



Recycling External Prostheses' Waste to Create a 3D Printing Filament

Design and Manufacture of a Mechanical Hand

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O principal objetivo desta investigação centrou-se na criação de um material 100% reciclado a partir de resíduos industriais provenientes de uma empresa de próteses e ortóteses. O poliuretano (PU) foi obtido de moldes positivos de membros, enquanto o poliuretano termoplástico (TPU) originou-se de cosméticas externas impressas em 3D com erros de impressão. Embora existam algumas soluções para a reciclagem do Poliuretano, as tecnologias de reciclagem atualmente em uso ainda estão pouco desenvolvidas.

O passo preliminar consistiu na moagem do TPU, com adição do PU em pó, permitindo injetar diferentes misturas (TPU com 10, 20, 30 e 60 % de PU, em peso), com o intuito de avaliar as potencialidades dessas formulações para a criação de um novo filamento para impressão 3D destinado à produção de novas próteses. De cada conjunto foram retirados 4 provetes para ensaios de tração e para determinar as características mecânicas do material. A formulação escolhida (10 % PU com 90 % TPU) demonstrou melhor desempenho em termos de propriedades mecânicas, extrudabilidade e qualidade de superfície. Posteriormente, o material foi extrudido para granulado e utilizado na extrusão do filamento.

Os primeiros testes de impressão resultaram em peças com flexibilidade semelhante à do TPU e com maior rigidez. Obteve-se uma cor próxima do tom de pele e bom acabamento superficial, o que torna o material adequado para futuras aplicações em próteses externas.

Por fim, procedeu-se ao design e fabrico de uma prótese mecânica de uma mão para um caso real do projeto E-Nable. Desta forma, foi possível aplicar o material desenvolvido e promover a inovação com um novo modelo para uma criança apenas com polegar, e, com um pulso funcional. O enfoque no design da mão consistiu em criar um dedo inteiro, que, até então era desenvolvido por partes. Assim, ligando com as capacidades do material, tornou-se ser algo inovador, flexível, semelhante a um dedo real pela estética anatômica e cor, e, facilitando os passos de montagem.

Palavras chave : Poliuretano; Poliuretano termoplástico; Próteses; Mão mecânica; Desperdício Industrial; Design de Produto

The main goal of this project is to create a 100% recycled material using industrial waste from a prosthetics and orthotics company, specifically polyurethane (PU) from positive limb moulds production and thermoplastic polyurethane (TPU) from 3D printed external cosmesis with printing errors. Although there are existing solutions for polyurethane recycling, current recycling technologies remain relatively underdeveloped.

The preliminary work carried out with the grinding of TPU, and mixing with Polyurethane PU, allowed to inject different mixtures (TPU with 10, 20, 30 and, 60% PU by weight). These formulations were then evaluated for their potential in producing a new filament for 3D Printing, specifically for the fabrication of prosthetics.

Four specimens were obtained from each mixture for mechanical testing and characterization. The formulation consisting of 10% PU and 90% TPU demonstrated superior mechanical properties, extrudability, and surface quality. Subsequently, the material was extruded into pellets, which were used for filament extrusion.

The initial printing tests yielded parts with comparable flexibility to TPU but with increased rigidity. The material exhibited a skin-tone color and achieved a satisfactory surface finish, making it suitable for future applications in external prosthetics. Finally, a mechanical hand prosthesis was designed and fabricated for a real case with E-Nable. This allowed for the application of the developed material and the introduction of innovation through a new mechanical hand model specifically made for a child with only a thumb and functional wrist. The emphasis in hand design was placed on creating a fully integrated finger, departing from the conventional approach of assembling individual components. Leveraging the material's properties, the design aimed to deliver innovation, flexibility, anatomical aesthetics, and simplified assembly steps.

Keywords: Polyurethane; Thermoplastic Urethane; Prostheses; Mechanical Hand; Industrial Waste; Product Design

Presentations and Conferences:

1. Poster presentation:

Topic: Recycling Polyurethane and Thermoplastic Urethane Waste from External Prostheses for the Manufacture of Filaments for 3D Printing

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“Every act of creation is first an act of destruction” – Pablo Picasso

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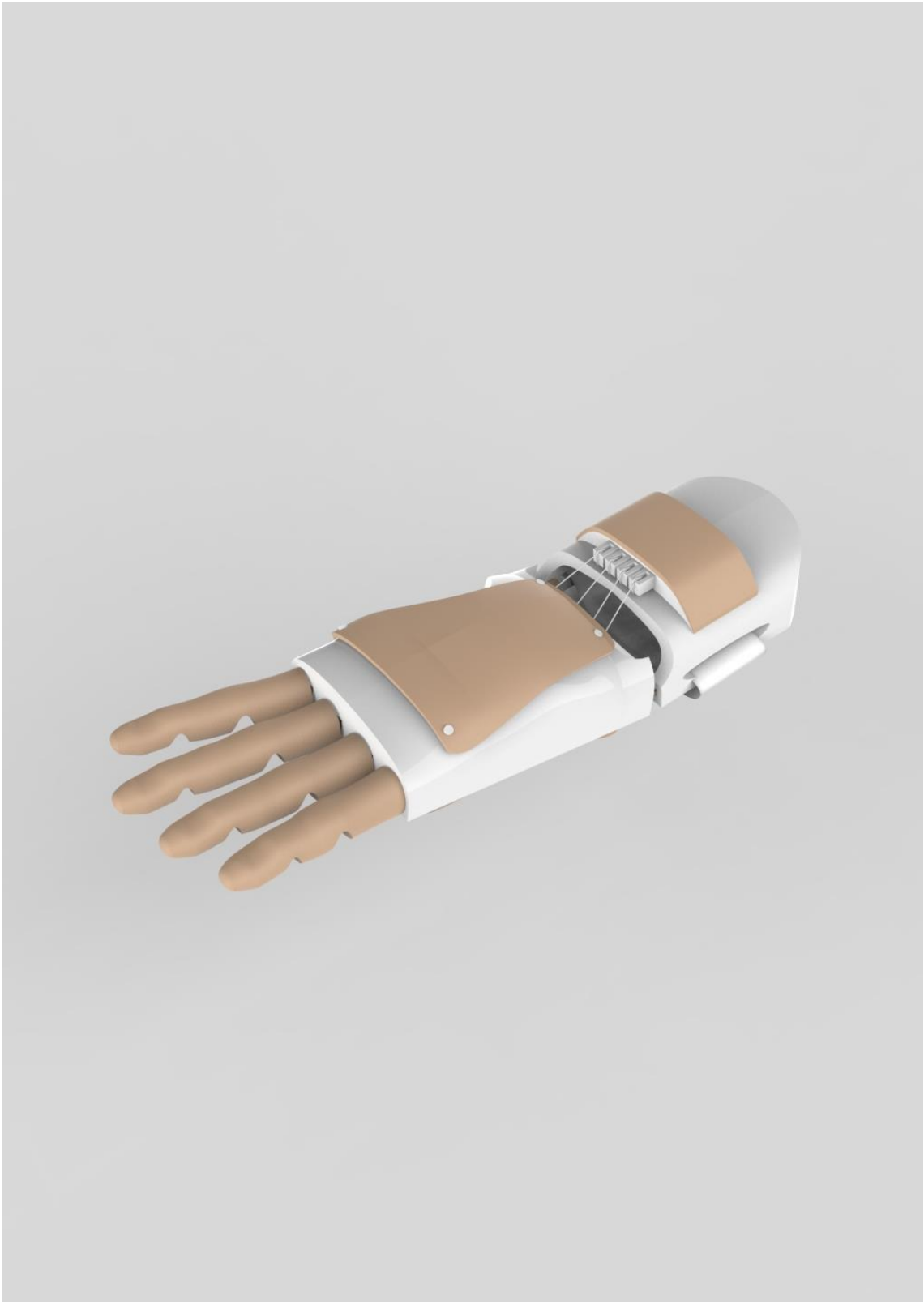
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LIST OF ABBREVIATIONS

AM	Additive Manufacturing
FBAUP	Faculty of Fine Arts of University of Porto
FEUP	Faculty of Engineering of University of Porto
GODP	Guide of Product Development
HDPE	High Density Polyethylene
MCS	Micro-Coated Silicone
MCV	Micro-Coated Vinyl
PE	Polyethylene
PIEP	Center for Innovation in Polymer Engineering
PLA	Polyactic Acid
PP	Polypropylene
PU	Polyurethane
PUF	Polyurethane Flexible
PUR	Polyurethane Rigid
PVC	Polyvinyl Chloride
TPE	Thermoplastic Elastomer
TPU	Thermoplastic Urethane



1.1 Introduction

This dissertation was conducted as part of the Master's degree program in Industrial and Product Design at the Faculty of Fine Arts and Faculty of Engineering of the University of Porto. This research aims to address the issue of industrial waste in the production of external prosthetics, specifically polyurethane (PU) and Thermoplastic Urethane (TPU). The objective was to develop a new material using the debris and utilize it in the design and manufacturing of a mechanical hand for the E-Nable Project.

The initial motivation behind this project was to create a sustainable solution by repurposing industrial waste. During the exploration of potential internship opportunities and collaborations, Padrão Ortopédico, a company specializing in external prosthetics and orthotics, emerged as a suitable partner. Within this work environment, the role of a Product Designer involved working on the external cosmetic aspects of the prosthetics and collaborating with the 3D Printing department. Through careful analysis, PU and TPU were chosen due to their abundance as waste materials and their compatibility in blending together, with TPU as the bonding agent. This approach also demonstrated a recycling technique for polyurethane, a material widely used in various industries but known for its environmental impact.

The main focus of this study was to develop innovation in both material composition and design. By creating a material that combined flexibility and durability, it became possible to introduce innovation in the field of mechanical hands, particularly in the design of a fully functional finger. Previous approaches relied on multiple rigid components and flexible joints, whereas this new design offered a more integrated and realistic solution.

Overall, this project represents a significant contribution to the field of industrial and product design, offering a sustainable solution for utilizing industrial waste in the production of external prosthetics while promoting innovation in material development and design techniques.

1.2 Relevance

In the field of Industrial and Product Design, there is a growing responsibility to drive innovation and promote sustainability in new projects. The consideration of sustainability has become essential in the development of new initiatives, as it is no longer acceptable to overlook the end-of-cycle of products and creations, leaving a burden on future generations. As part of the current generation of designers, we bear the responsibility to address the environmental consequences resulting from past practices and initiate projects that challenge the disposable and polluting mindset that prevailed in society.

Undeniably, there is an increasing demand for companies to showcase their commitment to sustainability by incorporating recycled materials, practical and reusable functional design, and adopting environmentally responsible practices. This realization has been a significant motivating factor for my involvement in this project. I was driven by the opportunity to transform an industrial material and create a new product with sustainable values. The motivation behind initiating this project was rooted in the prospect of repurposing industrial materials into new products. Throughout the research of collaborations, the opportunity arose to utilize materials from the medical industry, specifically in the production of prosthetics and orthotics.

1.3 Methodology

The adopted methodology employed in this dissertation draws upon the 7 Principles of Universal Design, supplemented by the GODP framework, which includes the following stages: Opportunity, Prospecting, Data Gathering, Organization and Analysis, Creation, Execution, Viability, and Verification. These principles form the foundation of a comprehensive approach to design, ensuring inclusivity and accessibility for diverse user groups. The origin of the term “Universal Design” is attributed to Ronald Mace, the founder of the Center for Universal Design at the University of North Carolina. The Center’s core mission revolves around enhancing the built environment and products for all users, influencing policy and procedures through research, assistance, information, training initiatives, and design.[1]

Universal Design principles are conceived to foster the development of products and environments that accommodate the widest possible range of individuals. Conceived and formulated by an interdisciplinary team of product designers, engineers, architects, and environmental designers, these principles uphold a shared commitment to universal inclusivity and accessibility. By adhering to these guidelines, designers aspire to create solutions that

transcend the boundaries of individual differences and cater to the diverse spectrum of human abilities and preferences. [2]

The seven Principles

- Equitable use
- Flexibility in use
- Simple and intuitive use
- Perceptible information
- Tolerance for error
- Low physical effort
- Size and space for approach and use

Throughout the project, the 8 stages of the Guide of Product Development (GODP), represented in Figure 1, were meticulously applied to ensure a systematic and effective approach in developing the sustainable mechanical hand.

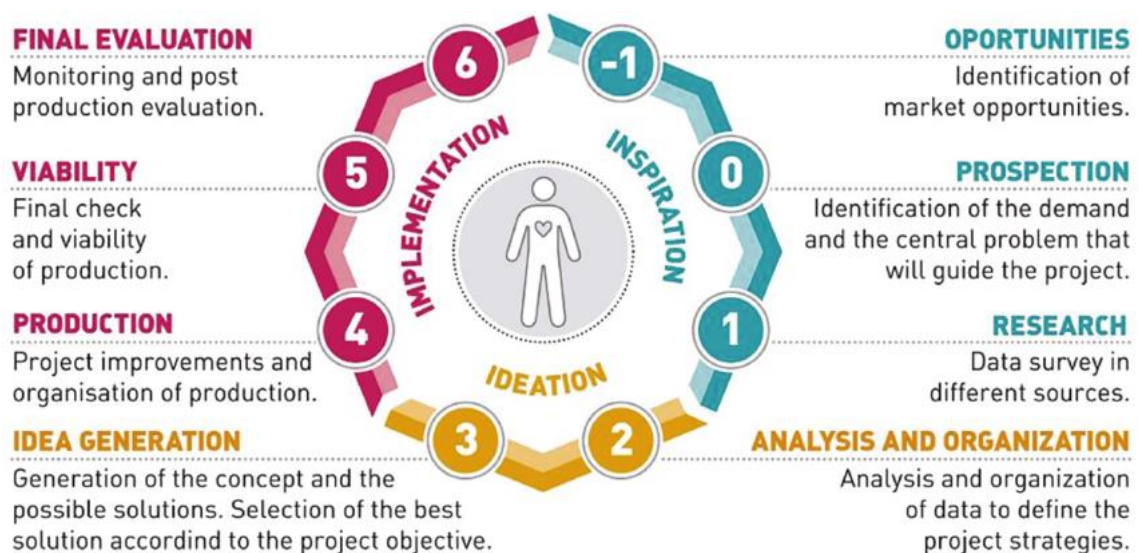


Figure 1 - Representation of the 8 steps of the GODP [1].

8 stages of the Guide of Product Development:

Opportunity – Market opportunity identification

In this phase, it is important to identify and map trends, find demands and possibilities, promote and publicize the developed actions, and finally evaluate the technical capacity beforehand.

For example, we explored companies to do a possible internship and collaborate with the project. After choosing the company Padrão Ortopédico, of Prosthesis and Orthotics, the goal was to find the possible sources of waste to do a sustainable project.

Prospecting - Problem identification that guides the project

After a preliminary market survey, it is necessary to research the technical and legal feasibility of production methods. Field research should include samples, measurements, and photographs, and it is important to document all the steps. The theme evolves into a work proposal and the project timeline gets developed. Thus, it is possible to define the team, resources, and deadlines. At this point was identified the problem which a lot of produced waste that could be used for a new project.

Data Gathering – Collection of bibliographic material

By knowing analytical techniques, it is possible to identify standards and organization procedures. Studying the competition and consumers allows for better market analysis, mapping expectations, needs, and limitations. In this phase, it is important to ask questions, interact and observe the consumer.

The Literature review collects information about the chosen materials (PU and TPU), the possible opportunities of products made by these materials, Case studies, Upper Limb Prostheses, Hand Anthropometry, and The Definition of 3D Printing

Organization and data analysis

After gathering data from different sources of information, it is necessary to prioritize and organize it in a way that allows for selecting the most relevant information. Techniques such as functional, structural, usability, morphological, semantic analysis may need to be applied. In this phase, the planning is reviewed, and strategies are defined.

Were identified possible solutions to use the material and a map was constructed to define the advantages and disadvantages of each path. The material started to be developed and initial ideas for the product to develop after.

Creation

At this point, the concept should already be defined, contributing to the development of ideas, sketches, and proposal selection. Then, manual and digital renders should be created, showcasing the product's form, use, and functionality. The proposal is further refined with prototypes that are closer to the final product.

Some rough sketches start to appear to clarify the concept idealized.

Execution

With the final prototypes, it is necessary to specify the production with technical data sheets, budgets, and final proofs before authorizing production.

Viability

By testing in real-life situations, the project is made viable. For example, it can be tested at the intended location, in points of sale, using ergonomics and usability evaluation tools, ensuring satisfaction and comfort. Legal records are also required in this phase, along with preparing recommendations for the client and monitoring production while assessing production quality.

Verification

The demonstration of results verifies the product's life cycle and sustainability. It may also present opportunities for future projects.

1.4 Internship

The orthopedics firm, Quelhas, Ribeiro e Cardoso, Lda, was founded by Carlos Quelhas, Abel Ribeiro, and Manuel Cardoso in 1983. Padrão Ortopédico is situated at Oliveira Monteiro Street, number 633, in Boavista, Porto, Portugal. At this establishment, apart from showcasing its products, it serves as a customer support with departments dedicated to prosthetic manufacturing and 3D printing. Additionally, it offers prosthetic adaptation to the patients, providing guidance in a gym setting and medical supervision. Among its catalog of products are walking aids, support devices for daily activities, writing and bathing assistive devices, orthopedic footwear, compression stockings, and prefabricated orthoses. Continuously evolving, the company keeps pace with technological advancements, and a recent addition is the 3D printing department, where the internship took place. [3]

1.4.1 Projects developed

During the internship, several projects were undertaken in addition to the main one, addressed in this thesis. These projects included the development of a support for drilling polyurethane blocs, represented between Figure 2 and 4, which were later used in the foam milling robot for positive models' production.



Figure 2 - Render of the movement of the head of the drilling support for PU blocks.

The materials used were PLA filament and wasted steel bars from the company adaptteck. The 3D render on Figure 3 represents the utilization of this daily used support.

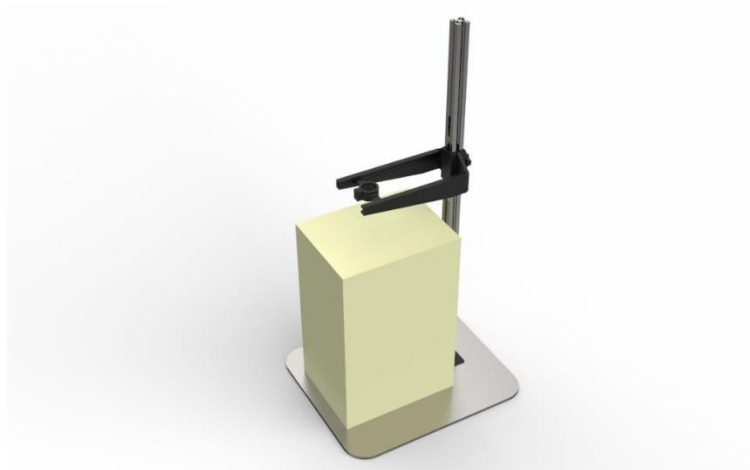


Figure 3 - Render of the Jig for drilling PU blocks.



Figure 4 - Developed Jig for drilling PU blocks.

Additionally, assistance was provided in the cosmetic area of external prostheses within the 3D Printing department. Also, decorative emblems were 3D modelled and 3D printed with layered printing in different colors to be placed on children's orthoses, as seen in Figure 5 and 6.

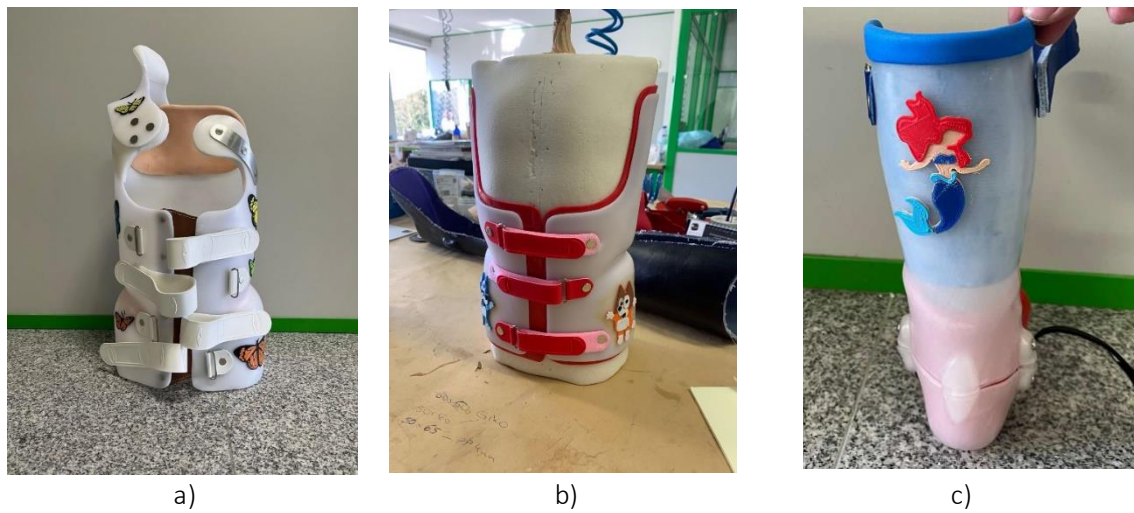


Figure 5 - Examples of children's orthosis with decorative 3d printed emblems. a) butterfly emblems, b) Blue and Bluey emblems, c) ariel emblem.



Figure 6 -example of 3d printed emblems.

Lastly, an adaptation disk for the foam milling machine was also developed to secure the foam block during the milling process. This part was 3D printed and then attached to the steel bar shown in Figure 7.



Figure 7 - Developed Disk for the robot.

1.5 Document Structure

The dissertation is structured into five key chapters namely Introduction, Literature Review, Material and Methods, Product Development, and Conclusion and Future Work.

In the Introduction chapter, the project's objectives and limitations will be thoroughly discussed, providing a comprehensive understanding of the development process. The relevance technique and document structure will be introduced after the context. It aims to make clear the primary goals, restrictions, and overview of the subsequent chapters.

The project's background will then supply the following information for the literature review, which will give context for related studies. Understanding what has been done previously involved analysing significant discoveries, techniques, common trends, etc. It is crucial that this initial research aids in the generation of ideas and the subsequent elimination of opportunities for the project's course to be changed. Introduction of the selected debris, Potential Opportunities, E-Nable Mechanical Hand, Polyurethane, Upper limb Prosthesis, Hand Anthropometry, and Definition of 3D Printing are the sections that will be fractured in this research.

The study of the material and all the methods for the conversation into 3D filament are shown in the next chapter, Materials and Methods.

In the chapter Product Development, the concept is subdivided into the E-Nable Project, Hand Analysis, Drawings, and E-Nable case. The examination of reprocessing and how to employ devices like the 3Devo to duplicate the 3D Filament will follow the material study. The design and production of the mechanical hand will then involve researching related products and developing the entire finished product using the developed material.



2 Literature Review

2.1 Introduction

The initial phase of this research involved the identification of the main wasted materials by the company of the internship, Padrão Ortopédico, located in Boavista in Porto, Portugal. The guidance provided by the company in the medical field was essential for this stage. The predominant materials considered as waste were polyurethane (PU) and various types of 3D filament, including thermoplastic polyurethane (TPU), thermoplastic elastomers (TPE), polylactic acid (PLA); among others. Smaller debris were excluded from the scope of the recycled material, as their collection would require significant quantities to ensure sufficient waste for the recycling process without requiring additional production.

After careful evaluation, TPU and PU were selected as the final compounds for the recycling material. PU came from the production of positive limb moulds and TPU from external prostheses with 3D printing errors. PU seemed an interesting but very challenging material to work with, as well as a significant source of waste that required innovation in its recycling possibilities. TPU was also a big source of waste in the company and seemed possible to work as a glue with the inert material that is PU. As illustrated in 8, various project paths were considered, and these possibilities will be explored in an overall review in the next subtopics.

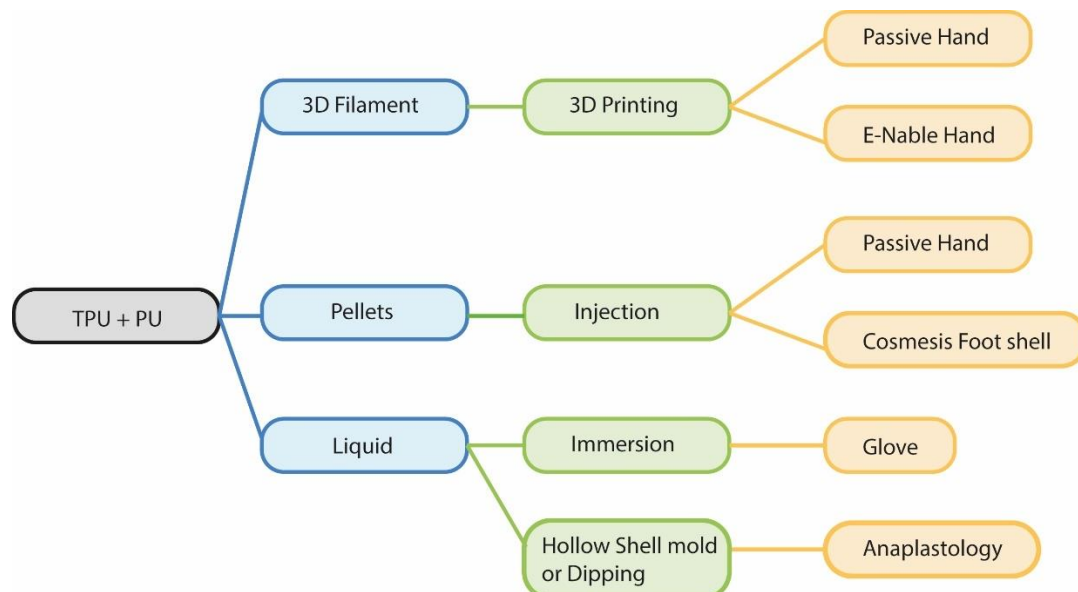


Figure 8 - Possible opportunities with TPU and PU.

2.2 Possible opportunities

2.2.1 Passive Hand

The Passive hand, as seen in Figure 9, as a type of prosthesis, endeavours to emulate natural aesthetics more than focusing primarily on functional capabilities. Despite the emphasis on appearance, according to Jan J. Stokosa in American Prosthetics Institute, passive prostheses can assist functions like pulling, pushing, stabilizing, supporting, and writing on the computer. This product holds particular significance for children, as it contributes to body balance, symmetry, and even provides a measure of protection in the event of a fall. Generally, passive hands require an outer PVC (polyvinyl chloride) or silicone glove. The developed material could be applied here as a 3D Filament or pellets to injection molding [4].

In the context of this study, the developed material exhibits potential as a 3D filament or in pellet form for injection molding to manufacture passive hands. While this represents a favourable application of the material, more complex and challenging opportunities exist in the domain of product design for this project.



Figure 9 - Passive Hand.

2.2.2 Cosmesis Foot Shell

A Cosmetic Foot Shell (Figure 10) serves the purpose of closely resembling a real foot in a prosthesis. It may be primarily to aesthetic considerations for individuals enabled to walk, but it can also significantly enhance the walking experience by emulating a natural gait. This product aims to effectively absorb ground impact, adapt to uneven terrains, and facilitate a smooth heel-to-toe walking motion to propel the gait. Ensuring comfort during use and seamless adaptation to daily activities are paramount objectives.

Regarding the most used materials, these differ depending on the user's activities, but wood, plastic and foam are generally used for low activity use and require stability more than ease of movement. For cases that require great shock absorption, lightness and adaptation to greater activity, carbon fiber is used. Ideally, as soon as weight is applied to the foot in question, it propels the gait by rolling the foot forward. The developed material could find application in this domain through the injection molding process, showcasing favorable use of the material. However, it is

worth noting that the product in question may not necessitate extensive innovation, giving its well-established design and materials existing in the market [5].



Figure 10 - Prosthetic Foot.

2.2.3 Cosmetic Glove

The Cosmetic Glove (Figure 11) is usually designed to wrap around a passive hand. This will serve as protection and to make the appearance more realistic. Gloves can be made of PVC or Silicone, MVC and MCS.

PVC gloves are the most economical option on the market. However, it is easily stained as it absorbs grease and ink, which are difficult to remove. It has greater resistance to mechanical damage, is more rigid and therefore has less flexibility and mechanical efficiency.

In the case of **silicone** gloves, these are very resistant and easy to clean, they hardly get stained. This material allows for a wide variety of colors but is the most expensive option on the market. It has high surface friction, which allows for greater adherence to objects, but also greater adherence to clothing.

Gloves made with Micro-Coated Vinyl (**MCV**) or Micro-Coated Silicone (**MCS**) have a very stain resistant and easy to clean. In addition, it has less friction with clothes.

The conventional method of gloves is hollow shell molding, usually through an electroplating technique. The material is poured, removed and repeated until the desired thickness is reached.

In a more current method, it can be done only by casting techniques [4].



Figure 11 - Cosmetic glove.

2.2.3.1 Possible Glove Process

The conventional process consists of a Hollow Shell mold with electroplating technique. Material (such as PVC, rubber, latex) is poured into the mold. It is then removed, leaving only a thin layer of material that adheres to the surface of the mold. The layer is cured to a solid state by heating. To define the desired thickness, the process of pouring and removing the material is repeated as many times as necessary.

There was a need to innovate in the process as it only allows gloves with an unnatural hand shape to be able to be demoulded. This new process only needs casting techniques, without the need for electroplating techniques.

The process then begins by making an impression of a donor hand with fast-curing silicone rubber, to withstand high temperatures and be quick. It is important to collect the correct hand position. This is achieved by installing pre-positioned rods in the casting pot. These must be placed in such a way that the tips of the donor's fingers are located at the ends of the rods. Because these rods are hollow, several other aspects of the process are made possible. Low pressure compressed air is fed individually through each rod/tube, whereby the air forces the skin-mold interface to separate around the fingers to the wrist. Then, soap is injected into the tubes with the effect of lubricating the withdrawal of the hand. After the donor withdraws their hand, the silicone-rubber mold is washed without soap and subjected to a temperature conditioning program in preparation for the next step which is a metal casting process. Molten pewter (melting point 238°C) is poured into the wrist section, displacing trapped air through the fingertip holes remaining after removal of the positioning rods. The metal is then allowed to solidify, whereupon the mold material is broken. Light fingertip flashes are small and easily removed at this stage. The positive metal hand now produced by this process is dipped in PVC plastisol, dripped without excess material and cured in an oven at 150°C in the usual way. The thin PVC sleeve is peeled intact from the metal and inverted. This glove is now mirror hand and features inside-out detailing. To use this glove as a donor for a repeat of the above procedure, it is necessary for the glove to be in a dimensionally stable, rigid or semi-rigid state. For this, the glove can be filled with light plastic spheres of approximately 1mm in diameter. This low-density filler virtually eliminates the bulge commonly caused by plaster or wax filling. The hand is then made rigid by reducing the pressure inside the low-atmospheric glove by means of a vacuum pump. The effect of the pressure difference across the wall of the glove causes the contents to be compressed until the entire hand is almost rigid, thus allowing the glove to be used in subsequent casting processes as long as the vacuum is maintained. At this stage, minor setup adjustments can be made as the glove takes on the consistency of hard clay. After melting into silicone, the vacuum is released

and the plastic beads are poured. The glove is easily removed from the flexible mold with the aid of air pressure applied at the fingertips – thus leaving a hollow silicone rubber mold ready for heat conditioning prior to metal casting. The solid positive detail, on the opposite hand, with the inverted metal casting detail, this is the mold for the manufacture of gloves by immersion. Excess material drips off and cures in an oven. For the desired layer, successive layers are made until the desired result. At the end, the glove is removed and inverted, with a realistic reproduction of a hand. [6]

2.2.4 Anaplastology

Anaplastology, is term coined by Walter G. Spohn, is a branch of medicine that deals with prosthetic rehabilitation of a critically missing, disfigured, or malformed anatomical location of the face or other parts of the body. The professional who possesses the knowledge to customize a facial prosthesis is called an anaplastologist, prosthetist, or maxillofacial technologist. “We meticulously replicate the texture, color, and translucency of living tissue to create prosthetics with a natural appearance. “[7] Certification in the field of anaplastology is provided by the Board for Certification in Clinical Anaplastology. This option for the project would involve the use of silicone in the created material, as seen in Figure 12.



Figure 12 - Anaplastology [7].

2.2.5 Mechanical Hand

A Mechanical Hand, as a prosthetic device, offers significant advantages compared to passive hands or gloves, primarily due to its capability for mechanical manipulation and grasping. This feature provides users with enhanced functionality and mobility.

The E-Nable project represents a global movement with the noble purpose of supporting individuals in need of upper limb assistive devices. Driven by a community of volunteers equipped

with 3D printing technology, the project involves the creation and donation of hands and arms to those requiring such aids with few financial possibilities.



Figure 13 - Mechanical Hand.

2.3 E-Nable Mechanical Hand

The chosen opportunity for this research was to focus on the mechanical hand through the E-Nable project. This decision was driven by the potential application of innovative material in the creation of flexible components for the mechanical hand, which offers the exciting possibility of achieving natural skin tone. By incorporating this material into the fabrication of essential elements within the mechanical hand's design, the project aims to enhance aesthetics and achieve a more lifelike appearance, ultimately contributing to the overall realism and acceptance of the prosthesis among its users.

2.3.1 E-Nable

The E-Nable project is a global movement to help those in need of upper limb assistive devices. 2" e-NABLE is an online global community of "Digital Humanitarian" volunteers from all over the world who are using their 3D printers to make free and low-cost prosthetic upper limb devices for children and adults in need." [8]. Volunteers connected to 3D printing create hands and arms and these are donated. Given the global scope of action of this movement, different political, religious, cultural and personal aspects are covered. Some of the volunteers are students, teachers, engineers, scientists, doctors, designers, parents, children, artists, among others.

2.3.2 Types of Volunteering on E-Nable

User - Everyone using the application is a user. It could be family members asking for help, volunteers, or someone asking for equipment.

Manufacturer – This produces the parts and then passes to the assembler

Expert – This is in charge of determining the correct sizes and methods. They review photos and videos submitted by users, and approve equipment.

Matcher – This has the function of matching volunteers with individuals who need the equipment. Intervene in the process of cases and help in their realization.

Chapter Lead – Lead of an E-Nable Chapter approves or declines requests to join an E-Nable Chapter, link volunteers with individuals, monitor cases.

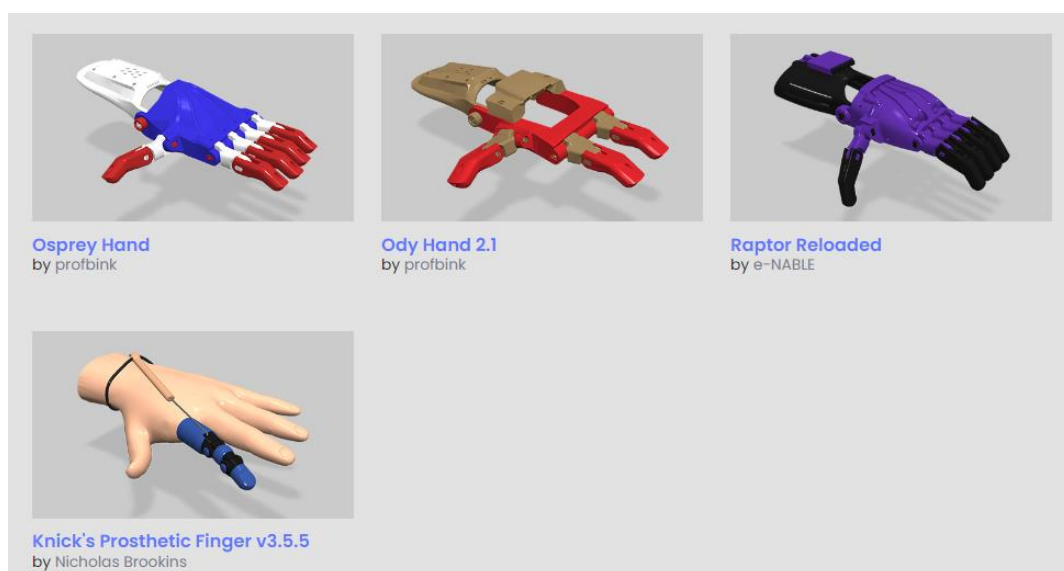
Each case needs 3 participants, the Expert, the Manufacturer and the assembler. The three functions can still be practiced by the same volunteer. But several volunteers can participate in the same case and there will always be guides throughout the process.

A new case is created with photos, videos and specifications of the need. So, e-Nable volunteers establish the ideal device for the case. Then other volunteers can get involved and print and assemble the device.

Professional advice is needed after a user provides photos and videos. This can advise more than one device just in case, along with instructions for the next volunteer.

In fact, each case requires three volunteer functions, which can all be performed by a single volunteer or one at each stage. It is then tested and feedback is sent by the user. The customer can accept the product or request an exchange. In case of exchange, only adjustments or a new device may be required.

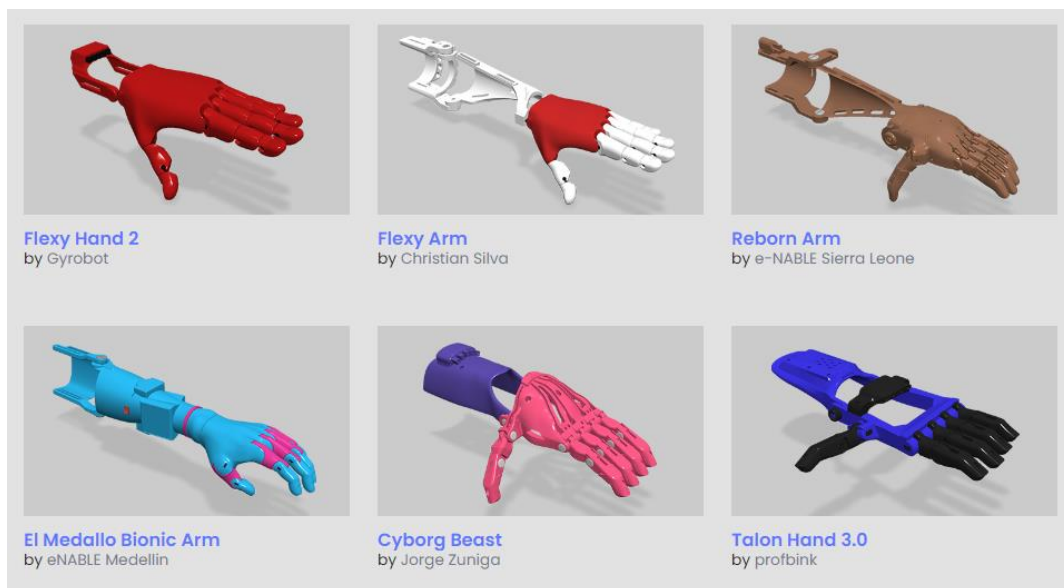
Some of the existing E-Nable standard hand are represented in Figure 14 a) b) and c)



a)



b)



c)

Figure 14 – a), b) and c) - E-Nable standart models [9].

2.4 Polyurethane

According to the European Diisocyanate and Polyol Producers Association, this material is considered as a polymer and is produced by the reaction of a polyol (a alcohol with more than two groups of reactive hydroxyl per molecule) with diisocyanate or a polymeric isocyanate, with the use of catalysers and adequate additives. "Polyurethanes are based on oil, a finite resource. However, the product qualities of polyurethanes are such that they help to conserve many resources, while at the same time safeguarding high and ever increasing standards of living." [10]

The PU is a thermosetting polymer, and therefore does not allow its rigidity to be altered by manipulating the temperature. Thus, if a temperature increase is applied, the material melts and decomposes instead of softening and being possible to remould. There are currently some recycling options such as Mechanical Recycling, Chemical Recycling, Biological Degradation, Energy Recovery and Landfill Deposition. The most practical and economical is Mechanical Recycling. Currently, the most common applications of recycled polyurethane are insulation and acoustic panels, rehabilitation mattresses and protective materials for sport facilities. Polyurethane is divided into two groups: foams and CASE'S (Coatings, Adhesives, Sealants, Elastomers). Within the foams, we have the flexible ones, applied for example in car seats, and the rigid ones, applied for example in building insulation and commercial refrigerants. In CASES'S subdivision, some examples are: footwear, athletics tracks, electronic products and boat structures.

2.4.1 Timeline of Polyurethane Applications

The German Scientist Otto Bayer discovers polyurethane in 1930s, according to Mir Nikje et al. in *Polyurethane Waste Reduction and Recycling From Bench to Pilot Scales*" [11].

1937 – DR. Otto Bayer discovers PU during his research into polymeric fibres at I.G. Farber Laboratories, a subdivision of Bayer Corporation in Germany.

1940 – The Practical application of polyurethane begins in World War II with the idea of replacing rubber. Polyurethane coatings were used in this era for high gloss aircraft finishes with resistance to chemicals and corrosion to metal, wood, and masonry. In addition, Polyurethane coatings have also been used for paper impregnation and the manufacture of mustard gas resistant clothing. DuPont Corporation have introduced polyurethane materials.

1950 – In this decade, synthetic polyurethane leather was introduced as an innovation in shoe soles. Also flexible foam seat cushions, first in Europe and later in the US. This material started to be used in furniture upholstery and car seats.

1960 – The company DuPont created the Spandex fibre, Lycra, for use in the clothing industry. It was introduced in lines of swimwear, Olympic ski apparel. In Germany, the company Bayer AG Corporation in Dusseldorf launched the first all-plastic automobile made from polyurethanes.

1970 – In the Textile area, the “aerodynamic” spandex cycling shorts, dancewear, socks and elastic pants appeared. In the construction area, Polyurethane began to be used as insulation in buildings through spraying, due to the reduction of energy costs with the use of PVC, one of the most used synthetic construction materials.

1980 - In clothing, the material has a great presence in socks. In the automotive area, energy-absorbing polyurethane foams began to be used for passenger safety.

1990 – In the medical field, PU catheters appeared. In order to have greater ecological concern, CFCs are now replaced by hydrocarbons, HCFs, CO₂, among others.

2000 – In the continuation of a greater environmental concern, polyurethanes made from vegetable oil polyols were created. An example is given of the soy-based polyurethane used by the Ford Motor Company in automobile panels. The company Rimowa introduced the first polycarbonate suitcase to the market

2010 -The Mitchell Group business group introduced the first Sta-Kleen® stain resistant polyurethane upholstery fabric. In 2017, this same group creates Sta-Kleen Polycarbonate™, a Polyurethane made from 100% polycarbonate resins.

2.4.2 Market and Consumption of Polyurethane

Given the great diversity of properties of polyurethanes, as seen in Table 1, there are several areas of application. They may vary in physical, chemical, thermal and mechanical characteristics. In the case of PUF (flexible), it is usually used in car seats, furniture and carpets. PUR (rigid) is often used in refrigerators and insulation boards. Elastomers are most used in footwear, adhesive, medical applications.

Table 1 - Market and consumption of PU [12].

Application	Million Pounds	%
Building and construction	1459	26.8
Transportation	1298	23.8
Furniture and Bedding	1127	20.7
Appliances	278	5.1
Packaging	251	4.6
Textiles, fibres and apparel	181	3.3
Machinery and foundry	178	3.3
Electronics	75	1.4
Footwear	39	0.7
Other end-use markets for PU	558	10.2
Total PU production	5444	100.0

Figure 15 represents the Worldwide PU consumption between 1998 and 2005. As seen in Figure 16, the market of polyurethane use, is highly represented by flexible foam used in mattresses, cushions and car seats. The next big area of the use of polyurethanes is the rigid foam applied in construction and for insulation.

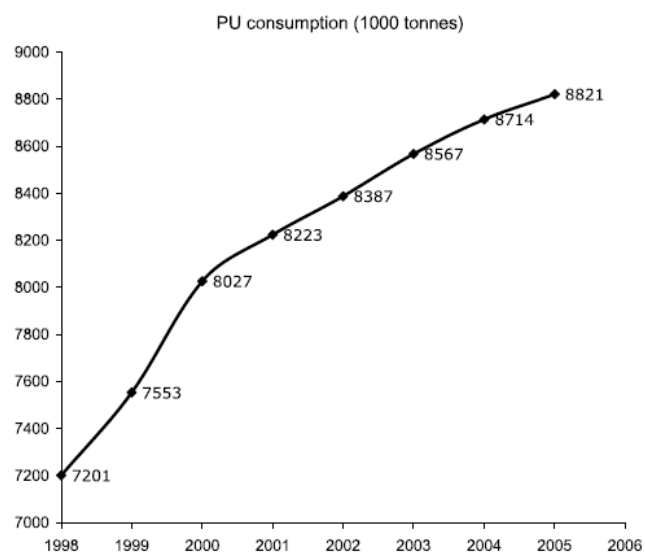


Figure 15 - Worldwide PU consumption 1998-2005 [11].

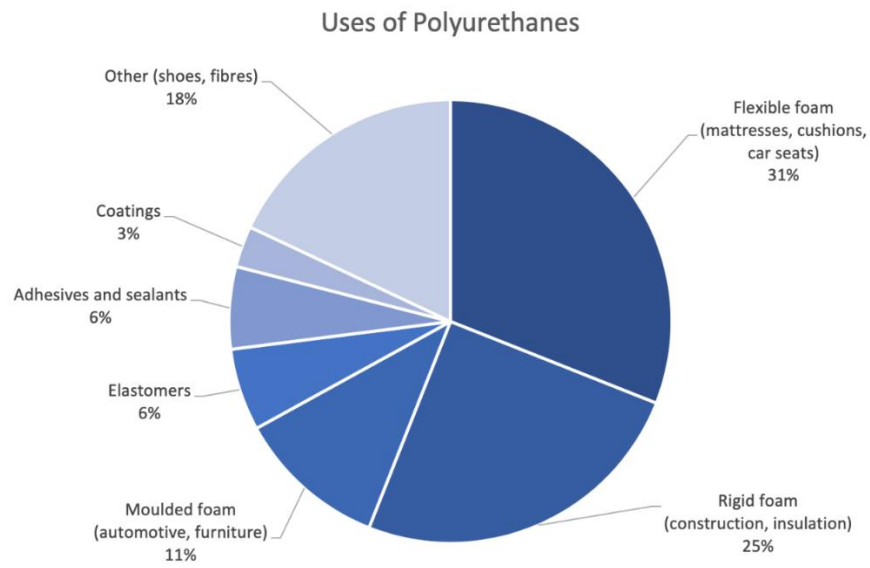


Figure 16 - Use of Polyurethanes [11].

2.4.3 Recycling Options

The recycling alternatives presented thus far are depicted in Table 2, with each method's process thoroughly elucidated. However, it is evident that these processes remain somewhat underdeveloped. Therefore, the exploration of a novel recycling approach for this material would constitute an innovative breakthrough with far-reaching implications across diverse fields that utilize polyurethanes. Notably, it is known to be environmentally hazardous, and a sustainable recycling solution would address critical environmental concerns associated with their disposal.

Table 2 - Recycling options [13].

Landfill	There is a large use of land and a lack of concern for the environment.
Mechanical Recycling	It is only applied to post-production waste and some of the processes require high temperature and pressure. The mechanical recycling of Polyurethane foam involves mixing ground foam with a high-performance binder and forming blocks and sheets for new products. Soft foam composite is the most common method of recycling flexible PU foam and applying it to a lower quality part than the original. This composite foam has been used for decades and represents 90% of the carpet filling market in the United States. Some applications for the production of rigid foam composite panels are car parts, refrigerator, industrial finishes, among others. Polyurethane parts are granulated and mixed with fresh polyurethane or a binder and molded by increasing temperature and pressure into sheets or frames. It can be used for furniture, floors and acoustic insulation. A variant of this mechanical recycling is pulverizing, which uses industrial or post-consumer polyurethane parts and is ground to a fine powder. This can be incorporated into the system polyol in small amounts to produce foam parts. The use of powder increases the viscosity of the raw materials and considerably affects the properties of the part.
Chemical Recycling	High temperature and pressure are required. Organic solvent catalysts and other hazardous chemicals are required also. In

	Acidolysis it is a process that uses carboxylic acids and applies high temperatures to chemically alter the polyurethane chain and convert it back into reactive raw material. This process suits flexible foams due to the recycled polyol resulting in a low OH number, which is a requirement for flexible foams. In Glycolysis a chemical reaction is brought about, together with high temperatures, using diols and producing recycled polyols with portions of the original polyurethane chain. These polyols can retain the function and properties of the originals used for foam production and can be recycled for the same application. In the case of Hydrolysis, a reaction is caused between the polyurethanes used together with water, resulting in polyols and various chemical intermediates. Polyols can be used as fuel and intermediates as starting materials for several types of polyurethane.
Energy Recovery	There is a release of toxic gases and ash can go to the landfill.
Biological Degradation	May liberate toxic components.

2.4.4 TPU vs. PU

PU is the abbreviation for the Polyurethane, in this case thermoset, widely used in mattress foam, cell phone covers, hoses, among others. Contains urethane bonds and are made from polyols and isocyanates.

TPU is the abbreviation for Thermoplastic Polyurethane, applied for example in footwear and household appliances. They are made of polyether or polyester or polycaprolactones. The material behaves like elastic plastics.

The most used manufacturing processes are extrusion, injection molding and blow molding. The current recycling of Polyurethane allows the creation of insulation and acoustic mats, insulation panels, protective materials for sports facilities and rehabilitation mattresses [14].

2.4.5 Case Studies with Polyurethane

2.4.5.1 Polyurethane innovation in the wind power industry

The European Union has set a binding target for 20% of its energy supply to come from renewable sources by 2020; to reach this target, more than a third of European electricity demand will have to come from renewable energies. The weight of turbine blades is one of the current challenges for the wind power industry. At the moment, in order to create sufficient levels of energy, larger blades are needed but it also becomes more easily sensitive to damage and more difficult to transport. There is now the possibility of creating wind turbines with polyurethane, adapting the material to the specific requirements of wind turbines. Final Parts turned out to be more beneficial, for example eight times more durable, stronger and lighter than other epoxy or vinyl ester tests. With these new blades, the levels of fatigue and resistance to fracture have been improved, which guarantees resistance to strong winds. "Mechanical test results for carbon nanotube-reinforced polyurethane show that this material outperforms resins currently used for wind blade applications," according to Ica Manas-Zloczower, Professor of Macromolecular Science and Engineering at Case Western [15,16].

2.4.5.2 Walking green: the sustainable polyurethane shoe

Recently, was developed a sustainable shoe, represented in Figure 17, that contains up to 90% eco-friendly properties. These are polyurethane raw materials based on natural resources, products for solvent-free coatings and adhesives, a blend of polycarbonate and thermoplastic polyurethane based on renewable resources. The environmental burden could significantly reduce, equivalent to 1% of Sweden's annual CO₂ emission, about 150,000 metric tons. This would be possible by replacing new products and techniques developed for textile coatings and adhesive raw materials without solvents and plasticizers. The outer and midsoles of the "Green Shoe" will consist of microcellular polyurethane elastomer systems, where around 70% of renewable materials are used. This is a good example of the application of polyurethane [16,17].



Figure 17 - Sustainable Polyurethane Shoe [17].

2.4.5.3 From Zero to Hero: Making polyurethane from Carbon Dioxide

After many years of research, a way was discovered to use CO₂ as an alternative to oil as the main source of the element carbon in the chemical industry. Concern about CO₂ reduction is currently significant, and a major reason for climate change. This is a waste gas, and until now no discoveries have been made for the use of carbon dioxide. So far, the solution is to reduce emissions or store underground. Polyurethanes manage to play an important role in reducing energy consumption and protecting the climate. For example, when they are used to insulate buildings from cold and heat, they can save approximately 70 times more energy than is used in their production. Discovered by scientists at Bayer and the University of Aachen, with support from the German state and federal governments and the CAT Catalytic Center. A chemical precursor (catalyst) was then developed in which CO₂ is incorporated and processed into polyurethanes. Polyurethane foams are now produced using carbon dioxide. This new project drives new sustainable methods. Thus, CO₂ can be used as a resource rather than discarded as waste [17].

2.4.5.4 New polyurethane foam gives a "green" light to green roofs

The development of "Green roofs" through the use of polyurethane can significantly transform the environment of urban homes. As an advantage, these roofs allow the building to evaporate moisture and can reduce a building's cooling loads by between 50% and 90%. The different layers are represented in Figure 18. Consequently, another advantage is the filtering of pollutants in the air and rainwater, as well as better acoustic insulation. As a disadvantage, there is the installation of these green roofs and the less appealing appearance. To solve this problem, Huntsman Polyurethanes developed VYDRO® foam, with the aim of reducing the weight of the roof layers. In addition to being lighter, it has a neutral pH, which facilitates the connection with water. It has a life expectancy of twenty-five years and aims to promote the sustainable use of polyurethane [17].

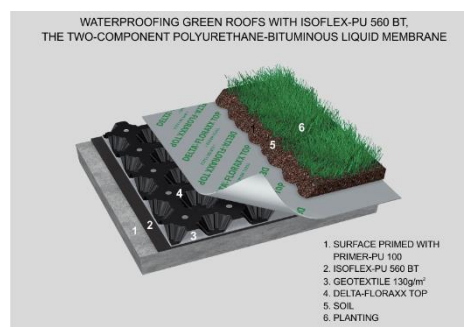


Figure 18 - Green Roof Project with Polyurethane [17].

2.4.5.5 Polyurethanes was key to building the house of the future: the Virginia Tech Lumenhaus

Inspired by the Farnsworth House by Mies Van Der Rohe, some students from Virginia Tech University, in the United States, created the Lumenhaus project, the most efficient pavilion in terms of ecology and energy. This project won the European Solar Decathlon 2010. One of the materials used was closed-cell insulation foam made of polyurethane, applied to the walls and movable panels of the house, which increased the thermal resistance five times more. The foam used does not contain CFCs or HCFs. Solar energy is also a striking feature of the house, mainly due to its ability to vary the angle [17].

2.4.5.6 Recycling polyurethanes in the automotive industry: Chrysler's pioneering initiative

American car manufacturer, Chrysler decided in 2010 to apply recycled polyurethane foams on the assembly line of the 2011 Grand Cherokee. In this way it used about 180,000 pounds of polyurethane foams that would go to landfill for headrests and seats. Chrysler claims to reuse all the post-industrial waste that recycling generates, and in the case of recycled PU foams, only energy is required for the recycling process. As a successful experiment, the company extended the practice to other car models, applying 10% recycled foam to the seats and 20% to the headrests. Even so, this material is used in more parts in the automotive area, and the company claims to apply some percentage of recycled PU to these parts in the future as well. The company's initiative demonstrates growing environmental concern in the automotive industry. Polyurethane is a petrochemical and it is essential to be concerned about recycling and recovering whenever possible, in order to save the planet's resources. The "glycolysis" method was used to produce regenerated polyols [17].

- Ecofriendly solar-powered refrigerators for Swaziland [9 September 2010]
- Polyurethanes give a shining spark to solar panels [25 August 2010]
- Elastogran has a new insulation technique which saves time, space and money. [25 August 2010]
- Polyurethanes composites provides outstanding thermal insulation for windows [25 August 2010]
- A solid basis for rail traffic [23 September 2008]
- A material that is very much on track [19 August 2008]
- Large-format commercial vehicle bodywork parts made of polyurethane [15 February 2008]

2.5 Upper Limb Prosthesis

2.5.1 Introduction

An Upper Limb prosthetics could be passive, triggered by the body, externally powered, myoelectric, hybrid or even for specific activities. It refers to an artificial device that can replace a non-functional upper limb, usually an arm, forearm, wrist or hand. This type of device can provide functionality and give a little more quality of life to the users [18]. Some examples are represented in figure 19.



Figure 19 - Types of Upper Extremity Prosthetic hands [18].

According to Jan J. Stokosa [3], “the main causes of limb amputation are Blood vessel (vascular) disease, particularly from diabetes or peripheral arterial disease, cancer, injury (for example, from a motor vehicle crash, work-related accident, or military combat), birth defect”.

The main goal of an Upper limb prosthetic is to enhance the user's independence and integration into society. The restore of essential daily functions can give the user movements like grabbing objects, open a door, or even perform activities. The success of the prosthesis depends on the medical situation of the user, these physical and cognitive capabilities, the level of amputation and also the correct fit to the body with comfort.

2.5.2 Limb Prosthetics

There are four main components required for a prosthesis: Interface, Suspension, Structural Components, and Cosmetic Components.

The various options for prosthetics aim to achieve a stable fit and maximum functionality. They can be designed for a daily mobility or specific activities. Limb prosthetics can be divided into two groups: Exoskeletal and Endoskeletal.

Exoskeletal prosthetics are recommended for more physically demanding tasks that require durability and strength. They are permanent and cannot be adjusted. The exterior, resembling the shape of the limb, can be made of rigid plastic or metal. [19]

Endoskeletal prosthetics allow for adjustability. The internal skeletal structure is also adjustable, and the exterior is soft to stimulate synthetic skin.

Amputation also has consequences for a person's identity and can interfere with social and professional relationships, work capacity, and more.

According to Jan J. Stokosa, CP, of the American Prosthetics Institute, Ltd., there are five general types of upper limb prosthetics [19].

2.5.2.1 Passive Prosthetics

Passive prosthetics closely resemble real limbs and primarily serve an aesthetic purpose. Although they lack movement, they can assist with activities that require balance and object stabilization. They are lightweight and cost-effective.

2.5.2.2 Body-Powered Prosthetics

These Prosthetics are activated by body movements and are among the most common due to their ease of maintenance and durability. For example, through a system of harnesses, movement is initiated by shoulder and triggers the function of a hook or gripper.

2.5.2.3 External Powered Myoelectric Prosthetics

Myoelectric prosthetics provide movement without the need to move the body. Sensors are used to detect the muscle movements of the residual limb.

2.5.2.4 Hybrid Prosthetics

These are typically used in cases of higher-level upper limb amputations, combining features of both Body-Powered and Myoelectric hands.

2.5.2.5 Prosthetics for Specific Activities

These can be passive or mechanical and are developed for specific activities that require different capabilities from a prosthetic device design for daily common tasks.

Examples include a prosthetic that allows gripping a golf club, holding a bicycle handlebar, or even holding a fishing rod.

2.6 Hand Anthropometry

The movements of flexion, extension, and radial and ulnar deviation occur in the wrist joint complex, specifically in the “true” wrist joint (radiocarpal joint) and the joints between the other small bones of the wrist (intercarpal joints).

The forearm consists of two long bones, the radius and ulna. These bones extended from the elbow to the wrist and articulate at their upper and lower ends. When the hand is in a palm-up position, these two bones are parallel. The radius is located on the pinky side and at the proximal and posterior part of the elbow, it forms a prominent structure called the olecranon. At the distal and medial part of the forearm, the ulnar styloid process is noticeable.

The skeleton of the hand is composed of small, articulated bones called carpals, long bones known as metacarpals, and phalanges [20].

2.6.1 Osteology – Carpal Bones, Metacarpal Bones and Falanges

“The hand consists of 27 bones, the eight short carpal bones are arranged into a proximal row (scaphoid, lunate, triquetral and pisiform) which joins with the bones of the forearm, and a distal row (trapezium, trapezoid, capitate and hamate), which joins with the bases of the five metacarpal hand bones.” [21].

The Hand bones can be divided in three groups, Carpal Bones, Metacarpal Bones and Falanges. Figure 20 represents the different parts of each group. The carpal bones are classified as long and they articulate proximally with the metacarpal bones and distally with the phalanges.

The phalanges are also classified as long bones, and each finger has three phalanges: proximal, middle and distal. In the case of the thumb, it does not have a middle phalanx.

When the Hand is in a palm-down position, these two bones cross each other. The Natural movements of the hand that we use daily regularly require actions of pronation and supination. Positioning the hand with the palm facing up allows the hand to be in a relaxing position, and anatomists refer to it as the resting position. In this position, the muscular tension of flexion and extension is balanced and at rest. Anatomists have conducted various studies on the infinite possibilities of actions and non-gripping actions, such as pressing. In gripping actions, the hand forms a closed kinetic chain that involves the object in question. In a non-gripping action, the hand is used in an open chain configuration.

Some daily actions fall into these two categories, where the kinetic chain of the hand is about to close. For example, the action of hooking that we use to carry a heavy suitcase and the action by which we pick up a handful of small objects.

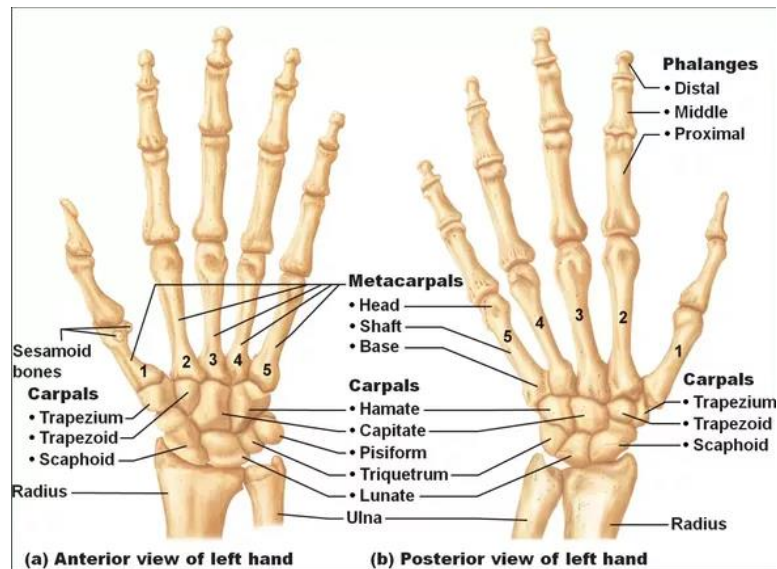


Figure 20 - Representation of the Hand bones: Carpals, Metacarpals and Phalanges [21].

2.6.2 Wrist and Hand Ligaments

Ligaments allow for the connection of two articulated bones as they are structures made of connective tissue that stabilize or limit joint movements. In the case of the wrist and hand, moving from proximal to distal, we have the radiocarpal joint (between the forearm and the hand). The remaining joints are located in the hand, connecting the bones to each other. These include the intercarpal, carpometacarpal, intermetacarpal, metacarpophalangeal, and interphalangeal joints.

2.6.3 Muscle of the Hand

The five groups of muscles in the hand are: thenar muscles, hypothenar muscles, lumbrical muscles, palmar interossei muscles, and dorsal interossei muscles.

2.7 3D Printing

The selection of 3D Printing as the production method was predicated upon its intrinsic potential to facilitate a cost-effective and personalized approach to patient-specific fabrication. Given the

array of production methods, this emerged as the most fitting recourse to assess the newly developed material's attributes while concurrently aligning with the low-cost project paradigm. Moreover, the existing resources both within the internship setting and the academic faculty further underscored the feasibility of this choice.

Also known as additive manufacturing (AM), this is a manufacturing process that works by adding layers (Additive Manufacturing Process). This process emerged in about 1980 and was initially called RP - Rapid Prototyping. Printing can be done using different processes such as SLA (Selective Laser Sintering), SLS (Selective Laser Sintering), DLP (Digital Light Processing), among others.

Plastic (especially ABS and PLA) and metal alloys are the most used materials, but many other materials can be used such as ceramics, sand, chocolate.

Some factors that influence the object to be produced are layer height, printing temperature, printing speed, shrinkage, printing direction, acceleration and density.

Prices can range from €200 to €10,000 or more.

2.7.1 FDM

Among the additive manufacturing processes, Fused Deposition Modelling (FDM) stands out as a polymer extrusion technique. Commercialized by the company Stratasys, this process involves the fabrication of prototypes through layer-by-layer addition, utilizing thermoplastic materials. The 3D printing material, in the form of filament, is fed into the 3D printing machine. The extrusion head then deposits the material layer by layer. The operational scheme of this process is illustrated in Figure 21. The movement of the extrusion head is guided by coordinates [22,23].

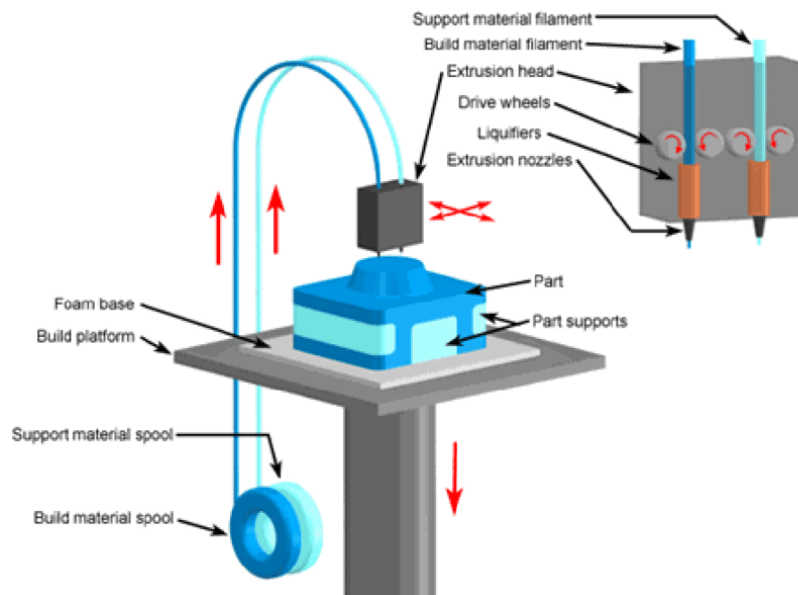


Figure 21 - Schematic of Fused Deposition Modelling (FDM) [24].

Each deposited layer has a specific thickness, which, if ignored, can cause several errors. First, it is recommended that the measurements of the piece are adequate for the measurement per layer, for example 3mm. The different materials have different behaviour and must be taken into account, for example their resistance to temperature.

It is crucial to know the indicated file for the required capacity, also depending on the technology. Selecting the correct file format is very important for good 3D printing practice. Common file formats include: STL, OBJ, FBX, DAE, 3DS, IGES, STEP, VRML or X3D.

For optimal results, a careful part orientation is crucial, considering factors like the placement of supports and noticeable lines on less visible sections of the object. Sometimes, dividing the model into multiple parts can facilitate the assembly, and tolerances between parts should be considered.

Moreover, it is essential to account for the laser's millimetres when dealing with intricate details, as measurements below the precision of the laser can lead to errors. Identifying anchor points within the design is advisable, as it prevents overloading the part and potential vending. Additionally, adding a thin plate, not exceeding 1mm, can help mitigate warping issues and stabilize the piece, reducing the risk of detachment during the printing process.

2.7.1.1 Process

1. Thermoplastic filament is loaded into the printer. When the nozzle reaches the desired temperature, the material is extruded layer by layer.
2. The extrusion head is connected to a 3-axis system that allows it to move in X, Y and Z directions. The molten material is extruded into thin strands and deposited layer by layer at predetermined locations, where it cools and solidifies. Sometimes material cooling is accelerated by using cooling fans connected to the extrusion head. It is important to keep the surrounding space at a constant temperature so as not to interfere with the piece.
3. To fill an area, several layers are needed. When a layer is finished, the build pad moves down (or in other machine configurations, the extrusion head moves up) and a new layer is deposited. This process is repeated until the part is completed [24].

2.7.1.2 Benefits

- FDM is the most cost-effective way to produce prototypes and custom thermoplastic parts.
- FDM delivery times are short, due to the high availability of the technology.
- A wide range of thermoplastic materials are available, suitable for prototypes and some non-commercial functional applications.
- Simplicity of use
- Easy to store
- The most suitable process for rapid prototyping
- Allows you to make study prototypes before the company starts producing the injection (sometimes they start producing the part by injection and notice errors that lead to a new mold being produced, thus losing about 5,000 euros, for example. What does not happen if there is the possibility of making an extruded prototype without molds, in an fdm printer)
- Competitive advantage, as it brings a better way to communicate a prototyped idea
- No worries about possible exposure to toxic chemicals, lasers or a liquid polymer bath.
- No material wastes.
- Various materials can be used and a single machine

2.7.1.3 Disadvantages

- FDM has the lowest dimensional accuracy and resolution compared to other 3D printing technologies, so it is not suitable for parts with intricate details.
- Post processing is required for a smooth finish because FDM parts are likely to have visible layer lines.

- The layer adhesion mechanism makes FDM parts inherently anisotropic, hence not recommended for mechanically critical components.
- Has a more limited size than other 3d printing technologies
- Slow printing speed
- Rough finish

2.7.2 Case Studies about Prosthesis development with 3D printing process

2.7.2.1 Biomechanical Simulation of Prosthetics for Dogs

With the evolution of technology in veterinary medicine over time, the prosthetics industry in this field has also been advancing. Limb replacement prosthetics contribute to gait stabilization and enhance the overall quality of life. The method of 3D Printing has garnered significant attention in the realm of animal prosthetic industry, primarily due to its capability for personalized products and cost-effective fabrication.

The primary objective of this study was to design five distinctive prosthetic solutions for thoracic limb replacement in dogs and subsequently analyse these designs using the Finite Element Method. Following this analysis, the intention was to identify the prosthetic design that most suitably aligns with the animal's needs and proceed to manufacture it using a 3D printer [25].

2.7.2.2 Development of Prosthesis for Transradial Upper Limb Amputation – Low-cost production through 3D Printing

Currently, there is a wide array of prostheses available in the market, ranging from simple ones designed primarily for aesthetic purposes to bionic variants equipped with motors linked to muscles, enabling a range of grasping functionalities. Despite the technological advancements in this field, costs remain notably high, with prostheses often exceeding twenty thousand euros. Consequently, combining the pursuit of developing a low-cost prosthesis with the advantages of the 3D Printing process, arises as a solution to address the lack of accessibility of this product for the general population [26].

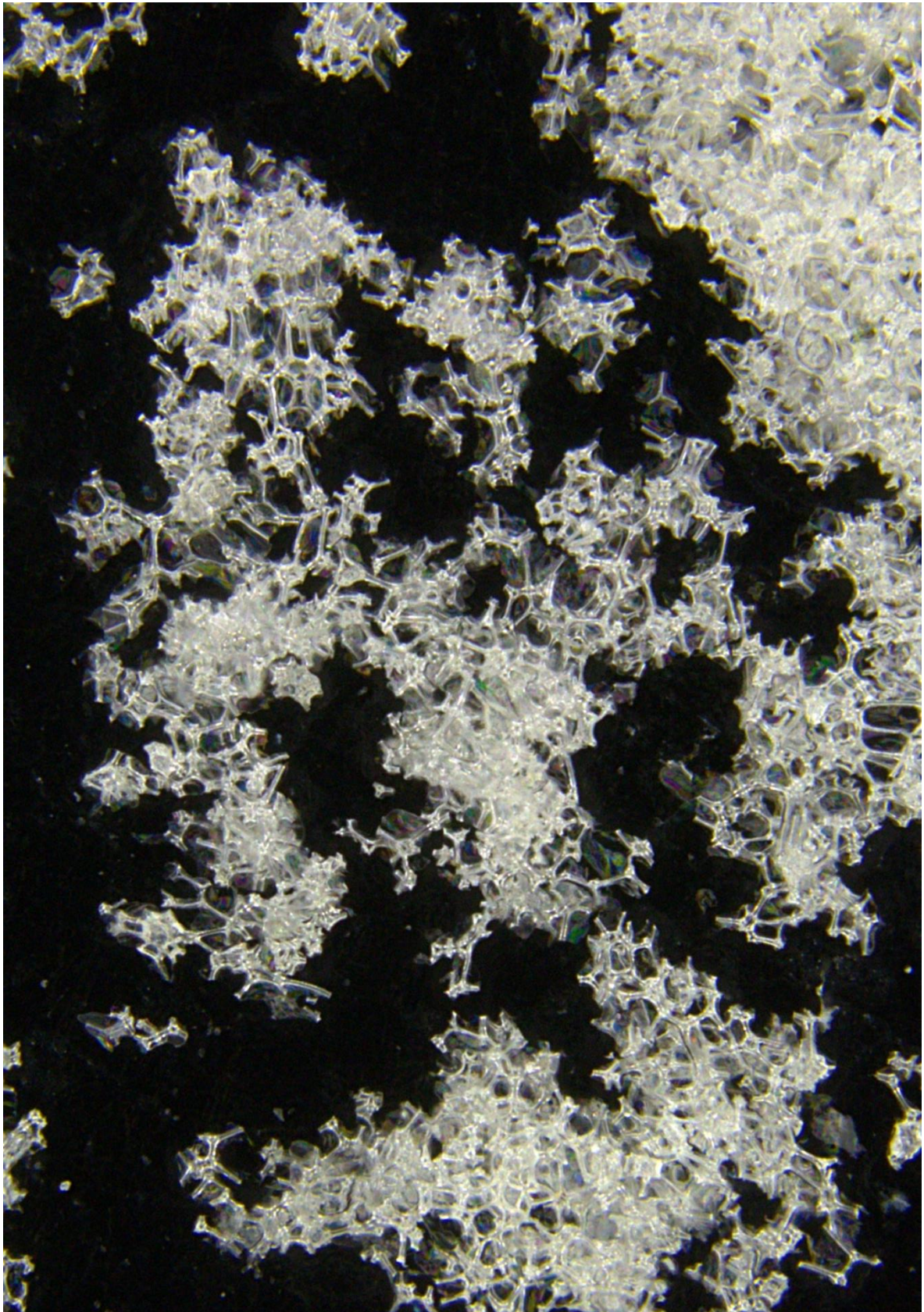
2.7.2.3 Study and Development of a Hand Prosthesis Using Soft Robotics Techniques

This project emerges as a response to the shortcomings of current conventional prostheses, particularly in terms of aesthetics, affordability, and mechanical functionality, all of which fail to adequately address the needs of their users. A human hand prosthesis was developed using soft robotics techniques, employing reverse engineering and 3D Printing. Concluded by the author,

Hugo Almeida, this project encountered significant challenges in harnessing the advantages of 3D Printing. As a potential avenue for future work, it has been suggested to explore the utilization of a more flexible material [27].

2.7.2.4 Affordable passive 3D-Printed prosthesis for persons with partial hand amputation

Partial hand amputations are a common issue affecting patients' quality of life. In this project, a passive hand was developed, using thermoplastic polyurethane, for a metacarpal amputation patient. Tests were conducted to assess the prosthesis' performance. The prosthesis significantly improved manual dexterity, particularly grasp stability. It was lightweight and easily worn by the patient. However, limitations included reliance on the contralateral hand for grasping and relatively low grasp strength. This research underscores the potential for an affordable, customized partial hand prosthesis [28].



3 Introduction

3.1 Material

The selected debris from the industrial medical waste were TPU and PU. Thermoplastic Polyurethane (TPU) comes from defective cosmetic prosthetics printed in 3D, and Polyurethane (PU) comes from machining residues of the production of limb models. Were tested different mixtures with injection moulding to evaluate the potentialities of using these formulations to create a new filament for 3D printing for the production of new prostheses. Figure 22 shows the wasted TPU and Figure 23 shows the wasted PU.



Figure 22 - TPU waste.



Figure 23 - PU waste.

The material was observed under a microscope LEICA M205 A with a Flexcam C3. From Figure 24 was possible to identify the different layers of the filament and conclude that there wasn't any contamination of the material. Figure 25 shows the PU waste in powder form and an approximate analysis of its composition.



Figure 24 - TPU waste - under microscope analysis.

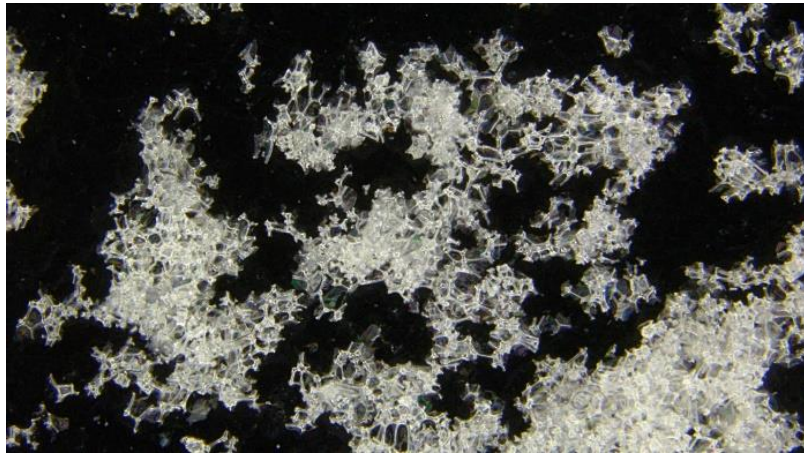


Figure 25 - PU waste – under microscope analysis.

3.1.1 Specific Weight

For Specific weight calculation, also known as specific gravity or relative density, a material's density is determined relative to the density of a reference substance. In this case, as seen in Figure 26, was used water as the reference substance.



Figure 23 - Recipients for Specific Weight calculation.

First, it was necessary to measure the weight of each of the four empty recipients. The noted down measurements are written in Table 3.

The next step was to fill the recipient with water up to a determined level marked by a blue line in each recipient shown in Figure 26. After filling, measure and record of the total weight were written down.

Then, the recipient was filled in with water and the material. Two were filled with PU and the other two with TPU. Again, it was measured the weight of each recipient.

To calculate the density of the two materials, it is necessary to divide the weight of the recipients with water and material, by the weight of the recipients with only water.

Finally, to obtain the average specific weight of the materials, the results were summed up and divided by the number of recipients used, that were two for each material.

Table 3 - Specific weight (g/cm³) of the components PU and TPU.

	Empty Recipient	Recipient with water	Recipient with material	Recipient with water and material	Results	Average results
PU1	27,57	80,02	28,01	74,38	1,128849	
PU2	28,85	75,44	26,76	65,16	1,210846	1,167
TPU1	29,36	79,67	33,69	79,85	1,087717	
TPU2	27,56	78,23	30,14	78,37	1,048482	1,07

Water Density -21°C 0,9979925 g/cm³

3.2 Process

3.2.1 Waste Gathering and Shredding

The creation of the material from debris required a rigorous and systematic approach, encompassing various essential steps. The process started with waste gathering of the PU powder and the TPU printed parts. It was necessary to shred the TPU, and it was done with a plastic geyser mill at Maitools Lda. Here was also possible to later test different formulations by injection moulding. The TPU required some manual shred, as seen in Figure 27, before entering the machine, due to its flexibility.



Figure 24 - Manual shredded TPU waste.

3.2.2 Injection molding and test of Possible Formulations

One crucial step was the injection of different formulations, a process that allowed to evaluate the viability and effectiveness of the resulting material for its intended applications. The choice

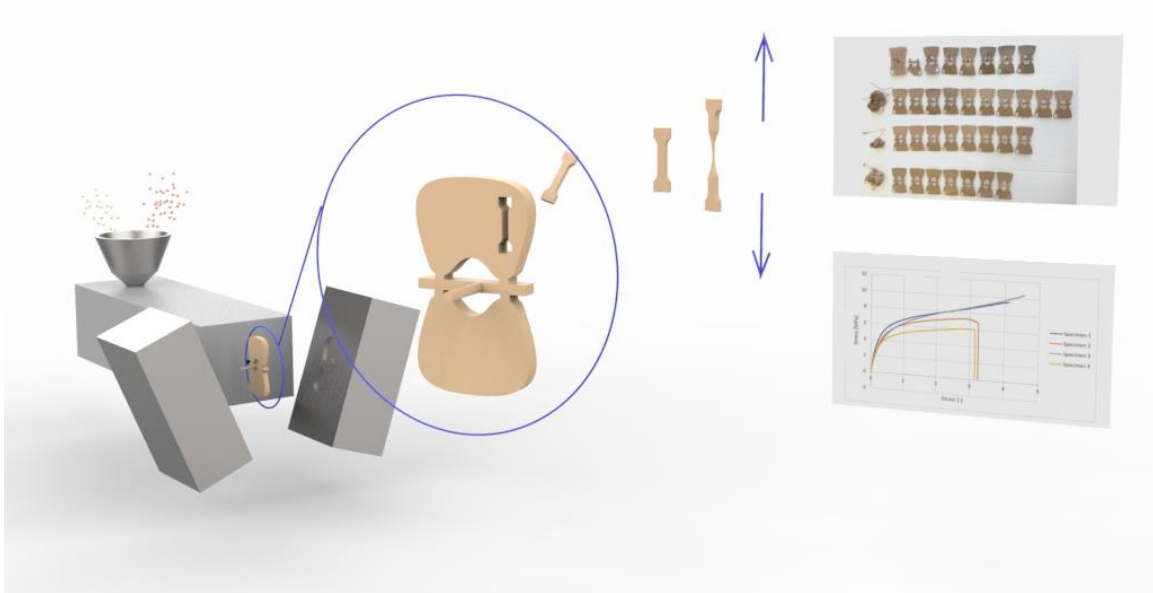


Figure 25 - Representation of the injection samples and tensile specimens.

of injection molding process was driven by several factors, including the equipment available for testing purposes. Figure 28 illustrates the injection molding process employed, utilizing an existing mold at the company maitools, Lda. The resultant parts were then used to extract small specimens for tensile testing. By injecting mixtures with different percentages of the material, was possible to explore the impact of varying compositions on the material's mechanical properties. Injection molding provided a practical and controlled method for producing specimens with a consistent shape and size, making it suitable for subsequent tensile tests and other mechanical assessments.

The Injection cycle, represented in Figure 29, goes through a dosing, injection, holding, cooling and extraction phase. This process may require more or less manual intervention depending on the machines.

In the dosing phase, the polymer is melted in the extruder screw and the amount of material to be injected into the closed mold is dosed. This amount depends on the weight and size of the piece. The material is first placed in the hopper. Then, the screw starts to rotate and the granules of material merge and are taken to the cannon. When the molten material reaches the nozzle, it is injected into the closed mold.

The screw pulls back to accumulate enough material in the barrel and pushes the material without turning to advance and fill all the mold cavities. After each shot, some material may back up in the nozzle and solidify after cooling. To avoid deformations, some pressure is applied to the nozzle by the thread and more material is injected to compensate for possible contractions.

After the part is injected, it needs to cool down before being demoulded. Depending on the capacity of the machine and the part, this phase of the process can vary in terms of time, taking a few seconds. Cooling can be through ambient temperature or liquid cooling methods for larger cases.

Finally, the part is extracted, which can be mechanical or through a pneumatic piston, depending on the geometry and complexity of the part. When the mold is closed again, the cycle starts again.

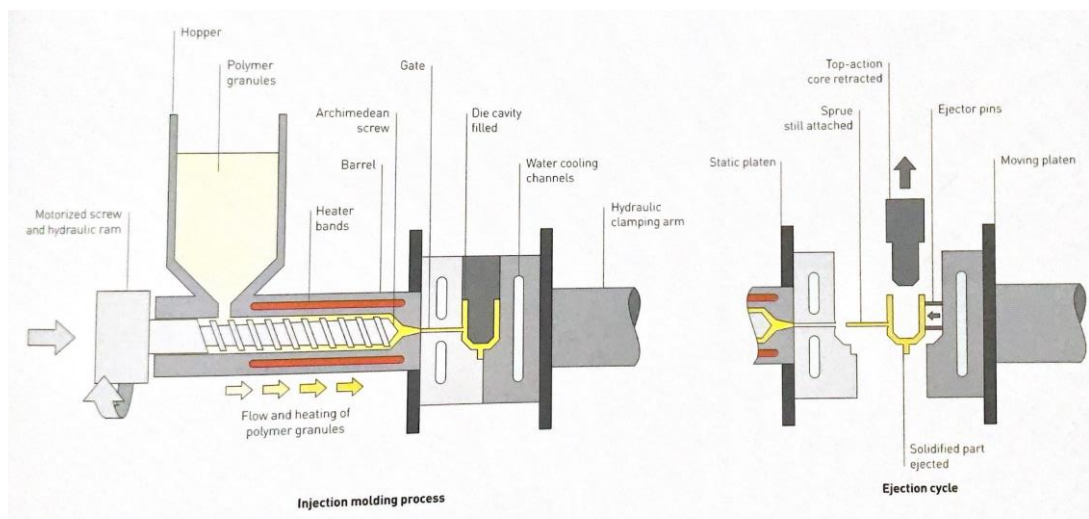


Figure 26 - Representation of the injection molding process [29].

The different parts of the Injection molding process are:

Hopper – The hopper directs the granules of material into the screw feed zone. In some more recent machines, this funnel is already replaced by silos that dry the material.

Cannon – Inside the cannon, the plastic is melted through electrical resistances

Screw – The screw is positioned inside the cannon and compresses and homogenizes the material for dosing. The three parts of the screw are the feeding zone, compression zone and dosing zone.

Nozzle – The nozzle connects the barrel to the mold bushing by contact only.

Mold – Metallic piece that shapes the product to be injected. This one has the ability to raise the temperature. Cooling pins ensure that the mold does not overheat.

Cooling channels – allow a fluid to circulate through the mold which ensures that it does not overheat.

Control system – Process monitoring, controlling temperature, injection speed, pressure, among other aspects. The correct use of the system influences product quality, process optimization and economic considerations.

Regarding the tests carried out, these presented conclusive results and that exponentially continue the project. The percentage of each component was calculated by weight. In terms of temperature, it was not necessary to heat the mold, that is, it was used cold and the material was easily injected and demoulded. The temperature used in the injection process ranged from 170°C to 200°C. The dosing phase was where the process showed more difficulties due to the low weight of the polyurethane. To get around this obstacle, the Funnel was removed and the material was injected more easily. In order to certify the correct mixture, it was placed in small doses in order to prevent the difference in weight of the components from altering the homogeneity of the mixture.

Through the documentation and identification of the samples of the different tests, shown in Figure 30, it was possible to immediately observe differences in color, both between the different percentages and in the sequence of samples of the same percentage.

Material Testing

- 0.5 kg – 10 % PU – 50 g
– 90 % TPU – 450 g
- 0.5kg – 20 % PU – 100 g
– 80 % TPU – 400 g
- 0.4Kg – 30 % PU – 120 g
– 70 % TPU – 280 g
- 0.3Kg – 60 % PU – 180 g
– 40 % TPU – 120 g

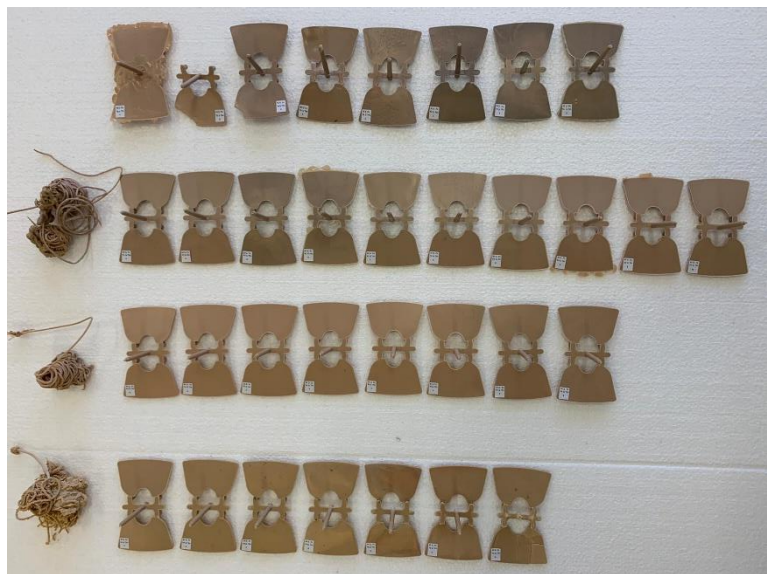


Figure 27 - Injection samples.

Some injection errors also made it possible to work around them in the following tests. These were dark spots when the temperature was higher (Figure 31 a)) or when there were problems in the dosage, non-homogeneity of the color in the tests with a higher percentage of polyurethane (Figure 31 b)), burrs in isolated cases, incomplete injection in an initial case (Figure 31 c)). Such errors were circumvented by adjusting the dosage, temperature, percentage of each component.

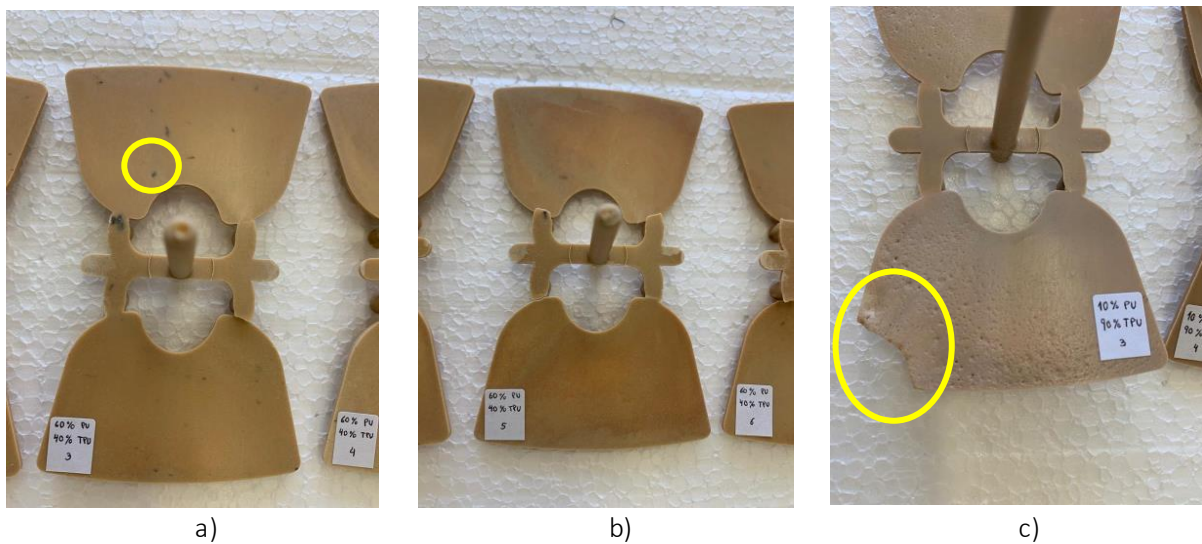


Figure 28 - Injected sample with errors – a) dark spots; b) non-homogenous color; c) incomplete injection.

3.2.3 Mechanical Characterization – Specimens from injection moulding samples

The formulations selected for injection samples were used for mechanical characterization by the standard EN ISO 527-2:1996 that specifies the test conditions for determining the tensile properties of moulding and extrusion plastics [30].

From each of the four Formulations, were taken four specimens, shown in Figure 32.

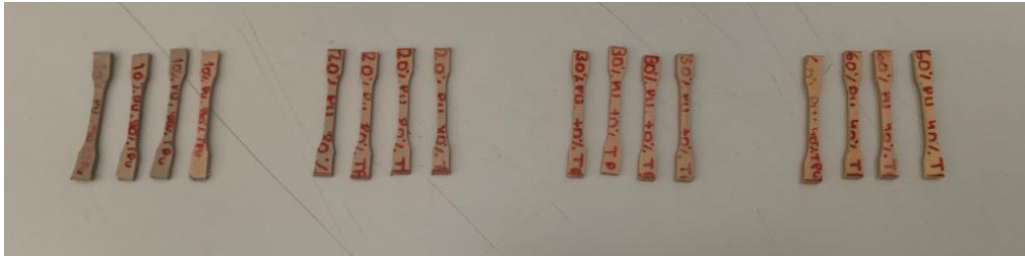


Figure 29 - Four Specimens from each Formulation.

The tensile tests were performed on this material to evaluate the mechanical properties of each formulation, particularly their strength and elasticity, under tension forces as seen in Figure 33. These tests were essential to provide the crucial information about a material's behaviour under stress. It is essential for designing safe and reliable products. The utilized machine for these tests was a MultiTest 2.5 -dv Mecmesin. Later in the process, were made tensile tests to 3D printed specimens to compare with the results obtained at this point.



Figure 30 - Tensile tests made to the different formulations.

From Figure 33 to Figure 36 are presented the stress vs. strain curves obtained by the experimental tests.

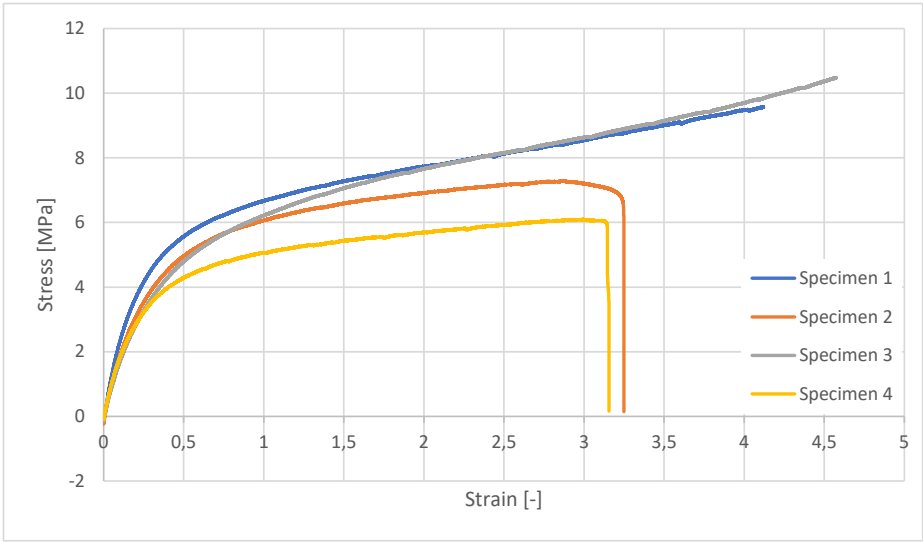


Figure 31 - Stress vs. strain curve for formulation 10% PU + 90% TPU.

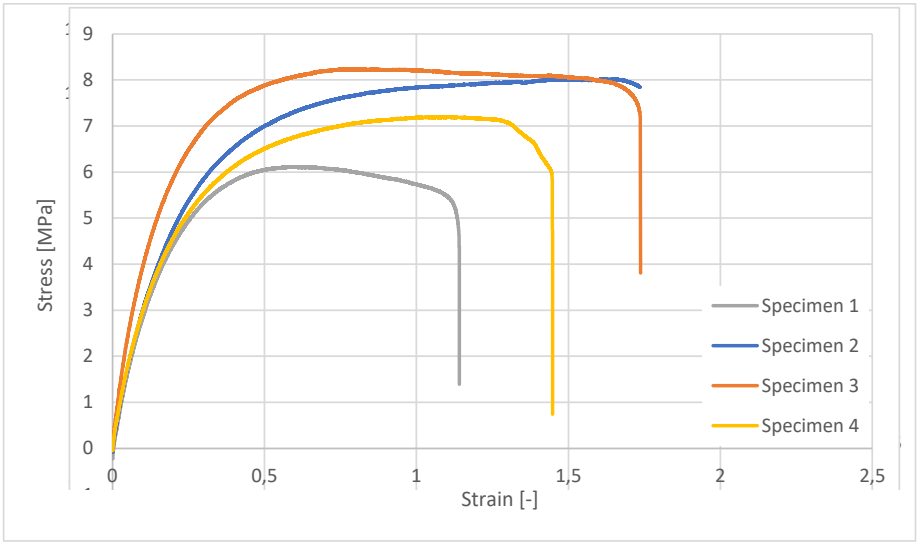


Figure 32 - Stress vs. strain curve for formulation 20% PU + 80% TPU.

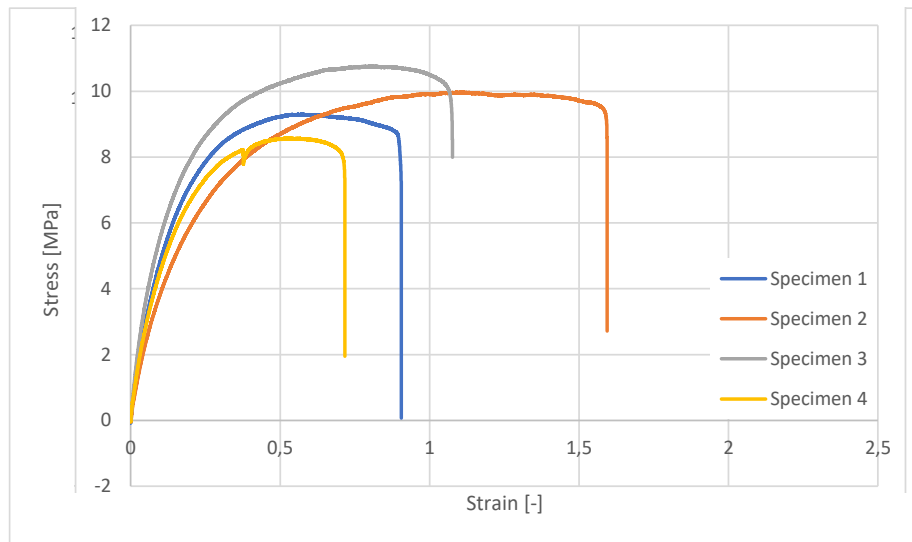


Figure 33 – Stress vs. strain curve for formulation 30% PU + 70% TPU.

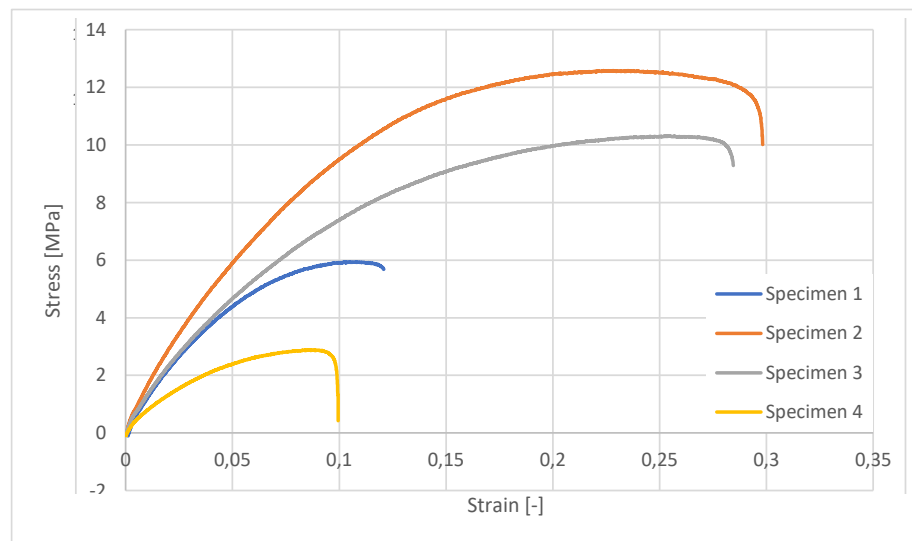


Figure 34 - Stress vs. strain curve for formulation 60% PU + 40% TPU.

Table 4 to Table 6 represent the results from the tensile tests. The mechanical characterization tests shown that as the percentage of PU increases, the modulus of elasticity increases, and the plasticity inherent to the material declines.

Table 4 - Results from tensile tests on specimens with the formulation 10 % PU and 90 % TPU.

20,7 MPa	Average
1,7 MPa	Standard deviation
8,0 %	CV (coefficient of variation)

Table 5 - Results from tensile tests on specimens with the formulation 20 % PU and 80 % TPU.

32,9 MPa	Average
0,6 MPa	Standard deviation
1,9 %	CV (coefficient of variation)

Table 6 – Results from tensile tests on specimens with the formulation 30 % PU and 70 % TPU.

47,1 MPa	Average
5,2 MPa	Standard deviation
11,0 %	CV (coefficient of variation)

Table 7 - Results from tensile tests on specimens with the formulation 60 % PU and 40 % TPU.

83,3 MPa	Average
14,7 MPa	Standard deviation
17,6 %	CV (coefficient of variation)

The standard deviation values for the different formulations suggest variations in tensile strength within each group of specimens. The lower standard deviation values in Table 5 (20 % PU and 80 % TPU) indicate more consistent results compared to the higher values in Table 7 (60 % PU and 40 % TPU).

The coefficient of variation, representing the relative variability of the data, is relatively low in Table 4 (8,0) and Table 5 (1,9), indicating more consistent behaviour compared to Table 7 (17,6), which exhibits greater variability.

From the results, it can be inferred that a formulation with 10 or 20 % of PU content may strike a balance between tensile strength and consistency. The formulation selected for the manufacturing was 10% PU + 90% TPU.

3.2.4 Extrusion to pellets

In order to achieve material homogeneity before the extrusion process into filament, it was essential to convert the material into pellets. To accomplish this task, the twin-screw, co-rotating, Coperion ZSK 26 Extruder machine was employed at the PIEP facilities, with the valuable assistance of Engineer Pedro Mimoso and Engineer Sónia Miranda. The resulted pellets were meticulously examined using a LEICA M205 A microscope with a Flexcam C3, allowing for detailed observation and analysis, as seen in Figure 38. The twin screw extruder was used due to the study in the article “Reprocessing Postconsumer Polyurethane Foam Using Carbamate Exchange Catalysis and Twin-Screw Extrusion”, when polyurethane is reprocessed with positive results into film by using a Twin-Screw extruder [31].



Figure 35 - Pellets - microscope analysis.

Figure 39 represents the pellet production process. Before mixing the components, each component was separately placed in the oven for 4 hours at 80°C for Polyurethane and 4 Hours at 90°C for TPU.

Subsequently, the material is introduced into the dosing units that serve the feeders for the extrusion machine. At the beginning of the extrusion process, TPU is introduced through a single-screw dosing unit. The powdered polyurethane is introduced through a side feed inlet with a double-screw dosing unit. This way, the TPU gradually heats up and passes through the screw, allowing the powder to be introduced midway and ensuring proper blending of the two materials. The temperatures used for extrusion range between 185°C and 190°C. Initially, HDPE is extruded to clean the machine and remove any possible material contamination. Then, the dosing units

are calibrated to dispense the correct percentage of each material into the screw. They are connected to the feed inlets are programmed to extrude at a rate of 1 KG/hour.

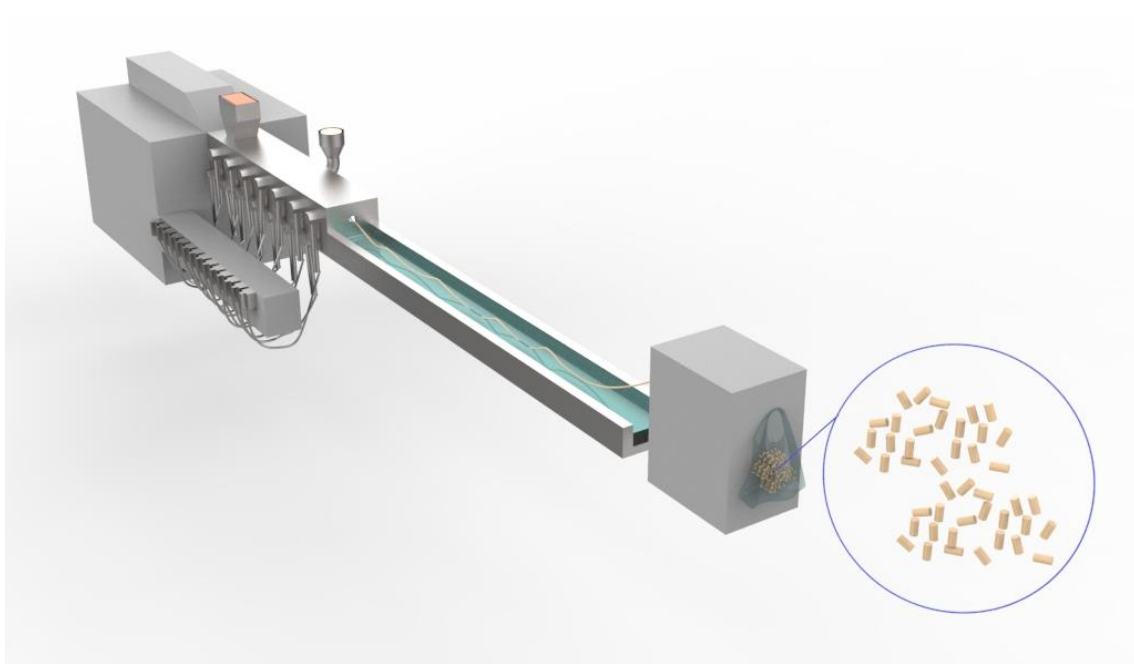


Figure 36 - Representation of the Pellet production process.

After extrusion into filament format, without proper filament calibration, the filament passes through water for cooling. Alternatively, it can be air-cooled. Before going through the grinding machine, the material has the appearance shown in Figure 40 and 41. The formulations with 20 and 30% PU content were subjected to testing as well. However, these formulations encountered challenges primarily related to the weight of the polyurethane component. Nonetheless, this testing indicated that with additional research and the use of alternative equipment or dosing methods, it may be feasible to successfully produce these particular formulations. At present, the most promising formulation is the one containing 10 % PU.



Figure 37 - Filament extruded before going through grinding into pellets (20 % PU + 80 % TPU).



Figure 38 - Filament extruded before going through grinding into pellets (30 % PU + 70 % TPU).

Then, the filament material goes through a grinding machine that transforms it into pellet format (Figure 42). Initially, there were difficulties in granulating due to the material being primarily an elastomer. Adjustments were made to the percentage, and the speed was increased to 2 Kg/hour. It became possible to granulate with the chosen percentage of 10 % PU and 90 % TPU. The result was approximately 3 kg of pellets, which then undergoes the oven process again and, finally, goes through a 3Devo composer, which transforms the material into calibrated filament for 3D Printing.



Figure 39 - Obtained material in pellets.

The used machine (Figure 43) had the following configuration of extrusion:

Temperature Range: 60 to 400°C

Minimum Speed: 180 rpm

Screw diameter: 26 mm

L/D ratio: 40

The extruder is composed of side feeders, gas vents, a vacuum extraction system, and can be used with a die size of either 3 mm or 4 mm.



Figure 40 -Extruder Coperion ZSK 26.

Figure 44 illustrates the modular formatting of the extruder cylinder. For better understanding, number 1 represents the hopper, number 2 and 4 are the Side feeders, the gas exhaust is placed in the number 3 and 5, and, finally, the vacuum extraction system at number 6.

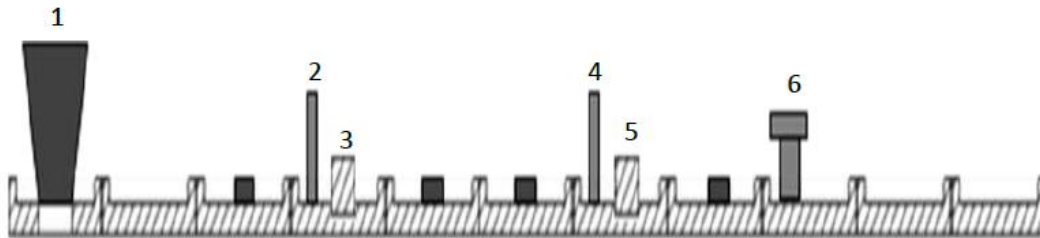


Figure 41 - Schematic illustration of the modular formatting of the extruder cylinder.

Figure 45 represents the used spindle configuration for the extrusion. As is usual in any extrusion compounding test, the phenomena of distributive and dispersive mixing must be critically and significantly taken into account in order to achieve a filament with ideal uniformity and homogeneity. For that, the polymer mixture was introduced into the hopper of the extruder through a gravimetric feeder with its corresponding single screw, shown in Figure 46 and Figure 47.



Figure 42 - Used spindle configuration.

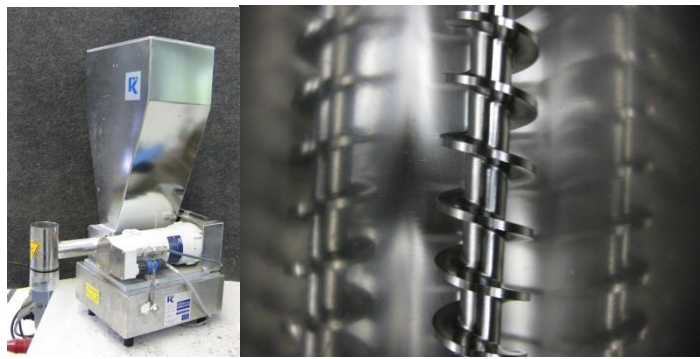


Figure 43 – Gravimetric doser K-SFS-24 and respective single spindle.



Figure 44 - Gravimetric doser K-SFS-24 and respective single spindle.

3.2.5 Extrusion to 3D Filament

After obtaining the material in pellet form, the next step was extruding to 3D Filament in a 3Devo machine. Figure 48 illustrates the extrusion process.

Was used a 3Devo composer machine at PIEP facilities, and also at FEUP. Prior to the extrusion process, the material underwent a crucial step of humidity removal, which entailed subjecting the material to a muffle before each trial on the machine. The material goes into the extrusion machine and passes through a spindle with four heaters. Then, the material extrudes through the nozzle and it starts to get pulled onto a spool. It is crucial to mention that the extrusion process parameters, such as temperature, screw speed, and extrusion rate, can significantly affect the final properties of the filament. Optimization of these parameters is essential to achieve consistent filament diameter, good surface quality, desired mechanical characteristics and printability. By extruding the material into a 3D filament with a standard size of 1.75 mm it can be used in various 3D printers. For the initial printing tests, Prusa MK3 printers were utilized.

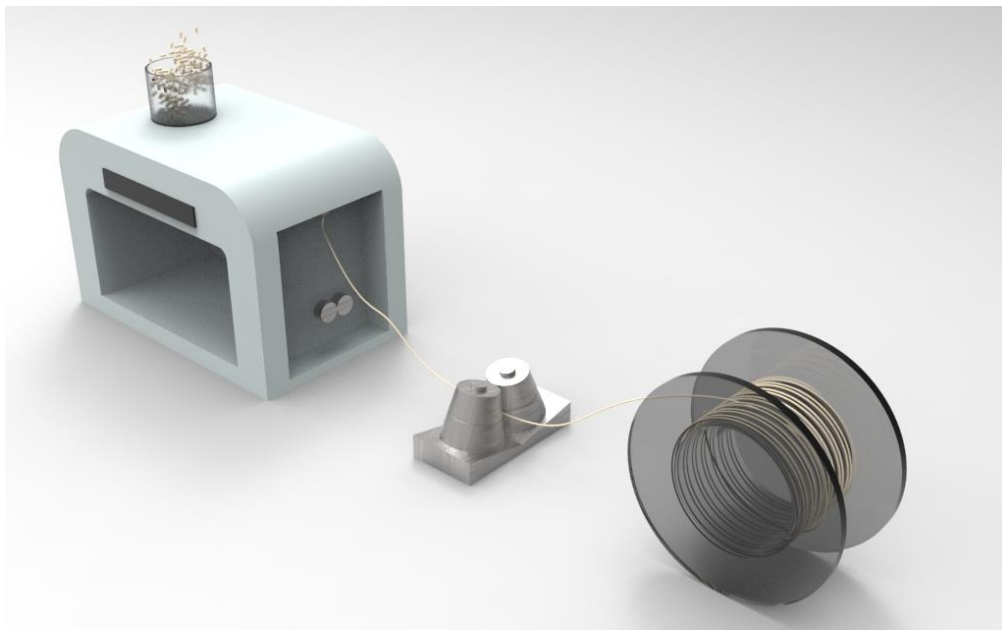


Figure 45 - Representation of the extrusion process to 3D filament.

Despite encountering challenges with temperature and speed adjustments, a consistent filament with minimal texture was eventually achieved. However, the process was hindered by a faulty resistance in the machine at PIEP facilities, leading to interruptions and filament breakage. So, it was required to use also the 3Devo extrusion machine at FEUP. In the next attempts, tests were conducted at different temperatures, and HDPE or PLA were used as transition material. The focus was on fine-tuning temperature control, screw speed, and cooling settings to improve the process.

For the third attempt, recommended base settings were provided by 3Devo support. A series of temperature and speed configuration were tested, ultimately leading to better outcomes with higher temperatures but necessitating improved cooling to prevent filament flattening.

In the fourth attempt, efforts were made to find the optimal configuration for material extrusion. The sensitivity of the material to small changes required several tests, and it was observed that the very high temperatures were necessary, leading to challenges in achieving sufficient cooling time. To address this, lower extrusion temperatures were attempted, but this compromised material mixing and surface quality. The proposed solution involves adapting the filament compression to allow for more cooling time and improved compression quality.

Throughout the attempts, adjustments were made to achieve the desired filament quality, and further configuration.

3.2.5.1 3Devo Machine

A successful extrusion process requires good equipment conditions and cleanliness, proper material selection, and correctly programmed settings.

The next subtopic represents the steps for extruding in a 3Devo machine. Subsequently, will be aborded some errors find through the process and how to avoid them [32].

Material Selection:

Starting by choosing the material for extrusion. It is important to ensure compatibility between the material and the extrusion process. Experimentation may be necessary, especially for the material with low viscosity. The properties of the material before and after extrusion may vary.

Drying:

Most polymers are hygroscopic and easily absorb moisture. Therefore, it is necessary to dry the material in an oven before extrusion to prevent moisture-related issues that can affect filament quality.

Extrusion Testing Preparation:

It is crucial to plan and structure extrusion tests to minimize material waste and quickly achieve desired results. Each material has its own technical specifications and it must be chosen a transition material with a similar melting point.

Transition material: It should be used a transition material at the beginning of the extrusion process to clean the machine and facilitate the passage of the main material. This transition

material helps to push out any remnants from the previous material, as the machine is never completely empty. It is also useful for transitioning between materials with different extrusion temperatures, as shown in Figure 49. In this case, the transition material does the passage between material A (with low temperature) to material B (with high temperature). Common transition materials include HDPE, PE, PLA and PP.

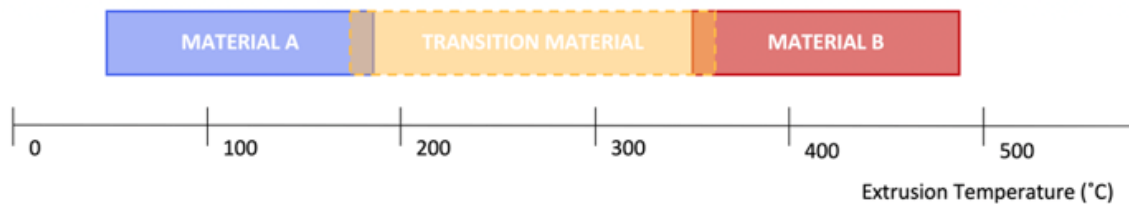


Figure 46 - Material Transition in a 3Devo machine [32].

Temperature settings:

Proper temperature settings are essential for successful filament extrusion. Low temperatures can result in improper material fusion. When working with a new material, it is recommended to test all the resistance heaters at 10% above the material's melting point. Adjustments can be made to find the optimal temperature settings.

Finding the Optimal settings:

Starting with temperature settings 10 % above the melting point, it may be necessary to make adjustments as needed. The recommended base speed is 5 rpm. The goal is to ensure that the material solidifies enough to be compressed by the rollers and pulled for collection. Can be done adjustments in increments of 5°C and allow time for the adjustment to take effect. Speed adjustments are typically made between 3 and 6 rpm, while fan settings are recommended between 10 and 80 %.

Filament winding

This next step required to wind the material at the ideal speed to avoid excessive tension and deformation. The roll measurements are entered into the machine, and it will adjust the settings accordingly.

Cleaning:

There is always some residual material left inside the machine, as it cannot be completely emptied. Therefore, a cleaning material is necessary. Commonly used cleaning materials include

HDPE, PE, PP and PLA, all of which are colorless to allow for the detection of any contamination. These cleaning materials ensure that the machine does not get clogged or damaged when cold and that there is no contamination from the previous material. 3Devo also offers cleaning materials such as Devoclean MidTemp EZ or Devoclean HighTemp. Using cleaning materials other than the recommended ones can cause irreversible damage.

Experimentation for Results:

Experimentation allows for the adjustment of extrusion settings specific to the material being used.

3.2.5.2 Surface Quality Filament defects:

There are many causes for filament defects and some of the mentioned below are a mixture of the study provided by 3Devo support and the conclusions from the extrusion of the created material [33].

Surface defects

Surface defects such as scratches and material contamination can result from a lack of nozzle cleaning, which can damage, or simply cleaning the nozzle if there is accumulated material.

Nozzle clogging

Material accumulation at the nozzle tip can occur if the nozzle temperature is too low, causing the material to solidify. This is more common with semi-crystalline polymers because the nozzle temperature is lower than the material's melting point.

Streaks caused after extrusion

This error can occur outside the extrusion unit and nozzle, by having a machine direction streak and the problem could be in the filament sensor and puller wheel or in the positioner and winder. This error is usually easy to detect and correct. It needs to be identified where or what is scraping or damaging the filament surface after the nozzle unit.

Distortion of Filament form

If the Filament comes out with rough surface it can be due to two causes.

Sharkskin – As seen in Figure 50 the appearance is something similar to this case. It happens when the outer layer moves faster than the inner layer. That can cause melting and consequently sharkskin. It can be corrected by increasing temperature in Heater 1 or drop all the heaters to less temperature, resulting in a more elastic output.



Figure 47 - Sharkskin example with the new material.

Melt fracture – This error usually has the appearance of helical distortion that can be so accentuated that the filament spirals or small ripples appear. To correct this the temperature could be increased in all of the heaters to solve the melt fracture. Or the screw speed can be decreased to decrease the shear rate. (Figure 51)



Figure 48 - Melt fracture example with the developed material.

Non-homogeneous mixture

This error, illustrated in Figure 52, usually occurs due to a melt fracture and a high speed off the spindle. This can be corrected by decreasing all heaters and slow down the speed configuration.



Figure 49 - Non-homogeneous mixture with the developed material.

Uneven Thickness

If the speed of the spindle is too high, it can result on an irregular extruded filament, in this case it can get too thin, as seen in Figure 53.



Figure 50 - Thin thickness example with the developed material.

Quick temperature drop

As a new material, it needs experimental configurations until finding the more adjustable. So, when in trials, if the temperature gets decreased too quickly, the filament tends to get like in Figure 54 and it could be avoided by changing temperatures a few degrees at a time.



Figure 51 - Example of a quick temperature drop on the developed material.

Short cooling time

In the case of this material, and it can happen with other new materials, it required high temperature for extrusion and it ended up not having much time for cooling until the phase of spooling. The filament, after being extruded out the nozzle, passes through the cooling vents and right after, through rollers that pull the filament and configure its thickness so it can be spooled. As seen in Figure 55, because there is no time for cooling, when the material gets into the rollers, it gets flattened. This way, the solution was to expand the cooling time by creating some adaptors as seen in Figure 56 and the error was successfully adjusted. The spooling was made manually right after the filament passes through the adaptor.



Figure 52 - Flattened filament example with the developed material.

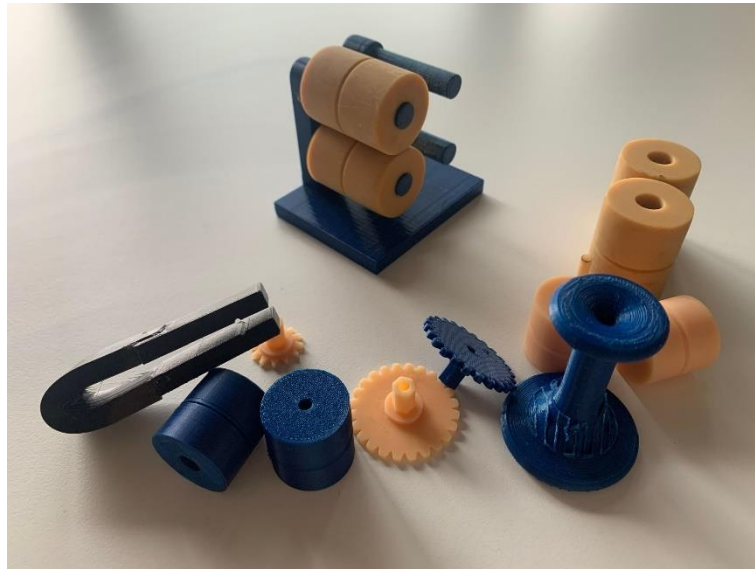


Figure 53 - Adaptors made to try out to spend the cooling time between nozzle extrusion and filament spooling.

Some adaptations were tried out, as seen in Figure 56, developed to provide more cooling time and better control over the filament's thickness. This final adaptation (Figure 57) was modelled in Rhinoceros and rendered in Keyshot.

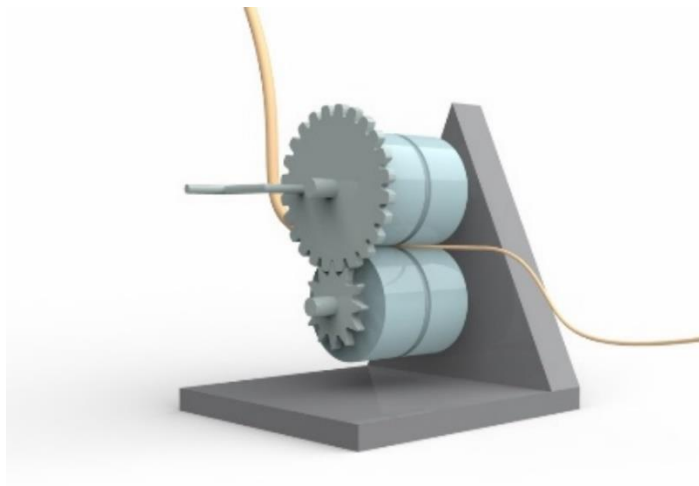


Figure 54 - Final adaptation to the 3Devo machine.

It was printed using PLA on the Prusa MK3 3D printer at the Faculty of Engineering of the University of Porto. The obtained result showed limited accuracy and quality in the part of the rolls that define the filament. However, the mechanical properties were good. Notably, the millimetre specifications demonstrated ample clearance for filament definition, coupled with substantial traction between the rollers. Subsequent experimentation involving resin, printed in a Prusa printer, however, yielded unsatisfactory mechanical properties, indicating the limitations of this alternative approach.

3.2.6 Printing Tests

Initial printing tests were conducted to assess the material's viability comprehensively. These tests aimed to evaluate critical attributes such as flexibility, color, durability, mechanical properties, and its resemblance to existing external prostheses cosmetics.

Additionally, a temperature tower (Figure 58 a)) was printed to ascertain the optimal temperature range for successful printing with the recycled material (between 200°C and 250°C). Such preliminary tests hold paramount importance in understanding the material's behaviour during the printing process, identifying potential challenges, and fine-tune the printing parameters to achieve desired results. As illustrated in Figure 58 b), a passive hand was printed to assess the material's suitability for external prosthesis applications, considering its color and surface quality. Furthermore, Figure 58 c) depicts the printed part used for evaluating the material's flexibility. These printed prototypes serve as crucial experiments to usage conditions. The results derived from such tests aid in determining the material's compatibility with specific prosthesis designs, its ability to withstand mechanical stresses, and its overall visual appeal. This comprehensive evaluation helps in making informed decisions about incorporating the material into actual prosthetic devices and highlights the material's potential for broader applications in the field of external prosthetics. These parts were printed in a Prusa MK3, with a nozzle temperature of 230 °C and a bed temperature of 60 °C. These specific temperatures settings were chosen to ensure proper filament extrusion and adhesion to the built platform, facilitating successful 3D printing of the prototypes. Temperature control plays a critical role in achieving the desired material flow and layer adhesion, directly impacting the final quality and mechanical properties of the printed parts.

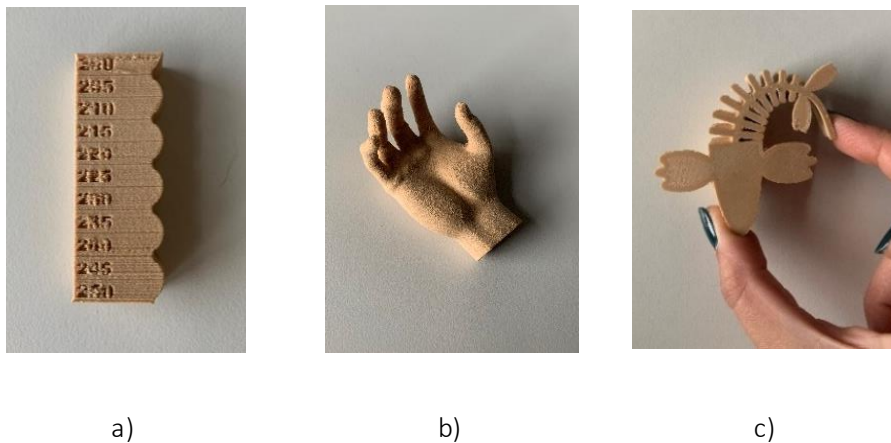


Figure 55 - Printing tests a) Temperature tower; b) Passive hand; c) Part for flexibility testing.

3.2.7 Mechanical Characterization – Specimens from 3D printed samples

Subsequent to the completion of the 3D filament extrusion process, it is essential to consider the potential influence of the various thermal and mechanical treatments the material has undergone. These intricate processes can impart alterations to the material's mechanical properties, necessitating further investigation. To address this, a series of additional tensile tests were conducted to discern any disparities between the 3D printed samples and their counterparts fabricated through the injection molding technique.

The significance of conducting these supplementary tensile tests lies in the comprehensive evaluation of the material's mechanical behaviour under distinct manufacturing conditions. By subjecting both the 3D printed and injected samples to the same testing protocol, a direct comparison can be made, enabling a precise assessment of any variations in their mechanical characteristics.

Additionally, the results obtained from these comparative tensile tests provide invaluable insights into the consistency and reproducibility of the material's mechanical performance. The formulations selected for injection samples were used for mechanical characterization by the standard EN ISO 527-2:1996 that specifies the test conditions for determining the tensile properties of moulding and extrusion plastics [30].

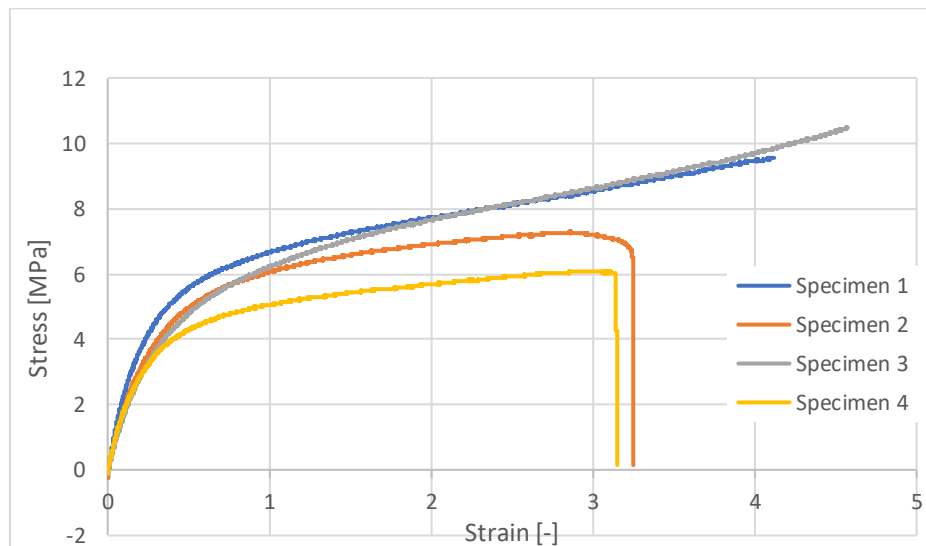


Figure 56 - Stress vs. strain - samples from injected moulding samples (Formulation 10%PU + 90%TPU).

Figure 59 shows the previous results of the chosen formulation (10%PU + 90%TPU) to be possible to compare to the data in Figure 60, done after the 3D Filament extrusion. These specimens were 3D Printed in a Prusa MK machine.

Certain irregularities become apparent in the graphics depicting the tensile tests, attributed to the stratification inherent in the 3D printing process. Nevertheless, the material's mechanical properties do not appear to have undergone substantial degradation.

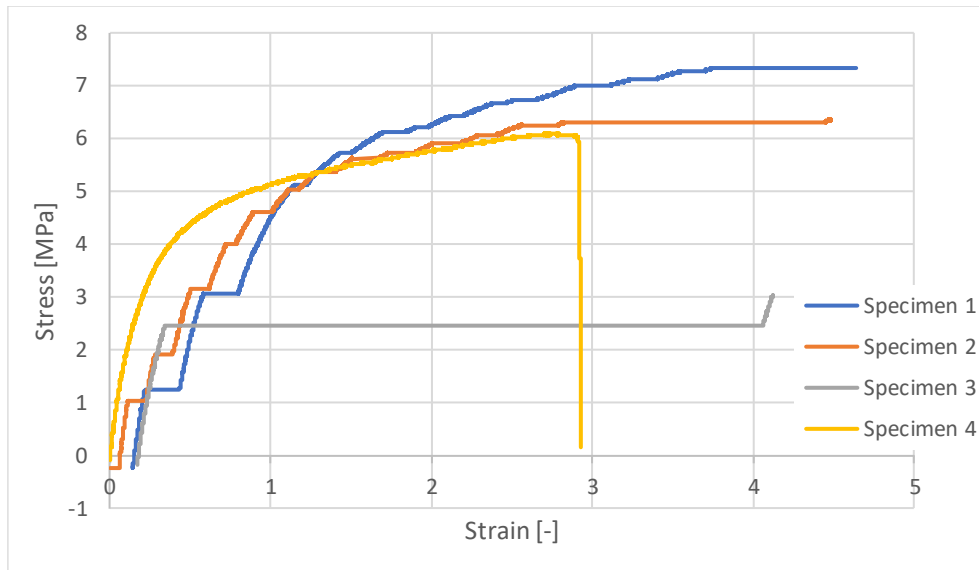


Figure 57 - Stress vs. strain - samples from 3D Printed samples (Formulation 10%PU + 90%TPU).

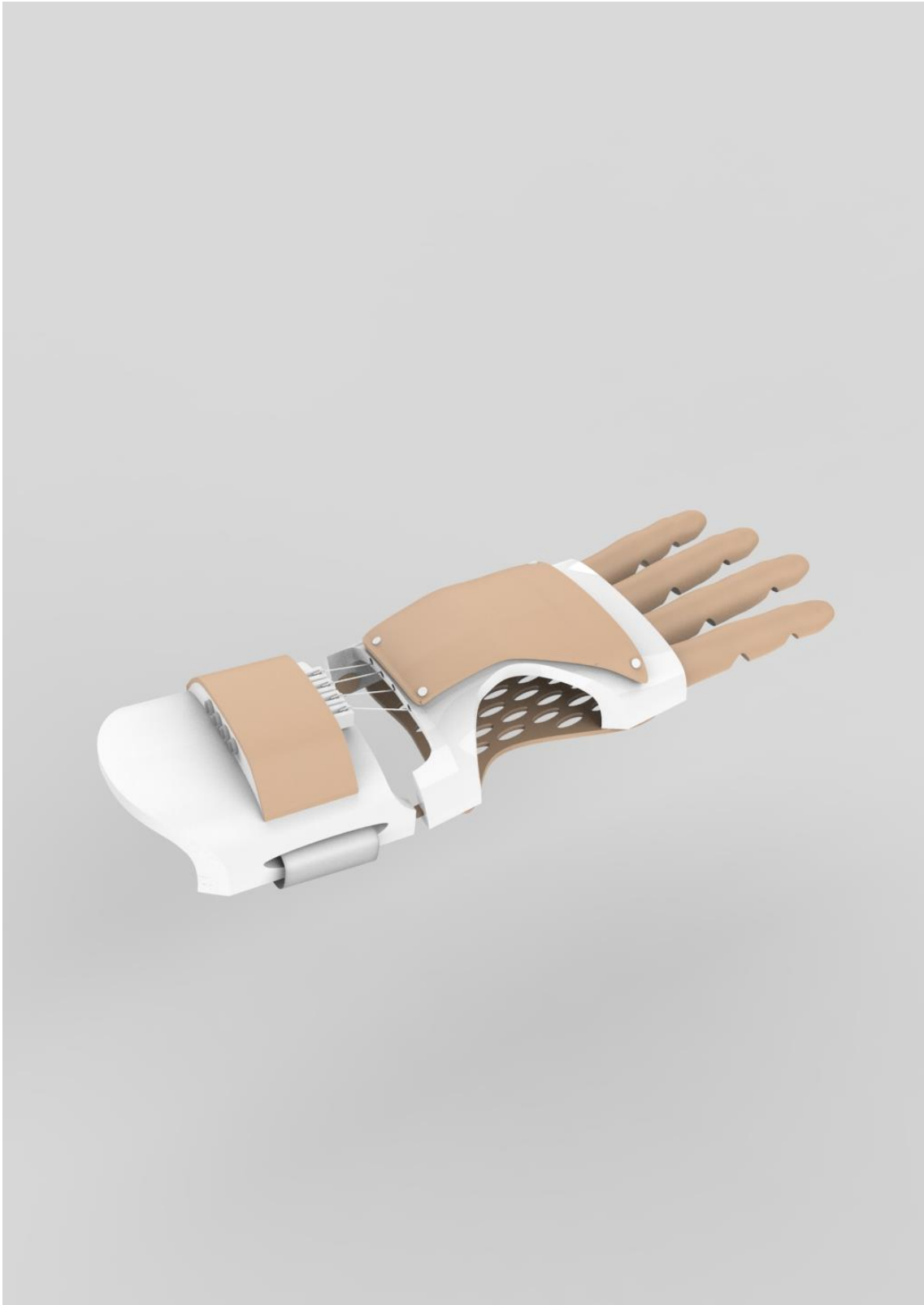
The data acquired from the comparison from the tests conducted on the injected molded specimens (Table 8) with those of the 3D printed specimens (Table 9), reveals that the 3D printed material showcases enhanced consistency, albeit with minor decrease in average values of tensile properties. This suggests that the 3D printing process may offer benefits in terms of material uniformity and has potential to be further optimized to maintain or improve average property values while capitalizing in its improved consistency.

Table 8 - Results of the Tensile Tests from Injected samples with the formulation 10 % PU and 90 % TPU.

20,7 MPa	Average
1,7 MPa	Standard deviation
8,0 %	CV (coefficient of variation)

Table 9 - Results of the Tensile Tests from 3D Printed samples with the formulation 10 % PU and 90 % TPU.

17,6 MPa	Average
2,1 MPa	Standard deviation
0,1 %	CV (coefficient of variation)



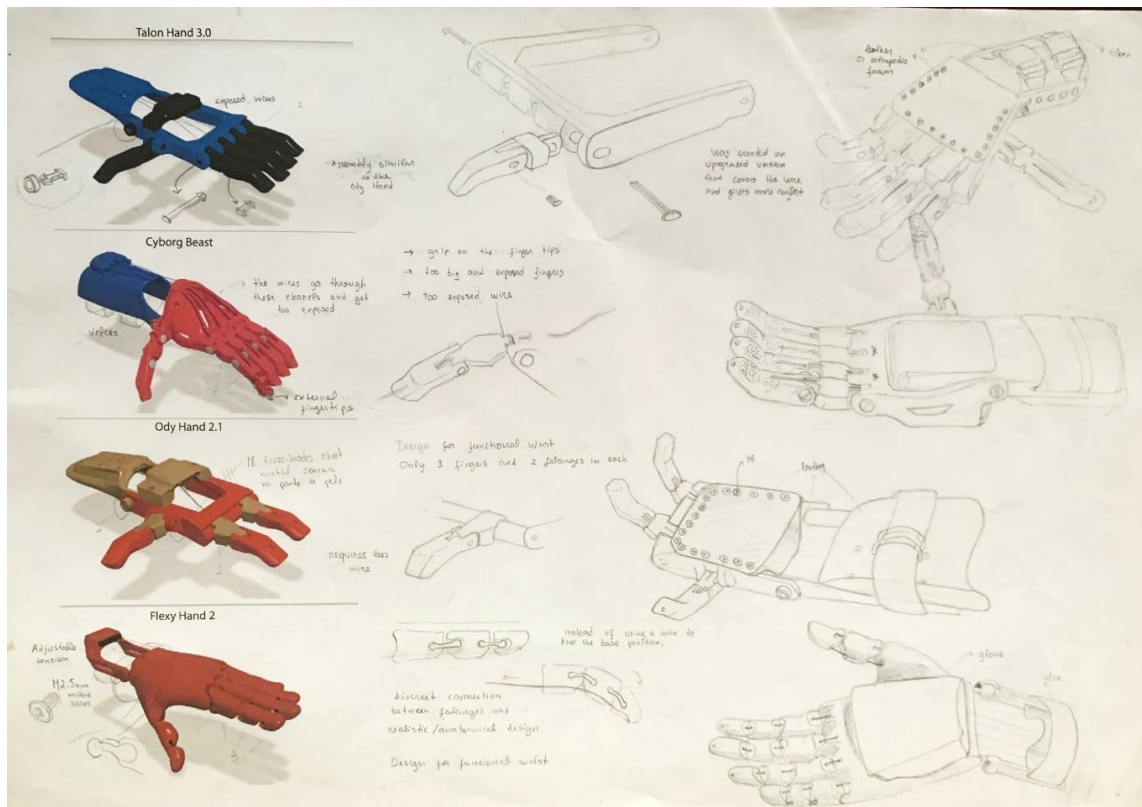


Figure 61 - Hand analysis of the models Talon hand, Cyborg beast, Ody hand and Flexy hand.

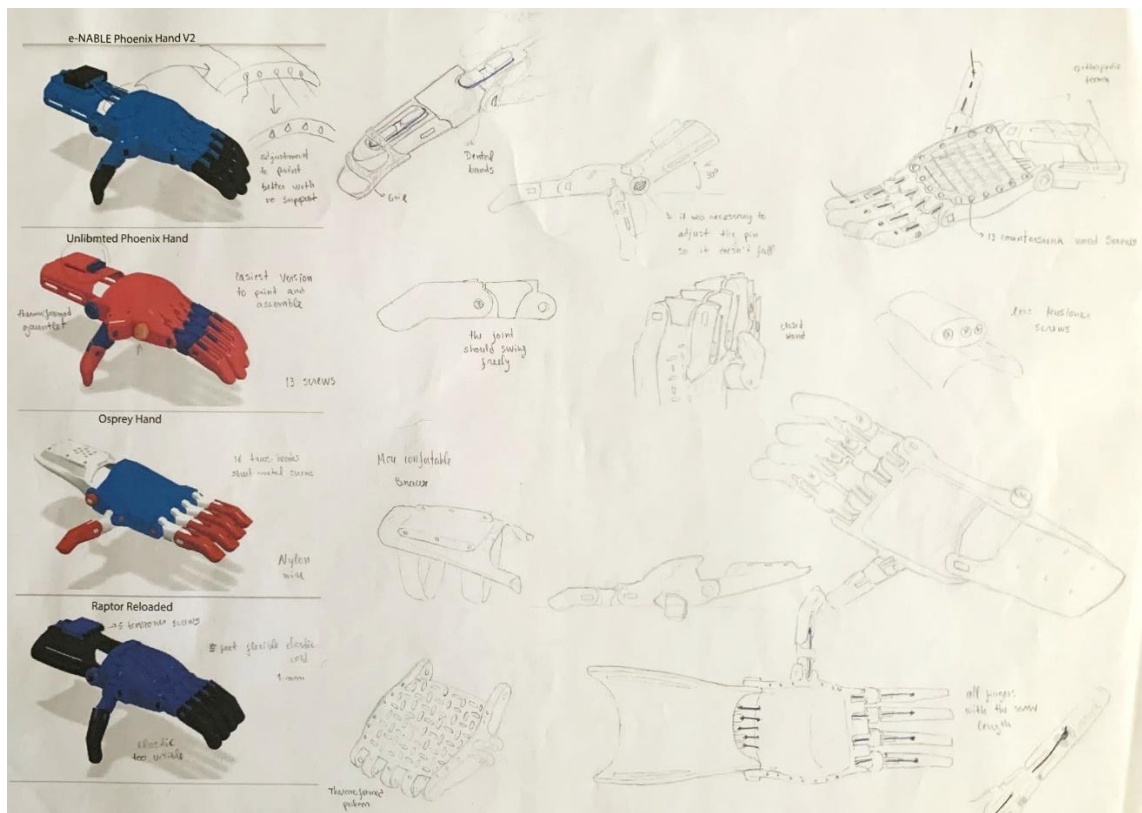


Figure 62 - Hand analysis of the models Phoenix hand, Osprey hand and Raptor reloaded.

The selected two models were printed and tested in terms of assembly, weight, comfort, among other factors, as shown in Figure 63. The models were 3D Printed using PLA (Polylactic Acid) on PRUSA MK3 printers. Some notable errors or characteristics observed in both printed were for example the assembly of numerous parts that could be reduced, as well as the need for print supports. It is essential to highlight that sustainability played a pivotal role in the project's execution. During the printing process, were used filaments that were nearly finishing and would otherwise be discarded as waste or kept for use of small prints. Consequently, the utilization of such remnants contributed to the unique characteristic of the printed parts, resulting in a variation of colors among the components.

Throughout the analysis, various aspects were thoroughly accessed, encompassing assembly complexity, weight, comfort, and other pertinent factors. Several noteworthy observations emerged from the assessment process, highlighting opportunities for improvement. For instance, it was noted that certain models necessitated assembly of numerous parts, which potentially could be streamlined through reduction. Additionally, the presence of print supports was identified as a characteristic requiring attention.

It is crucial to underscore that this comprehensive analysis was undertaken by the author, providing valuable insights into the strengths and weaknesses of the evaluated models. These findings served as a crucial foundation for informed decision-making during the development of the Flexy Grip, contributing to its enhanced design and performance characteristics.



Figure 63 - E-Nable standart hands 3D printed for study of the assembly and mechanical properties.

4.2 E-Nable Case

The “FlexyGrip” was meticulously crafted using the innovative recycled material derived from industrial waste, incorporating TPU and PU as the only components. This strategic choice of components for the material allowed to design a fully designed finger. In conjunction with some PLA parts, such as the main body, gauntlet, and pins, the hand was assembled, relying on a careful balance between design ingenuity and inherent qualities of the chosen materials. Vital components, such as the fingers, palm, covers and flexible connections, were expertly designed with the recycled material, taking advantage of its qualities.

The development process, while marked by significant achievements, encountered notable challenges, particularly in achieving a high-quality filament with the desired thickness, essential for seamless 3D printing. Compounded by the limitations of the filament-making equipment, attaining the desired final parts demanded unwavering dedication and perseverance, ultimately resulting in a resounding success.

The groundbreaking features of this hand stem from its harmonious fusion of cutting-edge design and the novel application of the recycled material. Additionally, the comprehensive analysis of existing standard E-Nable hands facilitated the integration of advantageous characteristics while avoiding potential pitfalls, elevating this product to the forefront of innovation in the field. This mechanical hand was designed for a 10-year-old girl through the E-Nable project. [34]

The drawings depicted in Figure 67 present preliminary concepts for the “FlexyGrip” model- They encompass rough ideas concerning the finger measurements and adaptations required for the hand’s fitting.

The work conducted by Daniel Ferreira in his master’s thesis has proven to be exceptionally relevant to the development of his mechanical hand. His contributions were thoroughly considered, and his methodological approach was carefully studied in this research [26].

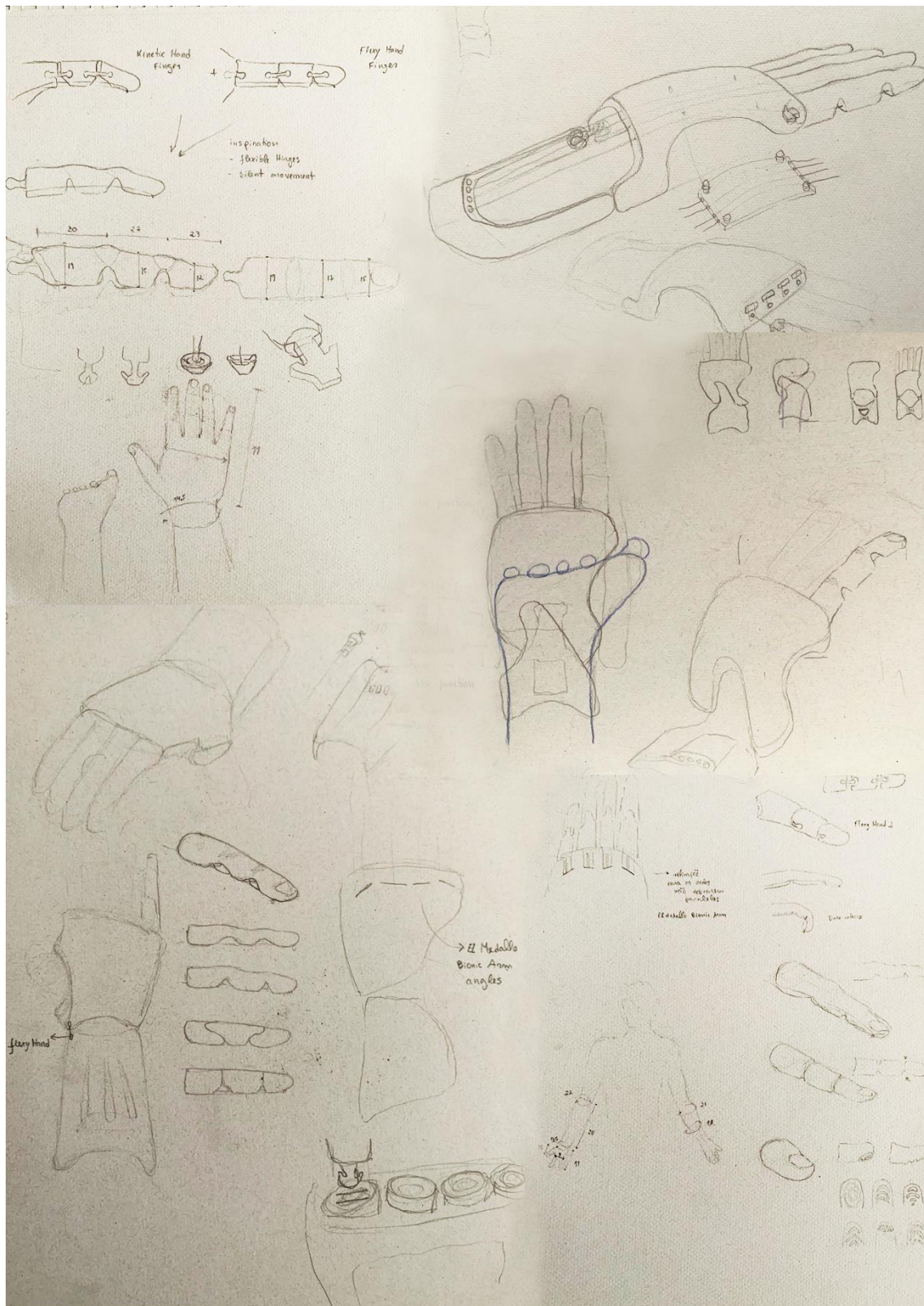


Figure 64 - Drawings of the mechanical hand in development.

The hand was created to a specific case for a 10-year-old girl called Carolina but, in mind was the possibility to be a standard hand for cases like this one. She had part of her thumb and it did not fit to any other E-Nable Hands. The case was given by the collaboration with NOVA School of Science and Technology (FCT NOVA) in Lisbon, Portugal. The team 3D Printing center for Health provided the information of the case and also the measurements in Figure 68. A lot of support was given by Prof. Claudia Quaresma and his student João Silva.

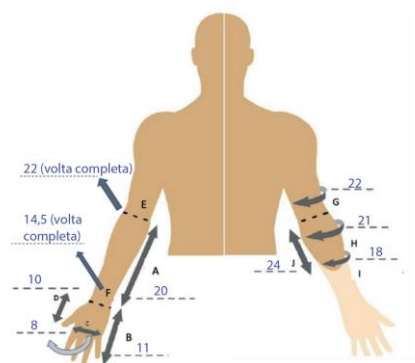


Figure 65 - Measurements of the E-Nable case.

This hand (Figure 69) was designed to show and test the viability of the 100% recycled material, and also to innovate in the design of a mechanical hand, giving a solution for Carolina. According to these goals, the solution was to create something that could prove its best potentiality of the material and also give innovation to the mechanical hands specially because in use of this material. The printers used for this hand were PrusaMK3 printers and a Snapmaker 2.0 F350.

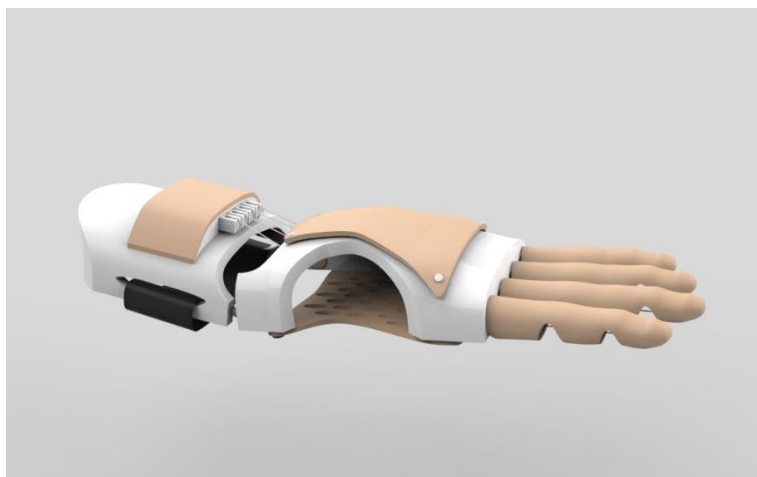


Figure 66 - Final Design Mechanical Hand.

4.2.1 Finger

The main focus of the study was on the finger (Figure 70). In addition to being a prime example of the application and viability of the created material, the fingers represent innovation in the field of E-Nable mechanical hands. With it, was possible to create a fully 3D printed finger with fewer assembly steps and fewer parts to print. The characteristics of the material allow for a more natural and less robotic movement. The color of the material also brings advantage of resembling a skin tone. The designed fit allows for easier hand assembly.

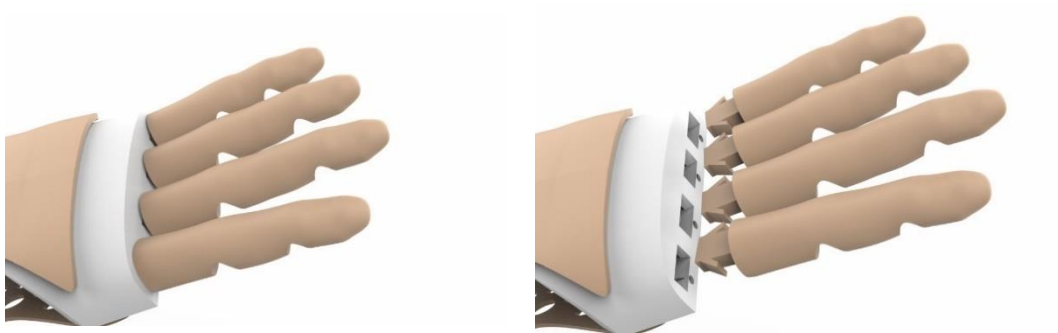


Figure 67 - Render of the fingers and fitting.

The printing settings were tested many times before the final part. In the Figure 71, in the left side, the part was printed in a horizontal direction, and in the right side the part has much better outcome due to the direction being in the vertical. Other features of the printing.



Figure 68 - Comparison between parts printed in different directions.

The inclination between fingers was inspired in the model El medallo Bionic Arm in order to provide a more natural movement when closing the hand, avoiding a robotic motion once more. This light inclination can be observed in the render of the Figure 72.



Figure 69 - Render with the angle of the fingers.

4.2.2 Main body

The mains body of the hand was developed using rigid PLA to provide structure to the product. Inspired by the model Cyborg Beast and Raptor Reloaded models, the wire path was designed to be open to facilitate printing and avoid issues with supports and printing errors. Throughout the research, was found that other models faced significant printing and support removal challenges when featuring the interior wire path. To address the issue of exposed wires, was applied a flexible cover over the hand, providing a more aesthetically pleasing solution.

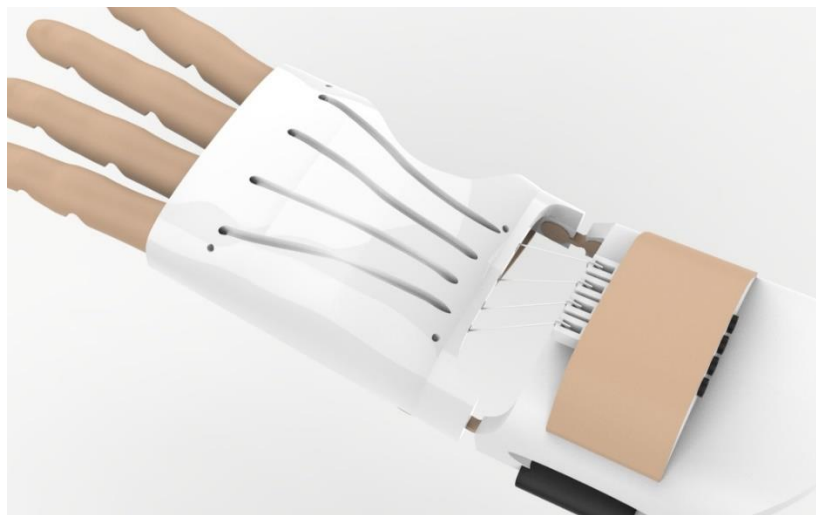


Figure 70 - Render of the main body.

4.2.3 Cover

The developed cover with the new material was applied on the top of the main body to create a more pleasing to the eye and to cover the exposed wires. The white pins were also 3D printed In PLA to reduce the use of screws.

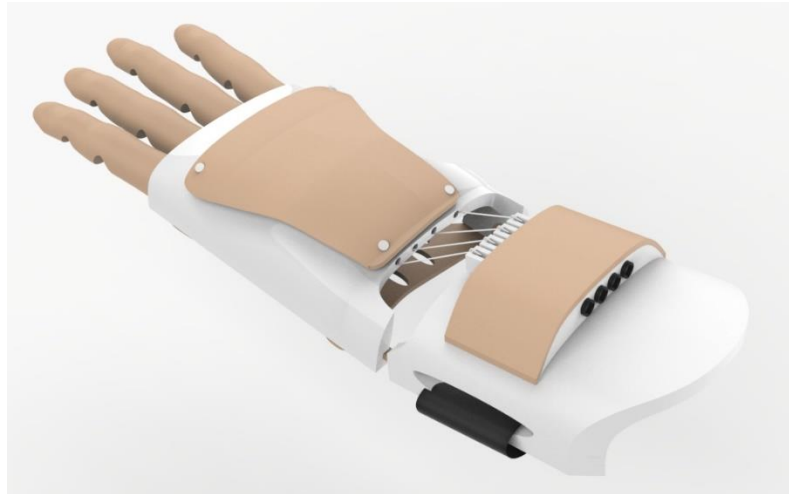


Figure 71 - Render of the cover for the hand.

4.2.4 Palm

The palm is another component of the developed mechanical hand that is made from the created material, as seen in Figure 73. The characteristics of this material allow the palm to be flexible, adaptable, and more comfortable for the user. Comparing it to other E-Nable hands, this design shares similarities with the Flexy-Hand and Raptor Reloaded models, with its pattern that allows greater flexibility and a design that requires fewer screws. In some cases of standart E-Nable hands, leather is used and requires many screws, while in this design, only 4 screws were used. For example, the model Ody Hand and the model Talon Hand, use 18 screws. In the case of models that use rigid parts, usually they need to thermoform them to adapt to each user, and that is another step for assembling the hand.



Figure 72 - Render of the Palm.

4.2.5 Flexible Connections

The connections between the rigid parts were also developed using the flexible material to facilitate the movement and mechanism of the mechanical hand. These connections were inspired by the model Flexy Hand, as they provide a more discreet and flexible linkage. Other hands typically use rigid and more visible connections, resulting in a more robotic movement.

4.2.6 Gauntlet

The gauntlet was developed with PLA and its main function is to secure the hand to the arm using velcro straps. Additionally, it serves as component for adjusting the wires to determine their tension and angle. The gauntlet consists of four pieces designed to hold the wires in place while allowing for screw adjustments on either side. To enhance its aesthetics, a strip of recycled material was added on top.

4.3 Assembly

The mechanical hand, Flexygrip, was carefully assembled, as depicted in Figure 76 and Figure 77, showcasing its distinct components. The initial steps involved removal of supports and through cleaning of the individual components. Subsequently, the assembly commenced with the insertion of the fingers into the main body. Integration of the gauntlet to the main body was achieved using flexible connections, which were securely affixed with the aid of super glue.

To enable finger articulation, the inclusion of pins in the gauntlet facilitated the assembly of a nylon wire, repurposed from beach findings and thereby contributing to waste utilization. The wire was meticulously threaded through the fingers, creating knots at the tips, passing through the main body, and ultimately reaching the pins on the gauntlet, where additional knots were made. Subsequently, the knots were reinforced with the application of super glue, and any excess wire was carefully trimmed.

To ensure optimal functionality and aesthetic cohesion, the main body was safeguarded with a cover to shield the exposed wire, ingeniously secured with designed pins, thereby minimizing the need for additional screws. Furthermore, the palm of the hand was firmly affixed using four screws, further consolidating the structure.

For aesthetic considerations, an additional cover was incorporated into the gauntlet. To complete the assembly, a Velcro strap was thoughtfully included to secure the hand to the user's arm,

alongside the integration of an EVA sheet to enhance interior comfort, delivering a comprehensive and user-friendly product. More renders are attached in Appendice I.



Figure 73 - Assembled mechanical hand.

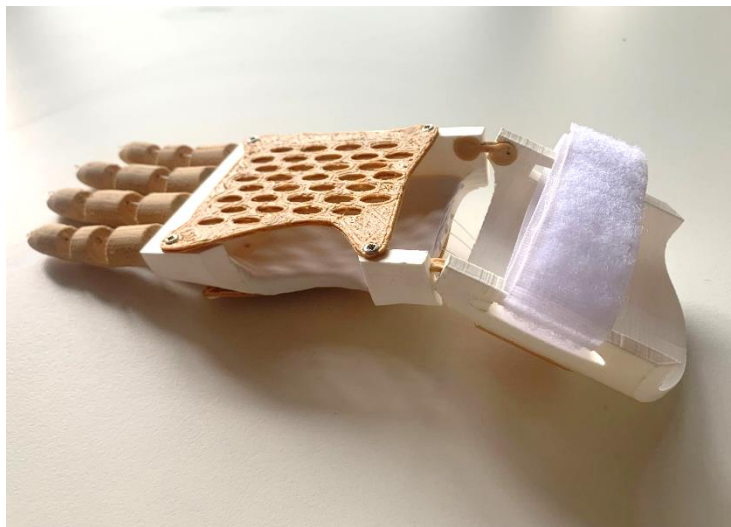


Figure 74 - Assembled mechanical hand.

Figure 78 illustrates the sequential mechanical motion and operational principles of the mechanical hand. Given the user's functional wrist, the closure of the hand is initiated by inward movement of the wrist. Consequently, the fingers adeptly close, and with the assistance of the thumb, a firm grip on objects can be achieved. The technical drawings are attached in Appendice II.



a)



b)



c)

Figure 75 - Representation of the mechanical movement of the Flexygrip.

5 Conclusion and Future Work

5.1 Conclusion

In this research, it was successfully developed a 100% recycled material from external prostheses waste with application in an innovative mechanical hand for a real case with E-Nable project. The material demonstrated positive results for injection molding, and also to the 3D Filament Extrusion. The chosen percentage of 10%PU and 90%TPU exhibited enhanced flexibility and strength capable of executing the desired functions and performance on the developed mechanical hand. This research, contributes to the scientific community, opening the possibility to explore and improve the composite material.

The study of the developed material has yielded significant insights that contribute to its comprehensive characterization and potential applications. The comparison between tensile tests results in the injected molded specimens and the 3D printed specimens reveals a nuanced perspective in the material's behaviour under distinct manufacturing processes. The enhanced uniformity seen in the 3d printed samples, evident from the lower coefficient of variation (CV), underscores the promise of the 3D printing process in delivering materials with reliable and predictable performance characteristics. The marginal reduction in average values of tensile properties, signifies a trade-off between consistency and magnitude of these properties.

By combining the created material with the 3D Printing technologies, it was possible to developed and manufacture the whole product. This way, it showcased innovative features and functionalities. By analysing the existing mechanical hands, it was possible to create an improved E-Nable hand for a particular costumer. The parts where the material was applied show potential to be improved in terms of quality of life for individuals with upper limb amputations, giving more comfort and better performance to daily functions. The design took into accountant also the E-Nable volunteers that can assemble or print this hand, by the reduced steps and parts of assembly. However, it was revealed some limitations that can be addressed to future research that is the improvement of the adaptations in the 3D filament extruder so the filament has a consistent thickness.

Looking ahead, continuing to share the work developed in conferences and scientific forums can inspire other designers to explore the possibilities of this recycled material. Collaboration has played a vital role in the success of this project, encouraging to further strengthen these partnerships in future personal work and inside the master's in Product and Industrial Design.

5.2 Future Work

The achievement of the 100% recycled material from medical waste, with application in an innovative mechanical hand, has open exciting possibilities for further research.

The main limitations identified in this study were the dependence on multiple machines and also on support and assistance by different sources. Future research and improvements on the project can be achieved by getting access to more advanced and streamlined machinery that reduces unforeseen events like machine breakdowns, waiting for availability on different machines, and the need to repeat the process until adapting to the features and limitations of each machine. This way, the study's findings can be further validated and expanded upon.

The collaborations established during this project have proven to be valuable contacts for future personal work but also to the Master's course. This includes for example PIEP, E-Nable, Maitools, 3Devo, INEGI, and FCT NOVA School.

To truly assess the impact of the material and the mechanical hand, it is crucial to follow the case and explore the potential applications. At the moment, the hand is finished and the user in this case-study can try and test the product.

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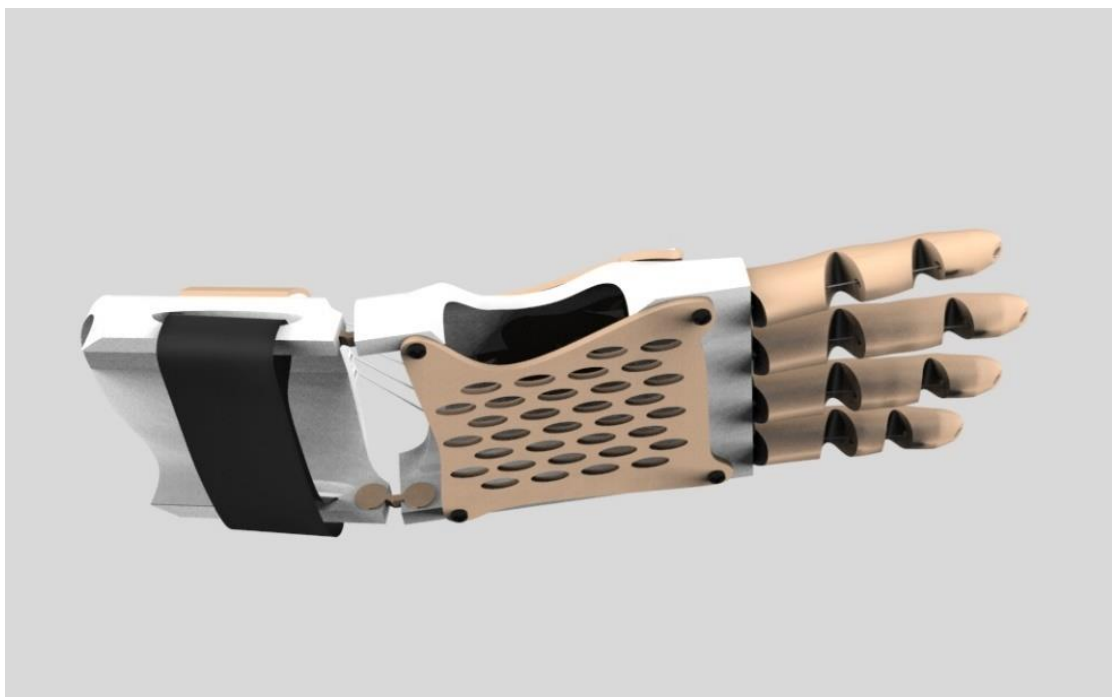
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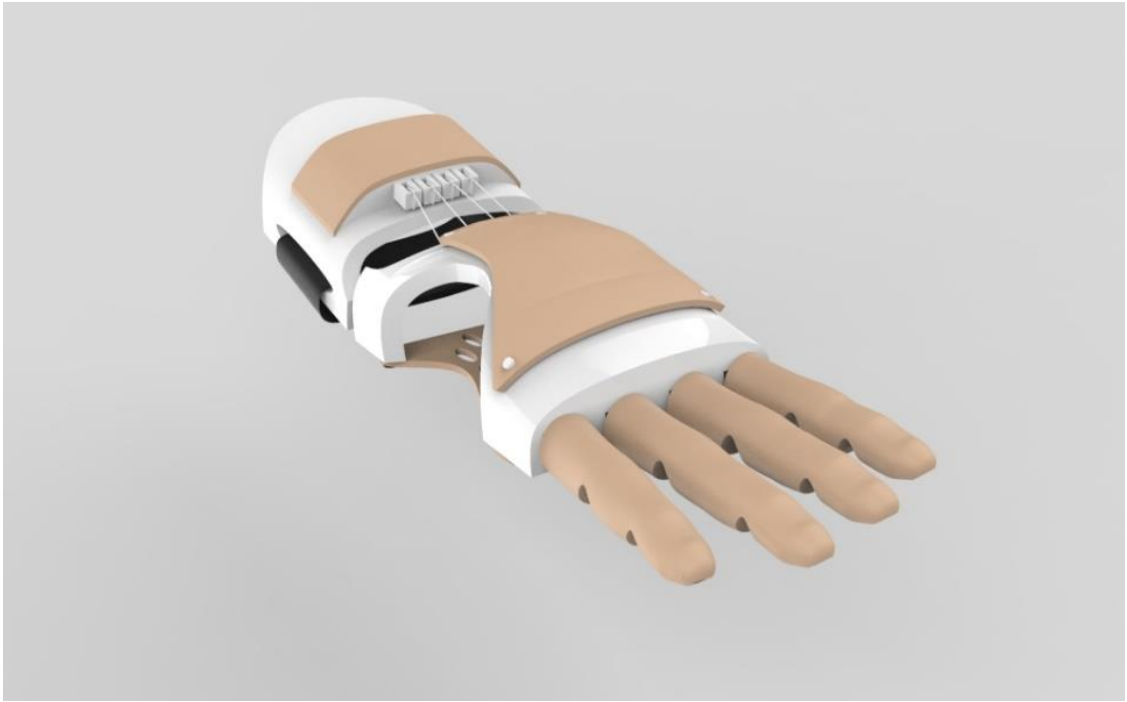
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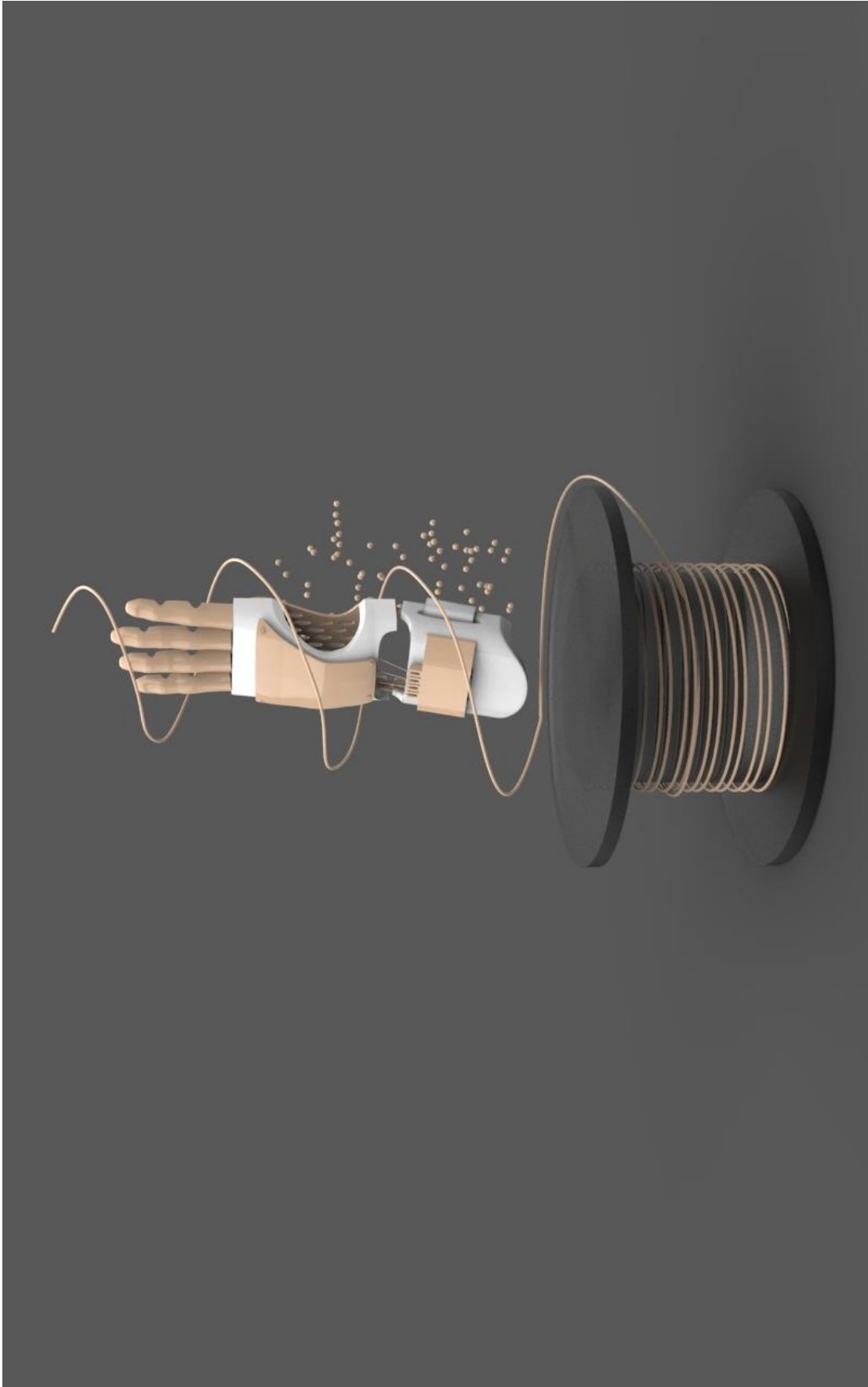
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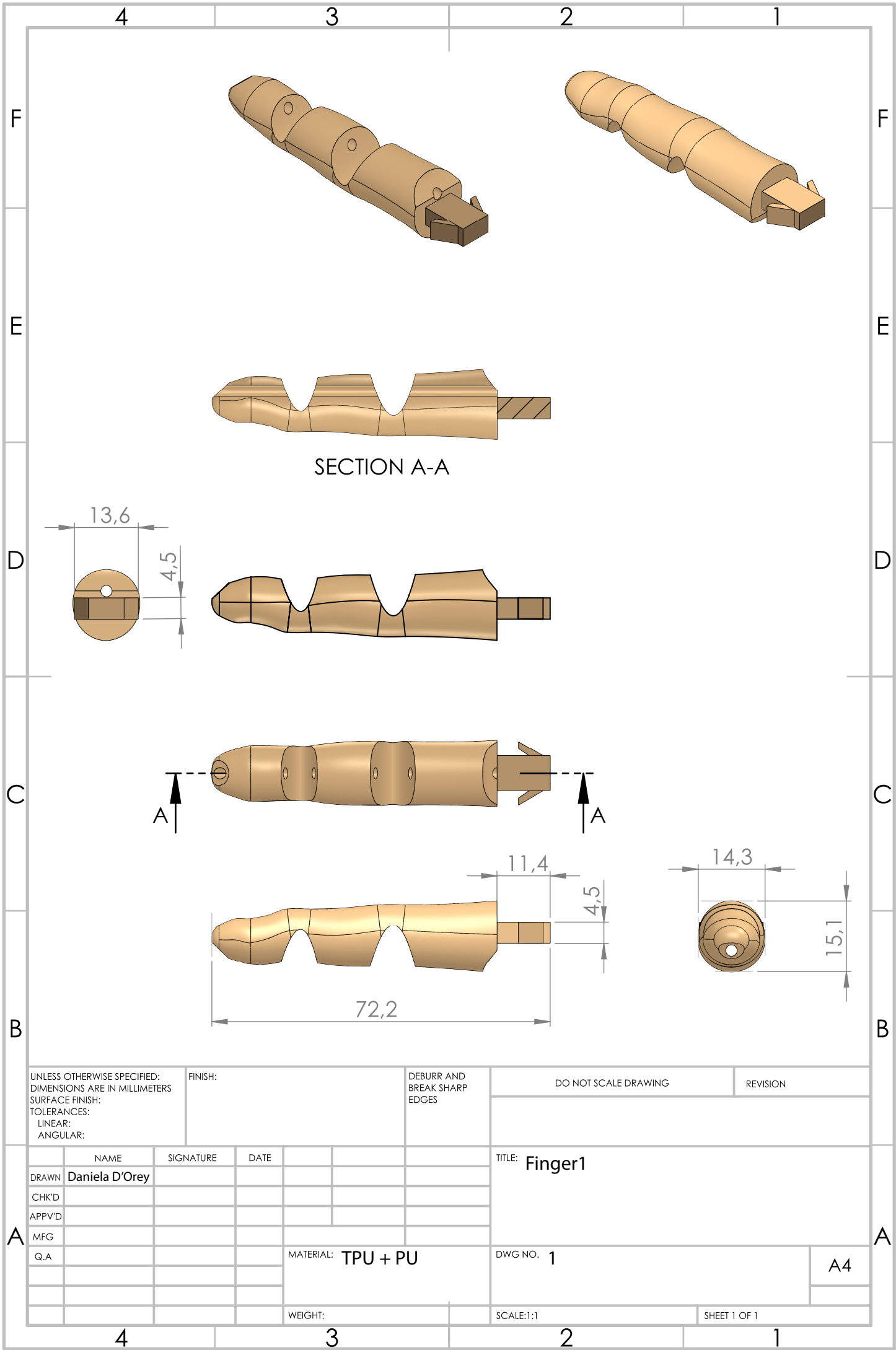
Appendice I - Renders

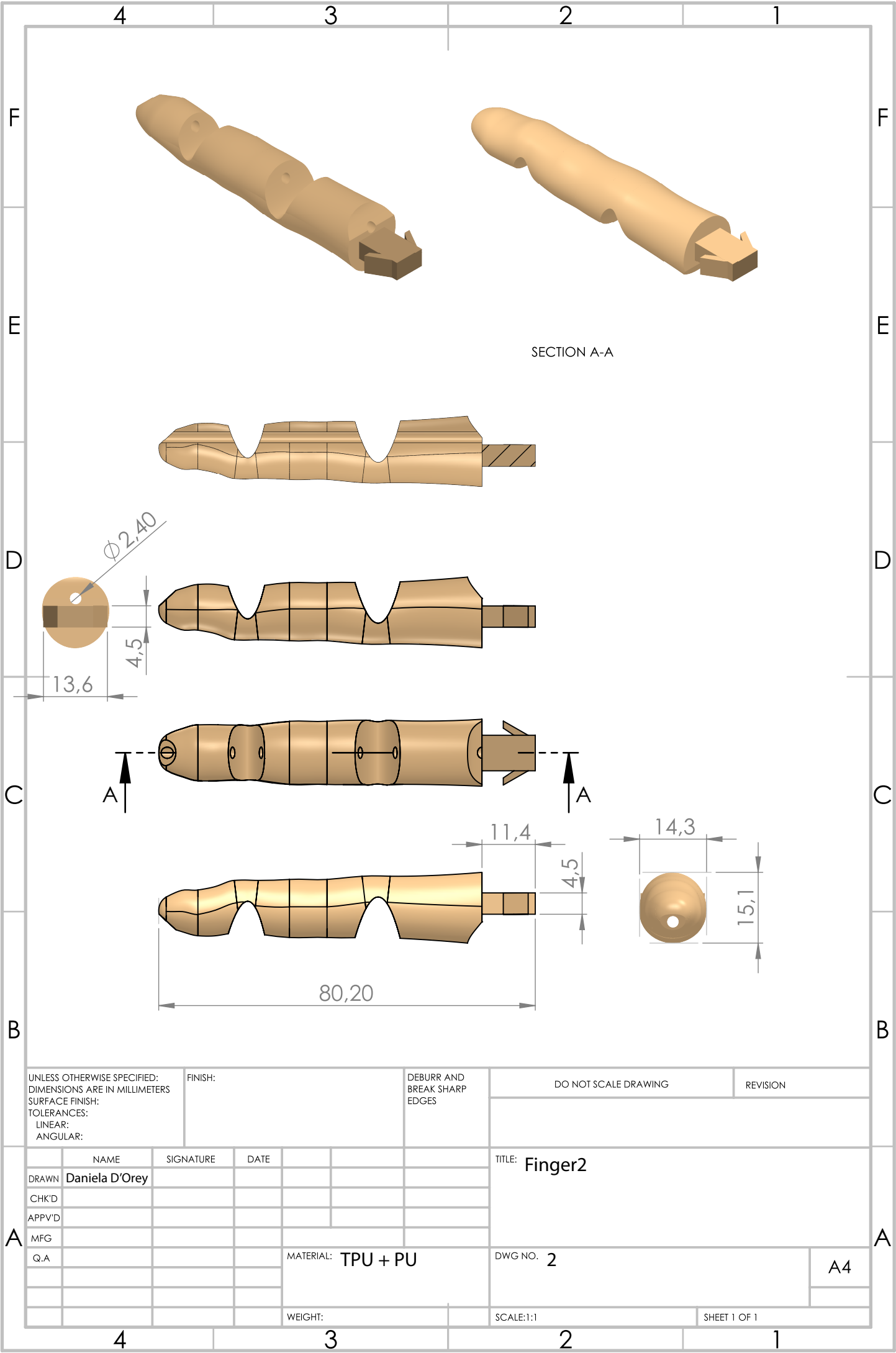






Appendice II – Technical Drawings





UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE		
DRAWN	Daniela D'Orey				
CHK'D					
APPV'D					
MFG					
Q.A					

MATERIAL: TPU + PU

TITLE: Finger2

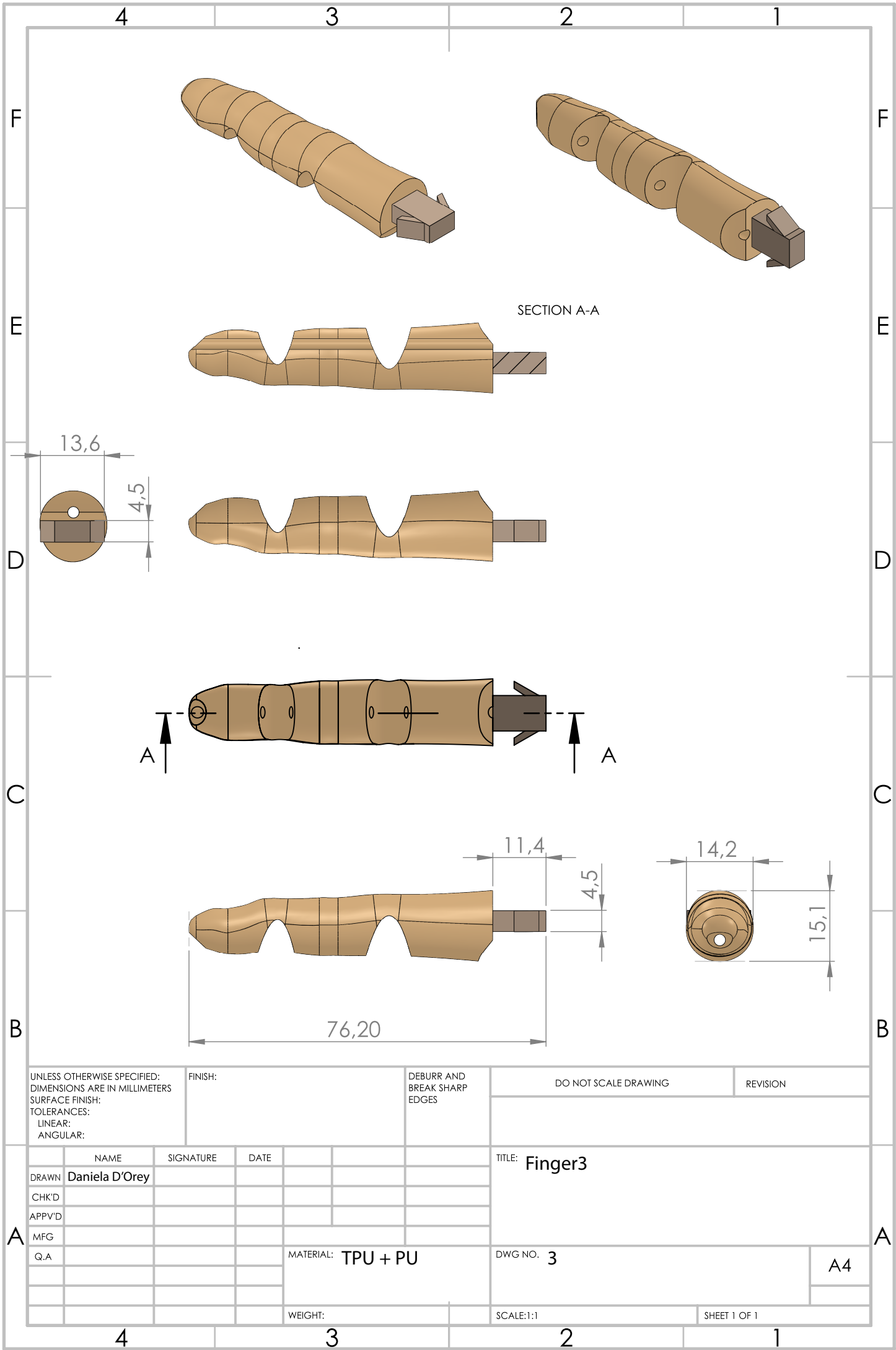
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A4

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SCALE:1:1

SHEET 1 OF 1



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TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

NAME	SIGNATURE	DATE			
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CHK'D					
APPV'D					
MFG					
Q.A					

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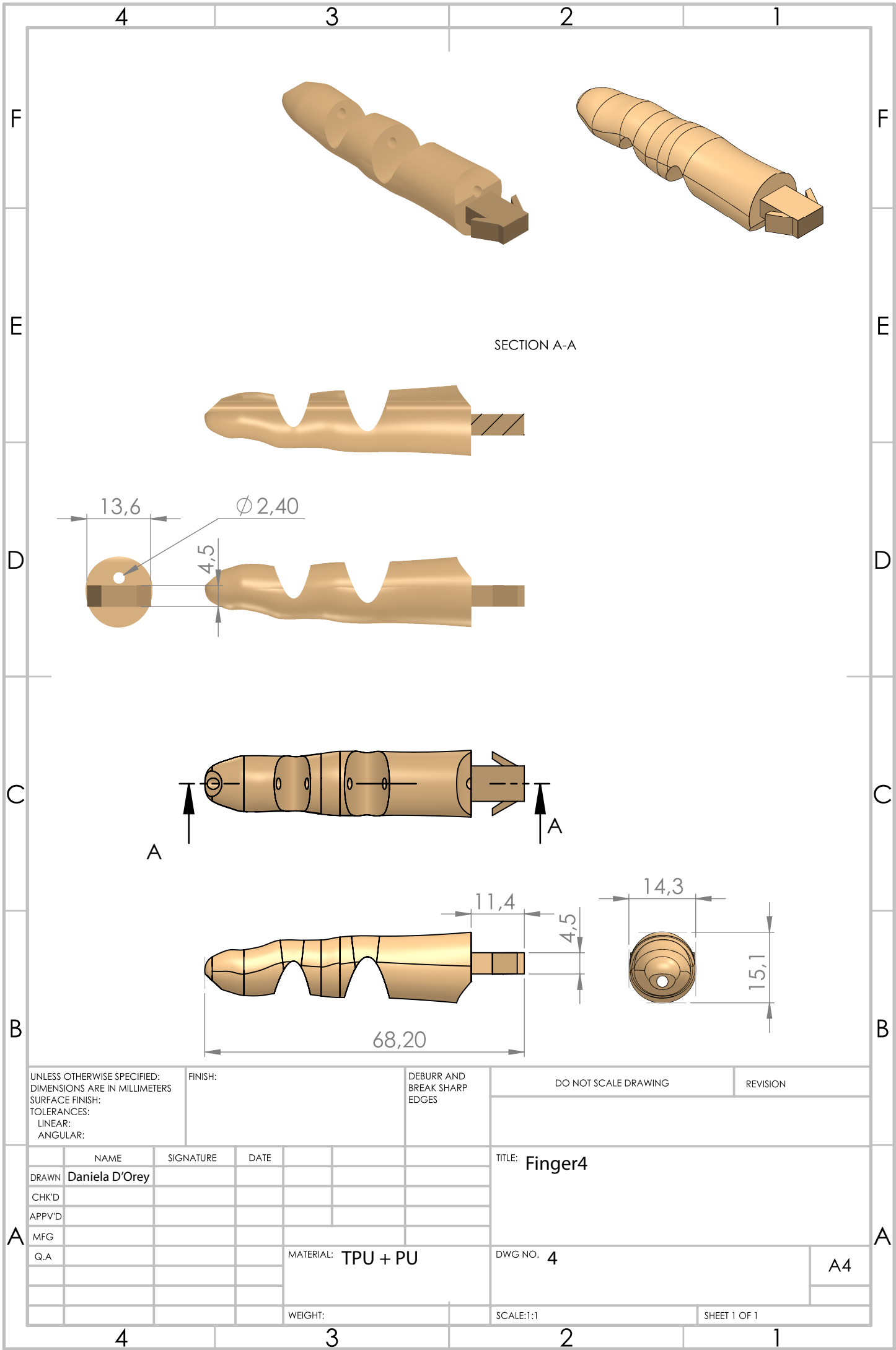
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SHEET 1 OF 1



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TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

NAME	SIGNATURE	DATE			
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CHK'D					
APPV'D					
MFG					
Q.A					

MATERIAL: TPU + PU

TITLE: Finger4

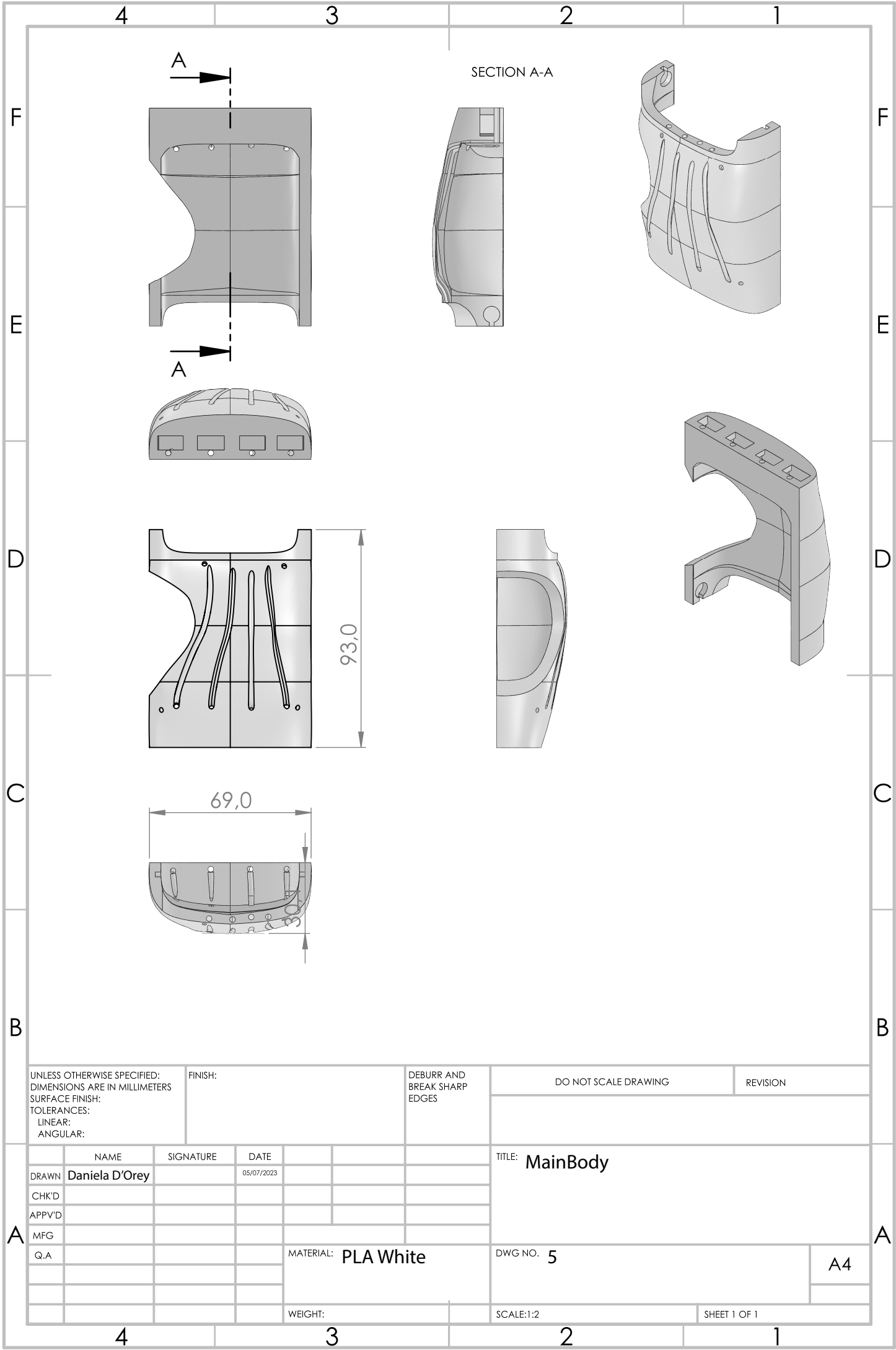
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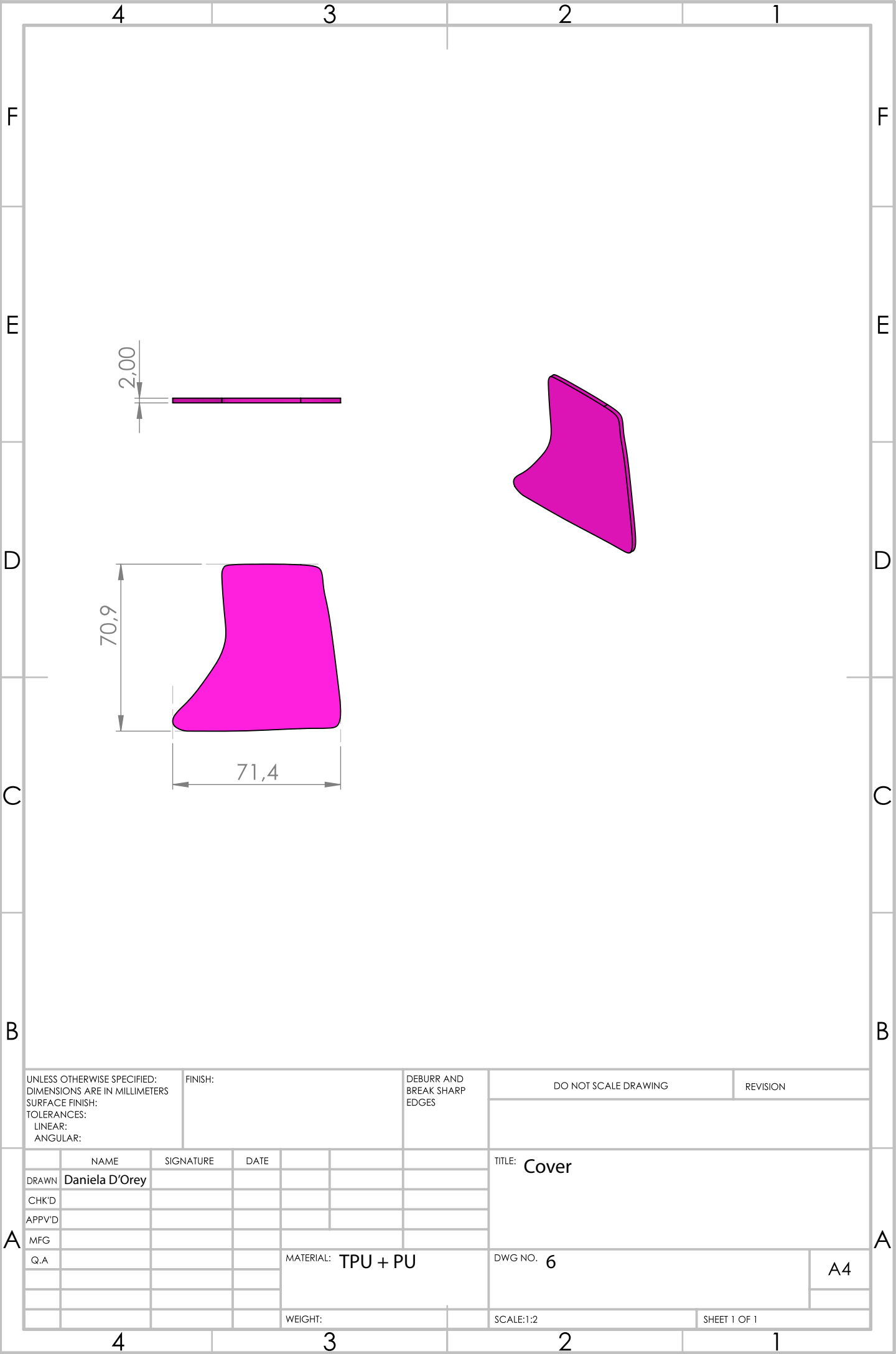
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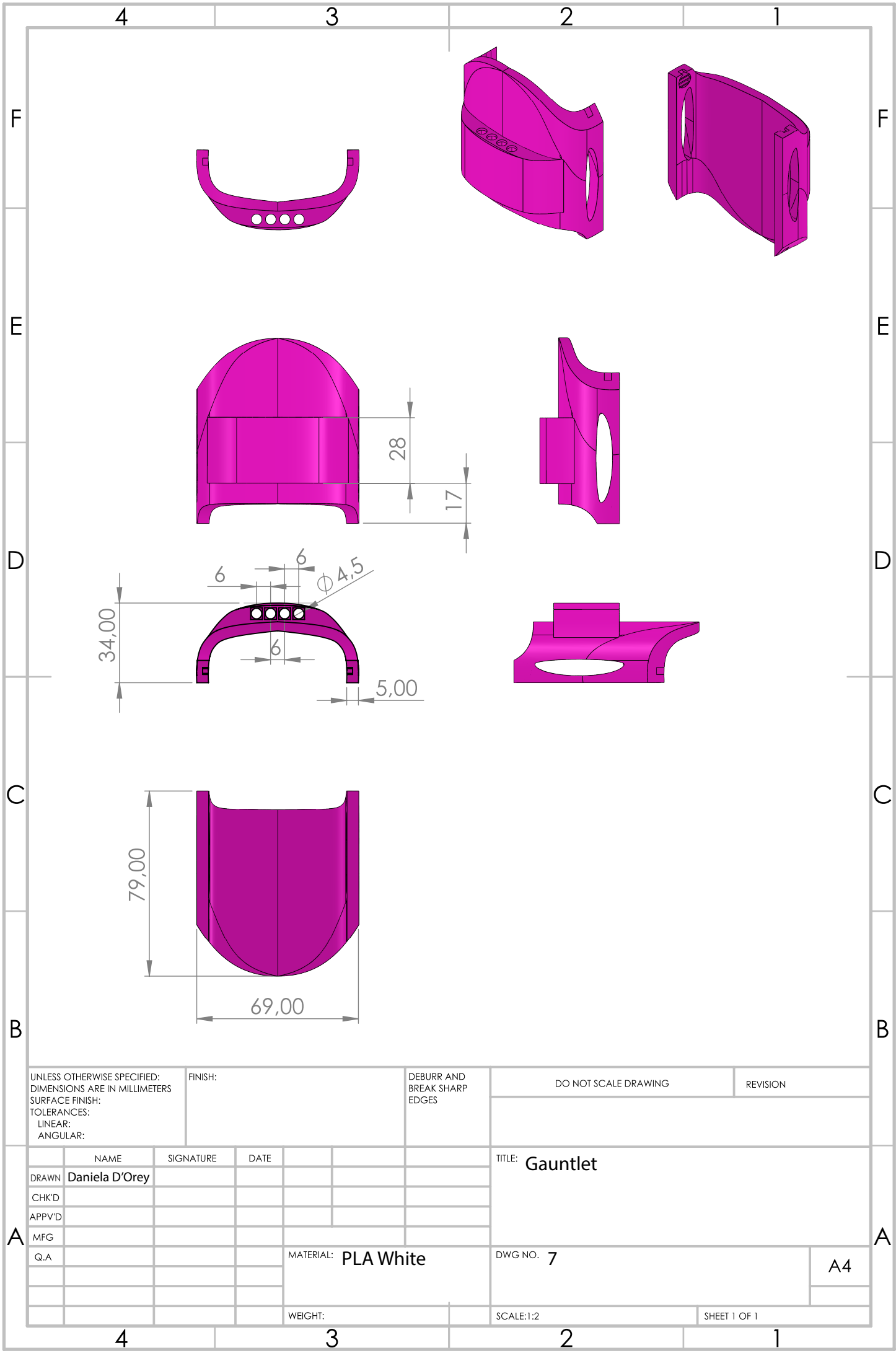
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SHEET 1 OF 1



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TITLE: MainBody											





UNLESS OTHERWISE SPECIFIED:
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SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

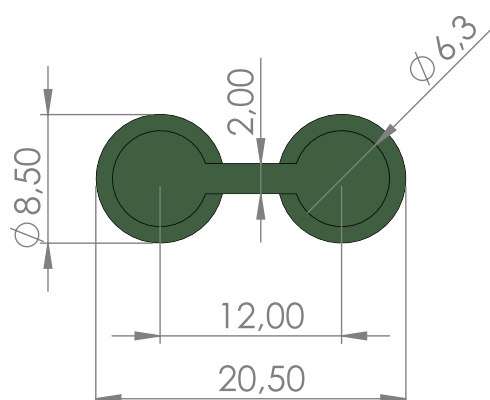
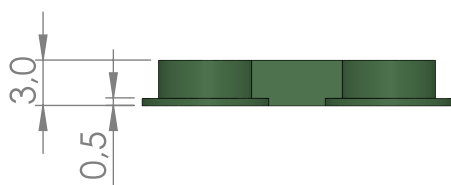
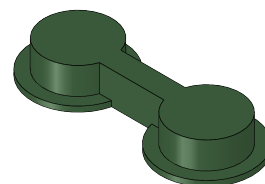
	NAME	SIGNATURE	DATE		
DRAWN	Daniela D'Orey				
CHK'D					
APPV'D					
MFG					
Q.A					

TITLE:	Gauntlet
DWG NO.	7
SCALE:	1:2
SHEET	1 OF 1

MATERIAL: PLA White

A4

WEIGHT:



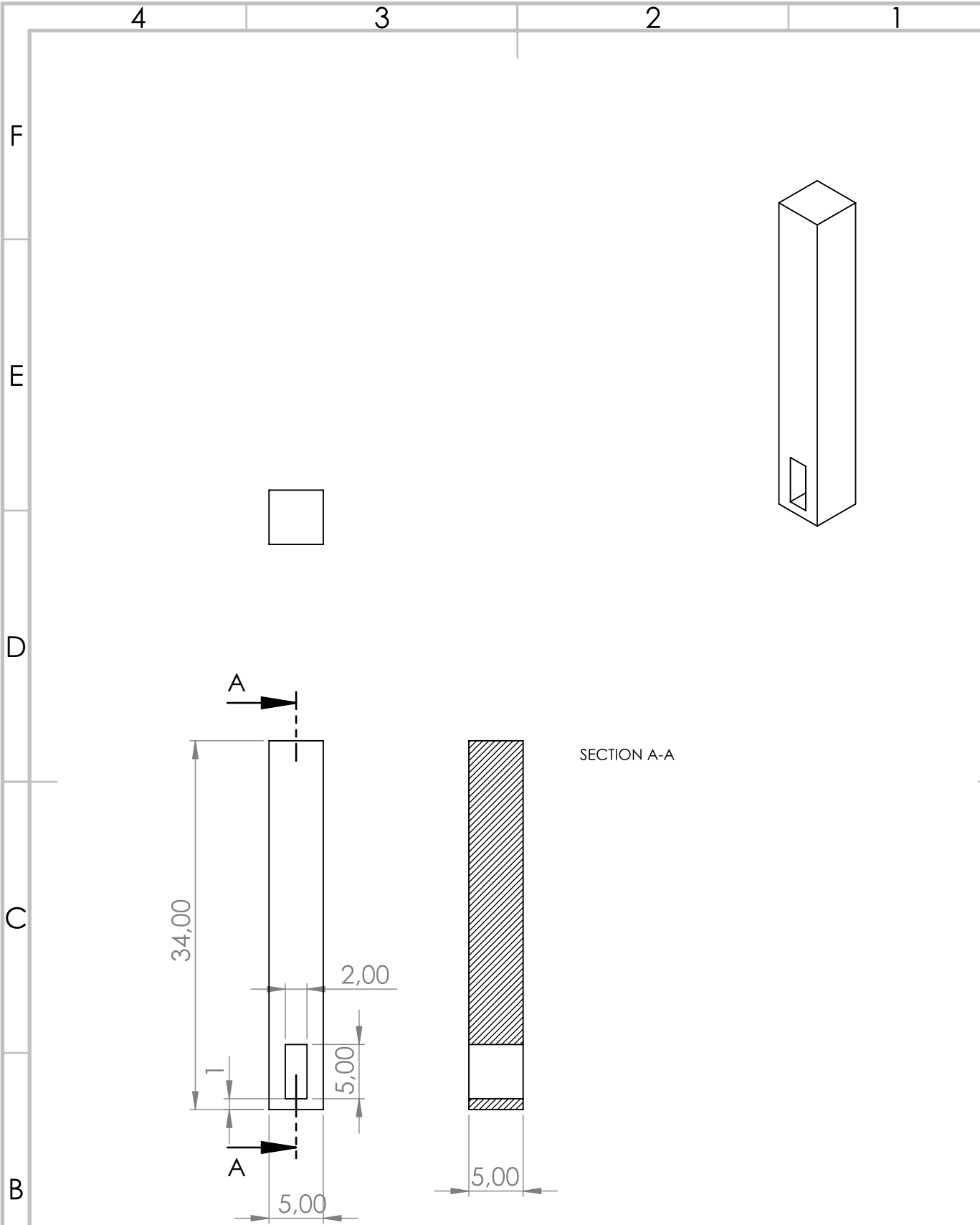
REVISION

 $2x$

A4

DWG NO. 8

SHEET 1 OF 1



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A	NAME		SIGNATURE		DATE						TITLE: Gauntlet Pins								
	DRAWN Daniela D'Orey																		
	CHK'D																		
	APPV'D																		
	MFG										4x								
	Q.A																		
															A4				
				MATERIAL: PLA White					DWG NO. 9										
											SCALE:2:1						SHEET 1 OF 1		
4				3							2						1		

Appendice III – Abstracts to conferences

In this Appendice, are attached the Abstracts submitted for conferences. Below are the Title and authors.

Recycling Polyurethane and Thermoplastic Urethane Waste from External Prostheses for the Manufacture of Filaments for 3D Printing

Daniela D'Orey Leal^{1*} , Jorge Lino Alves²

¹ Master in Product and Industrial Design, University of Porto

² INEGI, Faculty of Engineering, University of Porto

Recycling Polyurethane and Thermoplastic Urethane Waste from External Prostheses for the Manufacture of Filaments for 3D Printing

D'Orey Leal, Daniela - Master in Product and Industrial Design, University of Porto, Portugal

Lino Alves, Jorge - INEGI, Faculty of Engineering, University of Porto, Portugal

Recycling of External Prostheses Waste for Manufacturing 3D Filament. Low-Cost Hand for the E-Nable Project

Daniela D'Orey Leal ¹ , Sónia Miranda ² and Jorge Lino Alves ²,

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² PIEP, Center for Innovation in Polymer Engineering, Portugal;

³ INEGI, Faculty of Engineering, University of Porto

Recycling Polyurethane and Thermoplastic Urethane Waste from External Prostheses for the Manufacture of Filaments for 3D Printing

Daniela D'Orey Leal^{1*}, Jorge Lino Alves²

¹ Master in Product and Industrial Design, University of Porto

² INEGI, Faculty of Engineering, University of Porto

*ddleal.750@gmail.com

Keywords: Polyurethane, Recycling, 3D Printing, Prostheses

Abstract

Polyurethane (PU) is applied in a wide variety of applications in the automotive industry, civil construction, footwear or even mattresses.

PU recycling processes are still underdeveloped and the most common solutions are for acoustic insulation, carpets, rehabilitation mattresses, insulation panels and protective materials for sports facilities. Currently, at the end of life, PU products go to landfill, are mechanically or chemically recycled, or used in Energy Recovery or Biological Degradation.

The preliminary work carried out with the grinding of Thermoplastic Polyurethane (TPU) of defective cosmetic prosthetics, and mixing with PU machining residues of limb models, allowed to inject different mixtures and evaluate the potentialities of using these formulations to create a new filament for 3D printing for the production of new prostheses.

The main objective of this project is to create a 100% recycled material from industrial waste from a Prosthetics and Orthotics company.

TPU formulations with 10, 20, 30 and 60% PU were injected in a plastic injection machine Battenfeld BA 400/125 CDC, to produce the samples shown in Figure 1. From each set of samples, 4 specimens were taken for tensile tests (Standard EN ISO 527-2: 1996). The specimens were tested in an MultiTest-dV Mecmesin equipment (UK) to determine the mechanical properties.

The best formulation in terms of mechanical properties, extrudability and surface quality was used to produce a 3D printing filament.

The developed filament was used in material extrusion process of an external prosthesis, that is, in the development of a mechanical hand. It was intended to develop a low-cost prosthesis with 100% recycled material, which will also allow access to communities with lower financial resources.

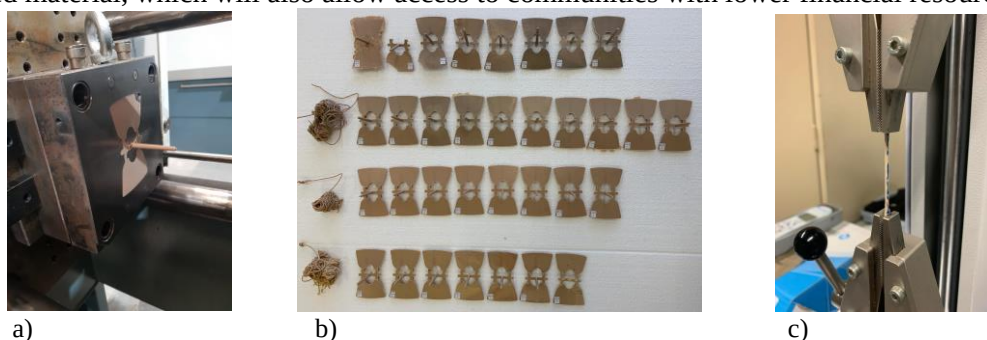


Figure 1. a) Injection moulding, b) Injected samples to evaluate the processability of the mixtures, c) Tensile tests

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Recycling Polyurethane and Thermoplastic Urethane Waste from External Prostheses for the Manufacture of Filaments for 3D Printing

D'Orey Leal, Daniela - Master in Product and Industrial Design, University of Porto, Portugal

Lino Alves, Jorge - INEGI, Faculty of Engineering, University of Porto, Portugal

Abstract

Polyurethane (PU) is applied in a wide variety of applications in the automotive industry, civil construction, footwear or even mattresses. PU recycling processes are still underdeveloped and the most common solutions are for acoustic insulation, carpets, rehabilitation mattresses, insulation panels and protective materials for sports facilities. Currently, at the end of life, PU products go to landfill, are mechanically or chemically recycled, or used in Energy Recovery or Biological Degradation. The preliminary work carried out with the grinding of Thermoplastic Polyurethane (TPU) of defective cosmetic prosthetics, and mixing with PU machining residues of limb models, allowed to inject different mixtures and evaluate the potentialities of using these formulations to create a new filament for 3D printing for the production of new prostheses. The main objective of this project is to create a 100% recycled material from industrial waste from a Prosthetics and Orthotics company. TPU formulations with 10, 20, 30 and 60% PU were injected in a plastic injection machine Battenfeld BA 400/125 CDC, to produce the samples shown in Figure 1. From each set of samples, 4 specimens were taken for tensile tests (Standard EN ISO 527-2: 1996). The specimens were tested in an MultiTest-dV Mecmesin equipment (UK) to determine the mechanical properties. The best formulation in terms of mechanical properties, extrudability and surface quality was used to produce a 3D printing filament. Firstly, was produced material in pellets format to later extrude in filament. PIEP – Innovation in Polymer Engineering, provided qualified machines and support. It was used a Twin-screw, corotating and modular extruder, model Coperion ZSK 26. For mixing, gravimetric dispensers were used. And the spindle was configured taking into account distributive and dispersive mixing. It was obtained with the percentages of 10%PU with 90%TPU (in pellet format). Thus, it was possible to extrude with homogeneity and uniformly using the 3Devo Composer machine provided by FEUP – Faculty of Engineering, University of Porto. The Filament extrusion phase required a lot of investigation to discover the suitable configurations for this new material. It was very sensitive to any alteration in terms of temperature, speed and cooling. It was concluded that the ideal temperatures would be approximately 210°C, with 5rpm Speed and 90% cooling. Because this material required high temperatures of extrusion, there were some difficulties in spooling the filament due to the short time given to cooling. This way, an adaptor was created to expand the cooling time. Also an adaptor for the Fan was inserted, to make a more distributed cooling. Printing tests were done to define the printing temperature. The ideal is to print at 235°C. Other printing tests were made and allowed to understand mechanical properties such as flexibility and strength. In conclusion, this material has more strength and less flexibility than TPU prints, although they have similar characteristics. A mechanical Hand prosthesis is under development to be applied with this new material created from Prosthetic Industry's waste. This product is being developed for a 10 year old girl with no hand, a functional wrist and few financial possibilities. This connection and providence of the case and respective measurements was possible through E-Nable, more specifically with the 3D Printing for Health Team, placed in the FCT NOVA School. This way, it was taken the opportunity to volunteer for E-Nable and develop a personalized Design for a child, using this 100% recycled material.

Keywords: Polyurethane, Recycling, 3D Printing, Prosthetics

Acknowledgments

The authors acknowledge the support provided by *Padrão Ortopédico*, External Prostheses company that provided the wasted material and internship development. A lot of support was also given by *Maitools, Injection and Mold Engineering, Lda.*, with the injection tests and material shredding. Also, by *PIEP – Innovation in Polymer Engineering* with the material extrusion and pellets making for subsequent filament extrusion. The extrusion of the pellets to filament was possible with machines in the *Faculty of Engineering* facilities (*FEUP*). And finally the connection with a case to design a mechanical hand was provided by *3d Printing for Health, E-Nable*.

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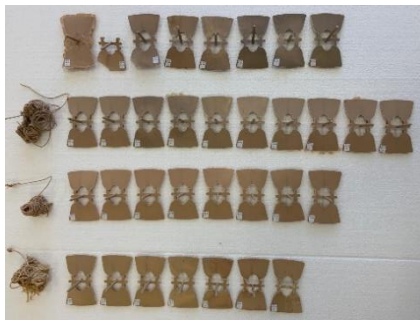


Figure 1: Injected Samples to evaluate the processability of the mixtures



Figure 2: Tensile Tests



Figure 3: PU, TPU and pellets from the mixture



Figure 4: Tests for Filament Extrusion



Figure 5: 3D Filament

Recycling of External Prostheses Waste for Manufacturing 3D Filament. Low-Cost Hand for the E-Nable Project

Daniela D'Orey Leal ¹, Sónia Miranda ² and Jorge Lino Alves ^{2,*}

¹ Master in Product and Industrial and Design, University of Porto, Portugal; ddleal.750@gmail.com

² PIEP, Center for Innovation in Polymer Engineering, Portugal;

³ INEGI, Faculty of Engineering, University of Porto

* Correspondence: ddleal.750@gmail.com; Tel.: +351926279910

Extended Abstract:

In order to reduce industrial waste and encourage a more conscious production and consumption, this project defines Medical Industrial Waste of External Prostheses as the main problem to solve. Starting with the gathering of external Prostheses debris, Thermoplastic Urethane (TPU) and Polyurethane (PU) powder were considered a considerable source of waste, enough to create a recycled material. TPU is applied in 3D printing by the extrusion process, to manufacture cosmesis that have often printed errors. These cosmeses are mainly applied to produce external parts of the legs, hands and ankles. The 3D filament typically has a shore hardness of 95A and a nude tone. Polyurethane is frequently used in the creation of limb models that are milled in a CNC machine, creating a significant amount of powder waste. Polyurethane has a wide variety of applications and the study of the reprocessing of this material represents an innovation in the medical field and also in the automotive industry, civil construction footwear and even mattresses. Currently, the recycling of this material is underexplored and the most common solutions are for carpets, acoustic insulation, rehabilitation mattresses, insulation panels and protective materials for sports facilities. The discard methods are landfill, mechanical or chemical recycling, energy recovery or biological degradation. Unfortunately, the difficulty in reprocessing this material turns landfill into the main target for the debris of polyurethane.

The main goal of this project was first to find a solution to reprocess the PU powder and mix it with a promising material that could make possible the creation of a 100 % recycled material. Then the created material was intended to be applied in a design of a new mechanical prosthesis to demonstrate its viability. To start the process of creating possible mixtures, it was necessary to shred the TPU. Formulations with 10, 20, 30 and 60 wt.% of PU and TPU were prepared and tested in an injection moulding machine (Battenfeld BA 400/125 CDC). The metallic mould was used in a cold condition due to its ease of injection and demolding of samples (Figure 1). The injection moulding temperature was set in the range of 170 °C to 200 °C. The dosing phase was the most problematic stage due to the low weight of polyurethane. To bypass this obstacle, the funnel was removed and the material was injected more easily and at small doses to guarantee a homogeneous mixture.

These preliminary tests allowed to evaluate the processability of the mixtures, and the surface quality and hardness of injected samples (Figures 1 and 2). Four tensile samples (EN ISO 527-2: 1996) of each composition were removed from each of these parts to determine the mechanical properties obtained with each mixture. The tensile tests were conducted in a MultiTest-dV Mecmesin (UK) machine.

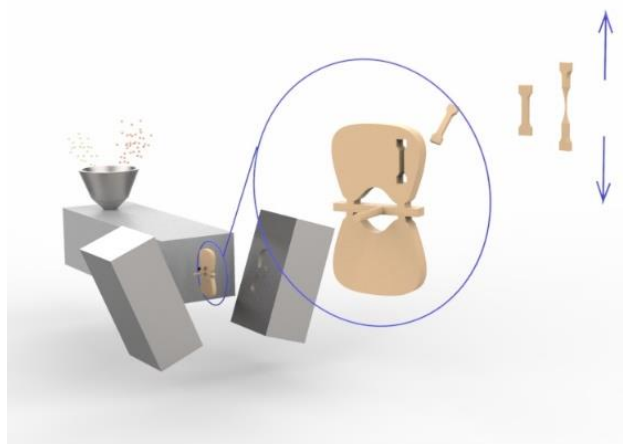


Figure 1. Representation of the injection moulding machine and removal of the tensile specimens.

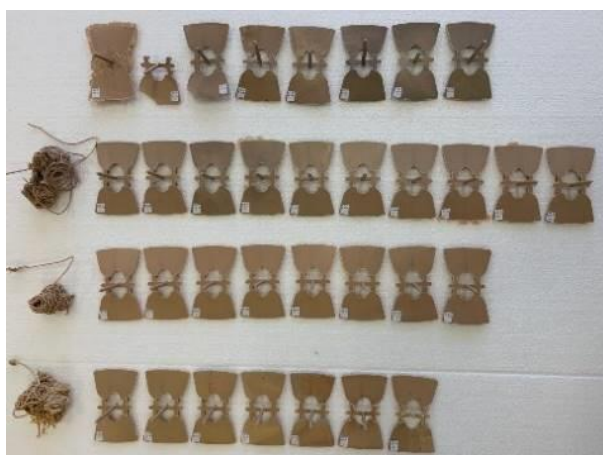


Figure 2. Injected Samples to evaluate the specimens.

The mixture of 10 wt.% PU and 90 wt.% TPU was the formulation that showed the best results for the 3D printing extrusion process, in terms of mechanical properties, extrudability and surface quality.

The next step was extruding the material into pellets. For that, it was used a Twin-screw, corotating and modular extruder, model Coperion ZSK 26, at PIEP (Center for Innovation in Polymer Engineering). The spindle was configured taking into account a distributive and dispersive mixing. The first dispenser introduced the TPU and started melting it so the polyurethane could be introduced later on, in a lateral dispenser. This allowed a better mixture of the material that was extruded into a thick filament, and shredded at the end into pellets, as represented in the scheme of Figure 3.

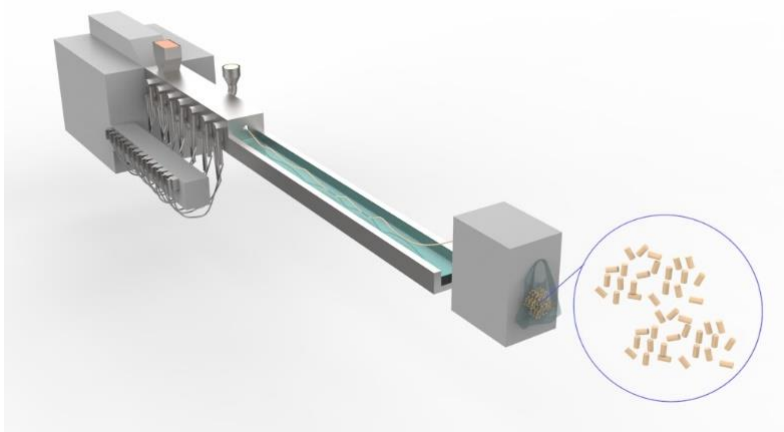


Figure 3. Representation of the production of the pellets.

This way, the next step of extruding the 3D filament guarantees a filament of a homogeneous material. Using a 3Devo machine, many trials were required to set up the suitable configuration for this new composite. The main parameters were the temperature, speed of the spindle, and cooling time. The material was revealed to be very sensitive to any parameter changes and the final configuration was defined as; 210 °C, 5 rpm and 90 % cooling. The cooling part was the most challenging to determine, because the material requires high temperatures to melt, and there was a short period of time for cooling between the nozzle of extrusion and the compression rollers. This made necessary a readaptation of the machine and the creation of rollers placed at a higher distance from the nozzle (Figure 4).

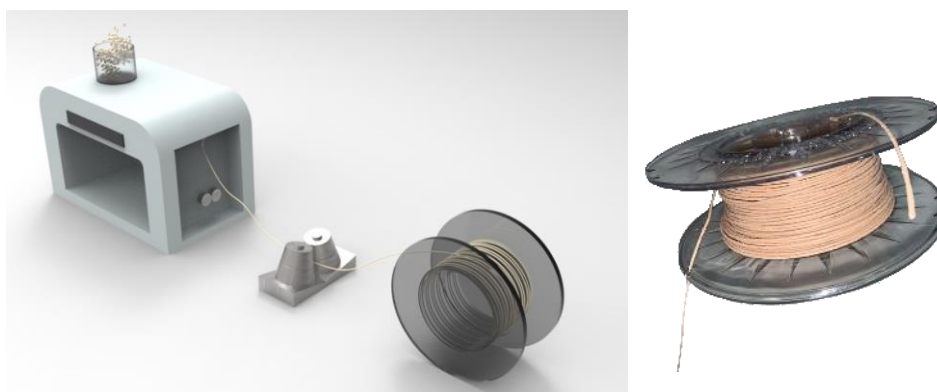


Figure 4. Representation the 3D filament extrusion and filament obtained.

After spooling the filament, printing tests were conducted. Firstly, as shown in Figure 5 a), was printed a part to test flexibility and printing quality. Figure 5 b) shows the sample made to define the temperature range for printing this new composite (215-250 °C). Finally, the part in Figure 5 c) shows a possible application in the medical field, a passive hand. The main advantages shown in these printing tests are the colour similar to the skin tone and flexibility similar to TPU filament but with more rigidity.

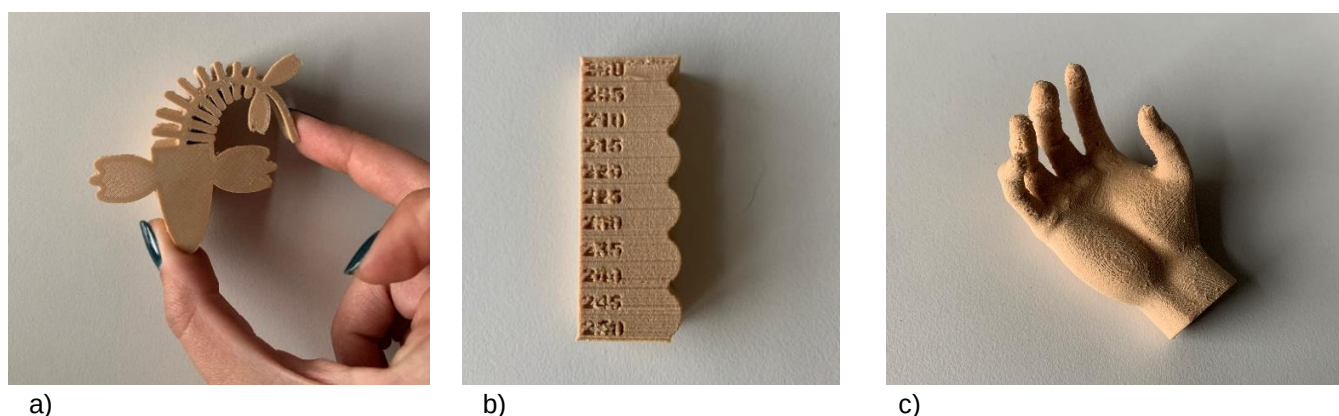


Figure 5. Samples were printed to evaluate the extrusion process and filament properties: a) flexibility, b) printing temperature, c) colour and practical application in the medical area.

A mechanical prosthesis for a real case of the E-Nable project is now under development. This product is being designed for a 10-year-old girl, born with a congenital disease. She has a functional wrist with no fingers but has a part of the thumb. This makes it harder to fit in a standard mechanical hand produced by the E-Nable. The connection and availability of this practical case and respective measurements were possible through the E-Nable project community, more precisely with the 3D Printing for Health Team, at the FCT NOVA School. This way, it grabbed the opportunity to apply the 100% recycled material from external prostheses waste production and show its viability in a real case for the medical field. This work opens also the opportunity for reprocessing TPU and PU for application in other areas, such as the automotive industry, footwear, mattresses and civil construction.

Keywords: Recycling; 3D Printing; Polyurethane; Prosthetics

Acknowledgment:

The authors acknowledge the support provided by Padrão Ortopédico, External Prostheses company that provided the wasted material and the internship during the master thesis. The support from Maitools, Injection and Mold Engineering, Lda., with the injection tests and material shredding, is also extremely appreciated. Also, PIEP – Center for Innovation in Polymer Engineering, with the manufacturing of pellets for filament extrusion. The extrusion of the filament at the Department of Metallurgical and Materials Engineering of FEUP. Finally the connection with a real case to design a mechanical hand provided by 3D Printing for Health, E-Nable.

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