)
G-01	10	2	44	0	2.6	3.3	9.5	0.5	95.0
G-02	10	3	58	1	2.9	3.9	9.2	0.8	92.0
G-03	15	3	64	0	2.8	3.7	14.3	0.7	95.3
G-04	15	3	71	1	3.1	4.2	13.7	1.3	91.3
G-05	20	3	86	1	3.2	4.3	18.8	1.2	94.0
G-06	20	4	103	2	3.4	4.6	18.0	2.0	90.0
G-07	25	4	114	2	3.5	4.7	22.5	2.5	90.0
G-08	25	5	138	3	3.7	4.8	21.8	3.2	87.2
Mean	—	3.38	85	1.25	3.15	4.06	—	—	91.9

PETG tests showed greater variability between repetitions than PLA, consistent with the less predictable fracture behaviour of the material. Notably, G-08 (25 g) required 5 cycles and 3 jams, the most demanding test in the Prototype 2 campaign, producing a yield of 87.2 %. Although this is the lowest value recorded, the test completed automatically without manual intervention, confirming that the NEMA 23 torque margin was sufficient even under this worst-case condition. The mean current in G-08 (3.7 A) and peak current (4.8 A) remained below the 5.0 A threshold, though the peak is notably closer to the limit than in any PLA test, indicating that PETG at 25 g represents the practical upper boundary of the current machine's processing capacity.

The mean yield across all PETG tests is 91.9 %, which falls below the 95 % target. This

result is expected given that the target was defined with PLA as the primary design material; PETG is inherently more difficult to reduce to a uniform particle size with a rotary shear mechanism [10]. At batch masses of 10 to 15 g, PETG yields of 92.0 to 95.3 % approach the target, suggesting that smaller loads allow acceptable performance with this material.

Comparative Analysis — PLA vs. PETG

TABLE 8
Mean performance comparison between PLA and PETG across all Prototype 2 tests.

Metric	PLA	PETG
Mean cycles per test	2.75	3.38
Mean processing time (s)	72	85
Mean jam events per test	0.63	1.25
Mean I _{mean} (A)	2.88	3.15
Mean I _{max} (A)	3.90	4.06
Mean yield (%)	94.5	91.9
Tests requiring manual interv.	0	0

PLA is processed more efficiently across every metric. The difference in mean yield (94.5 % vs. 91.9 %) and mean jam frequency (0.63 vs. 1.25 per test) reflects the material-property contrast between brittle fracture (PLA) and ductile deformation (PETG). Critically, no test in either material required manual intervention, which stands in direct contrast to Prototype 1, where three tests at 25 to 30 g could not be completed automatically.

Particle Size Compliance

The primary design requirement is to produce particles of 4 mm or smaller from PLA and PETG support waste (NFR-01), a size range shown to be optimal for re-extrusion into new filament [9]. The sieve yield values reported in Section 3.5 directly quantify compliance with this requirement, as the 4 mm aperture defines the acceptance boundary.

Figure 12 presents the yield for each of the 16 Prototype 2 tests grouped by material and input mass, with the 95 % target shown as a reference line. Figure ?? shows a representative sample of the shredded output collected after testing.

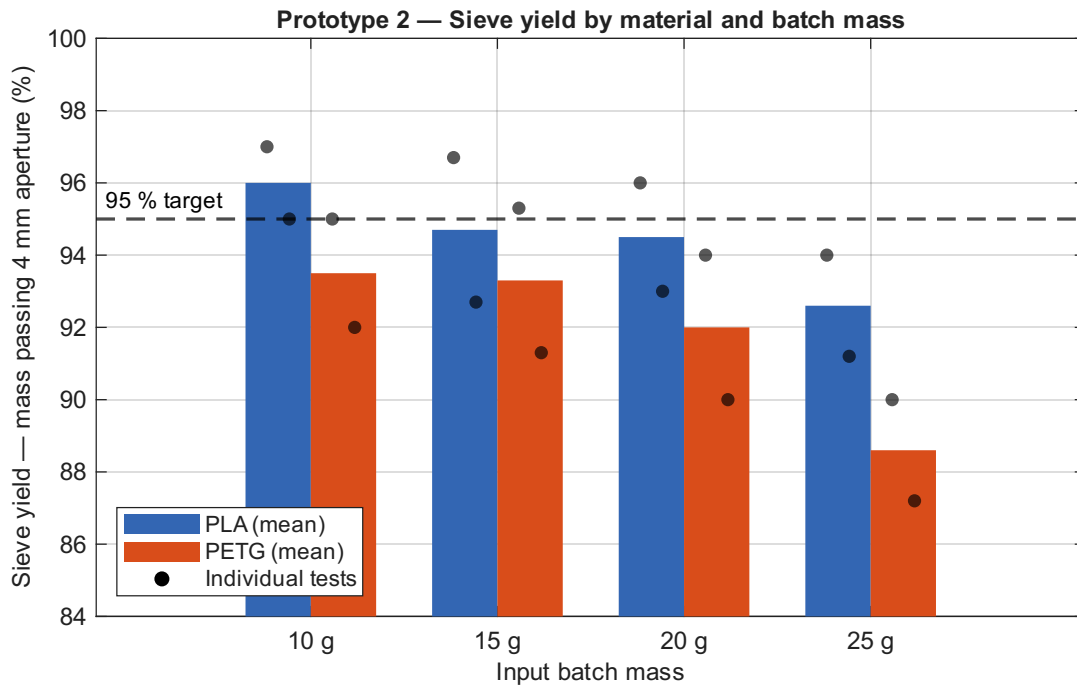


Fig. 12. Sieve yield distribution for Prototype 2 across all 16 tests, categorized by material type and input mass.

For PLA, the yields ranged from 91.2% (P-08, 25,g) to 97.0% (P-01, 10,g). With a mean of 94.5%, the performance was just 0.5 percentage points shy of the 95% target, and half of the individual tests successfully exceeded it. Conversely, PETG yields varied between 87.2% (G-08, 25,g) and 95.3% (G-03, 15,g). While lower input masses (10–15,g) allowed PETG to closely approach the target, larger loads (20–25,g) resulted in a slight performance drop, with yields falling between 87% and 94%.

Throughout all trials, the retained material consisted of flat or irregular fragments larger than 4,mm. Crucially, these pieces remained sufficiently intact to be re-introduced into the cutting chamber for subsequent cycles. This confirms that both the sieve (CON-05) and the recirculation mechanism operate exactly as intended. Ultimately, the overall mean yield of 93.2,

Electronic Control System and Safety Enclosure Validation

Electronic Control System

During the 26 tests: 10 for Prototype 1 and 16 for Prototype 2 , the jam-detection and reversal logic performed reliably or firmware faults. Figure 13 shows the LCD operator interface during an active shredding cycle.



Fig. 13. LCD 20x2 operator interface displaying the active shredding mode and cycle status during a Prototype 2 test.

For Prototype 1, 35 jam events were recorded: 32 were resolved automatically (91.4 %) and 3 required manual intervention (all at 25–30 g). For Prototype 2, 15 jam events were recorded across all 16 tests (5 in PLA, 10 in PETG), and all 15 were resolved automatically (100 %), confirming that the higher torque margin of the NEMA 23 configuration eliminates persistent jams under all tested conditions (FR-03). The improvement in automatic resolution rate from 91.4 % (Prototype 1) to 100 % (Prototype 2) is a direct consequence of the increased torque margin ($\text{Margin}_{P2} = 1.77$) and the elimination of inter-blade parasitic friction through the 4.4 mm PETG spacers.

The UART data logging system operated without interruption. All cycle-summary frames from all 26 tests were received and recorded by the Python logging script with no missing entries, confirming the reliability of the data acquisition architecture across both prototype characterisation campaigns and the complete fulfilment of FR-05.

Safety Enclosure Validation (NFR-02 and NFR-03)

Compliance with NFR-02 (enclosed chamber, no particle ejection) and NFR-03 (operator isolation from cutting elements) was verified by visual inspection and operational observation throughout all 26 tests. No particle ejection through the chamber walls or feed opening was recorded during any test cycle. The enclosed steel frame and the welded side panels (Section 2.8.1) effectively contained all shredded material within the chamber and collection tray.

The reduced-aperture feed cover (Figure 2) prevented any possibility of operator contact with the rotating blades during loading. The hatch opening — sized to admit flat support-structure fragments but narrower than a human hand in any orientation was confirmed to be

physically restrictive across all test sessions. The transparent PETG window in the hatch allowed visual monitoring of the shredding zone without requiring the operator to open the cover during operation. No safety incidents or near-misses were recorded across the full test campaign.

Discussion

Prototype Iteration and Torque-Deficit Resolution

The transition from Prototype 1 to Prototype 2 represents the central engineering outcome of the V-Model development cycle. The wiper motor delivered only 80 % of the minimum required shaft torque before dynamic losses, confirmed by the progressive increase in I_{mean} from 2.6 A at 10 g to 4.1 A at 30 g and the three manual interventions recorded at 25–30 g. These results are consistent with the behaviour reported by Baechler et al. [14], who identified drive torque as the primary failure mode in low-cost open-source shredder designs. The NEMA 23 configuration resolved this deficit by delivering a torque margin of 1.77 over the design requirement at $S_F = 2$, eliminating all manual interventions and reducing mean jam frequency from 3.5 events per test (Prototype 1) to 0.63 for PLA and 1.25 for PETG (Prototype 2).

Structural Adequacy of Cutting Blades

The FEA-derived safety factor of $S_{F,\text{FEA}} = 1.40$ is lower than the analytical design value of $S_F = 2$ applied to the torque calculations. This discrepancy is consistent: the analytical model distributes the 240 N shear force uniformly over the full contact area, whereas the FEA resolves the stress concentration at the blade cutting edge where the load is applied over a smaller effective area. These values confirm that the blade operates safely within the design load. The maximum displacement of 0.026 mm represents only 6.4% of the 0.4 mm clearance, ensuring it does not compromise the geometry of the cutting gap. Therefore, the A36 steel and the chosen blade geometry are structurally adequate.

Comparison with Prior Work

The developed crusher achieves a 93.2% yield across 16 tests (at masses up to 25 g), with a total implementation cost of 385 dollars using locally sourced components in Ecuador. While Zhong and Pearce [8] reported comparable shredding performance with a twin-shaft configuration, their system operated at a bench scale and relied on parts unavailable in local markets. Similarly, Baechler et al. [14] demonstrated a shred-and-extrude loop but observed inconsistent particle sizes from a single-shaft design. The twin-shaft topology proposed here resolves this issue via a two-drawer classification system, which automatically isolates the 2 to

4 mm fraction required for re-extrusion. Furthermore, Prototype 2 achieved a 100% automatic jam resolution rate. This represents a significant practical improvement over the manually supervised systems prevalent in the literature, which typically rely on operator intervention to clear blockages instead of addressing them mechanically.

Limitations and Scope of Validity

Several limitations bound the scope of the results presented. First, all tests used support-structure fragments from a single desktop FDM printer model; fragment geometry from other printers or slicer settings may produce different yield distributions. Second, the long-term dimensional stability of the PETG-printed spacers under sustained cyclic loading has not been evaluated; creep or thermal softening over hundreds of operational cycles could gradually alter the 0.4 mm clearance and affect shredding performance. These limitations define the scope of the recommendations presented in Chapter 4.

Project Implementation Cost

Table 9 presents the direct material and service costs incurred during the construction of Prototype 2. All components and services were sourced within Ecuador (CON-03).

TABLE 9
Project implementation cost summary.

Category	Cost (USD)
Mechanical components (A36 plate, SAE 1018 bar, fasteners)	85.00
Motor and gearbox (NEMA 23 + 20:1 planetary gearbox)	65.00
Electronic components (ESP32, TB6600, ACS712, LCD, relay)	45.00
Chain, sprockets, and pillow-block bearings	35.00
Laser cutting and machining services	120.00
3D-printed components (PLA enclosure, PETG spacers)	15.00
Miscellaneous (wiring, connectors, hardware)	20.00
Direct material and services total	385.00
Engineering labour (275 h at USD 3.50/h)	962.50
Total project cost (materials + labour)	1 347.50

The largest single cost category is laser cutting and machining services USD 120 dollars, reflecting the precision requirements of the blade hexagonal bores produced by wire EDM and the chamber frame fabrication. The motor and gearbox assembly 65 dollars represents the second largest component, a cost justified by the torque margin of 1.77 achieved over the design requirement, which eliminated all manual jam interventions in Prototype 2. The electronic components cost 45 dollars. For the engineering labor, we estimate a total of 962.50 dollars. This covers 275 hours of documented work, which includes designing, building, and testing the machine, paid at an intern rate of 3.50 dollars per hour. When looking at the direct materials and services, the total is 385 dollars. This shows that building the machine is much cheaper than buying a similar commercial desktop granulator, since those usually cost more than 1,200 dollars.

Chapter IV

Conclusions

1. The twin-shaft shredder met its main objective, reducing PLA and PETG waste to particles under 4 mm with mean yields of 94.5 and 91.9 percent, confirming the topology as an effective recycling solution.
2. The two-prototype approach was decisive: the wiper motor of Prototype 1 lacked torque, while the NEMA 23 motor and PETG spacers of Prototype 2 solved the problem, with the simulation confirming the blades stay within the elastic range.
3. The ESP32 control system performed reliably, clearing all jams automatically in Prototype 2 and logging every test without errors, while the enclosure kept the operator safe throughout the trituration.
4. The shredder is economically viable, with a material cost of 385 dollars using only local components, far below commercial granulators of comparable capacity.

Chapter V

Recommendations

1. Improve PETG shredding by using a sharper blade profile or a smaller blade pitch for cleaner cuts. Additionally, adding a 1 mm mesh sieve will separate fine dust from the usable 1 to 4 mm plastic, improving the final feedstock quality.
2. Increase cutting speed by changing the chain ratio from 3:1 to 2:1. This raises the shaft speed to about 22 rpm while keeping the torque at 30.9 Nm (well above the 26.2 Nm required), allowing faster batch processing.
3. Upgrade the jam detection by replacing the fixed current limit with a dynamic threshold that adjusts to the motor's running average current. Also, enabling the ESP32's WiFi would allow remote cycle monitoring through a simple dashboard.

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Appendix — Mechanical Assembly Drawing

Presents the general assembly drawing of the Crusher in A3 format. The drawing includes principal dimensions.