3D Printing with Bioplastics

Masters Thesis

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by
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09 October 2020
MSc Integrated Product Design
TU Delft

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Contents

Acknowledgements **4**

Executive Summary **6**

Glossary of terms **9**

Project Formulation **10**
1.1 Initial Problem Statement 12
1.2 Project Objectives 13
1.3 Relevance for stakeholders 14
1.3.1 Relevance for Ultimaker 14
1.3.2 Academic Relevance 14
1.4 Project Approach 15

Understanding **17**
2.1 Approach and Methods 18
2.2 Additive Manufacturing 20
2.2.1 Sustainability of AM 20
2.2.2 Sustainability of FDM in context of Ultimaker 21
2.3 Polymer materials used for FDM printing 22
2.3.1 What are bioplastics and fossil-based plastics? 22
2.3.2 Commercially available bioplastic filaments 23
2.4 Sustainability of FDM material filaments 24
2.5 3DP Users and user needs in industry 28
2.5.1 3DP users in industry 29
2.5.2 Material selection process 30
2.6 Converging 32

Testing **34**
3.1 Approach 36
3.2 Materials and Equipment 37
3.2.1 Filaments 37
3.2.2 Equipment 39
3.3 Material Tests *40*
3.3.1 Test 0 – Print Profile Optimization 40
3.3.2 Test 1 – Measuring Energy Consumption 44
3.3.3 Test 2 – Measuring Print Quality 52
3.3.4 Test 3 – Measuring Tensile Properties 56
3.4 Converging 58

Material Guide **61**
4.1 Approach 62
4.2 Final Design- Material Guide for Green 3D Printing 65

Evaluation **66**
5.1 Project Outcomes 68
5.2 Recommendations for Ultimaker 70

References **72**

Appendix **76**
Appendix A: Bioplastics available in the online market 77
Appendix B: Full Results – Test 0 - Print Profile Optimization 78
Appendix C: Project Brief 80

Acknowledgements

Erik, thank you for believing in my strengths, for overseeing this journey and driving me to tell a good story. Thank you for helping me learn a little about material science, business, design and sustainability, and a lot about being a good human and professional being.

Jeremy, thank you for sharing with me your impressive plethora of knowledge, wisdom, and professional expertise, which motivated and set the learning path for this project. Thank you for mentoring me every week with structuring work, staying on track, for providing consistent and pragmatic feedback, and encouragement when I needed it. You have been a mentor I could always count on.

Timon, thank you for helping me navigate through the various challenges that came with working remotely- creating opportunities for company visits, connecting with the team, etc. Thank you for helping me get access to knowledge, experts, and resources I required from Ultimaker, and for helping me expand my understanding of polymer materials and FDM technology. I appreciate the prompt actions and feedback I have always received from you.

Bas, thank you for the opportunity to execute this thesis. Thank you Andrea, Guenael, Jeremy E.; thank you Mercedes, Mario, and the rest of the Print Process team at Ultimaker, for sharing your expertise with different parts of the project content- the company, clients, materials, tests, end-users, and more.

Girish, Shreyas, thank you for being the ID-buddies assisting with the project from time to time- for brainstorming, video recording, and design feedback. Thank you Ehsan, for your crucial insights on research for design, and your guidance with reporting.

And finally,
Aai, Baba, I can never thank you enough for all that you have been for me.

Suku, Dev, Yash, thank you for supporting me in - and distracting me from - work and life, as and when either was necessary. I cherish having you as family throughout this pandemic lockdown and the last months of university.

Executive Summary

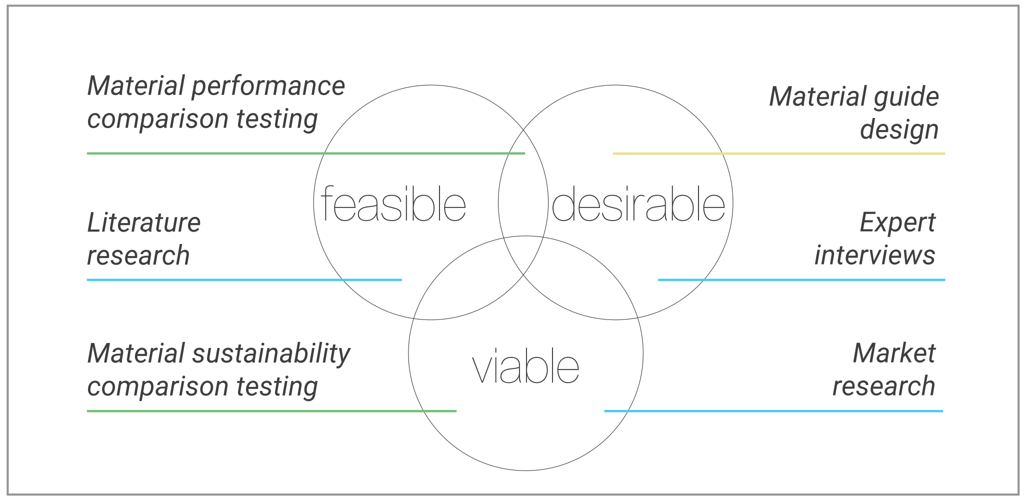
Additive Manufacturing (AM) is undergoing a radical evolution. AM businesses such as Ultimaker (UM) are speeding up industrial production through digital design and local manufacturing to enable industries to produce “what they need, where they need it, and when they need it” (“Ultimaker”, 2019), while also being cost-effective. AM is perceived as a key sustainable technology as it enables efficient design and is believed to make less waste (“AMFG”, 2020), thus putting Ultimaker in a position to offer sustainability enhancements for their clients’ manufacturing processes. One topic of debate for AM sustainability, and the topic of investigation for this thesis, is whether bioplastics are more sustainable than fossil-based plastics for Fused Depositon Modeling (FDM) 3D Printing. Although PLA, a commonly used FDM material, is bio-based, it was hitherto unclear how much using this material and other BBPs can reduce the ecological impact of the 3D printing (3DP) process.

This investigation was conducted in three phases-
First, gaining an understanding of the context through literature review, market analysis and expert interviews.
Second, material tests conducted to compare energy use and material properties of 3DP filaments.
Third, a synthesis of findings from the first two phases into a material guide and recommendations for reducing the environmental impact of 3DPrinting.

Whereas polymers are classified as bio-based/fossil-based and biodegradable/non-biodegradable, the 3DP filament materials available in the market often contain additives, fillers, or other polymers which make them difficult to categorize in a single type (Rohringer, 2020). Hence, a variety of polymers were selected for conducting material studies- including 3 UM-standard filaments, and 5 new filaments. Both environmental and functional properties were studied. For environmental impacts, literature showed that across the different parts of the 3DP filament life cycle, electricity use of the printer is the biggest contributor to ecological impact (Faludi et al., 2015). This motivated the investigation of energy use of a UM printer while printing selected materials. For functionality, expert interviews highlighted tensile properties, dimensional accuracy, and ease of printing as the most important criteria in the material selection process- thus motivating comparison tests for the same.

An energy use comparison test revealed that electricity use is mainly influenced by build plate heating. More research is recommended to minimize build-plate heating for UM printers through solutions such as insulating the build chamber, or localized heating of build plate. The print quality and tensile tests affirm BIOPETG as a potential drop in replacement for UM-CPE. For both tests, new materials performed slightly worse, albeit often at acceptable levels, as compared to UM-standard materials. However, this can be attributed to the rudimentary level of print process optimization conducted for the new materials. Thus, it is recommended that these materials go through an elaborate optimization process in order to gain a more accurate impression of functional performance.

As the final outcome of this investigation, the data collected was compiled into a material guide containing material properties and sustainability indicators. This visual can be referred by end-users like engineers, designers and production professionals to make appropriate material choices for their applications.



Glossary of terms

PLA - Polylactic acid
PHA- Polyhydroxyalkanoate
ABS - Acrylonitrile butadiene styrene
CPE - Co-polyester
PETG - Polyethylene terephthalate glycol

1

Project Formulation

This chapter introduces the initial problem statement that this thesis evolved from. Further, it presents an overview of the project structure and planning.

1.1 Initial Problem Statement

This project spawns from the following initial enquiry-

‘Are bio-based polymer filaments more sustainable than fossil-based ones for 3D printing?’

Supporting the demands of Industry 4.0, 3D Printing (3DP) applications are rapidly expanding from prototyping and tinkering for makers, towards customized tooling, end-use parts etc. for large industries like aerospace, automotive, manufacturing, healthcare, etc. (“AMFG 1”, 2020) Although the technology is gaining popularity as a reliable advanced manufacturing process, the sustainability benefits of this process for the industry continue to be a topic of multiple scientific debates (Ford & Despeisse, 2016), (Liu et al., 2019). One among these debates questions whether using bioplastics, i.e. either bio-based or biodegradable polymers results in reduced environmental impact compared to non-renewable, fossil-based polymers (Pakkanen et al., 2017). Is an application manufactured using PLA or other bioplastics more sustainable than one printed with a fossil-based one? Can an business make claims of improved sustainability performance by using bioplastics for its 3DP applications? Finding the answers to these questions for the current context was the initial motivation for this project.

To begin with, each of the stakeholders in the 3DP landscape understand material sustainability of 3DP differently. The 3DP hardware market is shifting its focus onto industry applications that often require high-performance materials, where material sustainability is often the last priority. The academic community on the other hand is developing radically new materials and processes like paste-extrusion which have a reduced environmental impact, but have a long way to go before being fit for industrial applications (Faludi et al., 2019) (Sauerwein & Doubrovski, 2018). Most end users tend to be under- or ill- informed about material sustainability- for eg. they may confuse bio-based plastics with biodegradable plastics, or associate low performance to so-called eco-materials. And while legislation on biopolymers is currently in preparation, no firm conclusions have yet been drawn about their sustainability performance. Studying this context to bring the stakeholders on the same page and identifying knowledge gaps is the first step towards finding the answers to the initial questions.

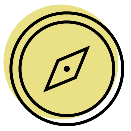
New bio-based filaments are being added in large numbers to the 3DP market. Sustainability assessment of these filaments is much needed, because few researchers or companies engage in the time-consuming empirical studies needed for quantitative comparisons. Further, assessing the material properties of these filaments is key to determine whether they are fit for industry applications. Finally, this knowledge needs to be accessible to the end users, to aid the process of selection and use of relevant bioplastics for their application. For this project, the goal is to perform the technical empirical studies that make this answer easily accessible for stakeholders in this industry without the time, skills, or resources to perform tests themselves.

1.2 Project Objectives

To structure this investigation, the initial objectives of this project were framed as follows-

Understanding sustainable 3DP in the context of bioplastic filaments

Testing commercial bioplastic filaments for sustainability and material properties



Guiding users in the industry towards green 3DP material and process choices

1.3 Relevance for stakeholders

1.3.1 Relevance for Ultimaker

Ultimaker is one of the market leaders in the 3DP industry, owing to their open and collaborative brand combined with superior products and services. The company is currently in process of scaling up its business from 'carpet floor' applications (e.g. product prototyping) to 'concrete floor' applications (e.g. manufacturing aids) in large industries. For these industries, one of the value added by AM technology along with process efficiency, is the sustainability benefits that the technology can offer. The outcomes of this project can thus be used for-

- Understanding the actual environmental impact of bioplastic filaments.
- If found to have potential benefits, appropriately promoting these filaments as sustainable material alternatives to interested clients.
- Referring the material selection guide created as a result, to end-users-clients of Ultimaker for their 3DP applications.
- Updating knowledge about new filament materials and material suppliers in the market.
- Identifying R&D opportunities to improve sustainability of printer/ print process/ materials.

1.3.2 Academic Relevance

- Filling knowledge gaps on how material choice affects printer energy use, since so little research on this topic exists.
- Filling knowledge gaps on customer requirements for 3D printing materials, so researchers know what functional attributes to prioritize.
- Identifying design opportunities to improve sustainability of 3D Printing through innovation in hardware or print processes.
- The other opportunities identified have been compiled in each chapter summary, and can be used for future investigation in this domain.

1.4 Project Approach

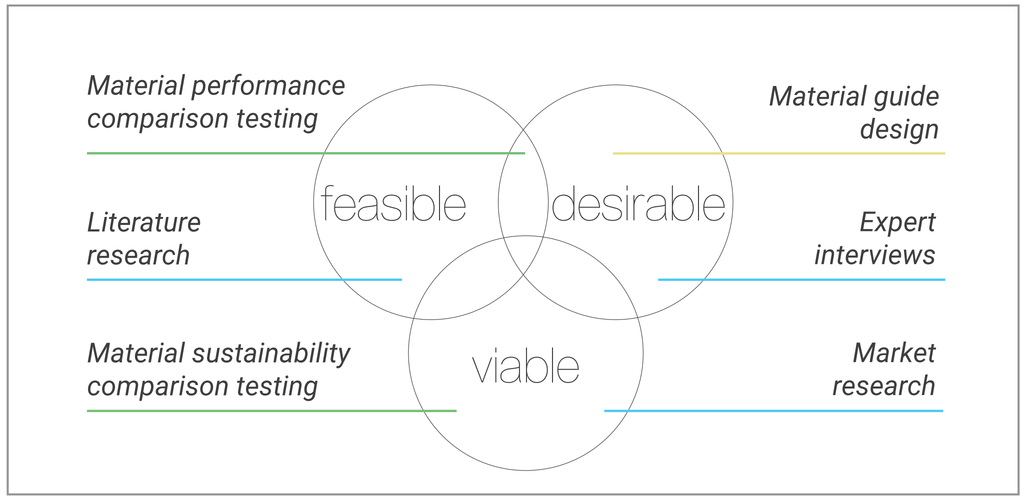
The project was divided into three phases each pertaining to the three project objectives-

In the first phase- **Understanding**, a thorough context study was conducted by analyzing scientific literature and market study reports, and through expert interviews that gave an insight into the industry as well as end users.

The knowledge gaps identified in this phase were used to formulate material studies for the second phase- **Material Testing.** In this phase, 5 commercially available bio-based and/or biodegradable filaments were compared with 3 Ultimaker standard materials, on their energy use and material properties. Analysis of these test results added to the understanding of their sustainability performance, and revealed opportunities for and challenges in the use of these materials.

This combined with user insights from the first phase were used to create a **material guide** containing an overview of the materials tested, and recommendations to improve the sustainability performance of the 3D printing process.

Figure1.1 Overview of project approach and processes



2

Understanding

This chapter presents an understanding of the context, market and users, covering the following themes:

Analysis of material sustainability for 3DP filaments

Meaning of sustainability for various stakeholders in the AM market

Introduction to bioplastics; types of bioplastics available for 3D printing

Material properties essential for industry applications

End-users' material selection process for particular applications

2.1 Approach and Methods

Information was collected in this phase through desktop research and expert interviews. First, scientific literature was studied within 3 broad research themes- Sustainability of 3DP technology, Bio-based polymers and polymer filaments for FDM, and Material properties assessment for FDM materials. Google Scholar and ResearchGate websites were used to search for relevant literature. To understand the current FDM market, market studies such as Wohler’s Report ("Wohler's Report", 2017), Ultimaker Global Sentiment Index (Ultimaker 1, 2019) were analyzed. An online market scan was also conducted to study the different types of bio-based filaments currently available.

As this phase of the project coincided with the pandemic lockdown, it was not possible to conduct in-person consumer research with actual clients and end users. Hence, it was adapted to include two methods. First, internal documentation and research on 3DP applications and material use was analyzed. Second, for understanding end users’ expectations from filament materials, expert interviews were conducted with Application Engineers (AEs) from Ultimaker. A large part of an AE’s job is identify potential applications of 3DP for the client, understand the client’s hardware and material requirements, and train end users such as engineers and factory technicians to independently use 3D printing hardware, software, and materials. This made them the ideal choice for expert interviews, in order to gain insights into the end-users’ journey of material selection and use.

2.2 Additive Manufacturing

Additive manufacturing, commonly known as 3D printing, refers to the computer controlled process of creating three-dimensional objects by depositing layer upon layer of material in precise geometric shapes. AM is an umbrella term for different types of manufacturing processes including binder jetting, direct energy deposition, powder bed fusion, sheet lamination, vat polymerization, wire arc additive manufacturing, and material extrusion. The technology of interest for this project is the material extrusion process called Fused Deposition Modeling(FDM) also known as Fused Filament Fabrication (FFF). This technology uses thermoplastic filament which is melted and extruded layer by layer to create a 3D object.

A market study conducted by AMFG (2020) mentions that the global market for AM was estimated to be worth more than $10bn at the end of 2019. The polymer 3D printing market in particular, has shown a steady growth in the last couple of years, as large number of applications for this technology are being identified. High returns on investment makes FDM the most popular and widely used AM technology for industry application in the current market: 72% of the companies in this study used polymer printing for various applications.

2.2.1 Sustainability of AM

AM has been proven to be more environmentally friendly while producing parts with complex geometries, customized for specific applications, and parts required in low volumes (Ford & Despeisse, 2016). AM also offers various economic benefits compared to conventional manufacturing processes, such as material efficiency due to design optimization, reduced lead time and reduced per-part cost, and reduced need of huge inventory, transport of products and spare parts. Furthermore, 3D Printing of spare parts also supports the design for repair movement (Kellens et al., 2017).

2.2.2 Sustainability of FDM in context of Ultimaker

As more and more industries make commitments towards sustainability- be it in terms of reducing emissions, or managing end of life of their products etc., it is imperative for FDM manufacturing services to demonstrate opportunities that can add value to their client companies in this direction. For Ultimaker, one of the major sustainability articulations is to reduce waste generation by optimizing hardware and print process for each material and producing a 'first time right' print, i.e. an optimum print in the least number of iterations. However, this approach is limited, in the sense that it essentially reframes product efficiency (i.e. the efficient performance of Ultimaker products) as a sustainability benefit. In this thesis, a new articulation is explored- one which investigates material sustainability, specifically in terms of using biopolymers in place of fossil-based, non-renewable polymers.

Why study polymers, and not other bio-based materials such as paste-extrusion materials?

A recent study demonstrates that paste printing of upcycled biomaterials or minerals can result in significantly reduced print energy, reduced embodied impacts of materials, reduced toxicity hazards compared to ABS, at half the cost of ABS (Faludi, 2018). The scope for this thesis however, is limited to polymer filaments. This is in order to maintain the relevance of the project towards Ultimaker. Currently, paste extrusion material as well as hardware development is still at a lower point in TRL levels. This means that more investment is needed before these are ready for launch. By contrast, bioplastic filaments are already compatible with existing hardware, and fit into the near-future product strategy for Ultimaker- which is towards optimizing hardware and software for polymers materials alone.

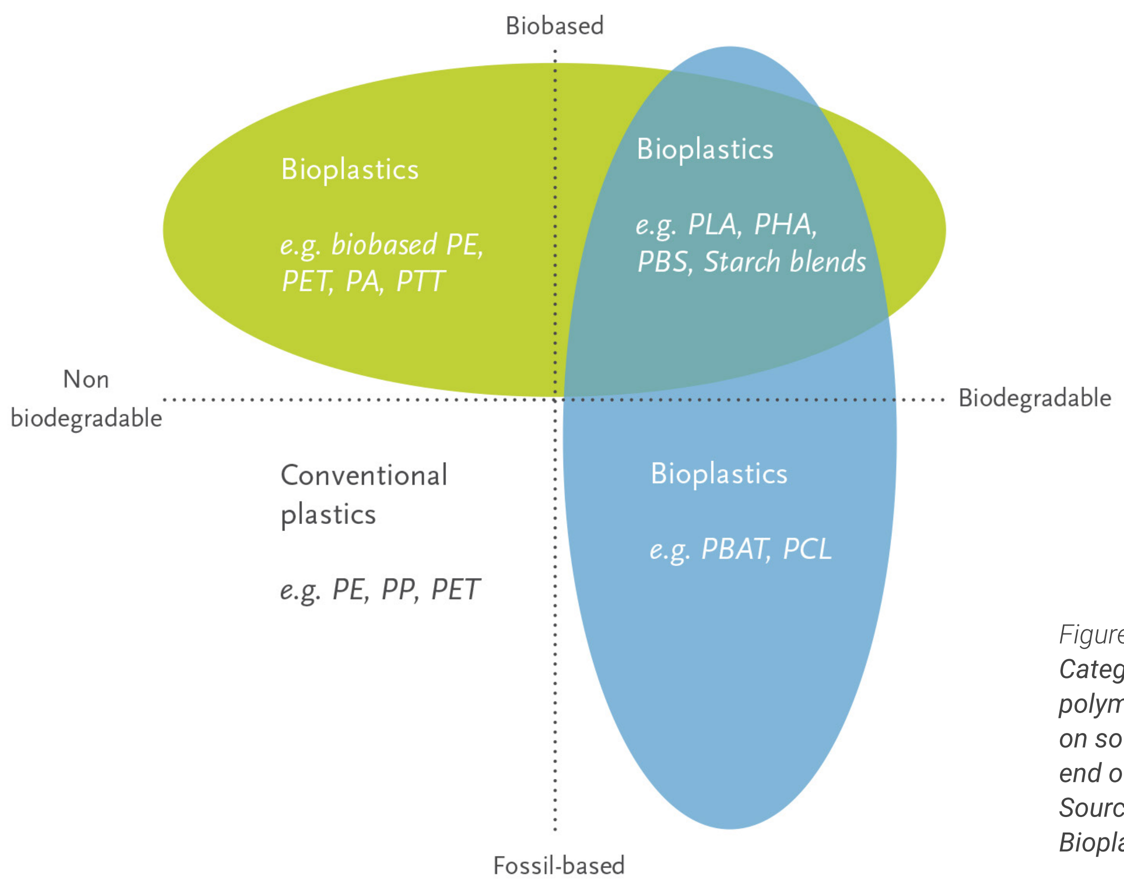


Figure 2.1 Categories of polymers based on source and end of life. Source: European Bioplastics e.V.

2.3 Polymer materials used for FDM printing

2.3.1 What are bioplastics and fossil-based plastics?

The European Bioplastics Association defines the umbrella term **bioplastics** as polymers that are bio-based, or biodegradable, or both.

Bio-based polymers or bio-based plastics – According to IUPAC nomenclature (2012), these refer to polymers “derived from the biomass or issued from monomers derived from the biomass and which, at some stage in its processing into finished products, can be shaped by flow.”

Biodegradable plastics - Degradable plastics in which the degradation results from the action of naturally occurring microorganisms such as bacteria, fungi, and algae, as defined by ASTM D6400 - 19 (ASTM, 2020). Plastics that are degradable in industrial organic waste management facilities are usually categorized as ‘biodegradable’, although this still means that they cannot be discarded in nature.

Compostable plastics are plastics that undergo degradation by biological processes during composting to yield CO2, water, inorganic compounds, and biomass at a rate consistent with other known compostable materials and leave no visible, distinguishable or toxic residue as defined by ASTM D6400 - 19 (ASTM, 2020) These can be discarded in nature- e.g. in a home composter.

Finally, **fossil-based polymers or plastics** are polymers derived from non-renewable petroleum-based sources.

Figure 2.1 clarifies the distinction, highlighting the bioplastics in green with examples from each type.

2.3.2 Commercially available bioplastic filaments

Most of the bio-based filaments available in the online market today are varieties of pure polylactic acid (PLA), or PLA-based filaments with filler materials such as powdered wood, algae fibers etc. PLA blended with PHA is another bio-based filament material, which is less brittle than PLA and has an impact strength comparable to ABS. Another type of ‘green’ filament is a fossil-based filament with additives that make the polymer biodegradable, for instance the filament ‘BIOPETG’ supplied by 3DprintLife, which is one of the materials tested during the project. Appendix A provides a compilation of bioplastics available for sale on the online market.

Figure 2.2 BioPETG and ENVIRO, two examples of biopolymers available on the online market. Source: 3DPrintLife

2.4 Sustainability of FDM material filaments

"When customers think of sustainable materials, they usually think of recycled materials, and not biomaterials."
(G. Morvan, personal communication, April 24, 2020)

The layperson currently understands sustainability mainly in terms of popular articulations, such as managing end-of-life of a product to 'close the loop'. Consequently, large businesses focus on improving their sustainability performance and branding through easily understood implementations, such as use of recycled materials. For instance, KLM's Drink to Ink project collects used PET bottles during air journeys and uses them to make recycled filament which can then be 3D printed as aircraft maintenance tools. However, a complete life cycle analysis (LCA) is required to understand the actual environmental impacts of any product or process, and to identify opportunities for improvement.

In order to gain a holistic overview of sustainability of FDM filaments, literature and market data was simultaneously analyzed through two lenses. The first lens looked at each phase in the life cycle of the filament- from converting raw material into polymer pellets, manufacturing polymer filaments, transport, use of the filament- i.e. printing an object using the filament, and the end-of-life of the printed objects. The second lens was the diverse interpretations of sustainability for each of the stakeholders in the landscape. Figure 2.4 illustrates the life cycle of a 3DP filament, with stakeholders specific to the FDM materials market mapped onto relevant phases in the cycle.

Figure 2.3 Maintenance jig (light blue) 3D printed from filament made out of recycled plastic (Source: KLM)

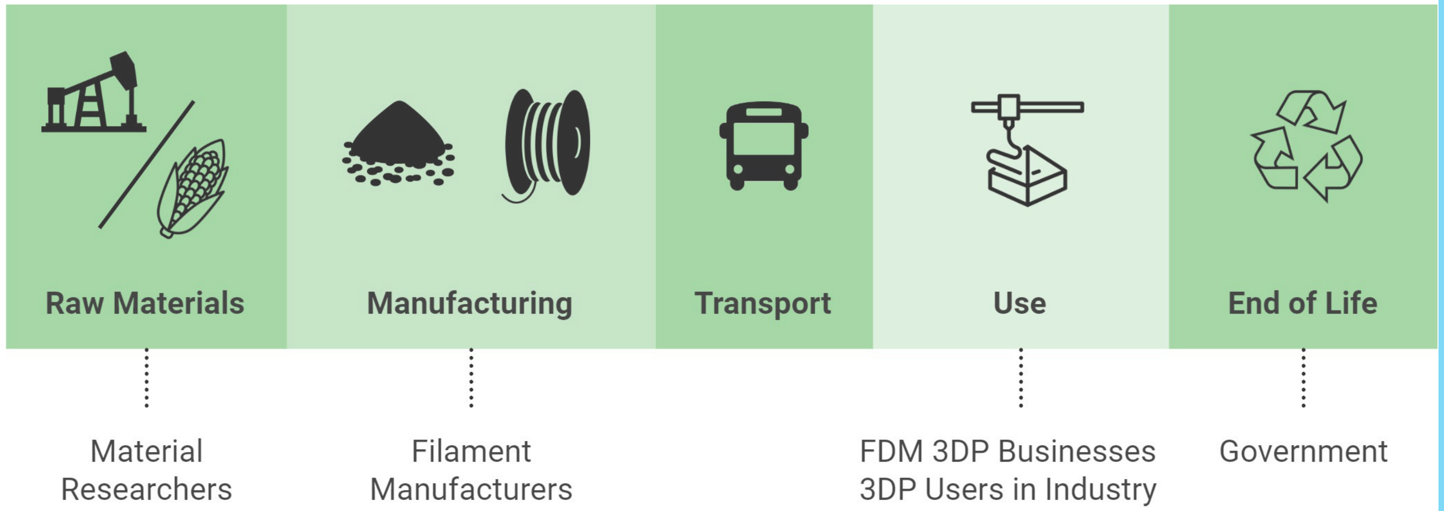


*Figure 2.4 **Life Cycle of FDM filament, and stakeholders engaged in each phase***

The first phase in the life cycle of a filament is the manufacturing stage, i.e. production of polymers from raw materials- these can be either bio-based, fossil based, or a combination. Tabone et al (2010) demonstrate that adherence to Green Design Principles is positively correlated with lower environmental impacts while assessing polymers. In other words, polymers fulfilling 'green design' principles such as ones produced from bio-feedstock tend to have better LCA scores than fossil-based ones. On the other hand, a more recent academic review reveals that the existing collection of life cycle assessment studies displays a wide variation in assessment methodology, making it currently impossible to conclude whether either of bio-based or fossil-based polymers themselves have better environmental performance in any impact category (Walker, 2020). It is important to note that this pertains to the polymers, and not the 3DP filaments or printed parts.

In the next phases, the filament is manufactured from the polymer, and transported to the location of use. No market study or academic research was accessible during the literature review, to compare embodied energy of 3DP filaments, i.e. the impact of manufacturing filaments from raw materials. And transport impacts are best evaluated on a case by case basis.

"So far, no material supplier we know of is doing LCA studies on their material"
(G. Morvan, personal communication, April 24, 2020)

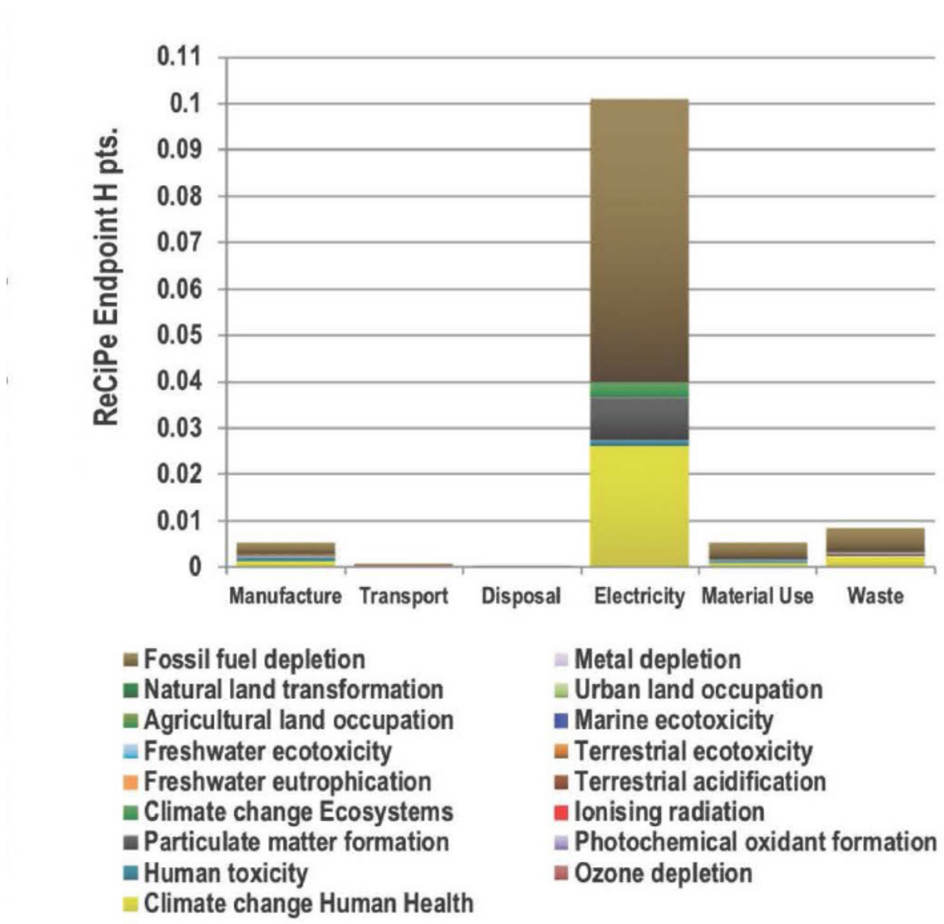


Figure 2.5 ***Ecological impacts per job measured using the ReCiPe LCA method, for a large FDM machine printing ABS. (Faludi, 2015)***

Next is the 'use' phase, i.e. when the filament is used for making a print. Faludi et. al. (2015) demonstrated that electricity use is a dominant contributor to ecological impacts of 3D printed parts (see fig. 2.5 demonstrating ecological impacts for a 3D printed part). Thus, this phase holds the highest influence in determining the overall sustainability performance of the filament. This study compared the electricity use for a range of materials and printers. In the existing literature, no study was found to focus on comparison of electricity use while printing different material types on the same printer. This literature gap has been addressed in the next phase of this project.

The last phase is the end of life. Many polymer filaments in the market are certified as biodegradable or compostable by various international standards such as ASTM D6400, ASTM D5338, EN13432 etc. The 2018 EU legislation recognizes bioplastics as more sustainable alternatives("European Bioplastics e.V.", 2020), acknowledging both bio-based feedstock and biodegradability potential as contributors to reducing environmental impact.

An example of a material that has been specifically developed for low environmental impact across various parts of the life cycle is **Ingeo, a PLA-based material developed by NatureWorks.** Manufacturing Ingeo produces approximately 80% less greenhouse gases and uses approximately 52% less non-renewable energy (NREU) than traditional polymers like polystyrene. (Vink & Davies, 2015). Multiple LCA studies comparing products made from Ingeo ranked Ingeo better than alternative polymers in various environmental impact categories ("NatureWorks Eco-Profile", 2020). Ingeo has partners on frameworks like the Circular Economy and Sustainable Materials Management, to enable appropriate end-of-life scenarios for their products. Currently, three grades of Ingeo PLA are available as FDM filaments. Similar large scale manufacturers such as Total Corbion are also gearing up sustainability-certified production of biopolymers ("Total Corbion", 2020).

To summarize, literature gaps and limitations in assessment methodology makes it difficult to form concrete conclusions on material sustainability of 3DP polymer filaments. However, some academic perspectives and stakeholder interests gravitate towards promoting bioplastics as potential sustainable filament materials. The biggest influencer for overall environmental impact of the FDM process and materials is the energy consumption of the printer while printing a part. To explore possibilities for reducing the environmental impact, it is essential to compare energy use of printers while printing various materials.

Figure 2.6 ***View of the site in Grandpuits, France where Total Corbion PLA intends to build its second Luminy PLA plant with a capacity ramping up to 100,000 tons per annum. Source: Total-Corbion***

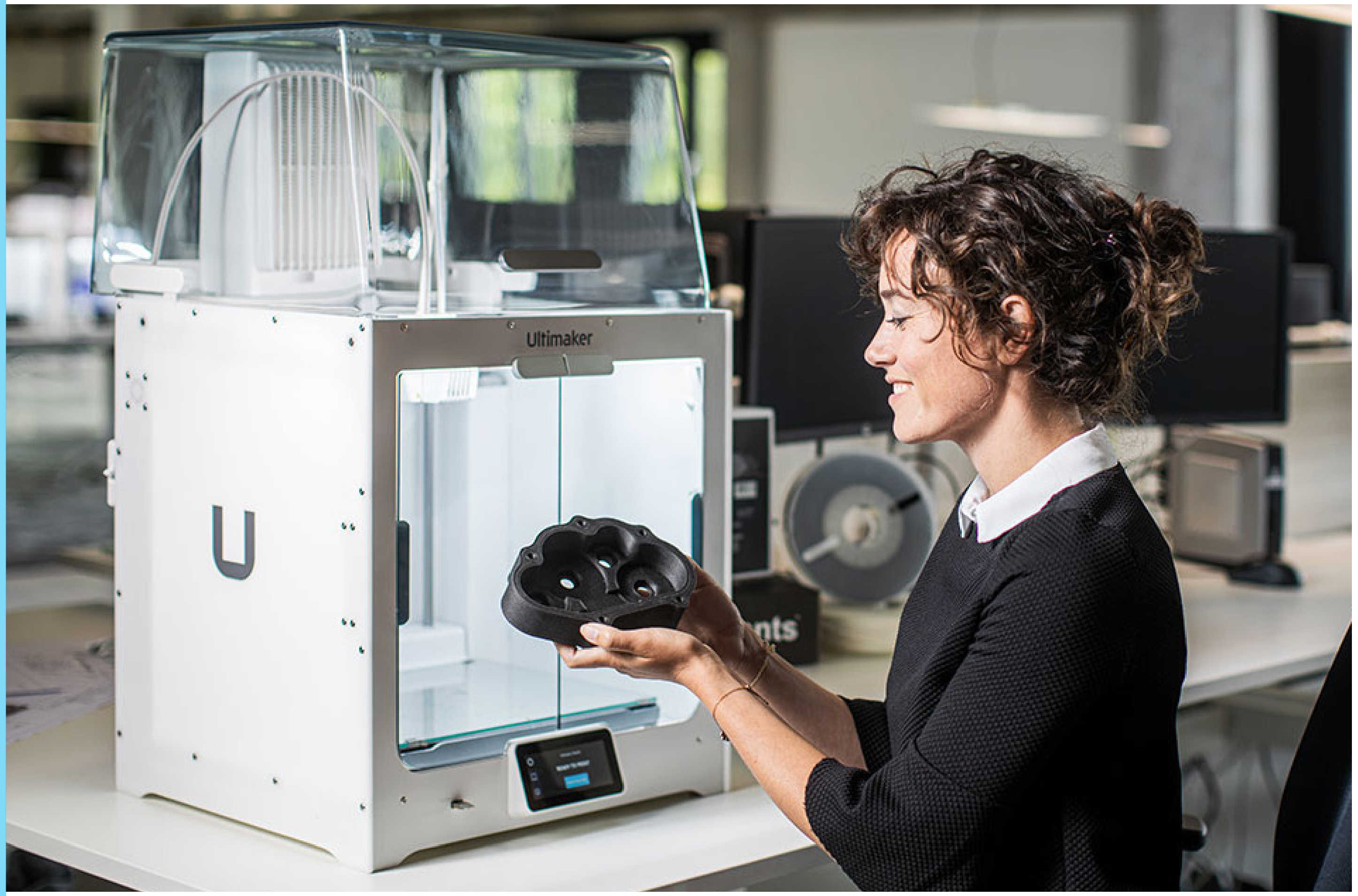


Figure 2.7 New 3D Printing user and industry application. Source : Ultimaker

2.5 3DP Users and user needs in industry

This section summarizes knowledge gained from expert interviews with AEs and analysis of UM's internal research such as the UM Sentiment Index. It describes the user base, what they use 3D printing for, what they demand from the technology in terms of materials, and how they select materials for their applications.

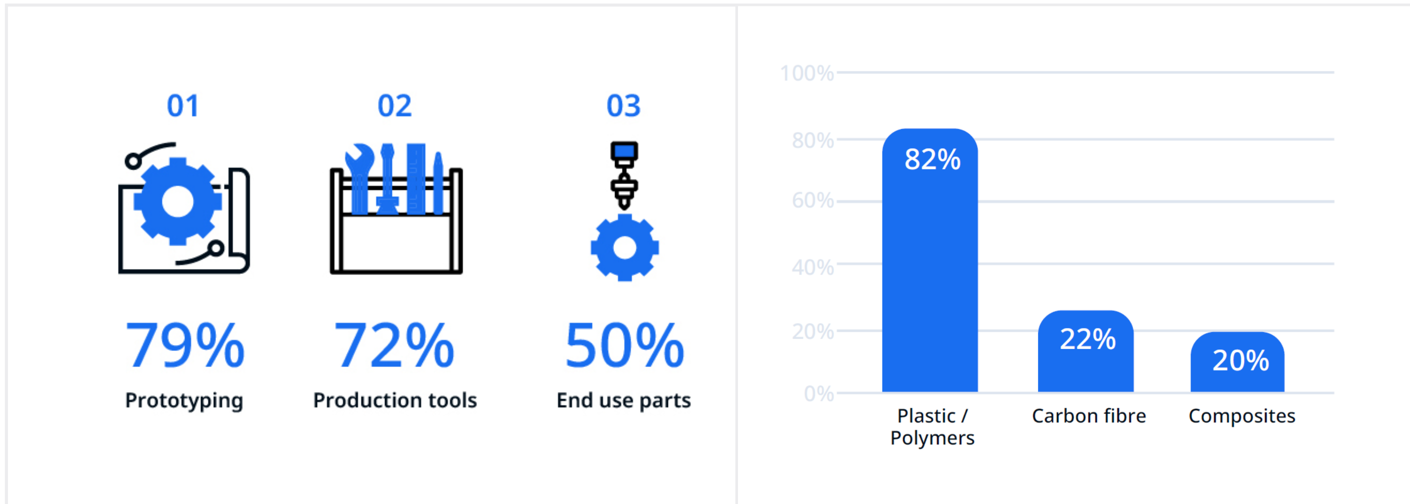
2.5.1 3DP users in industry

Although makers and tinkerers were a major user group when the 3DP technology was introduced, the latest products and services are now catering to industrial applications. Academics and educators, engineers, production professionals, medical professionals, architects, and designers form a large part of this new user base.

Prototyping is still the most common use, or application of 3DP in industry. This includes printing rapid prototypes and visual models for product development, functional prototypes for product validation, and show-models created to present concepts or aesthetic features in client presentations. Another common application is printing replacement parts for machinery and equipment, and tools such as jigs and fixtures to be used in production process, and molds for low volume production of products or components. There is also a rise in more advanced or niche applications such as printing tools like gauges for quality control, or solutions for organizing equipment in workshop areas.

Currently, only a small fraction of users are printing with carbon fiber, composites, ceramics, metal, wood or other biomaterials. Plastics/polymers are the most used printing materials. And there is a definite market demand for a greater range of material choices, as revealed in the UM Sentiment Index study.

Figure 2.8 Snippets from the UM Sentiment index 2019, illustrating percentage of survey respondents involved in printing a certain type of applications or materials. Source: Ultimaker



2.5.2 Material selection process

The general process to select a material for an application is illustrated in the figure 2.9 below.

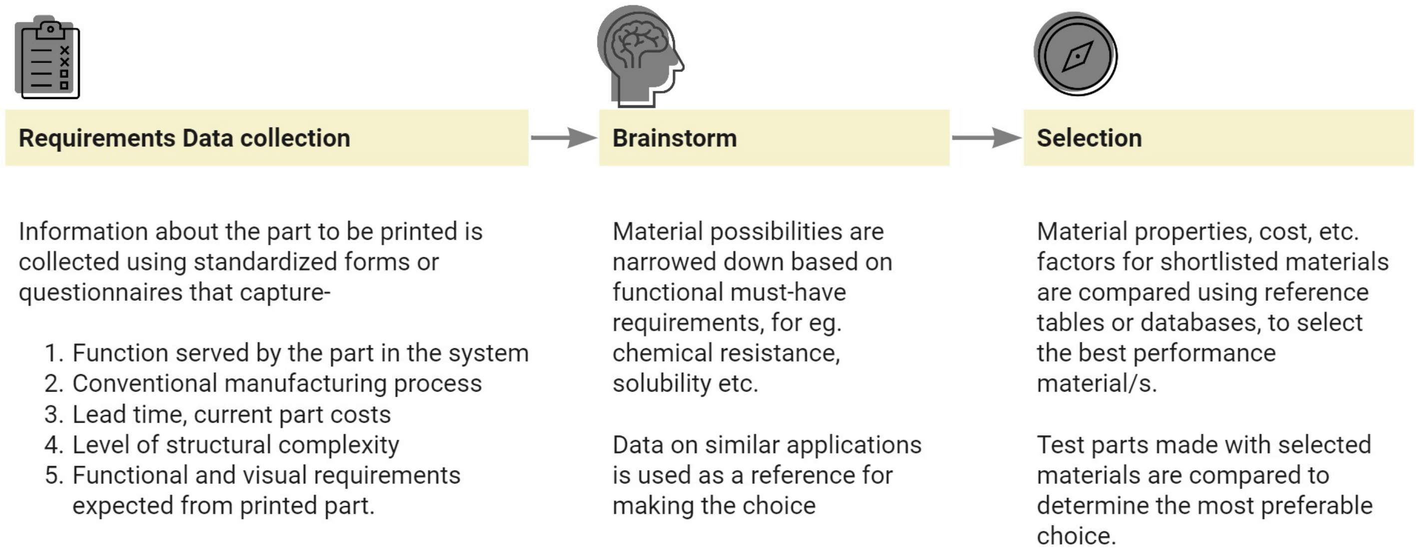


Figure 2.9 ***Process of selecting material for an application***

While identifying requirements, end-users most often consider functional properties such as tensile strength and stiffness, dimensional accuracy and process repeatability, i.e. dimensional uniformity across all parts printed from the same CAD model, and aesthetic properties like surface quality. However, the selection process is also influenced by other factors. For instance, ease of printing a material is a key criteria for adoption of the technology within a company. Hence, new users are often recommended PLA-based materials which are easier to print than materials like ABS, PP. Moreover, users having some experience with printing often tend to prefer using materials they are familiar with.

“It’s not always about having a part that never breaks... 3D printing allows you to be agile- you can 3D print on-demand, at a lower cost. If the material fulfils 3 out of 5 requirements and is a lot cheaper, the customers will prefer it over a more expensive material that can fulfil all requirements. So it’s not only about requirements.”
(G. Morvan, personal communication, April 24, 2020)

Currently, PLA-based materials satisfy a large range of applications documented by UM. Only a few applications require filaments with special properties like temperature resistance, chemical resistance, etc. which are not fulfilled by PLA-based materials.

“Around 70-80% industry applications are using PLA, or ToughPLA filaments. Customers always ask for the best material. But sometimes very basic materials can fulfil their requirements. When the customers say they need high stiffness, that doesn’t always mean they need carbon fiber. In fact many times, PLA is more than enough.”
(G. Morvan, personal communication, April 24, 2020)

2.6 Converging

This thesis explores a new sustainability articulation for Ultimaker by investigating the environmental impact of bio-based and/or biodegradable plastics as compared to non-renewable materials like fossil-based polymer filaments. This can supplement the existing strategy of the company, which mainly focuses on optimizing the print process to reduce the number of wasted prints.

Most types of PLA filaments available in the market are bio-based, and many of them also comply to international standards for biodegradability. These are an interesting selection for material study, as they are not only recognized as potentially sustainable materials, but also easy to print, and satisfy a majority of application requirements for end-users. Another category selected for study is co-polyesters which offer more elasticity and better thermal resistance (at the cost of printing ease), compared to PLAs. This category was also selected due to the availability of BioPETG, a material filament containing an additive that makes it biodegradable.
As energy use of the printer is the main contributor towards the environmental impact, the first material study in the next phase compares energy use of different polymer filaments. This is to enable investigation into material or print process parameters that affect the energy use of the printer, and to identify opportunities for improvement.

For a filament material to be adopted by end-users, it has to first satisfy the performance requirements expected for a certain application. Expert interviews revealed that sustainability is the last point of consideration, if at all, in the end users' material selection process. As ease of printing, visual quality, and tensile properties are the material properties most relevant to end-users, these properties are also compared for different filaments in the next phase.

The next chapter reports this material testing process.

3

Testing

This chapter describes the material tests formulated in order to bridge the identified knowledge gaps. It presents the results and discussions for each test and concludes with more opportunities identified for future work.

3.1 Approach

The research opportunities identified at the end of the understanding phase, were formulated into the following material comparison studies for a selection of filament materials-

Type	No.	Test
Sustainability	1	Comparing energy consumption of a printer for different filaments.
Material performance	2	Comparing printability and dimensional accuracy
Material performance	3	Comparing mechanical properties (tensile modulus, ultimate tensile strength, and elongation)

Table 3.1 Material Comparison studies formulated for the Testing phase

Eight materials were selected to be used for the tests- 3 UM-standard filaments, and 5 new filaments available in the online market.
Print Profiles were already available for the three UM-standard materials, i.e. for these materials, print settings and parameters optimized for good quality prints are available to use with the CURA software. In order to similarly optimize the print parameters for the other 5 materials, an initial test – Test 0 - was conducted before printing test objects for the 3 studies.

Organizations such as ASTM are in still process of developing standardized test objects to measure print performance of 3D prints. As of now, various test objects developed by 3D printing companies and tinkerers are used to measure a variety of combinations of print performance parameters. Many of these test objects are open-source projects available for free access on CAD libraries such as Thingiverse. For instance, 3D Benchy is a popular '3D Printer torture test' used to compare printer and material performance ("#3DBenchy", 2020). To avoid reinventing the wheel by designing yet another set of test objects, the studies in this project used existing CAD models, appropriately selected based on the objective for each test.

3.2 Materials and Equipment

3.2.1 Filaments

As mentioned in the previous chapter, material filaments widely vary in terms of composition and properties, and there are multiple ways to classify them. Taking this into consideration, filaments selected for testing were based on the following criteria in order to have multiple possibilities for comparisons-

1. Either bio-based and/or biodegradable filaments, or UM-standard materials
2. Enabling comparisons between a newly tested material and a similar UM-standard material
3. Enabling comparisons between two or more materials of the same type.
4. Feasible to acquire from the material supplier during the COVID lockdown restrictions

Accordingly, the following filament materials were used for the tests-

Table 3.2 Filament materials selected for study

Material	**Supplier**	**Composition**	**Source**	**End of life**
UM-PLA	Ultimaker	PLA	Bio-based	Biodegradable
UM-TPLA	Ultimaker	PLA+ additive	Bio-based, partially	Non-biodegradable
ALGA	3DPrintLife	PLA+ filler	Bio-based	Biodegradable
OMNI	3DPrintLife	PLA+ additive	Bio-based, partially	Biodegradable
PLAYPHAB	3DPrintLife	PLA+ PHA	Bio-based	Biodegradable
PLAPHA	Colorfabb	PLA+ PHA	Bio-based	Biodegradable
UM-CPE	Ultimaker	CPE	Fossil-based	Non-biodegradable
BIOPETG	3DPrintLife	CPE(PETG)+ additive	Fossil-based	Non-biodegradable

3.2.2 Equipment

Test objects for all the studies were printed on the same Ultimaker 3 printer, except the tensile test bars of the three Ultimaker materials which used a different UM-3 printer. CURA software (ver. 4.6) was used for preparation of print files, i.e. for print parameter adjustment and slicing. A layer of UHU Stick Glue was applied to the build plate during each print, to improve adhesion. Power data was logged in Test 1, using a HAMEG HM8115-2 Power Meter. A Vernier caliper was used for measuring dimensional accuracy and print quality indicators in Test 2. Tensile properties were measured in Test 3, using the INSTRON Universal Testing System and Extensometer.

Figure 3.1 HAMEG Power meter (Source- HAMEG) ;
Figure 3.2 Ultimaker 3 Printer (Source: Ultimaker);
Figure 3.3 INSTRON Universal Testing System (Source: Instron)

3.3 Material Tests

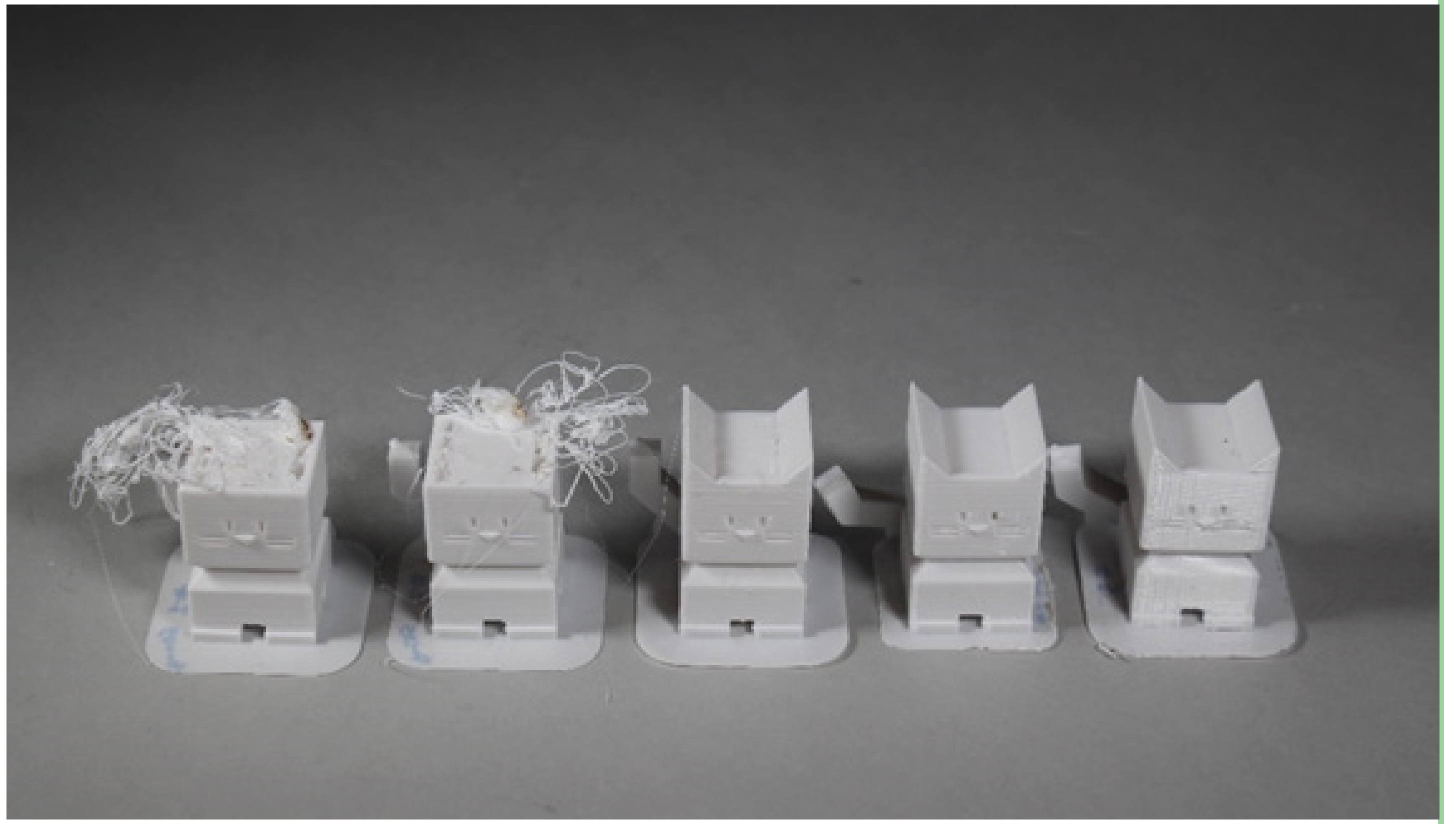
3.3.1 Test 0 – Print Profile Optimization

A 'print profile' refers to a set of print process parameters identified to produce a good quality 3D print in combination with a specific material and hardware. The existing print profiles for the 3 UM-standard materials have been developed using an internal Ultimaker standard procedure for print profile optimization. This procedure was time intensive and more elaborate than essential for the scope of this thesis. Hence, Test 0 was formulated as a fast-track method with the objective to optimize print profiles for the other 5 filaments. 'Calicat'- an open source model available on Thingiverse was selected as the test object based on the following criteria –

1. Short print duration (~ 1hour) allowing for multiple iterations in a short time
2. Ability to inspect print quality indicators such as dimensional accuracy as well as surface quality parameters like overhangs, bridging, and flow control.

All the Calicat- test objects were printed without support, using the 'brim' setting for build-plate adhesion. For all prints, layer height was kept constant at 0.15mm, and infill at 20% wherever needed. The first iteration was printed using the 'Generic PLA' or PETG print profile from CURA (as per base material). Multiple Calicat iterations were printed for each material, adjusting print parameters in each iteration based on print settings suggested by the filament suppliers. Qualitative assessment of the material was conducted through visual and tactile inspection of each iteration, while looking for the quality indicators mentioned above. The print parameters for the iteration demonstrating the most optimum print quality were considered as a 'pass'- to be used for the next three tests.

Figure 3.4 ***Calicat models printed during the tests, showing a progression from poorly-optimized to well-optimized.***



Results and Discussion- Test 0

Appendix A provides full information on print parameters adjusted for each material or iteration, and quality notes on each print. For most of the materials, extrusion temperature, build plate temperature, and print speed were the only parameters adjusted while keeping the rest of the parameters constant. The final outcome of Test 0 was the set of print parameters identified for the selected materials. This can be found in Table 3.3.

As this was intended to be a fast-track process, only the 3 parameters mentioned were adjusted for most materials, while keeping the base print profile constant. For instance the layer height, and infill percentage were kept at constant values of 0.15 mm and 20% respectively.

Table 3.3 Print parameters identified through Test-0, for good quality prints.

Material	Printing Speed	Printing Temperature	Build Plate Temperature
	mm/s	°C	°C
ALGA	70	195	60
BIOPETG	60	250	85
OMNI	80	205	50
PLAPHA	80	200	60
PLAYPHAB	80	210	50
UM-CPE	60	245	70
UM-PLA	70	205	60
UM-TPLA	45	215	60

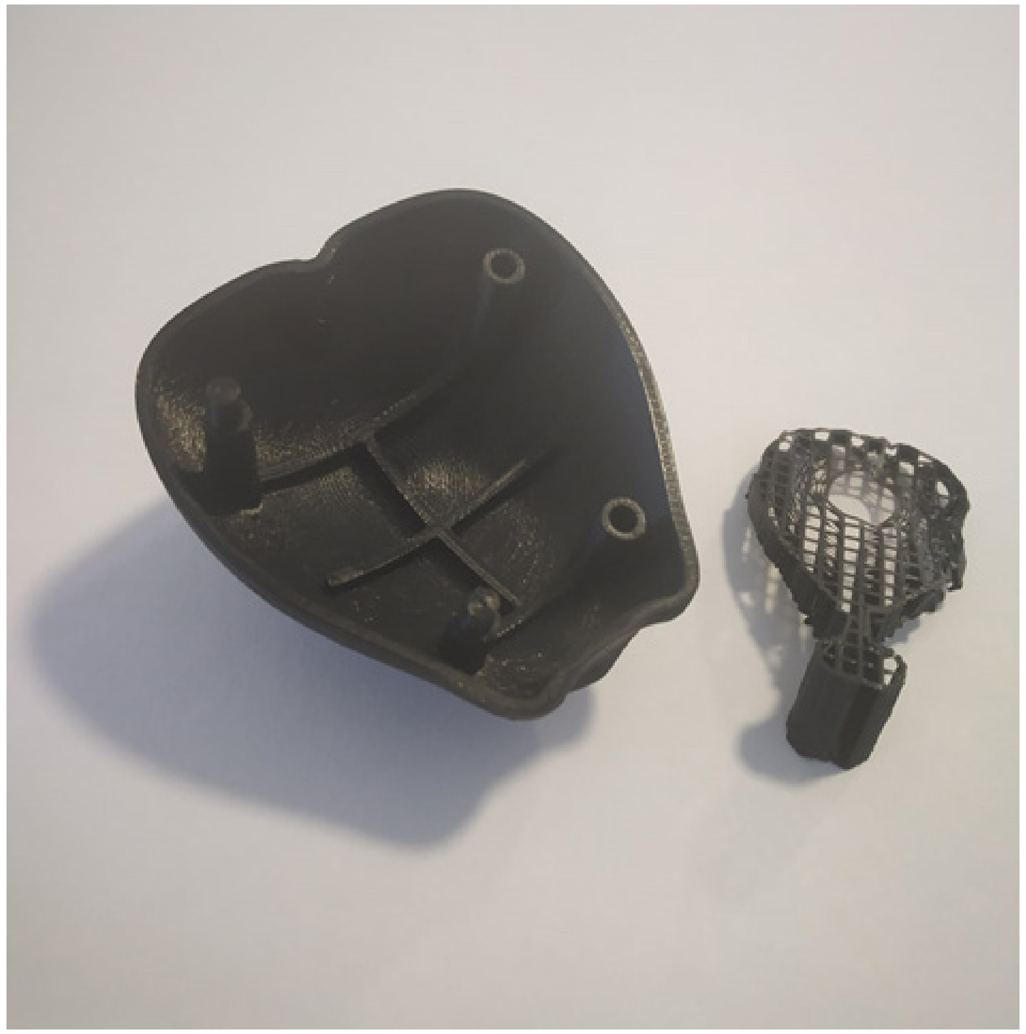
3.3.2 Test 1 – Measuring Energy Consumption

This test was formulated with the objective of measuring and comparing energy consumption of the printer while printing each material, to observe the effects of various print parameters on energy use. The 'Apple shell' test object, seen in the image below, was selected as the unit for comparison, considering the following criteria –

1. As a representative of commonly-printed prototypes for commercial parts
2. To enable a fair comparison with data collected in previous research, which measured energy use for different materials and printers using the same 'Apple shell' test object.

Pilot prints of the 'Apple shell' for 3 different materials showed that the part geometry required the use of support material. Hence, PVA support was used for all the prints in the tests, to maintain uniformity. The power meter logged the instantaneous power consumption at each second, starting from the printer startup time, until the end of the print. Heating and lighting features in the printer were hypothesized to have a high influence on the energy use. Thus, LED lights in the printer were switched off during all the tests to ensure that the energy consumption data only reflects the effects of relevant print parameters. The effect of printing temperature, build plate temperature and print speed on power and energy consumption was analyzed.

Figure 3.5 ***Test object- Apple shell printed in T-PLA with T-PLA support for a pilot test***



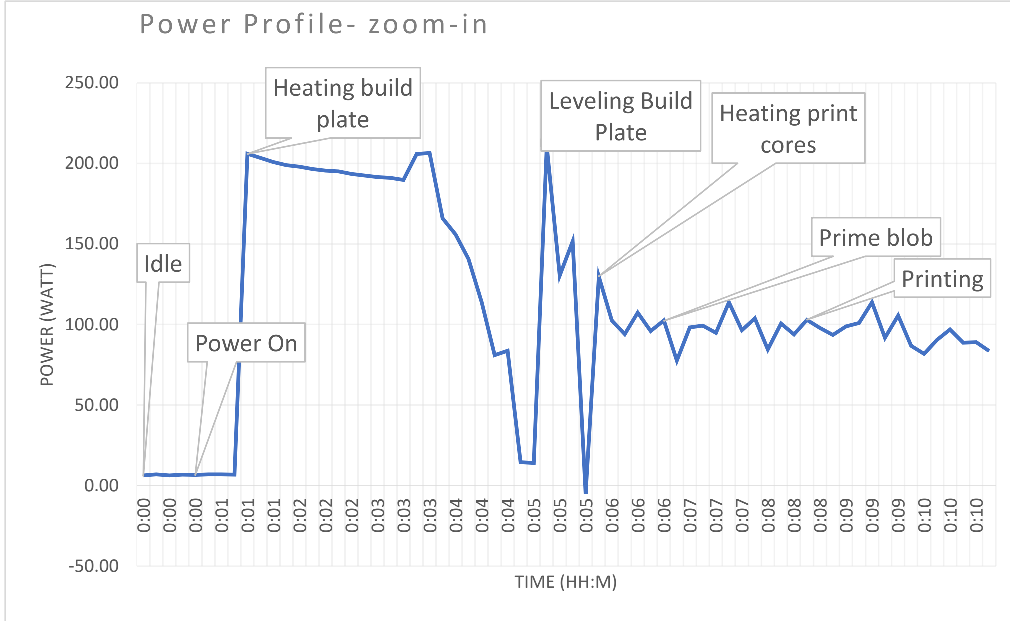
Results and Discussion

Test	Printing time (hh:mm)	Mean Power (Watt)	Energy (kWh)
1	03:14	123.94	0.4
2	03:15	120.11	0.39
3	03:14	117.58	0.38

Table 3.4 Results for Test 1, while printing Apple shell part with UM-TPLA

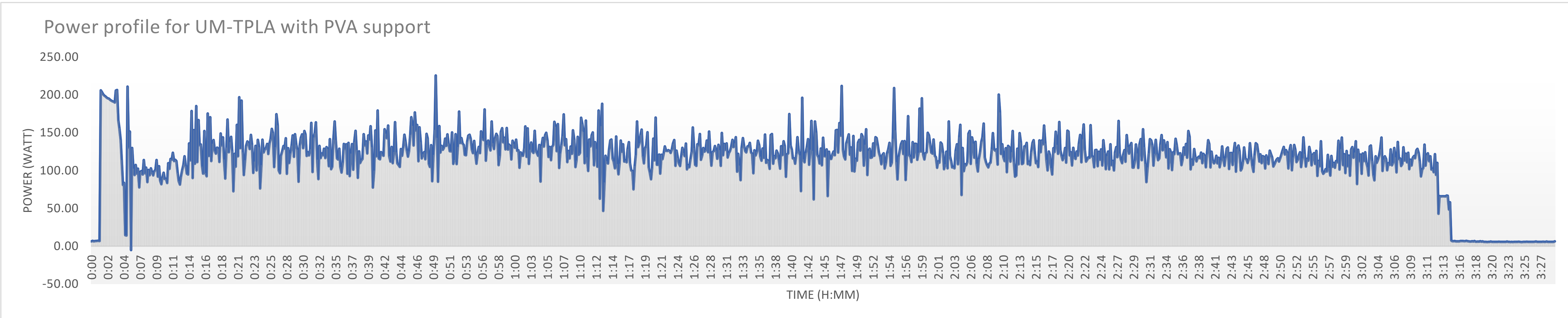
The first material, UM-TPLA was printed three times using the same print parameters, to confirm that there is no significant variation in energy use measurements. These prints were made one after the other with some time between two successive prints, to cool down the build plate. Table [fixme] shows the printing time, mean power consumption, and energy use. The small reduction in energy use for each successive print as observed in this table, may be a result of residual heat in the build plate. Figure 3.6 shows the power profile of the first test printed in UM-TPLA, and figure 3.7 a zoomed-in section of this graph, illustrating the events from start-up to printing.

Figure 3.7 Power profile zoom-in view, from start-up to printing



From these graphs it can be seen that the first few minutes of build plate heating consumes a high amount of power. there is a direct relation between the mean power consumption and build plate heating. The small fluctuations in power after printing begins may be attributed to factors such as maintaining of build-plate temperature, as well as gantry motors switching on/off during print-head travel moves, etc. A more elaborate study of power consumption for each part of the printer system will be required to confirm this assumption.

Figure 3.6 Power profile of Apple shell part printed in UM-TPLA with PVA support



The table 3.5 below displays the mean power and energy consumption for prints made with each of the 8 materials, along with print parameters. All prints except UM-TPLA were printed in about 2 hours and 45 minutes. 4 out of 8 materials tested display an average power consumption between 115-120 Watt. Co-polyester filaments consumed higher average power and energy. These filaments also had higher printing temperatures and build plate temperatures compared to PLA-based ones. BIOPETG consumed the highest average power as well as total energy, at 179.5 Watt and 0.651 kWh respectively.

Material	**Printing Speed**	**Printing Temperature**	**Build Plate Temperature**	**Printing Time**	**Mean Power**	**Energy**
	mm/s	**°C**	**°C**	**hh : mm**	**Watt**	**kWh**
ALGA	70	195	60	02:43	118.842	0.386
BIOPETG	60	250	85	02:49	179.490	0.651
OMNI	80	205	50	02:44	97.348	0.316
PLAPHA	80	200	60	02:44	116.254	0.377
PLAYPHAB	80	210	50	02:43	105.470	0.343
UM-CPE	60	245	70	02:42	137.458	0.447
UM-PLA	70	205	60	02:45	119.590	0.330
UM-TPLA	45	215	60	03:15	120.110	0.390

Table 3.5 ***Mean power, energy use and associated print parameters for all materials***

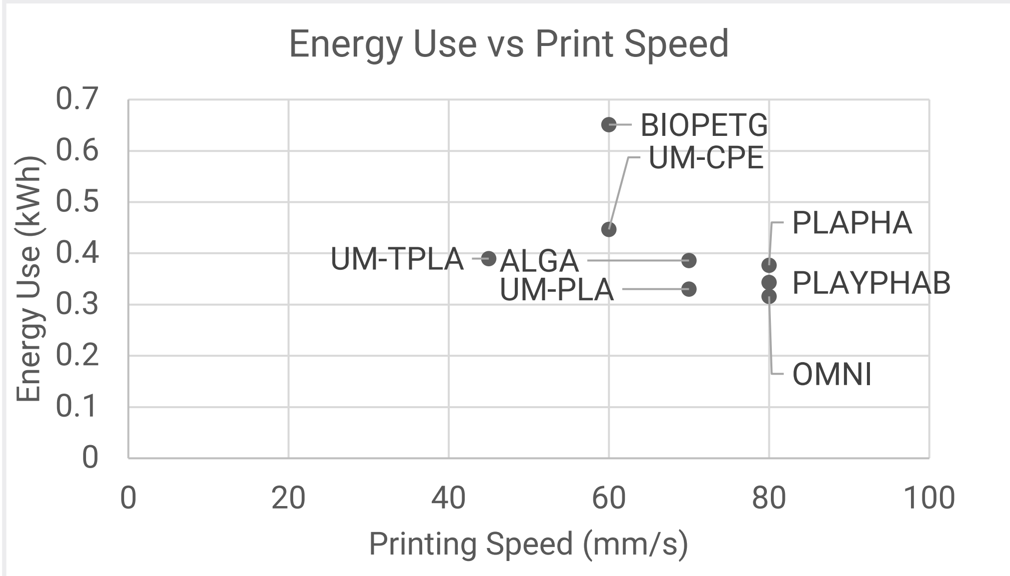


Figure 3.8 ***Energy Use versus Print Speed for Apple shell parts printed in Test 1***

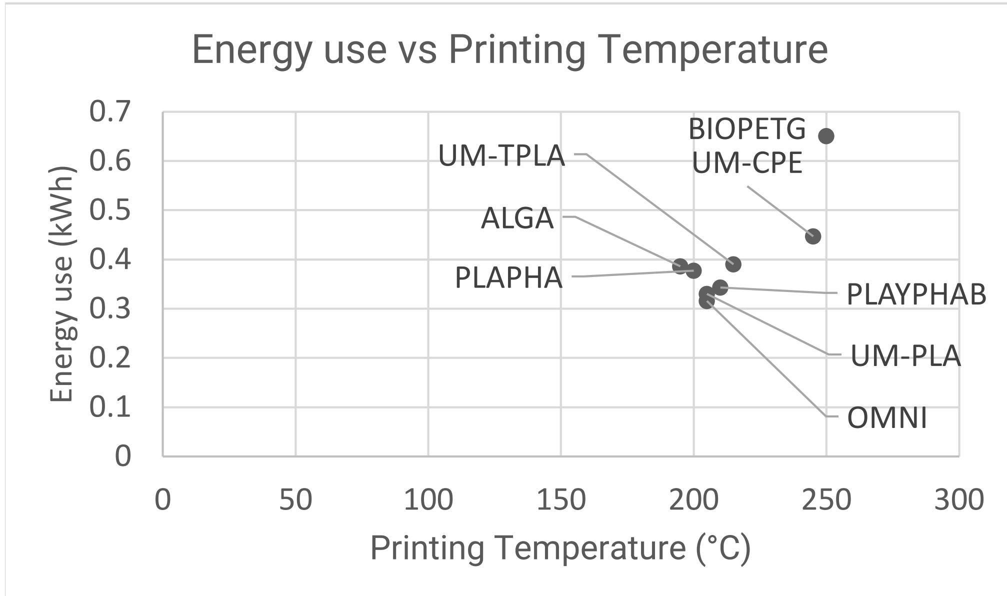


Figure 3.9 ***Energy Use versus Printing Temperature for Apple shell parts printed in Test 1***

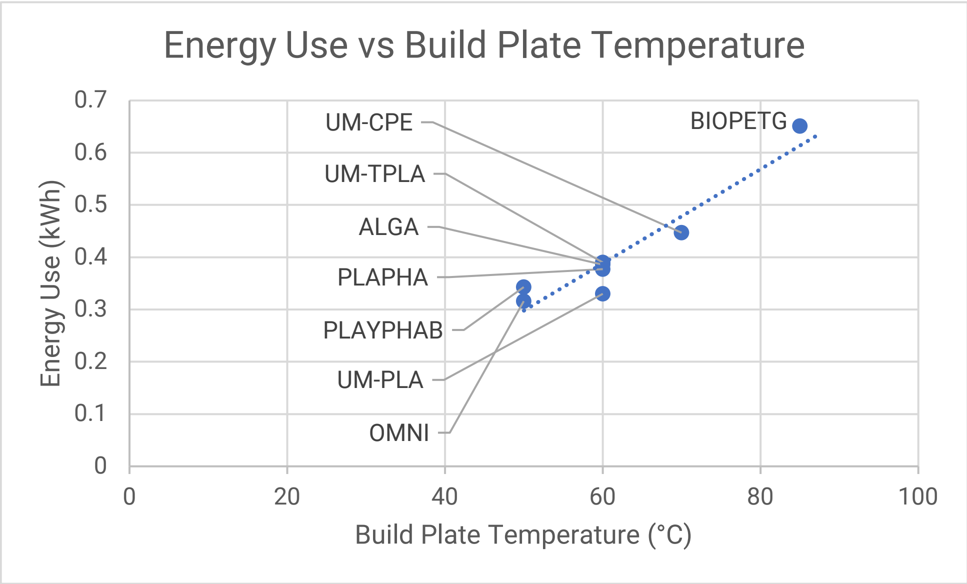


Figure 3.10 ***Energy Use versus Build Plate Temperature for Apple shell parts printed in Test 1***

From Figure 3.10, it is evident that higher build plate temperature correlates with higher energy use. Printing temperature and print speed in comparison, do not seem to have a significant effect on energy use (fig 3.9, 3.10). Thus to reduce energy use, one of the solutions can be to optimize build plate heating.

Appropriate build plate heating serves an important function in the print process. A heated build plate heats up the build volume immediately above itself, and maintains the temperature of the bottommost layers of the print just below the point where the material solidifies (i.e. glass transition temperature). This minimizes warping of the material. A heated build plate improves adhesion between itself and the bottommost layer of the print, reducing chances of the print peeling off from the plate mid-print. Further, it becomes easy to remove the completed print from the build plate once the plate has cooled down. Hence, the solution to optimize energy use would not be as simple as reducing the build plate temperature but instead, to explore more radical solutions for build plate adhesion. Alternatively, some incremental benefits can be gained by enclosing the build volume and improving insulation. This can prevent heat loss and reduce the energy consumed in maintaining the build plate temperature. It is also recommended to study the effect of localized build plate heating – for instance by converting the build plate into an array of 'cells' and heating only a limited number of cells onto which the material is being extruded. Structural and chemical solutions to enhance adhesion can also be explored as alternatives.

The energy use data was further compared with findings from a previous research, on energy use while printing on 3 other printers Dimension 1200, Afinia H480 and Type A. Table 3.6 illustrates this comparison. As seen in this table, the Dimension printer has the highest energy use, whereas Type-A printing PLA has the lowest. The Ultimaker 3 ranks in between. Also, the energy use for the materials tested on Ultimaker 3 fall within a narrow range. This could mean that differences in the overall hardware design may be equally critical to energy use along with process parameters such as build plate temperature which are material-dependent.
Additional experiments are recommended for studying the effects of external factors that were not rigorously controlled during this test, such as room temperature and airflow. This comparison study can also be extended by investigating the role of other print parameters such as layer height and infill percentage on the overall energy use while printing with the same set of materials.
Although these interventions are likely to reduce the energy use of the printer, the biggest limitation to improvement is the inherent process of melting polymers. Faludi et al. demonstrate that 75% print energy reduction (compared to ABS) can be achieved through new manufacturing methods such as paste printing of upcycled biomaterials and minerals.

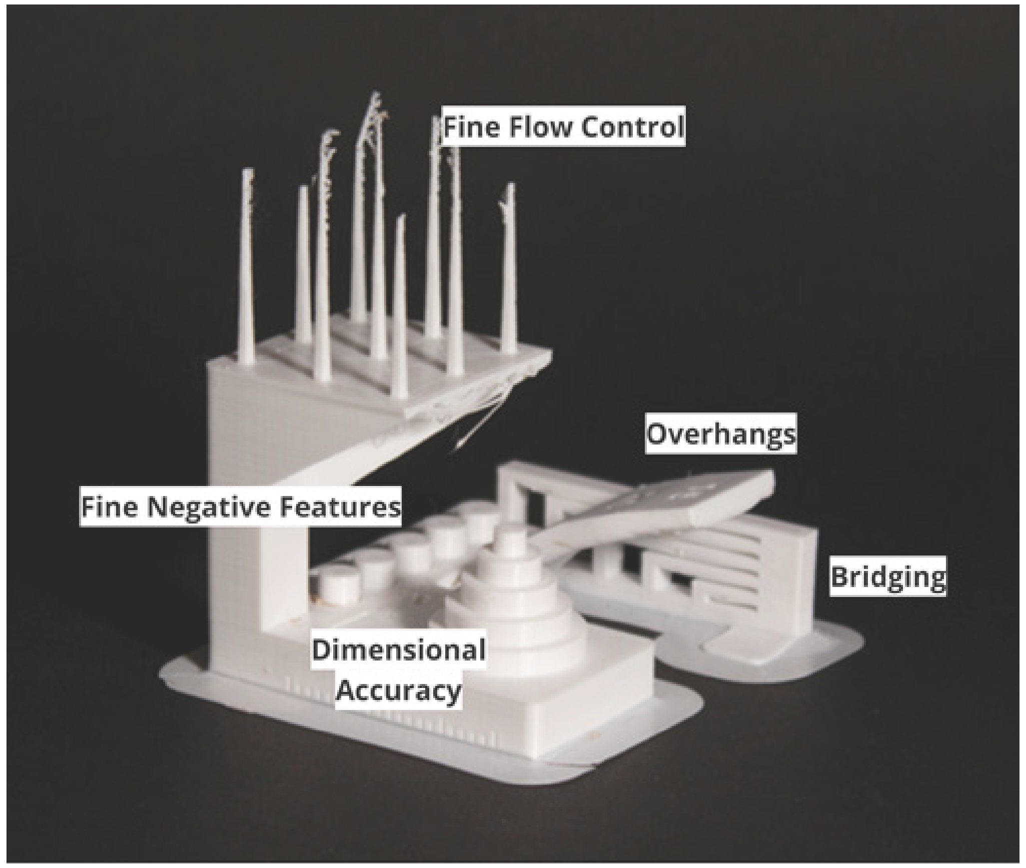
Table 3.6 ***Energy use (kWh) per 'Apple shell' printed using various printers and materials***

Printer	Material	Energy Use per part printed (kWh)
Dimension 1200	ABS	1.08
Ultimaker 3	BIOPETG	0.65
Ultimaker 3	OMNI	0.32
Afinia H480	ABS	0.16
Type A	PLA	0.06
Type A	PET	0.08

3.3.3 Test 2 – Measuring Print Quality

The previous chapter mentioned various aspects of material performance that end users prioritize while selecting materials for their applications. Of these, 'print quality' generally refers to the structural and visual aspects of a print. To enable print quality comparison between the selected materials, the test object seen in the image below was printed using each material. This test object is part of an open source test developed by Kickstarter and Autodesk in 2018 ("Toward Better 3D Printers: A New Test From Autodesk and Kickstarter", 2020), with the purpose of comparing performance of different printers. The same object along with the evaluation method proposed, was used for this test ("Kickstarter Autodesk FDM test", 2020). Figure 3.11 highlights the various print quality parameters evaluated in this all-in-one test.

Figure 3.11
The Autodesk-Kickstarter test object for Test 2, printed using BIOPETG filament



Material	Dimensional Accuracy	Fine Feature Flow Control	Fine Negative Features	Overhangs	Bridging
ALGA	1	2.5	0	5	1
OMNI	3	0	1	3	2
PLAPHA	4	2.5	3	1	2
PLAYPHAB	2	0	2	4	2
UM-PLA	4	2.5	3	3	4
UM-TPLA	4	2.5	3	3	4
BIOPETG	4	0	3	4	1
UM-CPE	3	2.5	2	2.5	3

Table 3.7 Print Quality test results

Table 3.7 shows the scores of the print quality test. The 5 new materials are compared with 3 UM- materials in this table. PLA's are compared to UM-PLA and UM-TPLA, whereas BIOPETG is compared with UM-CPE. In addition to the above assessment, a few qualitative notes were also documented based on visual inspection of the objects printed for Test 0, 1 and 2.

Parts printed with the material ALGA has a matte finish, unlike the others which tend to produce a glossy print. Hairs of algae fibers are prone to be sticking out from the surface of the print. This can either be used in a creative way as an aesthetic feature, for instance in an architectural prototype, or be removed through post-processing. Further, compared to other materials, and layer distinction is hardly possible, creating a unique homogeneous, isotropic-looking surface finish. These features may perhaps make this material suitable for certain visual model applications, and architectural models.

BIOPETG scores similar/slightly better in print quality compared to UM-CPE. With better print quality and biodegradability, this material can potentially be a drop-in replacement for UM-CPE .

It is observed that the method of print profile optimization has an effect on print quality. For instance, the material PLAPHA has better quantitative scores than the other PLA-based materials. This material also had a print profile optimized by its supplier for CURA and Ultimaker- using an elaborate method. Further, most new BBP's tested score better in overhangs compared to UM-materials. This is possibly a result of an optimization bias. The print profiles used for this test are based on optimizing the material to print the Calicat model in Test 0. A distinct marker observed to assess print quality in this model was the surface quality of the overhang on the tail part, which may explain this result. Thus, the print quality for these materials has a potential for improvement by optimizing the print profiles for specific geometries, thus making these materials viable for use in industrial applications.

3.3.4 Test 3 – Measuring Tensile Properties

For tensile testing, a large number of studies in existing literature use the dogbone-type test object (Mazzanti et. al, 2019). However this test was originally designed for isotropic parts made using processes such as injection molding. Instead, the test object used for ASTM D3039 standard method – i.e. a rectangular bar seen in the image below, is identified by Ultimaker as the ideal object for tensile testing- as 3D printed objects are non-isotropic, the uniform geometry of this test object results in a more reliable outcome.

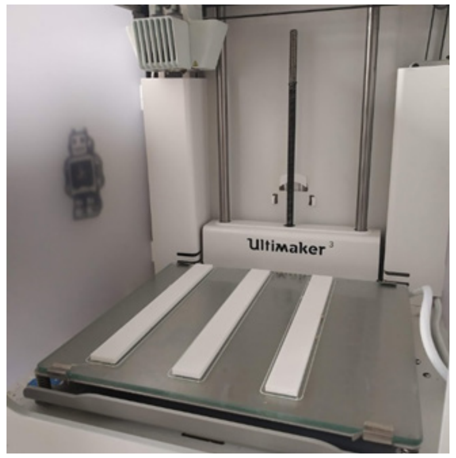


Figure 3.12 UM3 printing tensile test bars using BIOPETG

Figure 3.13 INSTRON Universal Testing System measuring a tensile bar printed in BIOPETG

Material Name	Young's Modulus	Ultimate Tensile Strength	Tensile Strength at Break	Elongation at yield	Elongation at break
	GPa	MPa	MPa	%	%
ALGA	3.0	35.4	33.9	2.79	3.87
PLAPHA	2.4	34.53	28.8	3.53	5.90
BioPETG	1.6	32.48	20.2	4.57	8.0
UM-PLA	3.3	52.51	45.5	3.41	7.84
UM-TPLA	2.8	45.32	15.0	3.17	10.27
UM-CPE	1.6	31.1	23.3	4.32	5.61

Table 3.8 Tensile testing – results

Results and Discussion

The table 3.8 showcases the results of the tensile test.

Overall, the new filaments tested perform slightly worse than the UM-standard materials, with certain exceptions. For instance- PLAPHA is more elastic than UM-PLA and UM-TPLA, but UM materials are stronger. Thus, PLAPHA may be used for applications where elasticity is a higher priority than strength. Secondly, BIOPETG has lower stiffness than CPE, and higher strength and thus performs better than CPE. Hence, it can be a drop-in replacement for applications that use CPE.

Although the tensile properties are not at par with the UM-standard materials, they are comparable to other PLA based filament materials tested in previous studies. For instance, a review of mechanical properties by Mazzanti et. al (2019) reported tensile strengths between 20 and 40 MPa, Young's moduli between 2 and 3 GPa and elongation at break ranging from 1.5% and 10% for PLA-based materials. The superior properties of UM-standard materials may be attributed to material composition as well as rigorous print profile optimization.
Hence, it can be concluded that the performance outcomes of the tensile test for the new materials are likely to improve if their print profiles are further optimized.

3.4 Converging

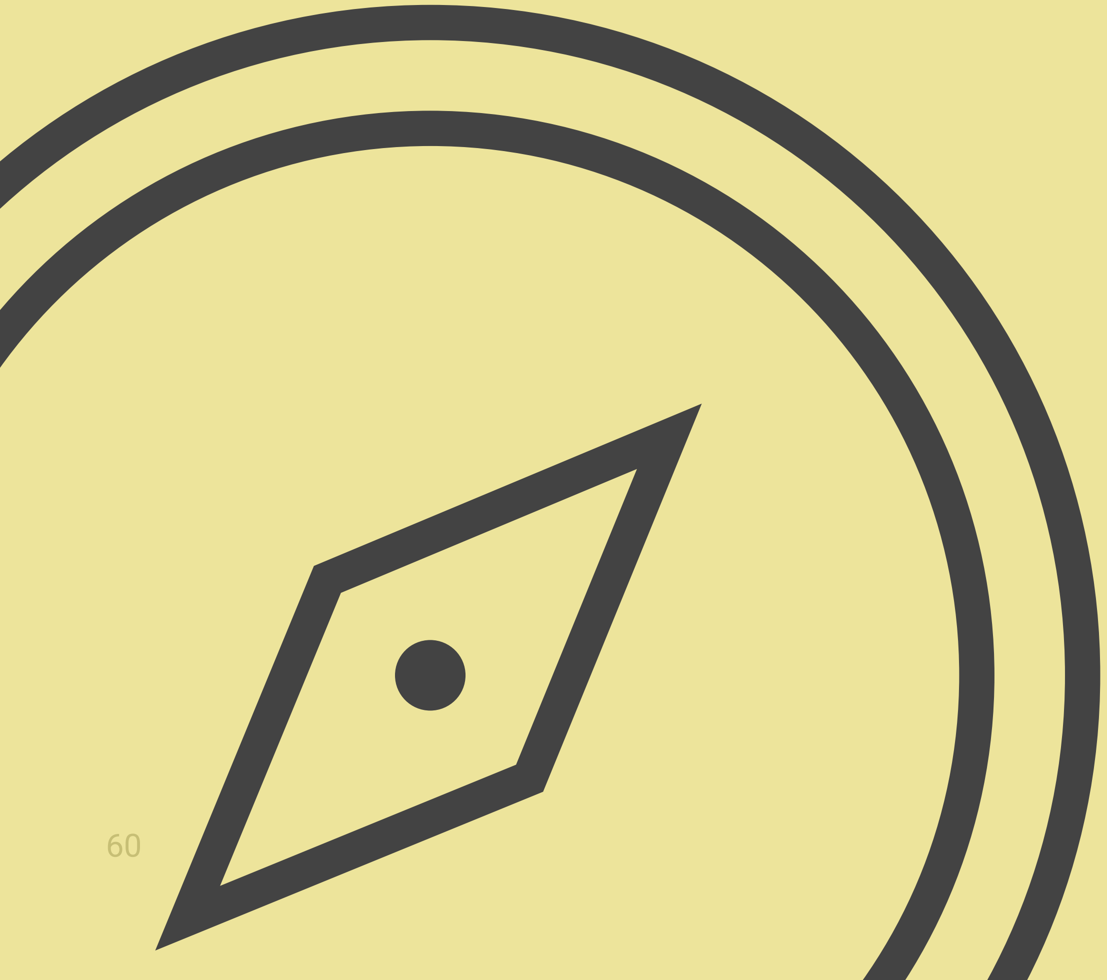
In the testing phase, comparison studies measured the energy use, print quality and tensile properties of 5 new materials and 3 UM-standard materials. The effects of various parameters on sustainability and material performance was discussed.

In terms of material performance, the new PLA-based materials scored similar or slightly worse than the UM-standard materials in terms of both print quality and tensile properties. However, these scores are likely to improve with better print profiles, making these materials competitive alternatives for industrial applications. BIOPETG, the biodegradable filament alternative to UM-CPE scored slightly better, thus making it a potential drop-in replacement for UM-CPE in both aspects of material performance.

While measuring energy use of the printer, build plate heating was identified as the most dominant parameter. Thus it can be concluded that print jobs or filament materials requiring lower build plate temperatures have lesser overall environmental impact. Hardware innovation is recommended for reducing energy use while retaining the positive aspects of a heated build plate. This can include design interventions such as localized build plate heating, enclosed and insulated build volume, and physical or chemical solutions to enhance surface adhesion.

The performance and energy use data collected during this phase adds to the available material knowledge for Ultimaker, which is currently used for making material choices for specific applications. Materials with similar performance parameters, which fulfil the requirements for an application can be compared based on sustainability indicators to select the 'greener' material for printing. Thus, in the next phase this information is curated in an accessible way for end-users.

The next chapter describes the process of curation of this material guide.



4

Material Guide

This chapter presents the final outcome of the project- a material guide that curates the material data collected during the project.

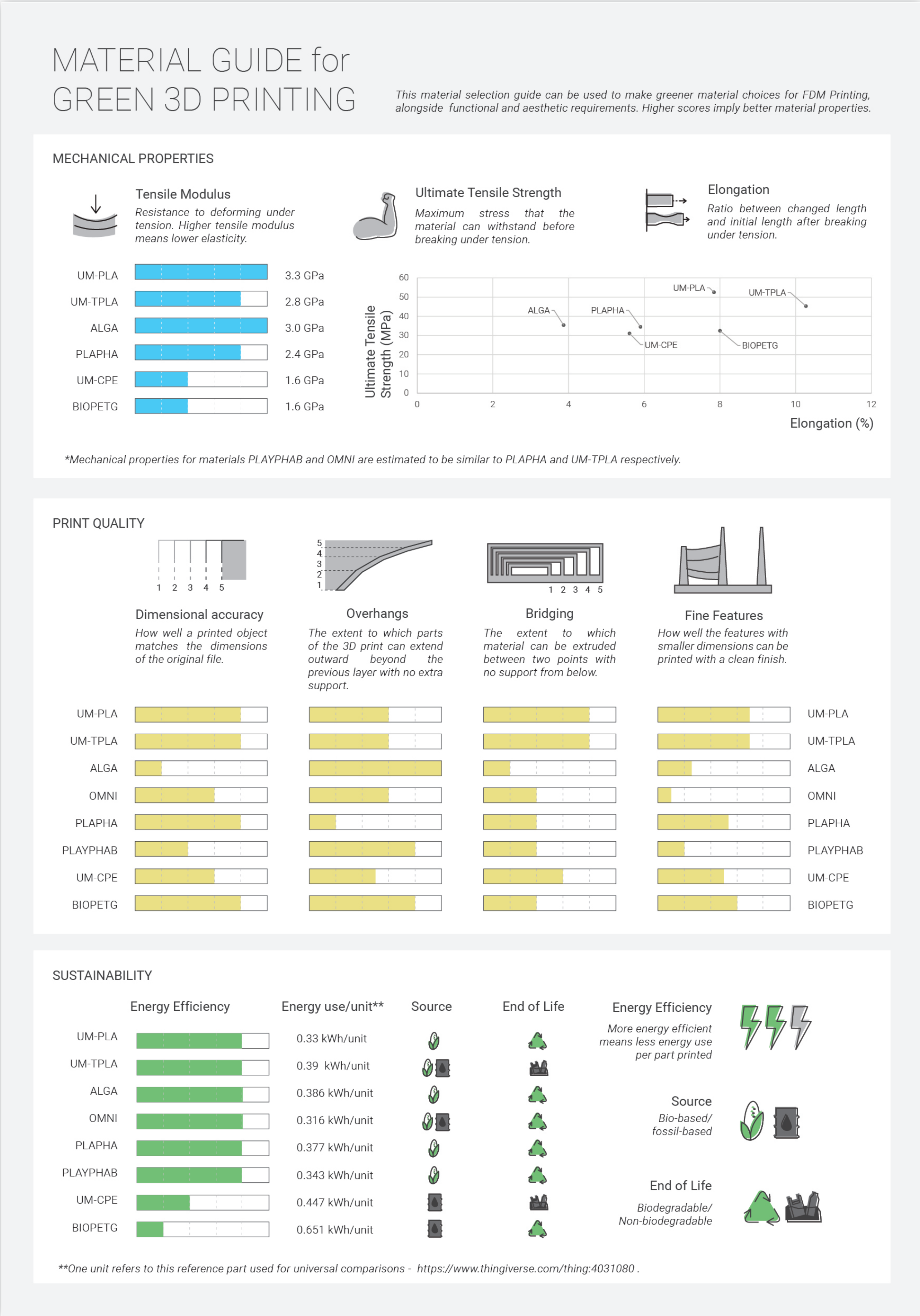
The user insights gained at the start of the project were used to identify material performance indicators relevant to end-users while making material choices. The same parameters were measured during the material testing process. The goal of the final phase of the project was to create a concise Material Guide which can be used by end-users to select appropriate materials.

4.1 Approach

The following set of design criteria was framed for the material guide-

1. The guide presents material information in a brief, visual form that is easy to interpret for end-users having limited knowledge of 3D printing materials.
2. The guide presents sustainability indicators alongside material properties, to enable greener material choices.
3. The guide has a scope for generalization- to replace or add more materials or performance parameters to future versions.

Design iterations mainly focused on converting the numerical material data into visual form. A single-page overview was found to be the most concise way of presenting this data. Icons with brief explanations along with score-bars, were created to illustrate performance parameters. The layout of the overview was iterated until it fulfilled the design criteria.



4.2 Final Design- Material Guide for Green 3D Printing

The final design of the material guide is presented on the adjacent page.

The layout presents the content in a way that matches the steps taken during the material selection process , i.e. starting with material properties and print quality, and at the end illustrating sustainability indicators. Although sustainability is usually not a point of consideration in the material choice, the sustainability section follow the same visual hierarchy as the other two categories in order to emphasize their importance for green 3DP.

Figure 4.1 Material Guide for Green 3D printing

5

Evaluation

This chapter summarizes and evaluates the project outcomes, viz. the results of the context study, material testing and the material guide design. It also mentions the final recommendations for Ultimaker, derived from the overall investigation.

5.1 Project Outcomes

Chapter 1 mentioned the initial objectives of this thesis, which were framed as follows-

1. Understanding sustainable 3DP in the context of bioplastic filaments
2. Testing commercial bioplastic filaments for sustainability and material properties
3. Guiding users in the industry towards green 3DP material and process choices

Further, the relevance of the outcomes from each of these objectives for Ultimaker and for Academic research was highlighted. Here, an overview of project outcomes achieved for both stakeholders is presented.

First, the analysis reported in the understanding phase provided insights on the state of the art, and identified gaps in the current understanding on the environmental impact of 3D Printing using bioplastic filaments. Further, useful insights on end-user priorities in the material selection process were also documented.

Energy use comparison of polymer filaments was a relevant literature gap for this thesis. This was addressed through the energy use study in the next phase. The material performance comparison study conducted, added to the limited knowledge available on material properties of biopolymers available in the market. The results of both the studies also generated opportunities (see sections 2.6, 3.4) for future scientific research as well as innovation in hardware and print process development, which can be conducted by Ultimaker as well as in an academic setting.

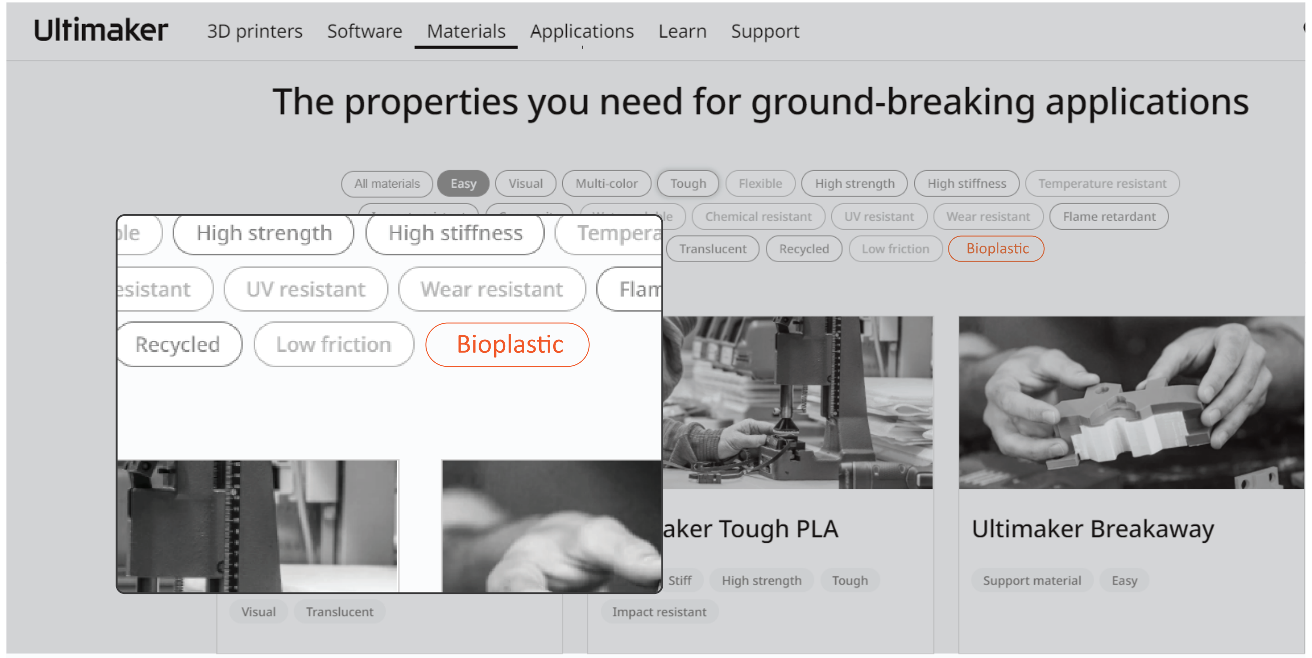
Finally, the material guide compiles all the data collected, in a single concise visual. This guide serves as a reference for the material properties of the tested materials, but also as a concept that can be used to present similar information for more materials. The guide has been designed to add sustainability considerations into the selection process, thus nudging the user to make greener choices.

The visual design was briefly evaluated with the experts (i.e. Application Engineers) interviewed earlier during the project, who positively received the outcome as a visual material selection concept. The visual icons and descriptions for material properties were noted as a useful design feature for users with limited material knowledge. However, a detailed evaluation of the guide for its role in green material selection, could not be conducted with either the experts or the actual end-users. Hence, it is recommended that this evaluation is conducted to identify potential scope for concept improvement.

5.2 Recommendations for Ultimaker

Maximizing the use of biopolymers is certainly one of the lowest hanging fruits for sustainability improvements in 3D printing. The increasing demand and projected growth in production of these materials points towards a higher potential market adoption of bioplastic filaments in the near future. For Ultimaker, the Material Guide concept can be a starting point for the curation of a bioplastics specific portfolio that can be marketed to interested clients as potential sustainable materials. Further, the material selector on the UM website can include 'bioplastic' as a category filter, alongside the existing 'recyclable' category, to enable users to identify the already available variety of bioplastic materials in the UM Marketplace.

Figure 5.1 Bioplastic as a material category filter on Ultimaker website



On the other hand, it is also important to note that the potential environmental benefits achieved through this articulation are fundamentally limited. Hence, the next step towards radical sustainability improvements is to look beyond polymers, and at another material extrusion technology- paste extrusion. As mentioned before, paste printing of upcycled biomaterials or minerals can result in significantly reduced print energy, reduced embodied impacts of materials, reduced toxicity hazards compared to ABS, at half the cost of ABS (Faludi et al., 2018). Hence, paste printing hardware and materials are essential to consider as long-term research interests for Ultimaker, although this knowledge domain is different from UM's current print process technology & materials.

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Appendix

Appendix A:

Bioplastics available in the online market

Brand	Material Name	Composition	Certifications	Source
ColorFabb	Woodfill	70PLA + 30 wood fibres	unknown	https://colorfabb.com/woodfill
Floreon	Floreon Yellow PLA	PLA + bioadditive	unknown	https://shop.3dfilaprint.com/floreon-yellow-pla-285mm-5-metre-3d-printing-filament-sample-10465-p.asp
Biome3D		Potato Starch	unknown	https://shop.3dfilaprint.com/biome-3d-285mm-samples-6704-p.asp
twoBEars	biofila silk		unknown	https://www.lulzbot.com/store/filament/biofila-silk
Willowflex	Willowflex	Unknown	EU standards (EN 13432), ASTM D6400	https://www.willow-flex.com/store/
3DPrintLife	BioPETG	modified PET (+glycol), +bioadditive?	ASTM D5338	https://www.3dprintlife.com/http/www3dprintlifecom/filaments/enviro-abs-bio-petg
3DPrintLife	PLAyPHAb™	PLA + PHA	ASTM D6400	https://www.3dprintlife.com/http/www3dprintlifecom/filaments/playphab-plapha-blend
3DPrintLife	3D-SOLVE™ Water Soluble	unknown	ASTM D6400	https://www.3dprintlife.com/http/www3dprintlifecom/filaments/enviro-abs-3d-solve
3DPrintLife	Enviro™ Eco-Friendly ABS	ABS + bioadditive?	ASTM D5338	https://www.3dprintlife.com/http/www3dprintlifecom/filaments/enviro-abs
3DPrintLife	DURA™ Ultra Durable Nylon-Like	unknown	ASTM D6400	https://www.3dprintlife.com/http/www3dprintlifecom/filaments/dura-ultra-durable-3d-filament
Algix 3D	OMNI™ High Strength ABS-Like	unknown	ASTM D6400	https://www.3dprintlife.com/http/www3dprintlifecom/filaments/omni-all-purpose-3d-filament
Algix 3D	ALGA	PLA + Algae	ASTM D6400	https://www.3dprintlife.com/http/www3dprintlifecom/filaments/alga
Algix 3D	APLA™ Advanced PLA	NatureWorks' Ingeo 3D860	ASTM D6400	https://www.3dprintlife.com/http/www3dprintlifecom/filaments/apla-advanced-pla-filament
Bioplastictech	Bioplastictech	unknown	unknown	https://bioplastictech.com/products/

Appendix B:

Full Results – Test 0 - Print Profile Optimization

Tests				Settings					Results	
Date	#	Material	Test #	Print Profile-Basic	Printing Speed (mm/s)	Printing Temp	BP Temp	Overrides	PASS/FAIL	Comments
23/04/2020	1	UM-TPLA		UM-TPLA-0.15	45	215	60	none	pass-final	Brim and UHU used for BP adhesion
15/05/2020	2	BIOPETG	1	CPE-0.15	60	245	70	none	fail	print failure while printing ears part. cause unknown
15/05/2020		BIOPETG	2	CPE-0.15	55	245	70		fail	print failure while printing ears part. cause unknown- possibly object cooling on top is not very good because fan speed is at 50%
15/05/2020		BIOPETG	3	CPE-0.15	55	245	0	PS=55, BPTEMP=0, FAN SPEED= 100%	pass	good bp adhesion even with a cold bp. UHU also used. Fan speed changed to 100%
15/05/2020		BIOPETG	4	Jabil-PETG-0.15	60	250	85	none	pass-final	good print quality. some extra extrusion on brim. Jabil profile has fan speed at 100%
15/05/2020		BIOPETG	5	Jabil-PETG-0.15	60	250	0	BPTEMP=0	PASS	Jabil profile with cold BP also gives a good result. some minor surface quality issues but overall good quality print
18/05/2020	3	PLAPHA	1	UM-PLA-0.15	80	200	60	none	pass-final	good enough print quality
25/05/20	4	3DPL-Alga	1	GenericPLA-0.15	80	200	60	none	fail	algae fibre hairs released on front face. overextrusion in multiple places- stringing between body and tail, and between ears. layer split near beginning of tail part lead to model splitting in two.
			2	GenericPLA-0.15	80	195	40		fail	testing for cold build plate- failed. print released from build plate. extrusion temp lowered to test effect on stringing, could not infer due to print failure
			3	GenericPLA-0.15	80	205	60		pass	extrusion temp raised- more fibres released, stringing still visible
			4	GenericPLA-0.15	80	210	60	Retract at layer change- enabled; retraction extra prime amount- enabled	fail	overrides to test effects on fibres and stringing. high temp lead to less viscosity of print material and thus more stringing
			5	GenericPLA-0.15	75	195	60		pass	good print quality, very less stringing and fibres visible. stringing only visible at ears.
			6	GenericPLA-0.15	70	190	60		pass	good print quality, very less stringing and fibres visible. stringing only visible at ears. further 3 tests to reduct print temp to check effect on stringing at ears
			7	GenericPLA-0.15	70	185	60		pass	good quality, strings visible
			8	GenericPLA-0.15	70	180	60		pass	good quality, strings less than prev
			9	GenericPLA-0.15	70	175	60		pass	good quality, strings almost none
2/6/20	5	OMNI	1	GenericPLA-0.15	80	215	50		pass	print quality ok
			2	GenericPLA-0.15	80	215	0		pass	tried cold BP- pass
			3	GenericPLA-0.15	80	205	0		fail by h/w	tried cold BP with 5deg lower printing temp, print fail due to hardware issue. print quality for printed part same as prev test, thus lower printing temperature is ok
5/6/20	6	PLAyPHAb	1	GenericPLA-0.15	80	230	50		pass	good print quality
			2	GenericPLA -0.15	80	210	50		pass	tried lower PT, print pass
			3	GenericPLA-0.15	80	210	0		pass	tried cold BP+ lower PT, pass

Appendix C:

Project Brief

Sustainable 3D Printing with bio-based polymers project title

Please state the title of your graduation project (above) and the start date and end date (below). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

start date 03 - 03 - 2020   25 - 08 - 2020 end date

INTRODUCTION **

Please describe, the context of your project, and address the main stakeholders (interests) within this context in a concise yet complete manner. Who are involved, what do they value and how do they currently operate within the given context? What are the main opportunities and limitations you are currently aware of (cultural- and social norms, resources (time, money,...), technology, ...).

Additive manufacturing is gaining popularity as a reliable manufacturing process, resulting in a growing demand from large industries like automotive, aerospace, packaging etc. 3D printers are being used for rapid and cost effective production of visual and functional prototypes, manufacturing aids like jigs and fixtures, as well as end use parts. The Wohler's Report 2019 predicts a substantial growth in this market, from $7 billion in 2018, to $35 billion in 2024. A surge in purchase of AM hardware is also having an impact on the 3D printing materials market, which is estimated to grow from $1.5 billion in 2019, to $4.5 billion in the next five years. As a consequence, there is increased involvement in material development from different parts of the value chain- from material researchers and suppliers, to AM hardware manufacturers.

The establishment of 3D printing as a fully-accepted manufacturing technology also brings an increasing interest into its overall sustainability, especially the environmental impacts. One particularly interesting topic here is that of bio-based polymers, i.e. plastics derived from renewable (as opposed to fossil) resources. Scientifically speaking, these materials hold the potential to substantially decrease e.g. the carbon footprint of 3D printing – yet most end users will confuse them with biodegradable plastics, i.e. plastics that decompose under specific circumstances but that may themselves be fossil-based. And while legislation on bioplastics is currently in preparation, no firm conclusions have yet been drawn about their sustainability performance.

What makes these bioplastic filaments more interesting is that they are unlikely to be drop-in replacements for existing ones: they are not just different in their origin, but (to some extent) also in their properties- both their "printability" (printer settings) and as-printed properties (e.g. mechanical strength) may differ from existing materials. From an end-user perspective, this knowledge gap is a major barrier in the adoption of bioplastic filaments. This is also a marketing challenge for manufacturers and suppliers dealing with bioplastic filaments.

In their recent (2019) review of biopolymers Liu et. al conclude that, "Limited variety of available, environmentally friendly, and printer-friendly materials is a key barrier to the wide-scale adoption of 3D printing technologies." This research project envisions to lower this barrier by filling a few knowledge gaps in terms of material properties, printability, and sustainability performance of bioplastic filaments, in order to enable adoption of these new materials. The focus is on FFF 3D printing filaments, serving the interests of the client company Ultimaker.

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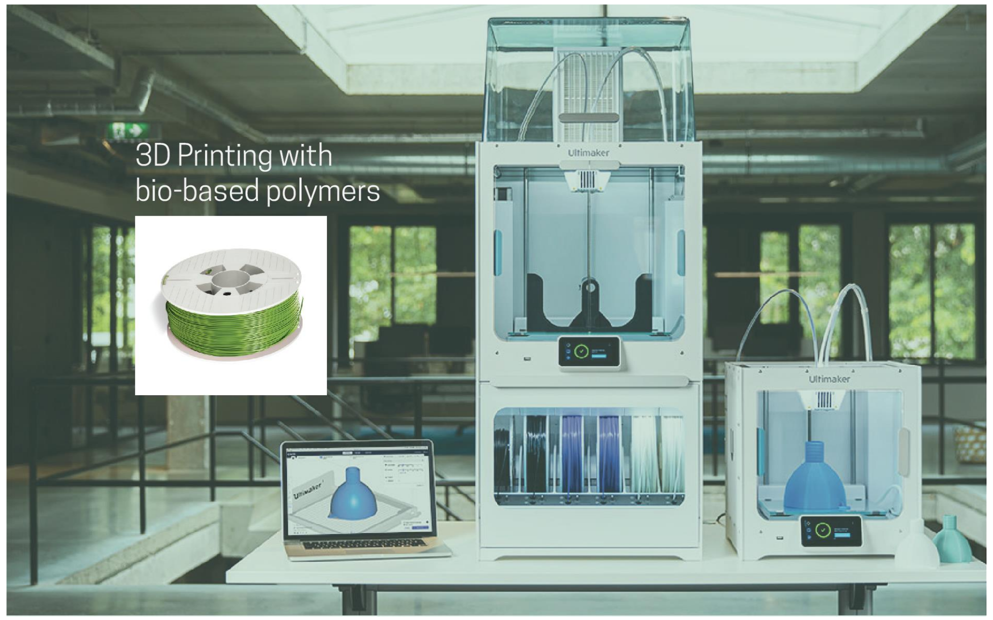


image / figure 1: Sustainable 3D printing with bio-based polymers

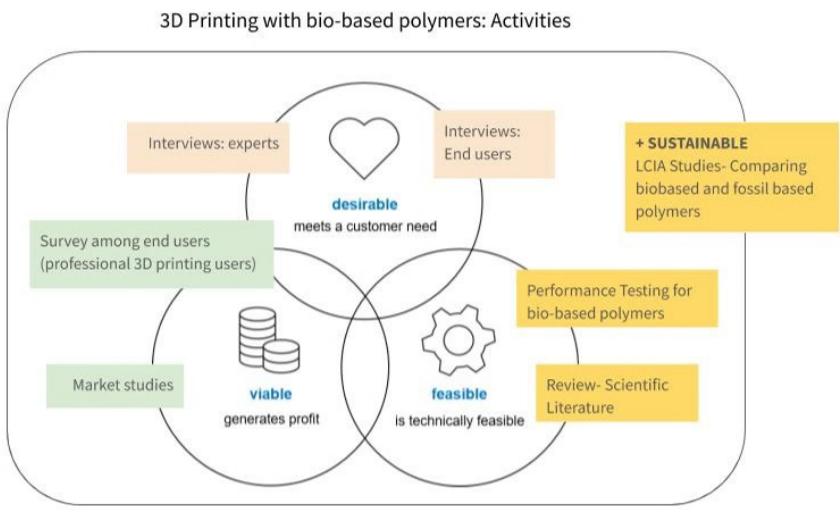


image / figure 2: An overview of methods used in the project

PROBLEM DEFINITION **

Limit and define the scope and solution space of your project to one that is manageable within one Master Graduation Project of 30 EC (= 20 full time weeks or 100 working days) and clearly indicate what issue(s) should be addressed in this project.

Determining the sustainability performance of the 3D printing process has been a subject of recent scientific investigation by researchers like Prof. Jeremy Faludi. However, there is a gap between what scientific experts know and what the general public- and among this, users of 3D printers- can comprehend. Current and upcoming legislation provides yet a third perspective on this, which affects the marketing of these materials. Em. Prof. Stevels referred to this as the 'three shades of green'. Studying the various perspectives on bioplastics- from scientific literature, market, and end-users, is the first challenge in this project.

Second, there is a research opportunity to study the material characteristics and sustainability performance of new biopolymer filament materials. For this project, the scope of the study will be 'bio-based+biodegradable' type of filament materials already available in the market. Thus, new polymers in their research phase, or ones not available in 3D printer filament form will not be tested. The results of this study will be used to identify appropriate markets where the unique properties of these materials are a selling point.

Finally, there is a need to present this knowledge in a form that helps end-users with selection of appropriate bioplastics for their applications, as well as their printability. Creating a guide to aid this process is the final challenge for this project.

ASSIGNMENT **

State in 2 or 3 sentences what you are going to research, design, create and / or generate, that will solve (part of) the issue(s) pointed out in "problem definition". Then illustrate this assignment by indicating what kind of solution you expect and / or aim to deliver, for instance: a product, a product-service combination, a strategy illustrated through product or product-service combination ideas, ... In case of a Specialisation and/or Annotation, make sure the assignment reflects this/these.

First, most relevant literature on 3D printing and bioplastics will be reviewed. Expert interviews and surveys will be conducted to understand end-user expectations from bioplastic filaments. This will be followed by characterization of as-printed properties of selected (max 3) bioplastic filaments (e.g. dimensional accuracy, physical appearance), and LCA studies to measure eco-impact. From this knowledge, a material guide for printing with biomaterials will be created.

The first expected deliverable is a summary of relevant literature and insights collected from interviews. This report aims to demystify the previously mentioned 'three shades of green' in bio-based polymers(BBPs). This will educate the reader about the state of the art in FDM 3D printing, BBPs, material filaments, and the future perspectives in this domain. A materials roadmap can be created for BBP filament materials, to illustrate what is available, what is coming soon, and what is in store in the long run- a big picture of the rapidly developing bioplastics market.

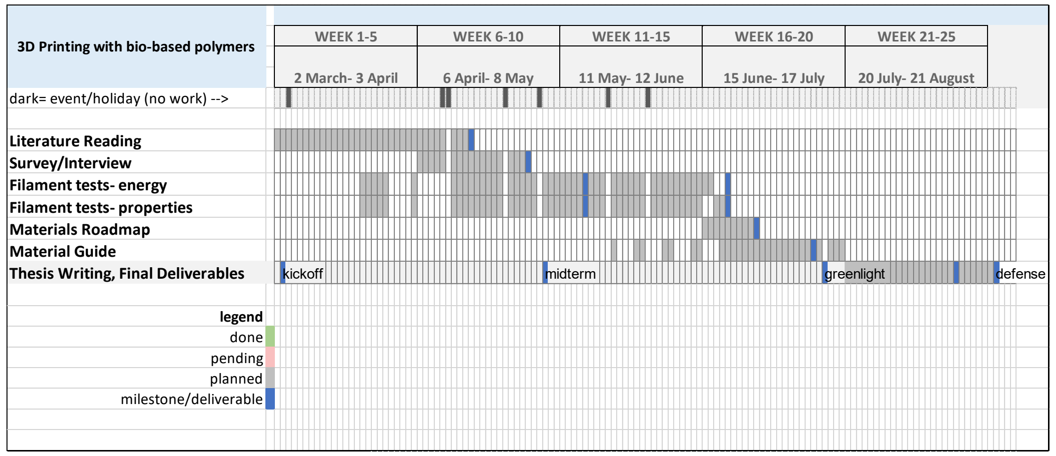
Selected BBP materials (max 3) will be evaluated for performance and environmental impact- by conducting characterization tests (that measure dimensional accuracy etc.) for the former, and LCA studies for the latter. The results of these tests will be shared as another deliverable.

Finally, this knowledge will be brought together in a 'materials guide' to help the users of 3D printers with clear and easy-to-use instructions for printing with (selected) BBPs. This could take the form of videos /text /presentations /interactive visuals etc. that collectively serve as a reference, informing the users to make the right choices, e.g. of materials, print settings,etc. as per their manufacturing requirements.

PLANNING AND APPROACH **

Include a Gantt Chart (replace the example below - more examples can be found in Manual 2) that shows the different phases of your project, deliverables you have in mind, meetings, and how you plan to spend your time. Please note that all activities should fit within the given net time of 30 EC = 20 full time weeks or 100 working days, and your planning should include a kick-off meeting, mid-term meeting, green light meeting and graduation ceremony. Illustrate your Gantt Chart by, for instance, explaining your approach, and please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any, for instance because of holidays or parallel activities.

start date 3 - 3 - 2020 25 - 8 - 2020 end date



Project Duration-
03/03/2020 to 25/08/2020
120 days= 100 working days + 5 days vacation + 10 days medical leaves + 5 days contingency
(Accounting for various types of tentative off-days, to create a realistic 100 working days plan)

The above chart is an overview illustrating the main phases of the project. Work will be divided in one or two week sprints depending on the phase. Detailed tasks will be planned a few days before each sprint begins. This will ensure that the plan can be adapted as per the evolving needs of the project.

Important Dates/milestones (tentative)-
Kickoff meeting- 3 March 2020
Mid-term evaluation- 5 May 2020
Green Light meeting- 14 July 2020
Final Deliverables submission- 18 August 2020
Thesis Defense- 25 August 2020

MOTIVATION AND PERSONAL AMBITIONS

Explain why you set up this project, what competences you want to prove and learn. For example: acquired competences from your MSc programme, the elective semester, extra-curricular activities (etc.) and point out the competences you have yet developed. Optionally, describe which personal learning ambitions you explicitly want to address in this project, on top of the learning objectives of the Graduation Project, such as: in depth knowledge a on specific subject, broadening your competences or experimenting with a specific tool and/or methodology, ... Stick to no more than five ambitions.

The motivation for setting up this project was its positioning in the three primary domains of my interest- materials, manufacturing, and sustainability. Thus, my personal learning ambitions are fairly aligned with the learning objectives of the project itself.

Additive manufacturing (AM) has radically transformed the processes of product development and manufacturing. During my last internship, I had the opportunity to experience this firsthand, by being involved in creating FFF and SLA 3D prints to be used as product prototypes, end-use parts for testing equipment, and molds for injection molded prototypes. This experience helped to develop essential competencies with CAD and AM. During this project, I aim to further this domain knowledge to position myself as a professional with cutting edge skills in industrial design practice.

This project demands a deeper understanding of the 3D printing process. This includes learning about the delicate balance of the 3D printing triad- hardware, software and materials. Specifically within materials, the project demands expansion of knowledge on material properties- structural, functional and visual. This knowledge will help me develop an overall understanding of engineering materials, and specialized knowledge about polymers. It will be interesting to study bio-based polymers not only as 3D printing filaments but as manufacturing materials in general, considering their potential as relevant materials of the future.

Finally, the thesis project is an excellent opportunity for 'learning how to learn'. Continuous learning and updating of knowledge and skills is essential part of being a competent professional. During the thesis, I would like to develop and reflect on my own methods of acquiring relevant knowledge and skills in an efficient way.

FINAL COMMENTS

In case your project brief needs final comments, please add any information you think is relevant.


49