ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

DESIGN FOR ADDITIVE MANUFACTURING FOR SMALL-VOLUME PRODUCTION: A CASE STUDY

M.Sc. THESIS

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Department of Industrial Design

Industrial Design Programme

JULY 2024

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DÜŞÜK HACİMLİ ÜRETİMDE EKLEMELİ İMALAT İÇİN TASARIM: VAKA ÇALIŞMASI

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Date of Submission : 24 June 2024
Date of Defense : 9 July 2024

To my family and friends,

FOREWORD

The field of industrial design has opened doors for me in many areas. First of all, it helped me to work in many different fields without being limited to product design and to understand the importance of design for me. The most important contribution of this field is that it helped me meet my wife. I am very happy to have worked with my advisor Elif KÜÇÜKSAYRAÇ and am grateful for her support.

I would like to thank my family, wife, and friends for their support during this process.

July 2024

Ahmet Furkan KELEŞ
(Animation Artist & Industrial Designer)

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ABBREVIATIONS

ABS	: Acrylonitrile butadiene styrene
AM	**:** Additive Manufacturing
ASTM	**:** American Society of Testing and Materials
CAD	**:** Computer Aided Design
CAM	**:** Computer Aided Manufacturing
CNC	**:** Computer Numerical Control
DfM	**:** Design for Manufacturing
DfAM	: Design for Additive Manufacturing
DLP	**:** Digital Light Processing
FDM	**:** Fused Deposition Modeling
SLA	**:** Stereolithography
SLS	**:** Selective Laser Sintering
PLA	**:** Polylactic Acid
3D	**:** Three Dimensions
STL	**:** Standard Triangle Language (Stereolithography file format)
FFF	: Fused Filament Fabrication
TPU	: Thermoplastic Polyurethane

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FOR ADDITIVE MANUFACTURING FOR SMALL-VOLUME PRODUCTION: A CASE STUDY

SUMMARY

Additive manufacturing (AM), also referred to as 3D printing, is an innovative manufacturing method that constructs objects by adding layers based on digital models. Contrary to conventional subtractive manufacturing, which involves removing material to form shapes, AM involves adding material in precise layers. This method provides enhanced design flexibility and enables the production of intricate geometries while minimizing waste. This technology is employed in diverse industries such as aerospace, medical, automotive, and fashion, to produce prototypes, functional components, and customized designs. The ability to customize products makes efficiently and sustainably is a fundamental aspect of contemporary manufacturing and design innovation. The goal of this research is to find out how AM techniques can be used by people or companies with limited funding to replace conventional production methods, which typically involve expensive machinery, molding, and production line setup. Fused deposition modeling (FDM) and stereolithography (SLA), two 3D printing technologies that stand out from other AM technologies in terms of cost effectiveness and adaptability for home-use applications, are the primary subjects of this study.

Case study and expert interviews are the research methods used in this study. An FDM-manufactured outdoor air quality control kit for the ITU campus is the focus of the case study. This kit was created as part of a scientific research project on smart and sustainable campuses. From the pre-production phase through the final form, the design process is assessed qualitatively and quantitatively. The design of the product, the choice of materials and printing technology, and surface quality are the main concerns of the assessment. The case study is supported by expert interviews, which provide a more thorough grasp of AM. Four specialists who work with FDM and SLA technologies development and apply it to different industries and contexts were selected. The experts are a mechanical engineer leading R&D at a company that makes classical mixers, and faucets, an industrial designer employed by a company that manufactures 3D printers; and a designer/owner of a startup company that uses FDM technology in R&D and final-product manufacturing processes.

The results clarified the distinctions between the application of FDM and SLA techniques, the potential for material and time savings during product development, and the strategies for minimizing or eliminate support structures completely. The study also shows situations where AM techniques are more advantageous than conventional techniques at specific production volumes. The case study’s numerical data demonstrated how alterations in printing and design techniques lower costs and speed up production. This study’s conclusion highlights the potential and necessity of AM technology for small-scale, resource-constrained enterprises and low-volume production. The advantages AM providing over conventional production techniques

hold great promise for the broad adoption of these technologies and the transformation of the paradigms that drive industrial production.

DÜŞÜK HACİMLİ ÜRETİMDE EKLEMELİ İMALAT İÇİN TASARIM: VAKA ÇALIŞMASI

ÖZET

Eklemeli imalat, katmanlı üretim teknolojisi kullanarak malzemeleri bir araya getirerek nesneler oluşturma sürecidir ve son yıllarda hızla gelişen bir üretim yöntemi haline gelmiştir. Bu teknoloji, 3D yazıcılar aracılığıyla plastik, metal ve seramik gibi çeşitli malzemeler kullanarak karmaşık geometrik yapılar üretmeye olanak tanır.

Eklemeli imalatın en büyük avantajlarından biri, tasarımda esneklik sunması ve bu sayede prototipleme sürecini hızlandırarak maliyetleri düşürmesidir. Ayrıca, özelleştirilebilir ürünlerin üretimini mümkün kılar ve daha az malzeme israfı yaratarak çevresel etkileri azaltır. Havacılık, otomotiv, sağlık ve mimari gibi birçok sektörde devrim yaratan bu teknoloji, hem bireysel tasarımcılara hem de büyük ölçekli üretim yapan şirketlere yenilikçi çözümler sunmaktadır. Bu üretim yöntemi ilk olarak 1981 yılında denenmiş ve 2009'da MakerBot ve Ultimaker'ın masaüstü üç boyutlu yazıcıları piyasaya sürmesiyle geniş kitlelere ulaşmaya başlamıştır. Masaüstü yazıcıları sayesinde düşük hacimli üretimlerde 3B yazıcılar kullanılmaya başlanmıştır. Eklemeli imalat için uygulanan tasarım yöntemleri konvensiyonel üretim yöntemleri sürecinden farklıdır. Bu noktada eklemeli imalat için tasarım kavramı ortaya çıkar. Bu kavram, tasarım sürecinde malzeme israfını en aza indirmek ve üretim süresini optimize etmek için yapılan planlamarın bütünüdür.

Bu araştırmanın amacı, eklemeli imalat tekniklerinin, sınırlı finansmana sahip kişiler veya şirketler tarafından, genellikle pahalı makineler, kalıplama ve üretim hattı kurulumunu içeren konvansiyonel üretim yöntemlerinin yerine nasıl kullanılabileceğini bulmaktır. Eklemeli imalat, başlangıçta maliyet etkinliği açısından küçük ve orta ölçekli üreticiler için önemli bir fırsat sunmaktadır. Özellikle, düşük hacimli üretim gereksinimlerinde ve özelleştirilmiş ürün tasarımlarında maliyet tasarrufu sağlamak için oldukça etkilidir. Maliyet etkinliği ve ev kullanımı uygulamalarına uyarlanabilirliği açısından diğer eklemeli imalat teknolojilerinden öne çıkan iki 3B baskı teknolojisi olan eriyik yığın modelleme (EYM) ve stereolitografi (SLA), bu çalışmanın temel konularını oluşturmaktadır. EYM, genellikle daha uygun fiyatlı yazıcılar ve daha ucuz filament malzemeleri kullanarak, geniş bir kullanıcı kitlesine hitap ederken, SLA, yüksek hassasiyet ve yüzey kalitesi gerektiren uygulamalar için idealdir. Bu teknolojilerin her ikisi de hobi amaçlı kullanıcılar, eğitim kurumları ve küçük işletmeler tarafından giderek daha fazla benimsenmektedir.

Bu çalışmada araştırma yöntemi olarak vaka çalışması ve uzman görüşmeleri kullanılmıştır. Vaka çalışması İTÜ Ayazağa Yerleşkesi'nde kullanılacak bir ürünün geliştirilmesini kapsar. Kampüs için EYM tarafından üretilen dış hava kalitesi kontrol kiti, vaka çalışmasının odak noktasını oluşturmaktadır. EYM teknolojisinin tercih edilmesinde literatür taraması ve uzman görüşmelerinden alınan öneriler etkili olmuştur. Bu kit, akıllı ve sürdürülebilir kampüslere ilişkin bilimsel bir araştırma projesinin parçası olarak oluşturulmuştur. Üretim öncesi aşamadan nihai forma kadar tasarım süreci niteliksel ve niceliksel olarak değerlendirilir. Ürünün tasarımı, malzeme ve baskı teknolojisi seçimi ve yüzey kalitesi değerlendirmenin ana konularıdır. Ayrıca vaka çalışması sürecinde SLA teknolojisinin daha iyi anlaşılması amacıyla baskı denemesi yapılmıştır. Vaka çalışması, eklemeli imalatın daha kapsamlı bir şekilde anlaşılmasını sağlayan uzman görüşmeleri ile güçlendirilmiştir. Vaka çalışmasını desteklemesi amacıyla eş zamanlı olarak yapılan uzman görüşmeleri literatür taramasında elde edilen bilgilerin desteklenmesi, literatür taramasında değinilmediği görülen sektöre yönelik pratik bilgilerin toplanması ve literatürde bahsedilen konuların sektördeki gerçekliğinin karşılaştırılması için faydalı olmuştur. Uzman görüşmeleri için EYM teknolojisini farklı endüstrilere uygulayan dört kişi ile görüşüldü. Görüşülen uzmanlar sırasıyla batarya ve musluk üreten bir şirkette Ar-Ge'ye liderlik eden bir makine mühendisi; 3B yazıcı üreten bir şirkette çalışan endüstriyel tasarımcı; eklemeli imalat teknolojilerini kullanarak müşterilere prototipleme hizmeti veren bir firmada Ar-Ge şefi ve nihai ürün üretim süreçlerinde EYM teknolojisini kullanan bir şirketin tasarımcısı/sahibidir. Uzman görüşmelerinde elde edilen bilgiler, konu hakkında farklı veriler elde edilmesini mümkün kılmıştır. Öncelikle, güncel eklemeli imalat teknolojileri ile ilgili tecrübelerine başvurularak literatürden elde edilen bilgilerin sektördeki karşılıkları görülmüştür. Bu sayede uzmanların görüşleri doğrultusunda vaka çalışması gözden geçirilmiş, aynı zamanda uzmanların doğrudan vaka çalışması hakkında yaptığı yorum ve öneriler derlenerek çalışmanın geliştirilmesi sağlanmıştır. İkinci olarak, eklemeli imalatın geliştirilmesi ve geleceği ile ilgili öngörüleri, karşılaştıkları mevcut problemler ve çözüm önerileri de derlenip veri haline getirilmiştir. Bu sayede konu hakkında gelecekte yapılacak çalışmalara referans oluşturan yeni konu başlıkları ortaya çıkmıştır ve öneri olarak tezin sonuç kısmına eklenmiştir.

Bulgular, EYM ve SLA tekniklerinin uygulanması arasındaki farklara, ürün geliştirme sırasında malzeme ve zaman tasarrufu potansiyeline ve destek yapılarını en aza indirmeye veya tamamen ortadan kaldırmaya yönelik stratejilere açıklık getirdi. Çalışma aynı zamanda belirli üretim hacimlerinde eklemeli imalat tekniklerinin konvansiyonel tekniklere göre avantajlı olduğu durumları da gösteriyor. Vaka çalışmasının sayısal verileri, baskı ve tasarım tekniklerindeki geliştirmelerin maliyetleri nasıl düşürdüğünü ve üretimi nasıl hızlandırdığını gösterdi. EYM baskıda yaşanan problemlerin en aza indirilmesi için literatürden ve uzman görüşmelerinden yardım alındı. Üç farklı tasarım oluşturularak sayısal veriler tablolaştırıldı ve karşılaştırıldı. Son aşamada destek kullanımı sıfıra indirilerek hem malzeme hem de baskı süresinde azalmalar gözlendi. Ayrıca destek yapısının yüzeyde oluşturduğu deformasyonlar sıfıra indirildi.

Bu çalışmanın sonucu, küçük ölçekli, kaynakları kısıtlı işletmeler ve düşük hacimli üretim için eklemeli imalat teknolojisinin potansiyelini ve gerekliliğini vurgulamaktadır. Eklemeli imalat tekniklerinin konvansiyonel üretim tekniklerine göre sağladığı avantajlar, bu teknolojilerin geniş çapta benimsenmesi ve endüstriyel üretimi yönlendiren paradigmaların dönüşümü açısından büyük umut vaat ediyor. Vaka çalışması ve uzman görüşmeleri sonucunda üç boyutlu yazıların yakın gelecekte yaygınlaşıp standart haline geleceğini söylemek mümkün olmuştur. Bu teknolojilerin gelişmesi ve daha iyi baskı sonuçları elde edilebilmesiyle eşzamanlı olarak tüketicilerin de kullanım alışkanlıklarının değişmesi, ürün estetiği konusundaki fikirlerin daha esnek hale gelmesi ve daha ulaşılabilir tüketim alışkanlıkları oluşmaya başlaması ile beraber üç boyutlu baskı ile üretiminin yaygınlaşağını öngörmek mümkündür. Bu çalışma, eklemeli imalat için tasarım yöntemiyle baskıların nasıl daha iyi hale gitirileceği ve bu iyileştirmenin baskı süresi ve malzeme kullanımına etkilerini açıklayarak bu gelişen yeni üretim kültürüne katkı sağlamaktadır.

1. INTRODUCTION

This chapter provides an overview of the study's theoretical background and an introduction to the research issue. It also presents the thesis's aim, specific research topics, and structure.

1.1 Background of the Thesis

Additive manufacturing (AM), also known as 3D printing, is an advanced manufacturing technique that involves the layering of materials to create three-dimensional objects based on digital designs. This technology has changed the manufacturing process of very complex geometries and customized products (Ngo et al., 2018). AM is a notable advancement compared to conventional subtractive manufacturing processes since it reduces material waste, enhances manufacturing flexibility, and accelerates the design process. Initially conceptualized in the 1980s, this groundbreaking technology has advanced and expanded its influence, becoming an essential tool in various industries. Furthermore, significant advancements continue to be produced in this quickly progressing field. The utilization of AM has become more prevalent in academic research, particularly since 2010. Figure 1.1 shows a tremendous growth in scholarly papers on AM and 3D printing, particularly since 2014. It can also be seen in this table that the AM concept has been replaced by 3D printing (Izdebska-Podsiadły, 2022).

The significance of 3D printing is more pronounced in the present period. Whether it is the rapid prototyping of products, the production of medical implants tailored to individual patients, or even the creation of structures for potential colonization on other planets, 3D printing offers unprecedented possibilities. New materials, including biocompatible resins and advanced metal alloys, have further extended the reach of 3D printing, making it an indispensable tool in modern research, development, and manufacturing.

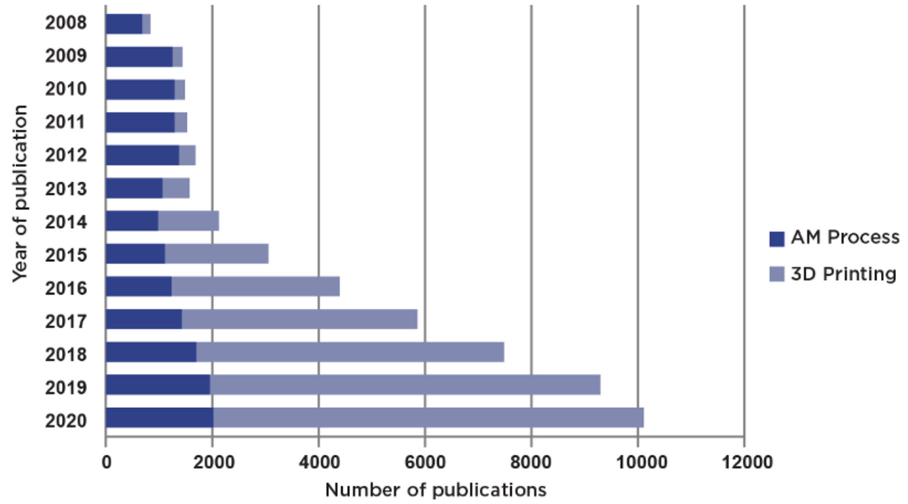

Figure 1.1 : Publications amount on 3D printing by year (Izdebska-Podsiadły, 2022).

The history of 3D printing is a testament to human innovation and technological progress. From its humble beginnings to its status as a technology that shapes various facets of our daily lives, 3D printing has demonstrated unparalleled potential. The value of its role in encouraging creativity, optimizing efficiency, and facilitating customization is increasing (Leary, 2020). As research advances and new frontiers are explored, the development of 3D printing is expected to evolve, further solidifying its crucial position in the contemporary technological domain.

The advancement of this technology has paved the way for direct manufacturing. Furthermore, it can be stated that another framework, known as home fabrication, has also emerged within this technology. Home fabrication is the key to the success of direct manufacturing at home (Benabdallah et al., 2021). Due to the widespread availability of cost-effective 3D printers and readily available design software, home fabrication has become feasible for many individuals. This trend has democratized the production process, enabling individuals to transform ideas into tangible products without requiring extensive manufacturing facilities. Home fabrication caters to a wide array of needs, from custom decorative items to functional spare parts. It has the potential to serve niche markets that conventional manufacturing methods may overlook. Home fabrication with 3D printers presents a profound shift in how production and business are conceived (Anderson, 2012). The potential that 3D printing technology offers for creativity, invention, and enterprise is growing along with its accessibility and sophistication. This new paradigm offers individuals and small businesses opportunities to manufacture in ways previously reserved for large corporations. Furthermore, it challenges traditional business models, supply chains, and regulatory frameworks. The future of home fabrication is still unfolding. Nevertheless, its capacity to fundamentally transform economies and society is undeniable.

1.2 Purpose of the Thesis

This research study aims to investigate how small-volume production companies or individuals can produce new products due to developments in AM technologies. The intention is to observe how the process can be accelerated not only in the manufacturing of a product but also in the R&D process of the product by using 3D printers.

Multiple categories of 3D printers exist to serve different purposes. This research aims to determine which technologies suit home fabrication by analyzing different types. A case study and semi-structured expert interview are conducted to support the research. This case study aims to evaluate the research, development, and manufacturing phases of a product intended for production in a research project. This framework aims to evaluate the required technologies for manufacturing this product and determine the most cost-effective, efficient, and suitable strategy.

This paper outlines AM technologies. However, three of these technologies will be examined in detail: SLA, Digital Light Processing (DLP), and Fused Deposition Modeling (FDM). In accordance with the scope of the research, these technologies were selected based on their suitability for low-budget production (Ntousia and Fudos, 2019).

1.3 Research Questions

The research questions of the study are as follows:

RQ1: What are the advantages of desktop 3d printers for small-scaled manufacturers?

RQ2: Which additive manufacturing technology and materials are more suitable for small-scale companies or individual home fabrication?

RQ3: What are the criteria and strategies of design for AM (DfAM) for desktop 3D printing to optimize printing process?

1.4 Structure of Thesis

The research is organized as follows: The subsequent section after the introduction seeks to present comprehensive information regarding 3D printing. The third chapter provides an explanation of the DfAM processes related to the study. Following the literature review, the research methods are explained. The research findings are presented, followed by a discussion and conclusion. The structure of the study is summarized in Figure 1.2.

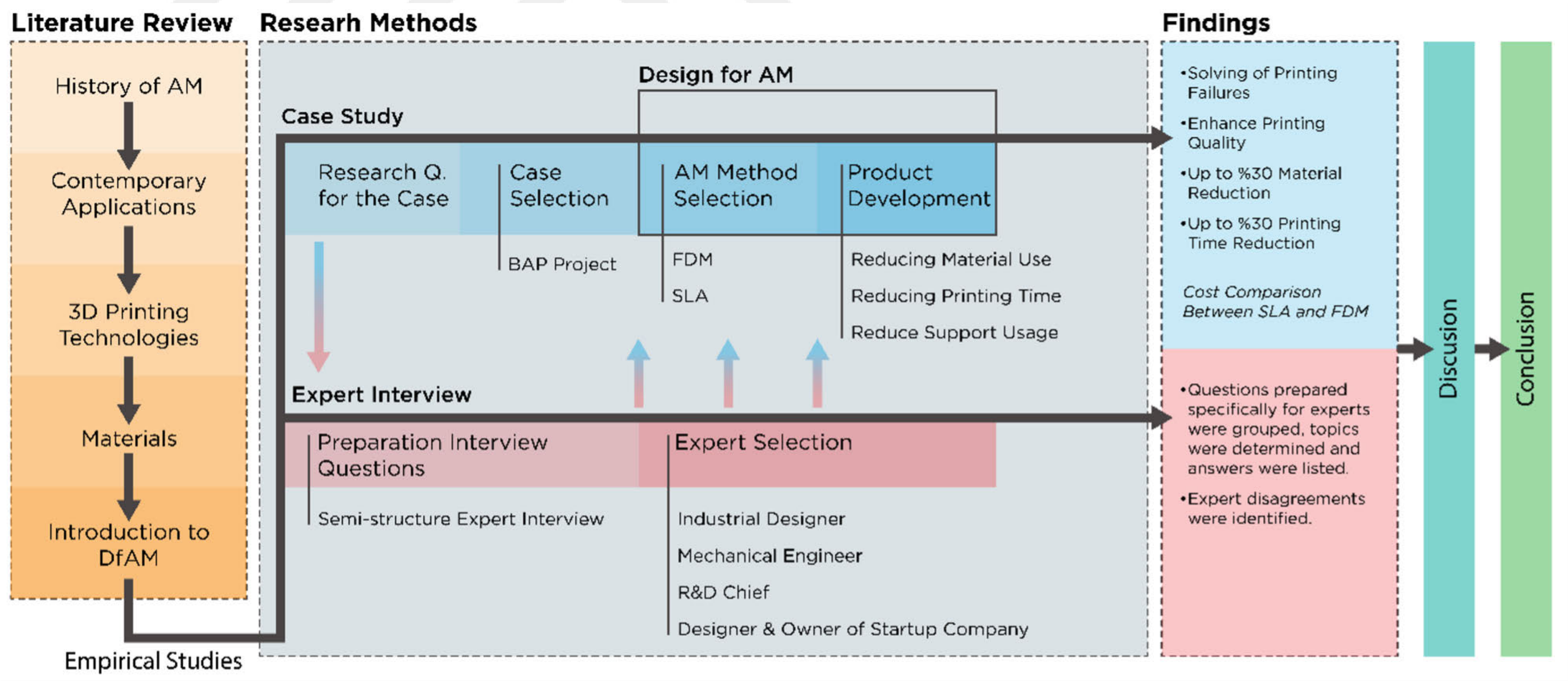

Figure 1.2 : Structure map of the study.

2. GENERAL OVERVIEW OF 3D PRINTING

3D printing, or AM, is a cutting-edge technology that uses digital models to create three-dimensional objects (Ngo et al., 2018). This method involves sequentially layering materials such as plastic, metal, or resin according to a predetermined pattern. The layer-by-layer production process of 3D printing enables the creation of intricate shapes and structures while minimizing waste compared to conventional manufacturing procedures. Since its establishment in the 1980s, the technology has made significant progress and is currently employed in many industries, including aerospace, healthcare, fashion, and education.

AM is also a technical term for what was formerly known as rapid prototyping. Rapid prototyping, as defined by the American Society of Testing and Materials (ASTM, 2012), is the practice of joining materials to create products based on 3D model data, typically by adding layers rather than using subtractive manufacturing techniques. ASTM (2012) also provides several synonyms for rapid prototyping, including 3D printing, additive fabrication, additive process, additive techniques, additive layer manufacturing, layer manufacturing, and freeform fabrication. Nevertheless, it asserts that the term most used today is 3D printing. In this article, the use of these technologies in the production of final products will be examined. As a result of advancements in the output quality of these machines, there is frequently a much closer connection to the final product. Gibson et al. (2015). state that numerous components are now manufactured directly on these machines, hence it is not appropriate to refer to them as "prototypes". This shift highlights the evolution of manufacturing processes where final products, rather than just prototypes, are produced. Gibson et al. (2015) also stated that AM is based on the premise that a model generated using a three-dimensional CAD system can be directly fabricated without needing process planning. Although they argue that this is not as simple as it sounds initially, AM technology significantly simplifies the process of producing complex 3D objects directly from CAD data. Other manufacturing processes require a careful and detailed analysis of the part geometry to determine, among other things, the order in which various features can be fabricated, which tools and processes must be used, and whether additional fixtures are needed to complete the part (Gibson et al., 2015). The increasing recognition of this technology can be attributed to the simplicity of its application.

3D printing utilizes multiple techniques, each with distinct benefits and applications. Method selection is influenced by considerations such as cost, material qualities, and the level of precision required. Metals, ceramics, and even biomaterials are now used in 3D printing (Lee et al., 2017). The application of diverse techniques and materials has expanded the range of possibilities in 3D printing, facilitating customization and introducing innovative approaches in the design and manufacturing of products.

2.1 History of Additive Manufacturing

It is accepted that AM, thought to be new and rapidly developing, was invented approximately 40 years ago. Charles Hull, later the founder of 3D Systems, is widely regarded as the founder of the AM process. However, the origins of this technology date back much earlier. French artist François Willême utilized a platform encircled by 24 cameras to capture the subject's profile every 15 seconds to produce three-dimensional replicas of a subject in 1860 (Zhai et al., 2014). Additionally, the origins of stereolithography can be identified in a system introduced by Munz in 1951, wherein a transparent photopolymer was extruded and cured selectively (Izdebska-Podsiadły, 2022). The publication of Ciraud (1972) was one of the other forerunners of AM techniques. The technology presently known as selective laser sintering (SLS) was founded on a technique reported by this author in 1972 for creating items of any geometry by adding material in powder form. As can be seen in Figure 2.1, intense developments took place between 1980 and 1990.

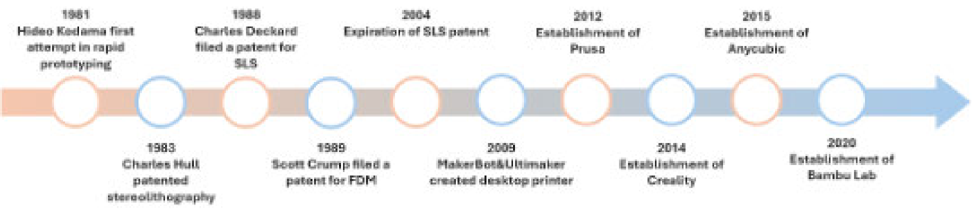

Figure 2.1 : Timeline of significant developments in AM history.

2.1.1 The beginning of AM commercialization

The decade of the 1980s was a period of numerous successive advancements in the commercialization of AM. In 1983, when he pioneered the stereolithography (SL) AM process, Charles W. Hull successfully manufactured a teacup using 3D printing technology for the first time (Prusa, 2023). Following Hull's teacup, Carl Deckard devised the idea for selective sintering in 1986 at the University of Texas after three years of working on the concept. Subsequently, in 1988, Michael Feygin conceived the notion of laminated manufacturing (LM) during his employment at Helisys at Stratasys, Inc. Crump (1989) was the one who first discovered fused deposition modeling (FDM). Emanuel M. Sachs, a professor at the Massachusetts Institute of Technology, is credited with developing the 3D printing process in the same year, 1989 (Jiménez et al., 2019).

2.1.2 Development of AM from 1990 to 2000

The first commercially accessible version of Selective Laser Sintering did not appear until 1990, and at the tail end of the 20th century, the bio-printer was developed. From 1990 to 2000, the visibility of AM has increased. In 1990, Belgian Materialise, the first 3D printing company in Europe and among the first globally, was launched (Izdebska-Podsiadły, 2022). In 2000, a 3D printer kit was made available for purchase for the first time. Massive three-dimensional objects can now be printed on industrial-scale printers. Kokovic (2017) suggests that almost anything can be printed using 3D printers. The innovation of AM, which produces a growing number of patented designs, is promising in terms of enabling the development of the fourth industrial revolution.

2.1.3 Development of AM from 2000 to 2010

The onset of the 2000s marked the commencement of AM, gaining broader prevalence. Object Geometrics introduced the first inkjet 3D printer and Z Corp, the first multicolor printer, to the market in 2000 (Izdebska-Podsiadły, 2022). 2005 was also the turning point in the history of AM. Adrien Boyer started working on the RepRap project to build a cheap, self-replicating 3D printer that creates plastic items (Petch, 2018). This project is also in the market of 3D printing materials. One of the project members, Vik Olliver, suggested using PLA and created the first PLA filament, which

Figure 2.2 : First maker faire in San Mateo, CA (Maker Faire, 2006).

is today one of the most often used consumables for inexpensive home 3D printers (Izdebska-Podsiadły, 2022).

Between 2000 and 2010, the Maker Movement was a crucial player in the development of AM and new-generation machines. Although the Maker Movement is considered a new concept, its foundations are much older. The origins of the Maker Movement may be traced back to the progressive education ideals of John Dewey and the Do-It-Yourself (DIY) culture that emerged in the 1950s and 60s (Dougherty, 2012). It had substantial growth in the early 2000s due to the emergence of user-friendly digital fabrication technologies, such as 3D printing, and the internet's widespread use, facilitating the sharing of ideas and collaboration. The official impetus for the movement is sometimes credited to the establishment of "Make:" magazine in 2005 by Dale Dougherty, which offered a medium for Makers to interact and share information. Shortly after, the first Maker Faire occurred in 2006 in San Mateo, California (Hatch, 2013). This event, the first of which can be seen in Figure 2.2, has now gained worldwide recognition and is known for showcasing the ingenuity and imagination of makers from all over the globe.

The Maker Movement is swiftly reshaping the realm of invention, design, and manufacturing. Driven by an inspiring enthusiasm for creativity and cooperation, Maker Movement prioritizes production being accessible to everyone and a transition towards practical, do-it-yourself (DIY) crafting. According to Chris Anderson (2012), the Maker Movement has expanded in time to establish a novel kind of entrepreneurial manufacturing, positioning itself as a potential candidate for being recognized as the 21st century's new Industrial Revolution. As technology became more widely available, people could turn ideas into physical products, erasing the distinction between creators and consumers.

The core of the Maker Movement revolves around the advancement of tools and technologies that are easily accessible. 3D printing enables anyone to create and manufacture products with outstanding details, avoiding the limitations of conventional production methods. Likewise, open-source software and hardware platforms like Arduino and Raspberry Pi allow those who lack technical expertise to explore the realms of electronics and programming (Söderby, 2024; Raspberry Pi Foundation, 2024). Open-source or free software started to stabilize and be usable to a non-expert customer, while open-source hardware became more prevalent (Horvath and Cameron, 2020).

In brief, the Maker Movement represents an occasional trend and a significant cultural transformation. Promoting creativity, collaboration, and individual autonomy facilitates the starting point of a novel period of invention. It ensures that individuals from every aspect of life can actively participate as creators and contributors.

2.1.4 Contemporary AM

Since 2009, 3D printers have become more widespread with the establishment of companies such as Prusa, Creality, Anycubic, and Bambu Lab, each contributing significantly to the accessibility and innovation of 3D printing technology. Prusa Research was founded in 2012 by Josef Prusa, a Czech hobbyist, maker, and inventor, who has since become one of the most renowned figures in the 3D printing industry (Prusa, 2023). Prusa Research quickly gained a reputation for its open-source philosophy and high-quality 3D printers, making them a popular choice among hobbyists and professionals alike (Kerr, 2022). Creality, founded in Shenzhen, China in 2014, gained widespread recognition with its Ender and CR series, which have become popular choices for those seeking high-quality, budget-friendly desktop 3D printers. By prioritizing accessibility and ease of use, Creality has played a significant role in democratizing 3D printing technology, making it available to a broader audience and fostering a culture of creativity and innovation (Kerr, 2022). Similarly, Anycubic has emerged as a prominent player in the industry since its inception in 2015, also headquartered in Shenzhen, China. Known for its wide range of affordable and high-quality 3D printers, Anycubic caters to both hobbyists and professionals. The company is particularly renowned for its Photon series of resin-based printers, which have brought the precision of Stereolithography (SLA) and Digital Light Processing (DLP) technologies to a broader consumer base at competitive prices (Anycubic, 2024). Anycubic's product lineup also includes the popular i3 Mega and Kobra series, utilizing Fused Deposition Modeling (FDM) technology to ensure accessibility and ease of use for newcomers to 3D printing. Most recently, Bambu Lab, established in 2020, specializes in the development of desktop 3D printers, making a significant impact with its X1 series (Bambu Lab, 2024). This line of state-of-the-art 3D printers is designed to bridge the gap between digital designs and physical creations, thereby elevating creative possibilities. By focusing on cutting-edge technology and user-friendly design, Bambu Lab aims to make advanced 3D printing accessible to a wider audience, encouraging innovation and creativity among users. Collectively, these companies have played pivotal roles in advancing the 3D printing landscape, each bringing unique strengths to the market and contributing to the technology's rapid evolution and integration into various fields.

Today, AM technologies are used in a variety of applications. However, it might be argued that it is used more extensively in specific fields. The report of Essop (2020) lists the following as the percentage of AM technology usage (Figure 2.3): R&D/research/education 42%, mechanical/spare parts 40%, personal interest/hobby 32%, tooling 26%, marketing samples 21%, art/jewelry/fashion 20%, and other 7%. A similar usage distribution is presented in a report compiled by HUBS (2020). The following section will explain the most prominent of these areas and give examples.

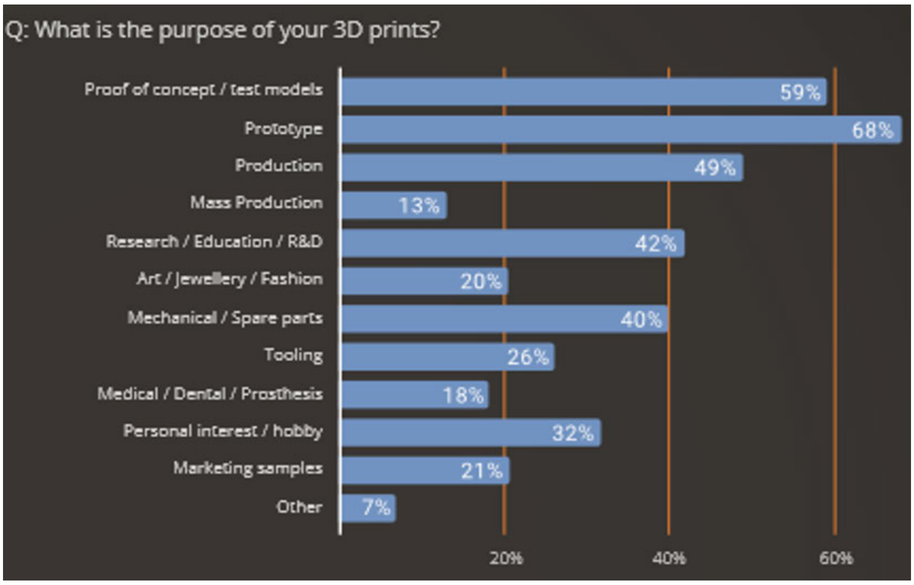

Figure 2.3 : The applications of 3D printing (Essop, 2020).

2.1.4.1 Healthcare

Medical science and engineering have advanced significantly with the use of 3D printing technologies in prostheses. This revolutionary method has significantly improved the accessibility, customizability, and functionality of prosthetic limbs while also wholly redefining the manufacturing process. Prosthetics are made via 3D printing, ranging from primary, cosmetic limbs to more intricate, functional ones, such as hands and arms with moving elements. The low cost of 3D-printed limb prostheses is essential in prosthetics for children since they outgrow the prostheses quickly (Dodziuk, 2016). Children's prostheses, which outgrow their artificial limbs swiftly, benefit significantly from the technique. Moreover, it is crucial in creating specialized parts for athletes' high-performance prostheses (Figure 2.4).

Figure 2.4 : 3D printed prosthetic arm (Birrell,2017).

AM enables prosthetic devices to be precisely tailored to the individual's anatomy, showcasing its technological adaptability (Rai and Pradhan, 2021). Conventional prosthetics may not always fit precisely and are frequently costly and time-consuming. Thanks to 3D printing, prosthetics that are made to fit each person's residual limb precisely can be created, which improves comfort and functionality. Furthermore, prostheses are now more widely available thanks to 3D printing's huge cost and production time reductions, particularly in low-resource or developing nations. Implementing 3D printing in dentistry has eliminated numerous laborious processes associated with producing dental implants, crowns, and other fixtures (Dodziuk, 2016). The conversion of digital scans into physical objects has the benefit of improved accuracy in terms of fit and accelerated timelines for manufacturing. Incorporating technology in dental practices enables the internal fabrication of various items, reducing dependence on external laboratories and speeding up patient treatment.

2.1.4.2 Aerospace industry

The application of 3D printing technology permits the production of complex shapes in components, which would present considerable difficulties or perhaps be impossible using conventional manufacturing methods. Manufacturing components for aircraft engines have continuously posed challenges due to their inherent difficulty and complexity. However, aerospace companies like SpaceX (Figure 2.5) and Boeing are increasingly adopting 3D printing technology for manufacturing components that are lighter in weight and more efficient in performance. Main Oxidizer Valve (MOV) body in one of the nine Merlin 1D engines in the Falcon 9 rocket launched by SpaceX. The mission marked the first time SpaceX had ever flown a 3D-printed part (SpaceX, 2014). This capacity significantly improves Performance and fuel efficiency, which offers substantial advantages. Some space organizations invest in 3D printing to manufacture spare parts for space missions. GKN Aerospace in Sweden (formerly Volvo Aero) has manufactured and proven a nozzle extension demonstrator for a possible upgrade of the Vulcain 2 engine (used on the Ariane 5 launch vehicle) (Dordlofva et al., 2016). In the past, astronauts were required to take additional components for repairs, which increased the payload and cost of flights. Using 3D printing, astronauts can build the necessary components on demand, which reduces the amount of redundant equipment that is required for space travel.

Figure 2.5 : 3D printed SpaceX rocket part (Grunewald, 2014).

2.1.4.3 Automotive industry

3D printing has been used extensively to build prototypes and components for the automotive industry (Sheng, 2022). Advancements in technology have enabled the production of end-use components. Manufacturers can now make components such as gears, interiors, and bespoke chassis effortlessly. In the automotive industry, AM has opened doors for lighter, safer, and environmentally friendly cars with shorter production lead times at reduced costs (Lim et al., 2016). This has implications not just for the speed and cost of manufacturing but also for the range of alternatives available for consumer customization. The automotive sector is currently riding the wave of personalization offered by 3D printing. AM can produce parts with a higher degree of design freedom. This versatility is significantly beneficial in the production of custom features, allowing for the addition of enhanced functionalities (Lim et al., 2016). From custom dashboards to elaborately designed wheels, car manufacturers today offer unprecedented personalization possibilities. This degree of customization was challenging to accomplish using conventional manufacturing techniques, and it serves as evidence of how 3D printing has the capacity to challenge accepted wisdom regarding mass production.

Glover (2023) states that the first 3D-printed supercar seen in Figure 2.6 is the Czinger 21C. According to founder Kevin Czinger, nearly every component of the Czinger 21C's suspension system—aside from shock absorbers—was designed, manufactured, and assembled using 3D printing technology.

Figure 2.6 : 3D printed supercar Czinger - 21C (Czinger, 2024).

2.1.4.4 Construction

In the construction industry, 3D printing is mainly utilized to create complete buildings or building components. It has been possible to print business structures, residential buildings, and even bridges with this technology. Most notably, it makes it feasible to construct intricate architectural designs that are impractical or impossible to realize when using conventional building techniques. Another vital use where expediency and resource efficiency are critical is emergency housing and shelters. The application of AM processes can, moreover, reduce labor costs. However, even if a smaller workforce and lower material usage are necessary, more expensive raw materials and equipment can lead to higher overall costs (Paolini et al., 2019).

The efficiency of 3D printing is by far the most significant benefit in the building industry. With the use of this technique, construction time, labor expenses, and material waste are all greatly decreased. In contrast to traditional building techniques, which are a significant amount of the earth's resources, AM processes have the potential to be environmentally friendly by utilizing efficient construction devices and materials (Jayanna and Muralidhara, 2022). 3D printing adds material only where it is required, reducing waste. Furthermore, it enables extensive customization at no extra expense. Not only are buildings made using 3D printing quick to install, but they also can be durable.

Even with its potential, 3D printing in the building industry has several difficulties. Building-construction-capable 3D printers come at a high initial cost. The size of the printer also determines the maximum and minimum sizes of structures that can be printed (Jayanna and Muralidhara, 2022).

2.1.4.5 Fashion

Beyond just experimenting, 3D printing is now used in the fashion industry to create wearable clothing, accessories, and shoes. The use of 3D printing by high-end designers has allowed them to produce complicated, avant-garde items that are incompatible with traditional tailoring methods. Additionally, the technology is being utilized to create uniquely tailored clothing and accessories that fit the wearer's body type and personal style. Nike states that it can develop shoes, as shown in Figure 2.7, "16 times quicker than in any previous manufacturing method," in addition to the fact that this means a personalized sneaker (Morby, 2018). Figure 2.8 shows the product from Ganit Goldstein's debut collection, "Between the Layers," which consists of six pairs of shoes and seven outfits that were 3-D printed using Stratasys equipment, namely a PolyJet that enables the blending of numerous colors (Sheng, 2022).

Figure 2.7 : First 3D printed footware upper, Nike - Flyprint (Morby, 2018).

Figure 2.8 : Between layers by IKAT (Sheng, 2022).

Customization is the main benefit of 3D printing in the fashion industry. Mass-market fashion brands also use AM to produce customized products for consumers (Nayak and Padhye, 2015). The need for adjustments can be minimized by designers who can make clothing that precisely fits the wearer's measurements. This technology also promotes innovation by enabling designers to experiment with intricate structures and forms that are unattainable with conventional sewing and weaving techniques. Furthermore, more environmentally friendly fashion methods may result from 3D printing. VanderPloeg et al. (2016) mentioned that the cutting of pattern pieces from rolls of fabric is a subtractive process, with leftover wasted material. On the other hand, AM allows the use of environmentally friendly, biodegradable ingredients and minimizes fabric waste by printing only the necessary amount of material.

2.1.4.6 Printers to make everyday items

The advantages of AM in production and design processes were mentioned. In this section, some examples of how it is used in the production of final products will be examined. A new era in manufacturing has begun with the development of 3D printing technology, distinguished by its capacity to produce intricate, personalized, and superior end products for a wide range of sectors. Engineering and design teams can significantly reduce the time between the idea and the finished product using AM (Sheng, 2022). In contrast to conventional production techniques, which often call for many materials, work, and time, 3D printing provides a simplified, effective, and creative solution. The widespread use of 3D printers enables some startups to deliver their product ideas to end users using this technology. Not only startups but many developed companies use this technology for different purposes. The manufacture of the Philips MyCreation Coastal Breeze lights (seen in Figure 2.9), which add value to the local fishing communities while also helping to clean up the seas off the Cornish coast, involves recycling fishing nets (Red Dot, 2024). Typically, products intended for purchase are produced using high-end 3D printing equipment rather than the less expensive type used in the Doogdesign studio (Designwanted, 2019).

Figure 2.9 : Philips MyCreation Coastal Breeze light (Red Dot, 2024).

These companies make most of their products with parts produced by 3D printers. In fact, some companies, such as Doogdesign, prefer 3D printers as a 100% production method. Some designs may contain parts that 3D printers cannot produce. They obtain parts such as electronic components, light bulbs, or metal structure elements using different methods and get help from printed parts when creating the final product(Figure 2.10).

Figure 2.10 : 3D printed vase (Designwanted, 2019).

ZM Design Lab is the one that produces the lamp, which is made up of five 3D printed parts, an aluminum base, and an LED module, and each part is made to be easily assembled and disassembled from the light (Marchese, 2022)(Figure 2.11).

Figure 2.11 : ZM Design Lab's lamp (Marchese, 2022).

Krill Design Studio brings the use of 3D printers to a different dimension. This company, which produces filament using waste orange peels, not only uses recycled materials but also provides a different surface feeling. Conventional production methods can cause considerable waste during production. This company has designed an environmentally friendly production process thanks to recycled biomaterial and 3D printers. Using 3D printing technology, Krill Design was able to "avoid any kind of waste during manufacturing (Finney, 2021)(Figure 2.12).

Figure 2.12 : Krill Design’s lamp (Finney, 2021).

Another advantage of the AM method is that there is no need for molds in production. In some examples, you can see how 3D printers are used to make personalized products (Figure 2.13). The only source required for production is the 3D design file. A new technology system created by the startup company Formify makes it possible to customize a gaming mouse that fits your palm precisely and improves your gaming experience (Bamford, 2023). This company manages to produce a product that can be customized for each user by getting rid of the limits of mass production.

Figure 2.13 : Formify gaming mouse (Bamford, 2023).

This thesis examines the revolutionary effects of 3D printers on the production of finished goods, emphasizing their uses, benefits, drawbacks, and prospects. One of the problems frequently encountered in start-up organizations is the inability to provide sufficient capital.

2.2 3D Printing Technologies

According to ASTM Standard F2792, the categorization of 3D printing technologies into seven groups was undertaken, which included binding jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination, and vat photopolymerization (Shahrubudin, 2019). Each of these methods addresses different purposes (Table 2.1).

Table 2.1 : AM techniques and descriptions (Leary, 2020; Gupta, 2023; Loy et al., 2023; Dizon et al., 2021; Okezie et al., 2023; Yee et al, 2017).

AM Technique	Professional Background	Related technologies	Materials
Vat photopoly-merization	Vat of liquid photopolymer resin that is selectively cured by light-activated polymerization.	SLA, DLP	Photo polymers (resins), ceramic, composite
Materials extrusion	Extruding thermoplastic filament through a heated nozzle that moves in the axes, building up layers.	FDM	Polymers (ABS, PLA, PETG, PC, TPU)
Material jetting	Deposits droplets of photopolymer material onto a build platform, which are then cured layer by layer using UV light.	Multi-jet modeling (MJM)	Polymers, waxes, ceramic
Binder jetting	A powder bed is selectively sprayed with a binding agent (binder) in the shape of the current layer.	Powder bed and inkjet head, Plaster based 3D printing	Polymers, foundry sand, metals
Powder bed fusion	High-powered laser selectively fuses powdered material (metal, plastic, ceramic) together.	Electron beam melting, Selective laser sintering, Selective heat sintering, Direct metal laser sintering	Polymers, metals
Directed energy deposition	Focused thermal energy (from a laser or electron beam) melts and fuses materials as they are deposited onto a substrate.	Laser metal deposition	Metals
Sheet lamination	Bonding together sheets or foils of material layer by layer to create a 3D object.	Laminated object manufacturing, Ultra sonic consolidation	Paper, metals

In the present era, the utilization of 3D printing technologies has surpassed prototyping usage and has expanded to include the production of a diverse range of products. The growth in this field has been rapid, with significant developments occurring within the last 20 years. New technologies are expected to emerge in the coming year (Kocovic, 2017) The branches of the technologies are shown in Figure 2.14 .

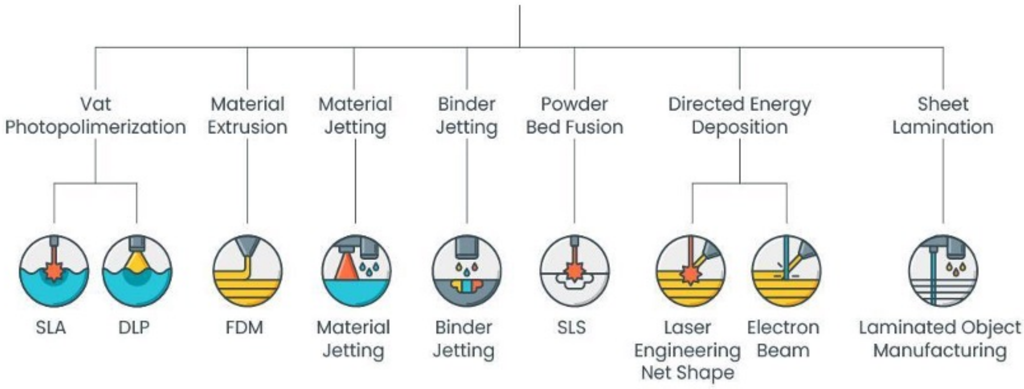

Figure 2.14 : 7 types of AM (Dhanunjayarao et al., 2020).

2.2.1 Vat photopolymerization

Vat photopolymerization is a type of AM technology that uses a liquid resin that is selectively cured by a light source, typically an ultraviolet (UV) laser or projector (Ilangovan and Guna, 2022). The resin is contained in a vat or tank, and the light source is used to selectively solidify the resin layer by layer to create a three-dimensional object. There are two primary types of vat photopolymerization: SLA and digital light processing (DLP). As seen in Figure 2.15, the two printers are almost identical in appearance.

Figure 2.15 : Elegoo Mars 4 DLP (Left), Anycubic Photon Mono M5 SLA (Right)

The key difference is that DLP projects light digitally across the whole production plane, whereas SLA uses a galvanometer-controlled light source (Leary, 2020). Vat photopolymerization is known for its high accuracy and ability to produce parts with very fine details and smooth surface finishes. This technology is commonly used in the production of dental and medical models, jewelry, and other small, high-detail objects.

2.2.1.1 SLA

The AM technique known as SLA was initially invented by Chuck Hull in 1986 and has had a significant impact on the field of three-dimensional printing (Pagac et al., 2021). Through the use of ultraviolet (UV) light to solidify the liquid photoreactive resin, SLA produces products that have outstanding surface quality and fine details. Examples of applications that benefit greatly from this technology include prototyping, artwork, jewelry design, and medical models. These are all examples of applications that require precision and detail.

The method involves the utilization of a UV laser to solidify the liquid monomer in precise regions, as indicated by the tool routes (Gupta, 2023). After each layer is applied, a platform is put above the resin pool and slides lower, reflecting the laser onto the resin. This process repeats until the complete item is constructed layer by layer. One of the most significant advantages of SLA technology is the level of detail that it can generate. This level of precision makes SLA perfect for producing items with small yet complex shapes. The high surface quality and level of detail provided by SLA greatly reduce the need for post-machining, resulting in substantial time and cost savings. Nevertheless, SLA has certain disadvantages. Resin materials typically have a higher cost compared to FDM filaments, and they can deteriorate over time when exposed to UV exposure. Furthermore, Prusa (2023) claims that SLA printing is very sluggish and hence may not be suited for large-volume parts, while the most significant downside of this technology may be the narrow printing area and the toxicity of the epoxy resin. On the other hand, in addition to the frequently used epoxy resins, biocompatible resin types have also become widespread recently. Detailed descriptions of these resins can be examined in the commonly used materials section. SLA is also frequently used in creating a master model that will become a mold for casting (Loy et al., 2023). High surface quality ensures that these molds are of higher quality. This practice can be encountered in jewelry production.

To summarize, SLA technology is an excellent choice for scenarios needing high resolution and superior surface quality. This technology has a significant impact on

3D printing and continues to transform design and production processes. Although there are significant restrictions to its application, the benefits of SLA are invaluable, particularly for prototype production and custom product designs.

2.2.1.2 DLP

As a member of the vat polymerization family DLP is a kind of 3D printing technology that uses light to cure photopolymer resin. DLP is substantially faster than its close relative, SLA, which cures the resin with a laser. Since every layer in the DLP process is fully exposed to the curing light projected from the digital screen, it operates more quickly than the SLA method (Pagac et al., 2021). In order to cure the resin in precise places, the DLP printer's projector projects UV light through an LCD screen that shows black-and-white images where black blocks UV light and white permits it to pass. In professional settings where speed and detail are critical, DLP is highly preferred due to its efficiency and precision.

2.2.2 Materials extrusion

The 3D printing technology based on material extrusion can produce prints in multiple materials and colors. The low-cost printing process has gained widespread usage. Additionally, this process can create fully operational parts of a product. Most used material extrusion technology is FDM (see Figure 2.16).

Figure 2.16 : Creality Ender 3 Pro FDM printer.

As seen in Figure 2.17, FDM is not only the most preferred technology of this type, but also the most used compared to other 3D printing techniques (Beyerlein and Aboushama, 2020).

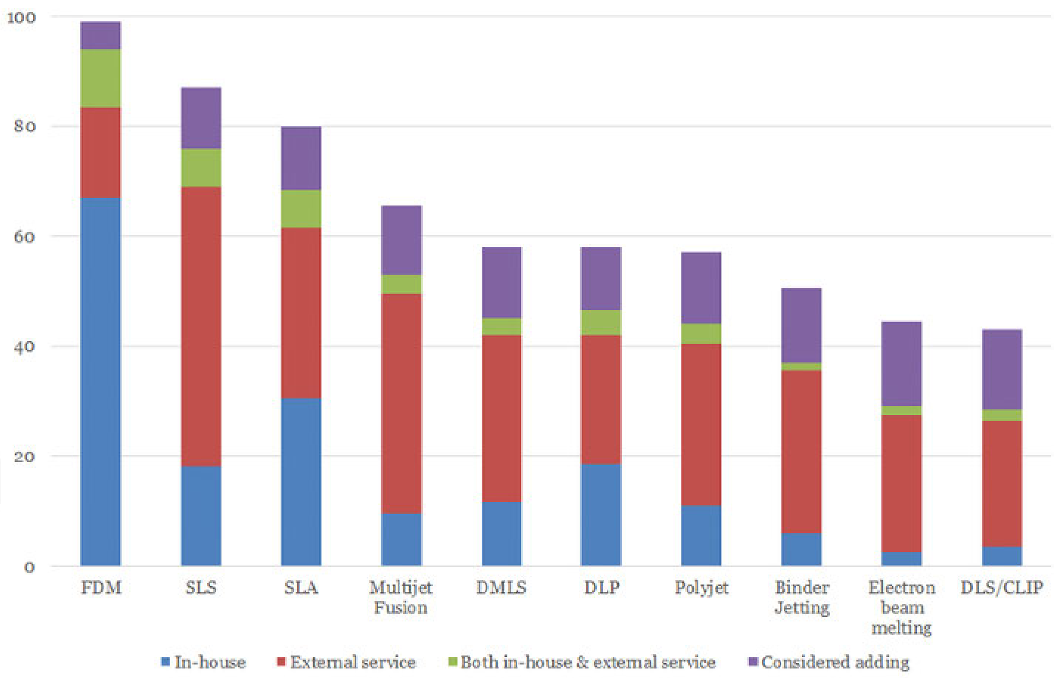

Figure 2.17 : Most used 3D printing technologies (Beyerlein and Aboushama, 2020).

2.2.2.1 Fused deposition modeling (FDM)

FDM is one of the AM technologies that will be used in the method section of this thesis. FDM technology is a revolutionary 3D printing process that primarily uses thermoplastic materials supplied as filaments (Dizon et al., 2021). These materials include polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS), which are notably popular due to their widespread availability and ease of handling within the 3D printing community (Advíncula et al., 2020). These thermoplastics are preferred for their ability to be easily melted and reshaped, which is essential for the FDM process. Material extrusion in FDM is an efficient technique that enables the creation of complex and customized items that can be used in various industries, ranging from automotive to consumer goods, illustrating the technology's flexibility and adaptability (Dizon et al., 2021). The FDM printing process involves a specifically designed extruder or print head equipped with precisely controlled nozzles. These nozzles play a critical role as they contain resistive heaters that accurately maintain the filament's temperature just above its glass transition point

(Hozdić, 2024). This careful temperature control is crucial as it renders the filament into a semi-liquid state, enabling it to be laid down in successive layers to build the 3D object. The range of materials used in FDM printing extends to several polymers such as acrylonitrile styrene acrylate (ASA), polyamide (PA), polylactide (PLA), and polyethylene terephthalate glycol-modified (PETG) (Hozdić and Hozdić, 2023). Each of these materials offers distinct mechanical properties that make them suitable for different applications, from durable machine parts to flexible and impact-resistant items, thus broadening the scope and utility of FDM technology in industrial applications.

FDM printers come in various types, each tailored to meet specific needs and scales of production (Figure 2.18). Entry-level FDM printers are widely popular among hobbyists and home users due to their affordability and user-friendly interfaces (FDM 3D Printing, 2023). These printers are typically suitable for small-scale projects and learning environments. For professional applications, such as in engineering and product design, industrial-grade FDM printers are employed. These high-end models offer greater precision, larger build volumes, and the ability to use a wider range of advanced materials that have higher strength and thermal resistance. Additionally, some FDM printers are designed with dual extrusion capabilities, allowing them to print with two different materials or colors simultaneously (Dave and Patel, 2021). This feature is particularly beneficial for creating complex parts with support structures or multi-material prototypes. Each type of FDM printer supports a range of applications, from prototyping to full-scale production, making FDM a versatile and widely adopted AM technology. This paper focused on entry-level printers. In the case study, printing will be done with an entry-level machine.

FDM printers have various types but the main ones: cartesian, delta, polar and robot arm. The most common type is Cartesian printers (Martel, 2022). Delta, polar and robot arm type FDM printers can be preferred according to different purposes and requirements.

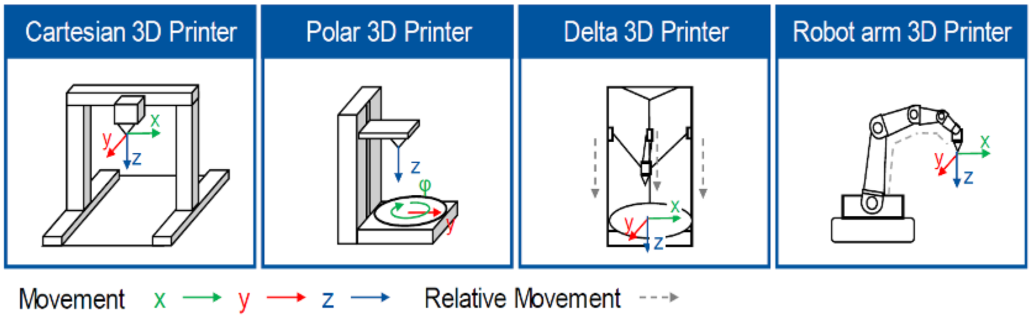

Figure 2.18 : Machine platforms for FDM printers (Kampker et al., 2019).

Cartesian 3D printers with Fused Deposition Modeling (FDM) technology are an essential for many industries, from production to prototyping, in the quickly developing field of AM. Cartesian 3D printers use X, Y, and Z axes to control the movement of the printer head and bed, which are based on Cartesian coordinate systems (Kakabadze, 2020). The outcomes of the Cartesian system are rather stable (Ali and Abilgaziyev, 2021). The easy design of Cartesian FDM printer is another advantage, since it typically results in higher dependability and easier maintenance (Okezie et al., 2023). Because of the exceptional precision that the linear movement mechanism provides, these printers are ideal for producing large parts with consistent mechanical qualities. Cartesian FDM printers have several drawbacks, despite their advantages. When compared to other kinds of 3D printers, like Delta or SLA machines, the printing speed is frequently slower, which might reduce productivity in high-volume industrial environments.

The way that Cartesian 3D printers move the print head or bed along the X, Y, and Z axes using the Cartesian coordinate system distinguishes them from one another. Depending on their mechanics and design, each type has a unique set of benefits and can be used for a variety of purposes. The main categories of Cartesian 3D printers are XZ-head and Y bed Printers, and CoreXY, H-Bot.

One of the most widely used models of Cartesian printers is XZ-head printers. With its simple, open-frame construction, the print head moves along the X and Z axes, while the print bed moves along the Y axis. This design is extensively used because of its simplicity, ease of assembly, and strong community support (Madison, 2023).

A Cartesian printer variation with improved print quality and speed is called a CoreXY printer. A system of belts designed to lower the moving mass of the print head assembly allows the print head to move in both the X and Y directions in a CoreXY system (O'Connell, 2023). This makes printing more quickly without compromising quality. Another factor contributing to print stability is the fact that the print bed normally only moves in the Z-axis.

The H-Bot design use a single belt to drive motion in the X and Y axes, however it has a belt layout similar to that of CoreXY (Shaik et al., 2021). The goal of this design is to lower costs and decrease mechanical complexity. But at faster speeds, it may experience problems with torque and belt tension, which could compromise print accuracy (O'Connell, 2023).

Three arms on vertical rails are used in Delta 3D printers to move the print head in a synchronous manner. In contrast to cartesian printers, which move in linear directions, Delta printers use a system of rods attached to stepper motors at the top of the printer to drive the print head, resulting in a circular print area. Because the lightweight arms can quickly change their lengths and angles, this structure enables the print head to move very quickly in both vertical and horizontal directions with remarkable precision (Ali and Abilgaziyev, 2021). Delta printers often have a stable print bed, which lessens vibrations and any printing problems.

The speed of Delta printers is one of their most significant advantages (Prusa, 2023). Faster print head travel made possible by their movement mechanics can considerably shorten print times, particularly for taller objects. Because of this, high throughput applications are a perfect fit for Delta printers. Furthermore, compared to Cartesian printers of comparable size, Delta printers' vertical architecture frequently permits a higher build height, which makes them appropriate for printing long, vertical things. Additionally, fewer moving parts make temperature control easier (Schmitt et al., 2018).

Delta printers have drawbacks despite their benefits. The intricacy of their calibration procedure might be problematic; accurate calibration is necessary to guarantee that every arm moves in unison, and this can be more challenging than with Cartesian systems. Furthermore, there may be occasions when the print quality varies at different locations within the print area due to the circular print area and converging arms. Compared to the center, the print base's outer margins may have distinct qualities related to accuracy and resolution (Bell, 2015). Furthermore, not all prints or materials may be compatible with the unique motion mechanism and build area form.

Polar is a recently developed kinetic scheme introduced by the firm of the same name, Polar (Ali and Abilgaziyev, 2021). The print head moves vertically (the Z-axis), and the print bed revolves along a circular axis (the R-axis), moving in and out radially. By minimizing the number of moving elements, this arrangement may speed up printing and simplify the mechanical design. Polar printers are very good at printing round or cylindrical objects because of their ability to utilize the print area efficiently due to their rotational movement. However, because ordinary Cartesian coordinates must be transformed into polar coordinates, the non-linear movement can present difficulties for slicing software (Prusa, 2023). Notwithstanding these difficulties, polar printers provide a small and effective solution for geometric applications, highlighting the wide range of uses for 3D printing technology to meet specialized production requirements.

A robot arm FDM printer, which takes advantage of the flexibility and range of motion provided by robotic arms, is an inventive take on standard 3D printing technologies. This kind of printer mounts the extruder on a multi-axis robotic arm. It uses a standard FDM mechanism, where material is extruded through a heated nozzle to build objects layer by layer. The system's high degree of flexibility, resulting from the printer head being mounted on the end of the robot arm, makes it appropriate for the additive production of complex and large-volume structures (Kampker et al., 2019). The printer's increased maneuverability improves efficiency and expands its capacity to print more intricate geometric models. The robot arm FDM printer is especially useful in industrial settings where large-scale customization and on-demand manufacturing are necessary.

2.2.3 Materials jetting

Material jetting, one of the many AM technologies, offers a diverse range of colors and materials. This enables the fabrication of hard and soft polymeric materials in a single process. Material jetting printers layer photosensitive polymer resin onto the build platform to make the desired object, UV lamps cure each layer. After depositing each layer, a roller removes superfluous material and maintains layer thickness. (Tee et al., 2020). According to Tee's findings in 2020, polyJet technology can produce micro-composites as small as 62.5 m in scale. However, it is stated that it may not be suitable for fabricating parts that require a high level of accuracy.

2.2.4 Binder jetting

Binder jetting is a 3D printing and rapid prototyping technique where a liquid binding agent is selectively deposited to fuse powder particles. The process involves the application of chemical binder through jets onto the powder layer to create each layer. According to Lee (2017), the benefits associated with the binder jetting technique encompass freedom from support structures, unrestricted design capabilities, a substantial build volume, rapid printing speed, and a comparatively low cost. It can print various materials including metals, sands, polymers, hybrid, and ceramics.

2.2.5 Powder bed fusion

Powder bed fusion (PBF) is a type of AM technology in which a high-powered laser or electron beam is used to selectively fuse layers of powdered material to create a three-dimensional object. The powdered material is spread in a thin layer on a build platform, and the laser or electron beam selectively melts and fuses the powder particles together based on the 3D design data. The build platform is then lowered by a small amount, and the process is repeated layer by layer until the final object is complete. PBF is commonly used to create complex metal parts with high accuracy and detail. Due to their smaller beam size, these methods are capable of producing parts with high accuracy and excellent surface finish, making them suitable for small-scale production (Singh et al, 2021).

2.2.6 Directed energy deposition

Direct energy deposition (DED) is an AM technique that involves focusing energy into a confined area to heat the substrate and melt the material being deposited. Typically, a high-powered laser is utilized to melt metal powders, and the resolution of the printed component is directly influenced by the quantity of metal powder deposited during the DED process (Yee et al, 2017). The concept of directed energy deposition follows a similar principle to material extrusion. However, in this process, the nozzle is not restricted to a particular axis and can move in various directions.

2.2.7 Sheet lamination

Sheet lamination is a type of AM technology in which thin sheets of material, such as paper or plastic, are bonded together layer by layer to create a three-dimensional object. The bonding is typically achieved through the use of an adhesive, heat, pressure, or a combination of these methods. Sheet lamination is often used for creating models, prototypes, and architectural models, as well as for producing low-cost, low-resolution parts. This technology is advantageous for its low cost, ease of use, and ability to produce large objects. Shahrubudin's (2019) article highlights the benefits of sheet lamination, including its ability to produce full-color prints, its relatively low cost, ease of material handling, and the ability to recycle excess material.

2.3 Commonly Used Materials in 3D Printing

A variety of materials, including ceramics, metal, sand, plastic, wax, and biomaterials, are used in these 3D printing technologies. The scope of this research will concentrate on two specific technologies, namely "Vat photopolymerization" and "Material extrusion". These methods have been chosen as they are better suited for low-cost manufacturing, which aligns with the research's objectives. While material extrusion technologies use the filaments seen on the left in Figure 2.19, Vat photopolymerization technologies generally use the resins seen on the right.

Figure 2.19 : Filaments and resins.

2.3.1 ABS

The filament material utilized in 3D printing is a pivotal factor significantly influencing the result. ABS, short for Acrylonitrile Butadiene Styrene, is a highly popular filament in 3D printing. ABS is a thermoplastic polymer recognized for its durability, dimensional stability, and high-temperature resistance. The three main components of the ABS repeat units are styrene, which lowers costs and improves processability; butadiene, which gives impact resistance; and acrylonitrile, which offers chemical and temperature resistance (Leary, 2020). Generally, the temperature range of -20 to 80 °C would be advantageous for ABS properties (Swetham et al., 2017). The material is commonly used in everyday products such as keyboard keys, refrigeration equipment, and numerous household items. ABS is a durable substance, and items made from ABS are more resistant to breaking when subjected to force than other plastics. On the other hand, ABS exhibits a higher melting point in comparison to certain other prevalent 3D printing materials, such as PLA, rendering it well-suited for uses that demand resistance to high temperatures. In contrast to PLA material, ABS is a plastic product with better mechanical and thermal qualities (Patel et al., 2022). Besides these capabilities, ABS has some difficulties in the printing process. Since ABS is a material that shrinks when it cools, printing requires a heated printing plate (Noorani, 2017).

ABS possesses a degree of flexibility, which can be advantageous for applications requiring some give or bend, despite its toughness. After printing, ABS objects can be readily sanded, drilled, or machined, providing options for post-processing. Hovewers, ABS, have a tendency to become slightly white in color when they are sanded (Horvath and Cameron, 2020). Additionally, ABS can be smoothed with an acetone vapor bath, which imparts a high-gloss finish to the printed object (Bernier et al., 2015). It is essential that this material goes beyond the prototype with post-production processes and is able to create a final product.

2.3.2 PLA

Polylactic Acid (PLA) is a widely utilized substance in the field of 3D printing, renowned for its ease of use as well as its environmentally favorable composition. Biodegradable polymers, such as polycaprolactone and PLA, also produce greenhouse gas emissions during their production (Muralidhara and Banerjee, 2021). PLA is derived from renewable sources, including cornstarch and sugarcane. Because PLA is biocompatible and does not negatively impact metabolism, it can be developed for use in medical applications (Kristiawan et al., 2021). This polymer, derived from biological sources, presents a distinct advantage over numerous alternatives derived from petroleum, which makes it particularly appealing to the environmentally aware subset of 3D printing devotees. PLA is highly regarded for its printing properties, which include a straightforward process, minimal warping, and the ability to produce complex structures with a significantly cleaner finish compared to several of its alternatives. However, despite all its benefits, PLA does have some restrictions to operate within. Due to the fact that it has a lower melting point, it is sensitive to deformation when subjected to high temperatures (Horvath and Cameron, 2020). Furthermore, it does not possess the durability and flexibility that certain applications may require, particularly when compared to materials such as ABS. On the other hand, Wickramasinghe et al. (2020) mentioned that PLA has a stronger tensile strength than ABS, despite ABS showing superior impact strength. PLA readily degrades under the right circumstances, whereas other polymers are recycled or disposed of. Therefore, although PLA is well-suited for prototypes, low-wear applications, and decorative objects, it may not consistently be the most suitable material for functional components requiring heat or stress resistance.

2.3.3 PC

Polycarbonate (PC), utilized in 3D printing, is a high-strength thermoplastic material that is known for its exceptional optical clarity, high-temperature resilience, and impact resistance. PC is a favored material in the realm of 3D printing due to its capability of producing exceptionally durable parts, which is particularly advantageous for applications that demand structural integrity or are exposed to extreme conditions. Because of these features, it is used in tooling and fixtures, blow molding expertise, and functional prototypes for the automotive and aerospace sectors (Lee et al., 2017). This material allows for translucent production and can be used for different colors and opacity. In addition, the PC is renowned for its exceptional dimensional stability, which ensures that printed objects endure shrinkage or warping. Nevertheless, due to its exceptional qualities, PC generally necessitates high extrusion temperatures and a heated print bed, which may require specialized 3D printers or configurations to achieve the most desirable results. Another use is in the composite form created by mixing it with ABS. ABS with a high percentage of PC content may provide better tensile and flexural strength (Gibson et al., 2015).

2.3.4 PETG

PETG (polyethylene terephthalate glycol) is in great demand because of its exceptional mechanical strength and resilience against chemical and water infiltration. PETG is a thermoplastic material that combines some of the advantageous properties of PLA (polylactic acid) and ABS (acrylonitrile butadiene styrene), two other well-known thermoplastic materials used in 3D printing (Guna et al., 2022). PLA is renowned for its printability, whereas ABS is noted for its strength. Polyethylene terephthalate glycol, or PETG for short, is a modification of polyethylene terephthalate. The chemical group cyclohexanedimethanol essentially replaces the ethylene glycol in PET. The research conducted in 1941 by two British scientists, John Whinfield and James Dickson, is where PETG had its start (Nisticò, 2020). PETG is a substance safe for food. It is thus in demand in the food and beverage industries as a packaging product. Due to its excellent thermal stability, harmless emissions, and great impact resistance, PETG is an ideal material for 3D printing. However, there are still several drawbacks to PETG when compared to ABS. PETG has a significant degree of hygroscopicity, which makes storage difficult. The fact that painting PETG is difficult, if not impossible, is another drawback. It is also renowned for being weak because of its limited resistance to ultraviolet (UV) radiation and poor effectiveness against scratches and frictional contact (Dizon et al., 2021).

2.3.5 TPU

In the realm of 3D printing, Thermoplastic Polyurethane (TPU) is distinguished by its exceptional combination of flexibility and resilience. TPU has elastic qualities that allow printed objects to stretch and compress like rubber, making it suitable for generating flexible and wear-resistant items such as phone covers and footwear insoles, unlike rigid materials like PLA or ABS. Its remarkable resistance to abrasion and capacity to endure dynamic loads without deformation is also notable. Although TPU is mainly utilized for flexible components, it may also be employed in other applications because of its great oil and grease resistance and very high impact resistance (Patel et al., 2022). However, TPU's elasticity can cause problems, requiring precise calibration and reduced print speeds to eliminate problems like stringing or leaking during printing.

2.3.6 UV resins

Resin in the realm of 3D printing is a unique category that utilizes photopolymer liquid materials designed for SLA and digital light processing (DLP) printing techniques. In contrast to conventional filament-based 3D printing, which operates on the principle of heat to dissolve materials, resin printing utilizes ultraviolet light to cure the liquid resin (Quan et al., 2020). Compared to other commercially available 3D printing methods, resin-based AM technologies like SLA and DLP exhibit superior resolution, accuracy, and Z-axis strength (Cullen and Price, 2018).

However, the use of resins is not without its challenges. The range of available resins can vary in consistency and texture, from rigid and durable to flexible and rubber-like, offering a wide range of applications but also requiring a deep understanding of the resin's properties. Objects often undergo a post-curing phase under uv light to ensure the material reaches its maximum mechanical strength after the printing process. The presence of enclosed volumes in resin printing can be a challenge. When the resin remaining inside cannot cure, it cannot solidify and remains in liquid form. The shape must include a hole to facilitate the outflow of the resin.

Liquid resins must be handled with caution. Ensuring the biocompatibility and general safety of the resins is crucial since some monomers have the potential to cause significant environmental problems (Joseph et al., 2022). The phrase biocompatible refers to materials that have been carefully developed to interact with live tissues without eliciting an immune response (Guttridge et al., 2022). Anycubic Eco resins made from plants seen in Figure 2.20 exemplify this type. These resins have low odor and are biodegradable.

Figure 2.20 : Plant-based UV resin (Anycubic, 2024).

Most used epoxy resins harm the environment also, including human health. Due to their chemical composition, numerous resins can release fumes or lead to skin irritation (Prusa, 2023). Therefore, it is crucial to have adequate ventilation and wear safety gear such as gloves and masks while working closely with these materials.

3. DESIGN FOR ADDITIVE MANUFACTURING

This chapter provides an overview of design for AM and includes a comparison of the AM design process with conventional manufacturing. Design for manufacturing (DfM) is mostly about optimizing and improving conventional production methods. It is the process of designing products with the intention of minimizing the challenges and costs associated with manufacturing and assembly (Gibson et al., 2020). On the other hand, design for AM (DfAM) is a specialized engineering approach that optimizes the design process specifically for 3D printing technologies. A new production technology typically opens new creative options for a designer (Bernier et al., 2015). This methodology goes beyond simply adapting existing designs to AM processes; This involves rethinking the entire design to take advantage of the unique possibilities of 3D printing. There is also an emphasis on the efficient use of material reduction (Diegel et al., 2019). By considering factors such as print alignment, minimizing support structure, and the physical properties of printing materials during the design phase, DfAM improves the functionality of products and the efficiency and sustainability of their production. AM offers design freedom for designers and engineers. Geometric flexibility is limited even though AM offers enormous creative possibilities (Kumke et al., 2017). In the following sections, detailed explanations of FDM and SLA design and printing processes will be given. Finally, the differences between DfM and DfAM will be explained.

3.1 3D Printing Pipeline

The 3D printing process entails several detailed and careful steps to create a 3D object successfully. Everything from the first design stage to the last quality control needs to be done precisely and with great attention to detail. Prusa (2023) states that there are three main steps in the 3D printing process: getting a printable 3D model, getting it ready for printing, and then actually doing the printing job. In this study, these three stages were expanded and explained in five stages (Figure 3.1).

Figure 3.1 : 3D printing pipeline (Livesu et al., 2017).

3.1.1 3D modeling

An essential aspect that distinguishes AM as revolutionary is its capacity to generate a readily usable component directly from a CAD file (Bandyopadhyay and Bose, 2015). The first step in 3D printing is to create a digital design of the object you want to print. This is usually done using CAD software. The design must be saved in a format that a 3D printer can read, commonly in stereolithography (STL) or OBJ format. Most 3D CAD systems are characterized by their solid modeling capabilities, which involve assembling surfaces or adding thickness to a surface (Gibson et al., 2015).

3.1.1.1 NURBS and polygon modeling

NURBS and Polygon modeling are vital methodologies in the domain of 3D printing, each catering to the specific requirements of a project. NURBS curves are formed by translating the constituent points of a curve, resulting in a flowing shape (Arion et al., 2014). NURBS modeling is characterized by its precise and smooth curves, which are often necessary for high-precision fields like automotive or aerospace parts manufacturing. The mathematical accuracy inherent in NURBS modeling ensures that the printed product adheres closely to the design specifications, which is crucial when tight tolerances and smooth surfaces are required. On the flip side, Polygon modeling, which uses vertices, edges, and faces to define the shape of a 3D object, finds its forte in scenarios where a high degree of geometric complexity or artistic expression is needed, such as in character modeling or prototyping. Though it may lack the mathematical precision of NURBS, Polygon modeling is often simpler and faster, making it suitable for rapid prototyping where iteration speed is more critical than surface smoothness.

NURBS modeling tools are highly beneficial in the realm of 3D printing due to their ability to create precise and complex geometries.

3.1.1.2 CAD software for AM

As the application of AM among individuals and professionals whose primary focus is not on AM continues to rise, user-friendly CAD software and readily available 3D data sets are becoming increasingly crucial (Gebhardt et al., 2019). From this perspective, the preferred program must be not only suitable for AM but also easy to use. Solidworks, Rhino3d, and Fusion 360 are just some of the software used for AM. These 3D modeling programs were selected for their nurbs modeling system and their widespread use.

Solidworks

SolidWorks is a comprehensive 3D CAD software suite developed by Dassault Systèmes. Renowned for its intuitive interface and robust set of features, SolidWorks facilitates the design, simulation, and management of complex mechanical systems (Solidworks, 2024). Engineers and designers leverage SolidWorks to create detailed models, perform simulations to test stress and motion and generate intricate assemblies and drawings. Its parametric design capabilities allow for easy modifications and updates, ensuring that all aspects of a project remain consistent and integrated (Solidworks, 2024). Solidworks is increasingly recognized for its capabilities in AM, offering tools and features specifically tailored to the needs of this innovative production process. By integrating design and manufacturing workflows, Solidworks allows engineers and designers to transition from digital models to 3D-printed prototypes and final parts (Onwubolu, 2017). Its robust suite includes tools for creating complex geometries and intricate lattice structures, which are ideal for AM. SolidWorks also supports optimizing designs for weight reduction and material efficiency, which is essential for AM (Nguyen, 2019).

Rhino3D

Rhino3D, formally known as Rhinoceros, is a 3D computer-aided design (CAD) software developed by Robert McNeel and Associates. Esteemed for its robust mathematical precision, Rhino3D facilitates the manipulation of intricate models, making it indispensable across diverse design disciplines, from architectural endeavors to intricate industrial prototypes. Rhino 3D models surface using NURBS, which facilitates the adjusting of complex curved surfaces (Sitotaw et al., 2020). Its advanced NURBS modeling tools offer unparalleled smoothness in design and surface modeling. Furthermore, Rhino3D's compatibility with various file formats underscores its pivotal role in interdisciplinary design workflows, consolidating its stature in contemporary digital design pedagogy.

Rhino3D can provide a number of issues when preparing models for 3D printing. One typical problem is manifold geometry, in which models may include non-manifold edges or surfaces that are not correctly connected or closed. Such flaws can cause mistakes during slicing or prevent the printer from appropriately reading the model. Furthermore, thin walls or fragile elements in the design may not translate well into physical prints, necessitating precise adjustments to characteristics like as wall thickness and supports to ensure structural integrity.

Fusion360

Fusion 360 is a modeling program that offers both solid modeling and sculpting (Autodesk, 2024). It is CAD/CAM/CAE collaborative product development tool hosted in the cloud. The collaborative features of Fusion 360 facilitated communication among the design team, allowing for real-time feedback and iterations. Fusion 360's integrated Computer-Aided Manufacturing (CAM) tools also supported the decision to utilize AM for production. Fusion360 is compatible with the 3D printing utility tools of the Spark platform, Autodesk Print Studio (Figure 3.2), and has the capability to integrate with Ember3D printers directly (Song et al., 2018). These tools ensure a smooth transition from design to production.

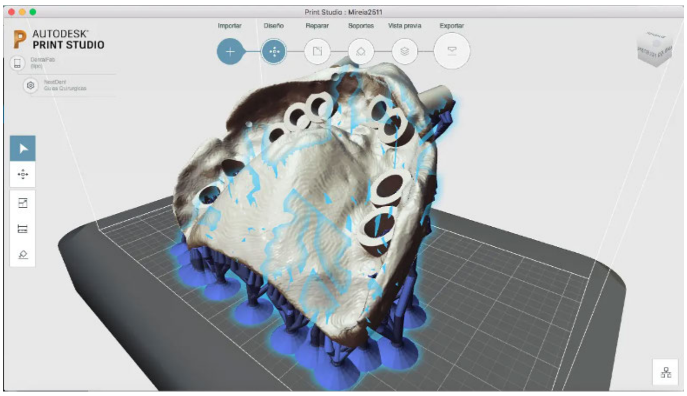

Figure 3.2 : Autodesk print studio UI.

Both Rhino3D and Fusion 360 have strengths and could be effectively utilized for the case study's design. Table 3.1 provides a general comparison of these two software programs. The choice ultimately depends on the project's specific requirements, anticipated design complexities, and production process.

Table 3.1 : Software comparison (According to the prices in Turkiye in 2024).

Variable	Rhino3D	Fusion 360	Solidworks
Design Flexibility	Creating complex forms with surface modeling techniques.	More precise and adjustable geometries with parametric modeling.	Precise and parametric modeling with different types of simulations. Manufacture-ready models.
Transition to Production	STL and OBJ file exporting.	Creating print-ready files directly.	STL and OBJ file exporting.
Simulation and Testing	Not supported.	Some simulation and testing tools.	Various simulation and testing tools.
Collaboration	Not supported.	Cloud-based collaboration	Cloud-based collaboration
3D printing compatibility	STL export (Issues can occur.)	Ember3D integration.	Print3D tool (Solidworks, 2024).
Price	€ 995/one-time payment.	2754 TL/monthly.	Free access for startup application.

The majority of items are developed using CAD programs that produce surfaces and edges that are mathematically precise (a process known as NURBS modeling), which needs to be transformed into a mesh (Loy et al., 2023). In order to be loaded into slicing programs, the NURB model is converted into a mesh model by exporting it to OBJ or STL format. Considering all this, Rhino3D was preferred in the concept design phase in the case study, while the production model was created in Fusion360 software. Although Solidworks offers comprehensive and mass production-oriented solutions, it was not preferred due to its file sizes and difficulty of use.

3.1.2 Slicing

After the 3D modeling process is completed properly, the next stage is the slicing stage. To do this, first, the model needs to be converted to STL format. In order to ensure uniformity, the STL format has been standardized within the 3D printing industry (Haq et al., 2023). STL is a format created by converting CAD data into triangular surfaces. The process of slicing using triangles can be performed independently from the original CAD data, which is considered advantageous because it eliminates the need to export the entire CAD model just for AM (Gebhardt, 2012). When converting to STL format, resolution can be adjusted in 3D modeling programs. This may have an impact on the tolerance for significant features, such as the space between completed parts (Loy et al., 2023). STL files exported from 3D modeling programs are ready to be imported into 3D slicing software. 3D printing software is a pivotal aspect of the 3D printing process, serving as the bridge between digital design and physical creation. This software, often called slicer software, transforms a digital 3D model into a series of thin layers or slices, creating a file readable by 3D printers. Advanced algorithms within the software determine optimal print paths, ensuring precision and material efficiency. Interfaces allow designers to customize settings like layer height, fill density, and support structure, tailoring the printing process to the model's specific needs. Moreover, these software often include simulation tools, enabling users to predict and rectify potential printing issues before initiating the physical print, thus saving time and resources. As 3D printing technology evolves, the software continues to become more sophisticated, offering enhanced features for both novice and professional users, further pushing the boundaries of what can be achieved with 3D printing. In the case study, the Ultimaker Cura slicer (Figure 3.3) is used for FDM printing, and Lychee Slicer (Figure 3.4) is used for SLA printing. They are both most commonly used open-source 3D slicing software with user friendly interface.

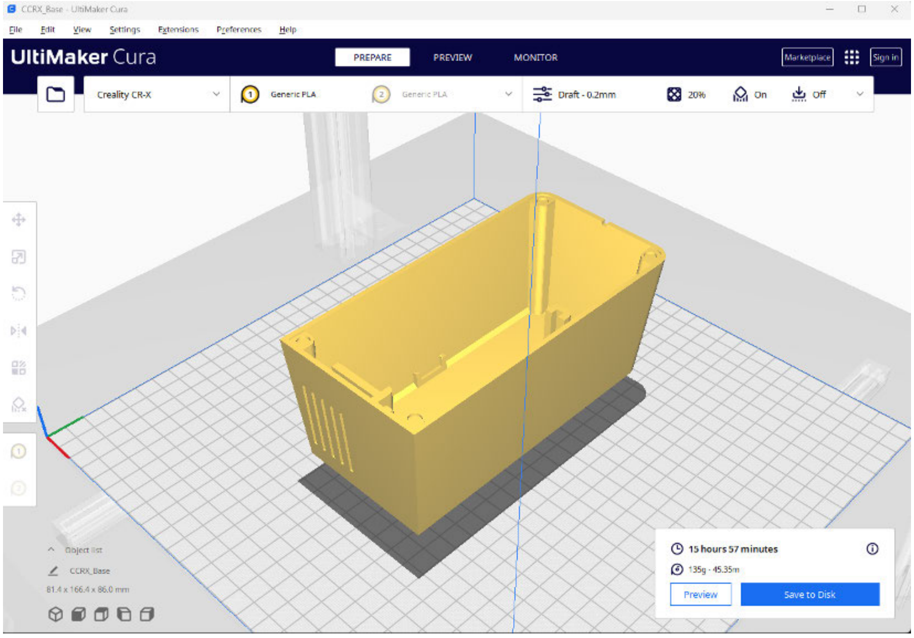

Figure 3.3 : Ultimaker Cura interface.

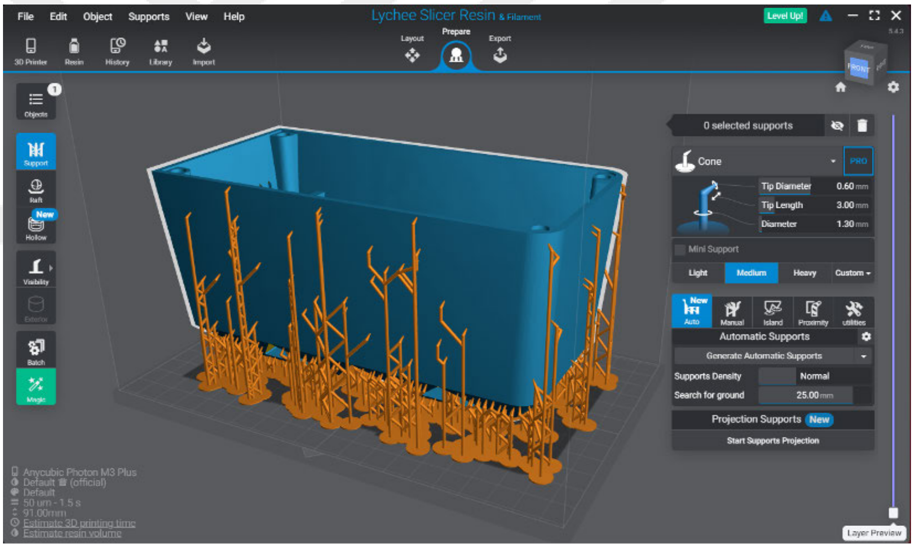

Figure 3.4 : Lychee Slicer interface.

3.1.2.1 Cura printing settings

Cura is a slicing software for both professionals and amateurs. Although the basic interface is ideal for beginners, there are also complex settings. (Prusa, 2023). The list below contains the basic settings which is seen in Figure 3.5 and a brief description of these settings:

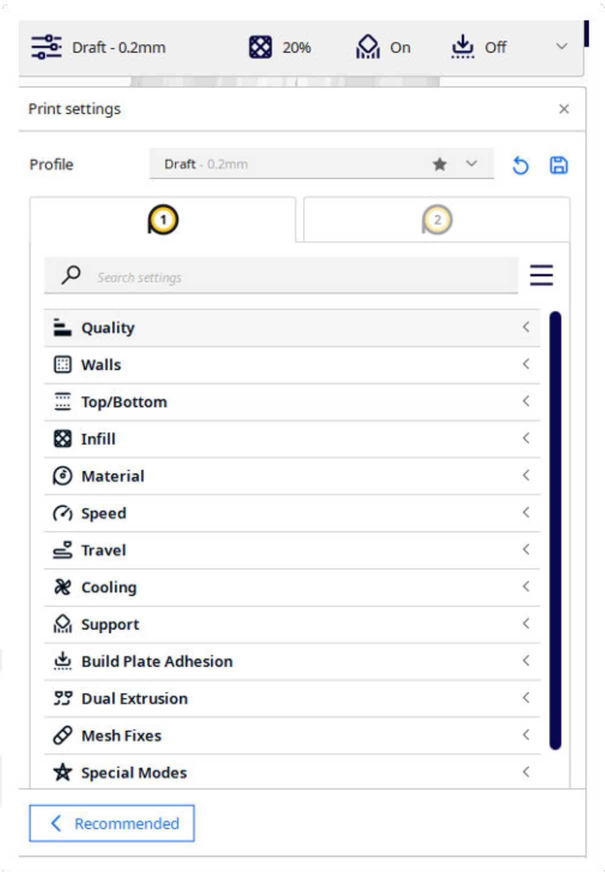

Figure 3.5 : Ultimaker Cura printing settings screen.

Layer height: This determines the thickness of each layer of the print. A smaller layer height increases the print's resolution and detail and the print time.

Infill density: This setting controls how solid the printed object is. A higher infill density strengthens the object but uses more material and takes longer to print.

Print speed: This is the speed at which the printer moves while printing. Faster speeds can reduce print time but may decrease print quality and increase the risk of errors.

Temperature settings: This includes the temperature of the extruder and the heated bed. Varied materials require different temperatures for optimal printing.

Support structures: Support structures can be crucial for models with overhangs or complex geometries. These are additional structures printed to support parts of the model during printing, which are removed after the print is complete.

Retraction settings: Retraction pulls the filament back slightly when the printer moves without extruding to prevent stringing or oozing of material.

Print bed adhesion: Methods like a brim, raft, or skirt can help the first layer of your print adhere to the print bed and prevent warping.

Orientation and placement: The position and angle of the object on the print bed can affect the strength and appearance of the final print.

Shell thickness: This setting determines the thickness of the printed object's walls. Thicker walls increase strength but use more material.

Cooling settings: Proper cooling is essential, especially for materials that are prone to warping. Cooling fans can be controlled via the software.

To create a rough surface, simply enable the "fuzzy skin" option (Figure 3.6) in the settings menu. (Ekaran, 2024).

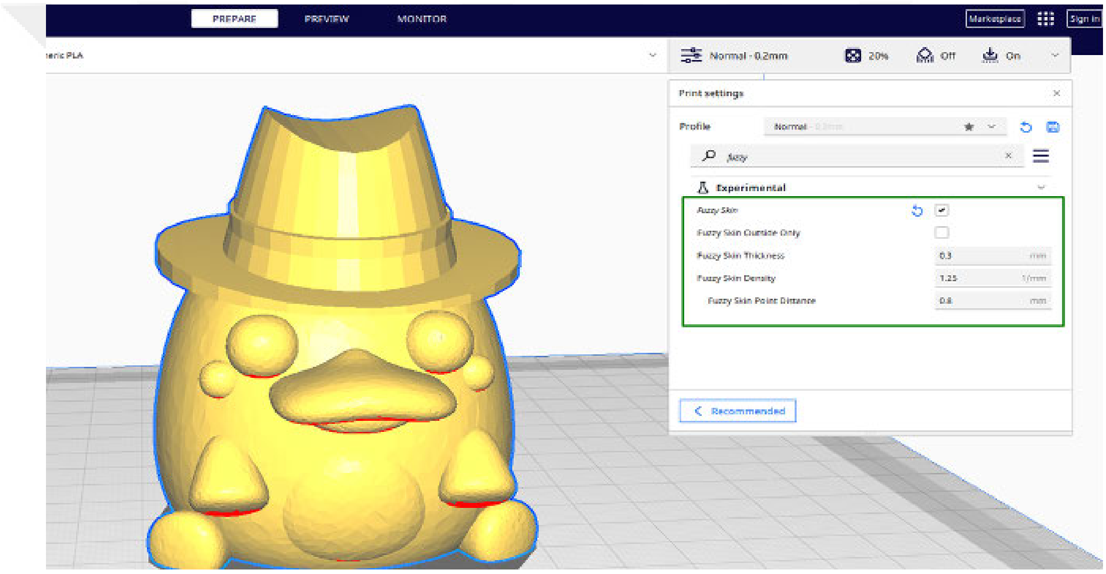

Figure 3.6 : Fuzy skin setting in Cura (Ekaran, 2024).

This approach is a choice decided during the design process. Therefore, no post-production methods are needed.

Each of these settings can be adjusted based on the specific requirements of the print, the material being used, and the capabilities of the 3D printer. Understanding and fine-tuning these parameters is key to achieving the desired results in 3D printing.

3.1.2.2 Lychee printing settings

Choosing the right resin profile is one of the most important factors. Lychee has a library of pre-installed profiles for several well-known resin printers and manufacturers (Lychee Slicer Documentation, 2024). These profiles provide as a base and include details on lift speeds, distances, bottom layer exposure time, and typical layer exposure time. It's crucial to keep in mind that these profiles are approximations and can need to be adjusted depending on certain elements like resin type and ambient temperature. An interface of Lychee settings can be seen in Figure 3.7.

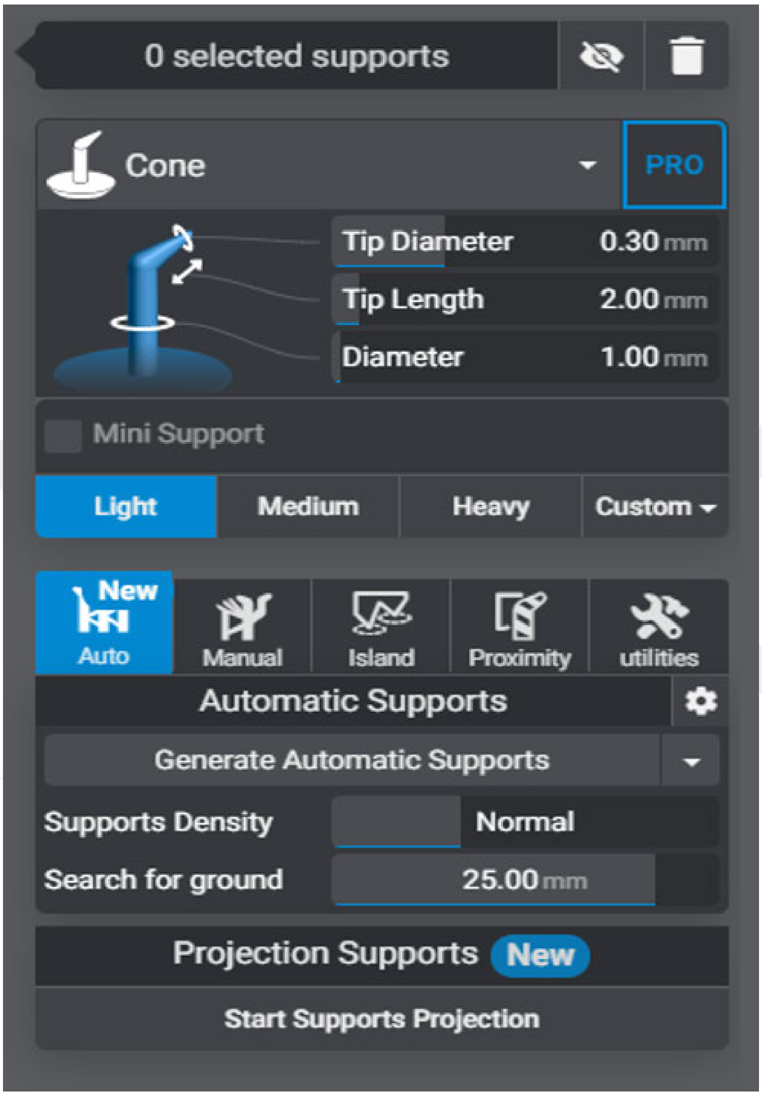

Figure 3.7 : UI of Lychee support tool.

The basic settings are listed below, along with a brief explanation of each:

Exposure time: This sets the duration of each layer's UV light exposure, which has an immediate effect on the detail and solidity of the print. While overexposure might result in excessive curing and make it difficult to remove the model from the build plate, insufficient exposure can produce weak, incomplete prints.

Lift distances and speeds: The build platform's layer-to-layer raising speed and distance are adjusted by these options. A balance must be struck since while quick lifting can speed up printing, it also increases the risk of suction forces warping the model. On the other hand, gradual lifting takes longer to print but guarantees a clean separation. Lychee has two settings: a quicker lift at first to break suction, and a slower lift for improved adhesion between layers (Lychee, 2024).

Retract speed: After lifting, the build platform will retract at the pace specified by this parameter. While a faster speed reduces stringing and dripping, it might also result in vibrations that degrade print quality.

Support creation mode: This mode was created especially to provide your 3D models with support structures. In this mode, you can adjust the supports' density, thickness, and location to ensure sufficient support without using up too much resin. Lychee's auto-support generation is a useful place to start, but for complex models, manual tweaks generally result in better support structures.

Hallow mode: This reduces the amount of resin needed and the weight of the finished product by enabling users to hollow out models prior to printing. For larger prints, this mode expedites the curing process and facilitates heat dissipation during post-curing. In order to guarantee equal curing, allow uncured resin to drain, and avoid internal pressure build-up and possible cracking, escape holes must be incorporated into the design (Mango3D, 2024).

For more experienced users, Lychee has extra settings beyond these basic ones. These include varying exposure for model portions that require varying levels of detail, light-off delay to minimize layer sticking, and anti-aliasing modifications to increase surface smoothness.

3.1.3 Printer preparing

The first step in getting ready for an FDM printer is choosing the right filament. Common plastics like ABS and PLA work well, but there are also more specialist materials available for certain uses or qualities. Before printing starts, the extruder must be prepared to extrude filament (Gregurić, 2023). After that, the build plate is leveled (this step could be automatic or manual, depending on the printer model) to guarantee consistent layer deposition (Crease, 2017). Furthermore, the temperature of the nozzle and bed are precisely adjusted in accordance with the specifications of the material to provide adequate adhesion and layer bonding, hence reducing warping and other problems.

On the other hand, packing the build plate, aligning and stacking parts, producing supports, simulating and testing the build procedure, and preparing the file for the 3D printer are all part of the printing preparation for SLA printing (Hogan, 2023). SLA printer preparation include working with a liquid resin that is UV light sensitive. A photopolymer resin is poured into the resin tank and the build platform is positioned just above the bottom of the tank before printing. The viscosity and UV reactivity of the resin are important considerations when correctly configuring the printer. The type of resin and required print resolution determine the machine settings, which include the UV exposure period for each layer. SLA printing requires a clean, accurately calibrated machine to produce the high detail and smooth surface finishes that are characteristic of the technique.

3.1.4 Printing

G-codes obtained after the slicing process are delivered to 3D printers via SD card, internal memories, or wireless transfer methods. The filament is heated before being extruded via a three-dimensional moving nozzle in the FDM printing process. The material cools and hardens as it is applied layer by layer, progressively building up the object from the bottom up. Due to its accessibility and ease of use, this approach is especially popular. In SLA printing, a platform descends into the resin vat until every layer is printed, with each layer curing under the light source (Hogan, 2023).

3.1.5 Post-processing

Post-processing activities within the realm of manufacturing can be classified into two distinctive phases. Primary post-processing comprises critical operations, including the removal of supporting structures and comprehensive cleansing. Conversely, secondary post-processing activities refer to non-essential operations that are tailored to specific user requirements and objectives (Dizon et al., 2021). These additional actions include aesthetic upgrades such as painting and surface refining techniques like vapor smoothing. This study will look at the post-production processes for two separate AM technologies: vat photopolymerization and material extrusion.

Despite being AM techniques (vat polymerization and material extrusion), their post-production procedures differ significantly. Vat polymerization, which includes SLA and DLP processes, typically requires the removal of supports, washing the printed part in a solvent (such as isopropyl alcohol) to remove uncured resin, and post-curing under UV light to achieve the desired mechanical properties and completely solidify the object (Anycubic, 2022). It may be required to take further processes, such as painting or sanding, for reasons that are either aesthetically pleasing or practical. However, material extrusion, which is primarily utilized in fused deposition modeling (FDM), requires the removal of support structures. On occasion, soluble supports can be utilized to accomplish this removal of support structures. Additional finishing processes, such as sanding, painting, or other processes, may be applied to parts that have been printed using FDM to enhance its appearance or functionality (Polygenis, 2023). The post-processing sequence for vat polymerization is often more complicated than other types of polymerizations, particularly for the purpose of ensuring that the resin has completely cured and, where necessary, achieving the correct level of transparency or transparency. There is a possibility that both printing methods will require further steps of refining after printing. Within the context of these two technologies, post-production techniques will be investigated in detail.

3.1.5.1 Post-processing of FDM

Material extrusion is a fundamental aspect of AM, commonly employed in Fused Deposition Modeling (FDM) and Fused Filament Fabrication (FFF) processes. Post-processing is typically performed to get the intended texture and enhance its mechanical characteristics (Dizon et al., 2021).

Supports in FDM printing: Supports are temporary structures printed alongside the primary object to uphold complex geometries, especially overhangs. Removing them might vary from a straightforward snap-off process for huge, bulky supports to more complex procedures for delicate, interwoven structures. Precision tools such as needle-nose pliers or craft knives are used to prevent damage to the main product (Polygenis, 2023).

Surface smoothing: FDM prints are known for their layered structure, which can create ridges that may not be suitable in all applications. Various strategies can be implemented to mitigate this problem. ABS plastics take advantage of acetone vapor polishing exceptionally well. Under controlled conditions, the object is exposed to acetone fumes, which gradually melt the surface and result in the formation of a glossy finish. According to reports, soaking an ABS part in acetone can reduce surface roughness by ninety percent (Colpani et al., 2019). It is feasible to achieve a surface that is similarly smooth through iterative sanding, wherein coarser grades are progressively replaced with finer ones, on materials that are resistant to chemical treatments.

Painting and coating: Proper surface preparation is crucial for painting FDM prints (Paul et al., 2021). Prior to applying the paint, which can be accomplished with brushes, mists, or airbrushes for intricate details, the surface ought to be primed to ensure paint adherence. Coatings can have practical properties in addition to improving aesthetics. UV-resistant or waterproof coatings can prolong the lifespan of an object intended for outdoor use.

3.1.5.2 Post-processing of SLA

SLA requires a thorough post-production procedure to ensure the final product's mechanical performance (Haq et al., 2023). Without post-processing, it may appear that the resin has not hardened sufficiently.

Support removal: The support structure is produced with the same material as the part (Hoskins, 2018). The support guarantees the object's shape stability and prevents it from collapsing or warping throughout the printing process. After the object has reached its final shape, these supports become unnecessary and must be removed with care. Depending on the complexity of the design, this may progress from a simple procedure to a more complex task demanding the use of specialized equipment and precision.

Washing: The washing phase consists of more than an ordinary rinse. Upon the object's removal from the container, it is enveloped in a semi-cured resin coating. To preserve the object's appearance and structural integrity, this residual resin must be removed completely. The item is usually submerged in a solvent, like isopropyl alcohol (IPA), to dissolve the uncured layer. To guarantee thoroughness, the object should be carefully brushed or agitated to ensure all areas are free of resin.

Post-curing: Although the initial UV exposure during printing initiates the curing process, it is the post-curing phase that brings concerning its conclusion. This supplementary exposure, which can be obtained through direct sunlight or a specialized UV curing chamber, is critical. It assures the resin's greatest potential with respect to its mechanical properties and solidity (Polygenis, 2023). This stage has a substantial influence on the lifespan of the product, making it crucial for components intended for practical or extended usage.

Painting and coating: Aside from the organic appeal of resin, many objects are painted to achieve a particular appearance or to blend them into a wider design. Coatings can also be applied to enhance surface qualities. For example, it can be used to increase the water resistance of the material (Dizon et al., 2021).

3.2 Support Structure for FDM Printing

Supports in 3D printing are temporary structures printed alongside the main object to support overhanging parts or features that cannot be built on thin air. These structures are necessary because most 3D printing processes build objects layer by layer from the bottom up. If a part of the object extends outwards beyond a certain angle, typically around 45 degrees from vertical, there's nothing beneath it to build upon. This is where supports come into play.

3.2.1 Why supports are necessary?

There are 3 main situations where support is needed: overhangs/bridges, improved surface quality and complex geometries.

Overhangs/bridges: Supports are essential for printing designs with overhangs or bridges – sections that span a gap without support underneath. Without support structures, these parts would likely droop, sag, or fail to print correctly as seen in Figure 3.8.

Improved surface quality: Supports help in maintaining the shape and surface quality of the overhanging parts, resulting in a cleaner and more accurate print.

Complex geometries: For intricate or complex designs, supports are crucial in maintaining the integrity of the model during the printing process.

Figure 3.8 : Distortions that occur when support is not used in the letter T (Hub, 2024).

3.2.2 Conditions for using supports

In most cases, you might need to employ supports to 3D print a model with an overhang or a bridge that is not supported by anything below. In Figure 3.9, the Y, H, and T comparisons used to understand these situations more easily can be seen.

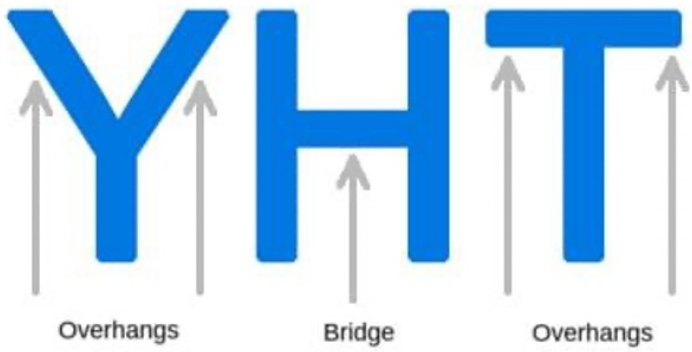

Figure 3.9 : Overhangs and bridges, illustrated with the example of the letters Y, H, and T (Chakravorty, 2023).

Overhangs beyond a certain angle: Supports are generally required when an overhang exceeds a specific angle relative to the vertical. This angle varies depending on the material and the printer, but it's often around 45 degrees.

Narrow and tall features: Tall features that are too thin or narrow to stand on their own during the printing process may require support to prevent wobbling or collapsing.

Large bridges: When a part of the design spans a large gap, supports may be needed to bridge the gap during printing. It is not necessary for narrow bridges.

3.2.3 Support reduction methods

Some of the many support reduction methods include:

Consider the print orientation: Adjust the orientation of your model on the print bed. Orienting the object so that overhangs are minimized can often reduce the need for supports.

Design with self-supporting angles: Try to design parts so that overhangs are at or less than 45 degrees (Figure 3.10). This angle is generally self-supporting for most 3D printers, meaning no additional support structures are needed.

Use bridges and arches: Bridges can span short distances without support, and arches utilize a natural, self-supporting shape (Horvath and Cameron, 2020). Incorporating these elements into your design can reduce the need for supports.

Splitting the model: For complex models, consider splitting the design into multiple parts that can be printed separately and then assembled (Horvath and Cameron, 2020). This way, each part can be oriented for optimal printing with minimal supports.

Utilize hollows and holes: Reducing the mass of overhanging parts by hollowing them out or adding holes can reduce the need for supports, as there's less weight that needs supporting.

Gradual inclines: Gradual slopes or curves are often easier to print than sharp overhangs. Where possible, smooth out sharp angles in your design.

Software optimization: Use slicing software to preview your print and adjust settings like support infill settings to minimize support usage (Aranda, 2022).

Support material can be the same material as the object (self-support) or a different, easily removable material in printers that support multiple materials. The choice of support material and structure is crucial, as it affects how easily supports can be removed and how much post-processing is required. Some advanced printers use dissolvable support materials, which can be removed by immersing the printed object in a special solution. One of the factors that most affects material consumption and printing time in prints made with FDM technology is support printing. Support printing may be mandatory depending on the geometry of the design (Aranda, 2022). Therefore, giving up the use of support will lead to errors in printing. However, it is obvious that material and time can be saved by developing the product according to this problem during design. Therefore, this point was taken into consideration while conducting the case study. A considerable amount of material and time was saved between the first prototype and the final prototype.

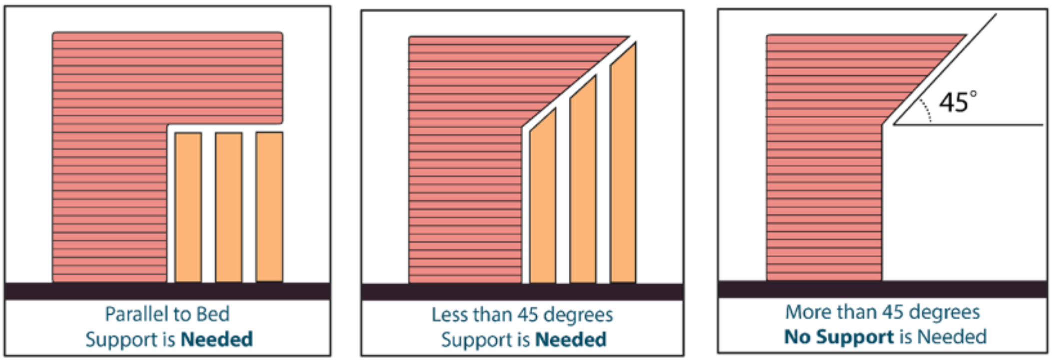

Figure 3.10 : Support material overhang angles (Diegel et al., 2019).

So how can support be reduced or eliminated altogether? First, what affects the support the most is the orientation of the 3D model relative to the printing bed. Once the model is complete, this routing should be optimized as much as possible. Another method is to print the print in separate pieces instead of one piece. This method is one of the frequently used support reduction methods. For example, if you are thinking of a cube, when printing this model, the internal volume of the cube must be either filled or a support must be placed under it so that the upper surface can be printed. However, if this cube is divided into two, this printing can be done without support with the correct orientation. The final and main method to consider is minimizing support by using up to 45-degree angles (Diegel et al., 2019).

3.3 Comparison Between AM And Conventional Manufacturing

Conventional production processes, in contrast to AM methods, involve the reduction of material. From this perspective, AM technologies produce a reduced amount of waste material. Keshavamurthy et al. (2021) reported that metal AM can yield raw material reductions of up to 40% compared to conventional manufacturing methods. Conventional production methods require a substantial amount of initial preparation, leading to a major investment of time and money before production can commence. Considering these expenses, the quantity of output becomes crucial. Therefore, when discussing conventional manufacturing techniques, it is often encountered that the practice of producing large quantities of goods. However, in cases where prototypes, spare parts, low-volume production, and masters are required, conventional production methods may not be the optimal answer due to the significant costs associated with installation. The setup expenses associated with AM processes are either highly affordable or completely absent. The digital model can be directly utilized for production purposes. 3D printing eliminates the need for molds, which increases cost-effectiveness.

Conventional manufacturing technology consists of a sequence of predetermined production procedures. The process starts with conceptual design, followed by the creation of appearance and structural design. Drawing design, with the use of CAD technology for auxiliary design, comes next. Finally, the product is produced. Employees utilize computer numerical control (CNC) machines to fabricate components in accordance with provided drawings (Haghsefat, 2020). If the manufactured items are non-metallic materials, such as plastic, the process requires mold design and mass production can only commence after successful mold testing. Furthermore, the entire procedure demands the operator to have extensive professional technical understanding. If an issue develops in one connection, it will influence many other associated connections, making the production process more complex and relatively difficult. The progress of AM technologies extends beyond low-volume production. In order to accommodate high volume production, which mostly involves conventional manufacturing methods, the design needs to be altered prior to being prepared for production. It is seen that AM is extensively utilized in this process.

In a study released by Xometry (2020), a comparison of the unit price difference in the manufacturing of a drone leg using several production methods is provided in Figure 3.11. It is indicated that AM techniques are more cost-effective for low-volume production when compared to conventional production methods. When the number of productions exceeds 100 units, the production fee per unit begins to equalize with conventional methods and then remains high. When 8192 units are produced, the unit price of injection molding production drops to 3 dollars. In production with SLS, this value is around 32 dollars. When we look at FDM, we see levels of 40 dollars. SLA technology offers a higher unit production price than FDM. One thing not considered in this comparison is machine fees. Although SLS provides a more economical unit price result, it is a more expensive technology compared to SLA and FDM machines. (Prusa, 2023).

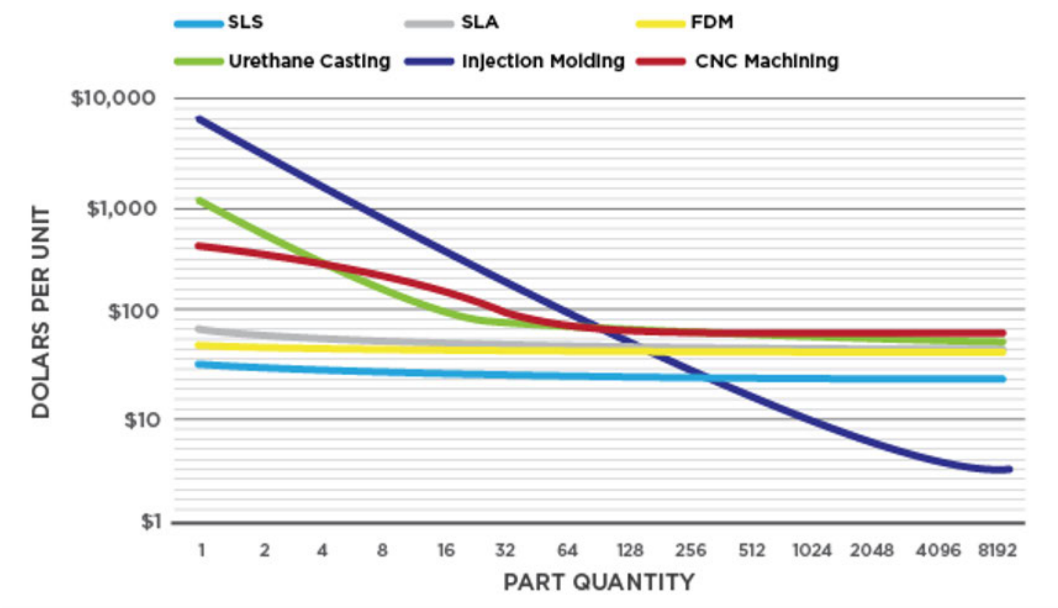

Figure 3.11 : Data results for the per-unit price of the drone leg over doubling quantities from 1 to 8,192 pieces (Xometry, 2020).

3.3.1 Comparison between conventional manufacturing and AM

Specialized or niche market items generally utilize low-volume conventional production methods, which necessitate less automation and greater flexibility compared to high-volume mass production methods (Haghsefat, 2020). These techniques enable the production of small quantities, or the creation of customized designs tailored to meet specific customer requirements. Examples of these methods include CNC machining, turning and milling, sand casting, and silicone molding. These methods provide cost-effective solutions, particularly for tailored items or situations that necessitate small-scale production. Furthermore, they are frequently favored during market testing or the initial phases of new product development.

3.3.1.1 Urethane castings (cast urethanes)

Urethane casting is a suitable technique for producing a limited quantity of items, particularly well-suited for small to medium-sized volumes. This method is commonly employed for the creation of prototypes or for manufacturing on a temporary basis.

Urethane casting is a method that bears a resemblance to injection molding, with the exception that the mold used is made of a soft material. (Kloski and Kloski, 2016). The urethane casting method involves the pouring of high-grade polyurethane ingredients into a silicone mold, which then undergoes a hardening process. These materials exhibit a diverse spectrum of hardness and colors and are distinguished by their exceptional wear resistance, flexibility, and mechanical qualities. Urethane casting is capable of creating components that imitate the characteristics of thermoplastic materials like ABS, polycarbonate, or nylon. This can be achieved by utilizing molds that are reasonably inexpensive. Urethane casting is highly favored in industrial design and consumer product areas due to its advantageous qualities. It is particularly ideal for market testing, functional testing, or meeting low-volume production needs.

From this standpoint, AM should not be perceived as a competitor to conventional production methods. Silicone molds can also be produced using AM techniques. This conventional manufacturing technique involves utilizing the master model silicone mold created through the FDM or SLA technology. This approach reduces the time required for several iterations of AM production.

3.3.1.2 Sand casting

Sand casting is a widely used method for casting metals, especially iron, steel, aluminum, and copper alloys. This technique utilizes a mold, which is a replica of the metal to be cast, usually made of sand and a substance that holds it together Horvath and Cameron (2020). Initially, a mold is created by compacting sand around the model, which is then extracted from the mold. Following this procedure, liquefied metal is poured into the space, subsequently cooled, and then permitted to solidify. Subsequently, the sand mold is fractured and eliminated, resulting in the production of a metal component. The popularity of sand casting in the industry stems from its cost-effectiveness and its capability to produce intricate designs. In addition, although the mold is not reusable, the sand may be reused, which makes this technique economically efficient.

3.3.1.3 CNC machining

CNC machining refers to the precise shape and cutting of various materials, such as metal and plastic, using cutting tools that are controlled by a computer. (Dezaki and Ariffin, 2021). This technology automatically cuts parts in three dimensions using pre-programmed software commands. CNC machines may execute a variety of machining functions, including turning, milling, drilling, and grinding. Machined parts are highly repeatable and consistent, making CNC machining indispensable in industries requiring precision parts, such as aerospace, automotive, defense, and medical. This method, unlike AM, involves removing material. In this aspect, it generates significantly more waste than AM. Faludi et al. (2015) noted that while the CNC machining process consumed less energy than the FDM method, the overall negative impact of CNC machining on the environment was substantially greater. However, this production utilizes costlier machinery in contrast to FDM and SLA. According to Horvath and Cameron (2020), sawdust and dust generated by CNC machines are unsuitable for home production since they endanger human health in enclosed spaces. They also add it is advisable to avoid storing them together with 3D printers as sawdust might potentially become trapped in the filaments, resin, or exposed nozzle or motor components of the printers. In addition, high technical performance is required for the use of these machines.

3.3.1.4 Laser cutting

Laser cutting is a method of using powerful lasers to cut and shape various materials. This technique involves the use of a highly concentrated laser beam that is directed toward the surface of the material (Horvath and Cameron, 2020). The tremendous heat generated by the laser causes the material to undergo processes such as melting, burning, evaporation, and ultimately cutting. A computerized system precisely carries out the cutting procedure, leading to exceptionally polished cut edges and intricate details. Upon examining (Table 3.2), it becomes evident that laser cutting is more cost-effective than CNC machining. However, it is important to note that laser cutting is incapable of producing three-dimensional shapes. However, it yields considerably faster results compared to the other two methods.

Laser cutting can be utilized for a wide variety of materials, including but not limited to metal, plastic, glass, wood, materials, and cloth. It finds major application in the production of architectural models, advertising, and artistic efforts, as well as in the manufacturing of industrial goods. The strategy is chosen because it provides a quick

Table 3.2 : Digital manufacturing comparison.

	3D Printers	Laser Cutters	CNC Machines
File type	3D (.stl, .obj), G-code.	M2D (.dxf, .svg).	2D or 3D G-code produced by CAD.
Machine Cost	Low (SLA, FDM, DLP), high (metal and powder-based printers).	Moderate.	Moderate to high.
Materials	Plastics, metal or composites.	Wood, acrylic, paper, cardboard, some plastics, etch metal.	Wood, soft metals, PCBs, most other solid materials.
Form	Complex 3D.	Complex 2D.	Simple 2D/3D
Speed	Slow.	Fast.	Slow.

processing time, low labor costs, and good precision in cutting. In addition to this, it is advantageous to the environment because it reduces the amount of material waste.

There are a few difficulties associated with the utilization of laser cutting for production on a smaller scale. When compared to FDM or SLA techniques, closed environments may present a number of challenges requiring consideration. Due to the fact that laser cutting includes burning the plate with high-power lasers, there is a higher-than-average possibility of a fire occurring. During the phase of laser cutting, there is a possibility that components will catch fire and put other people in danger. According to Horvath and Cameron (2020), the laser cutting process requires supervision. In addition, Horvath and Cameron (2020) assert that laser cutters must be either externally vented or operated with a dedicated air filtration system.

4. RESEARCH METHODS

The methodology of this study is intended to provide qualitative and empirical insights into the use of AM techniques, particularly FDM and SLA, as cost-effective alternatives to conventional manufacturing processes. To do this, the research uses two methods: a detailed case study and expert interviews. The case study investigates the product design of an outdoor air quality control kit for the ITU campus utilizing FDM technology as part of a scientific research project aiming at making campuses smarter and more sustainable. This test covers the full design process, from pre-production to final product, with a focus on essential topics such as design choices, printing technology, material selection, and surface quality. This process covers the concept of "Research through design," which is a concept that parallels Archer's (1995) "research through practice," which he identifies as a type of action research. Archer (1995) defines action research as a systematic investigation through practical action aimed at devising or testing new information, ideas, forms, or procedures to produce communicable knowledge. This specificity underscores the importance of the designer's skills in unfolding the problem area and emphasizes that the knowledge gained is applicable to situations rather than forming general laws (Frens, 2007). Research in product design can generate knowledge on two levels: the products themselves and the design process. These intertwined aspects highlight how products are created to explore theoretical implications in context, leading to practical experimentation and broader generalizations for future designs (Frens, 2007).

Interviews with industry professionals supplement the case study, providing significant insights into the actual applications and benefits of AM technologies. This approach enables a detailed examination of how FDM and SLA technologies might serve as cost-effective and adaptive solutions for individuals and enterprises seeking to manage the limits of limited financial resources in production. The research questions were partially answered in the literature, and the questions for the case study were revised and will be listed in Table 4.1.

Table 4.1 : Research questions.

Research questions	Revised Research questions
What are the advantages of desktop 3d printers for small-scaled manufacturers?	What are the important issues while using FDM and SLA printers for low-volume production?
Which additive manufacturing technology and materials are more suitable for small-scale companies or individual home fabrication?	How to decrease material usage and printing time in FDM?
What are the criteria and strategies of design for AM (DfAM) for desktop 3D printing to optimize printing process?	What are the basic printing failures experienced in FDM printing, and how can they be solved?

4.1 Case Study

One of the research methods used in this study is the case study. While Yin (2017) defines a case study as an empirical research approach that delves deeply into a contemporary phenomenon ("case") within the setting of a real-life scenario, Thomas (2015) defines it as a focus rather than a collection of processes or a technique. Case studies are a form of examination that centers on a particular topic, and they investigate practically every element of a topic in order to find patterns. Yin (2017) states case study research is a prevalent method utilized across various professional domains and social science fields.

The objective of a case study is to provide thorough knowledge on a certain subject that may be utilized in real-world circumstances. Muratovski (2015) suggests that it is necessary to gather several types of data to provide information about the subject and produce a case study. The research questions initially proposed in this study were investigated by a thorough, comprehensive analysis of existing literature. Based on the findings, these inquiries were further developed and adjusted to suit the requirements of the case study. According to Yin (207), research questions that begin with "how" and "why" are more leaning towards utilizing a case study. As mentioned before, the 3D printing process is a production method that can vary depending on many variables, such as air temperature, humidity, material structure, and slicing adjustments. Therefore, observing its real-life application in a case study can help elaborate and strengthen the research. As Yin (2017) suggests, the decision to utilize a case study is not determined by a specific formula, but rather by the research questions at hand, and he underlines that it is particularly useful for conducting a thorough evaluation when the research questions need a deeper examination. In this respect, the research questions are redesigned to clarify the points of the case study. Firstly, the decision was made to conduct the case study using FDM and SLA technologies. More specific questions about them were provided.

Case studies are classified into two types: instrumental cases and intrinsic case studies. Yin (2011) defines instrumental case study as the examination of a specific circumstance that is chosen for its possible relevance to similar situations despite its distinctiveness. Although a case study may be considered as a subjective approach to the specific topic, an instrumental case study is designed to yield results that allow the researcher to generalize the findings. On the other hand, an intrinsic case study is a study that focuses on a specific circumstance chosen for its distinctiveness and inherent interest, significance, or potential insights without considering its relevance to other situations (Yin, 2011). The case study method used in this thesis is instrumental.

4.1.1 Case selection and data collection

Numerous factors must be considered when choosing a case. Careful consideration of these elements is imperative to ensure that the case study's findings contribute to the research. Thomas (2015) highlights several key considerations while constructing a case study, including the case study's scope, research questions, literature review, research approach, research design framework, and procedure. This case study covers the product design phase of the study within the scope of ITU Scientific Research Projects (BAP), carried out by researchers from the Industrial Design, and Computer Engineering Departments. It is named "Interdisciplinary Product Development Processes and Environmental Sustainability within the Scope of Smart Campus Studies," and its project number is "44070". Project details can be reviewed in Table 4.2.

Table 4.2 : Project details.

Information Type	Information Detail
Project Title	Interdisciplinary Product Development Processes and Environmental Sustainability within the Scope of Smart Campus Studies
Project Executor	Asst. Prof. Dr. Elif Küçüksayraç
Department	Industrial Design
Researchers	Prof. Dr. Sema Fatma Oktuğ, Assoc. Prof. Dr. Yusuf Yaslan, Graduate Student Ahmet Furkan Keleş
Project Type	General Research Project

This project constitutes the preparation phase for collecting different data, transferring it to different target groups, determining the necessary hardware, and developing products with a software infrastructure that aims to produce digital solutions for smart campuses and smart cities. It aims to share sensor data obtained over a heterogeneous network for different internet needs for management and use. The main reason for selecting this case is the ten-unit production run of this product. Due to its limited production capabilities, AM offers a more logical choice as it provides increased flexibility in the research and development process and form ideation while also reducing mold expenses in comparison to conventional production methods.

Eisenhardt (1989) asserts that the collected data for a case study can be either quantitative, qualitative or a combination of both. Yin (2011) further explains that although a case study can rely on either quantitative or qualitative data, it typically contains some data acquired in the field. The integration of theoretical knowledge derived from literature reviews with sector experience gathered from expert interviews will be advantageous for the case study. The results obtained from the case study will also be utilized to guide the concurrent interview process.

4.2 Expert Interviews

The second research method used in this study is expert interviews. Interviews frequently serve as the primary means of gathering the qualitative data required to comprehend the phenomenon being investigated. (Merriam and Tisdell, 2015) During this study, expert interviews were conducted to develop the case study and combine theoretical knowledge gained from the literature review with sectoral experiences to provide a more complete grasp of the subject. Creswell (2013) outlined the primary stages of an interview as follows: determining the most practical and informative type of interview to obtain the necessary data, selecting the research questions to be addressed through interviews, identifying interviewees who are most capable of addressing these questions, and employing appropriate recording methods to document the data gathered. The interview technique, a widely used research method, has three different versions in terms of planning: structured, semi-structured, and unstructured interviews. The semi-structured interview technique, which combines pre-prepared questions with improvisation, is employed in this study. In addition to establishing a general framework around a pre-determined guide or protocol and centering on a primary subject, the semi-structured interview permits exploration and allows current directions to develop naturally as the conversation progresses (Magaldi and Berler, 2020). In this regard, semi-structured interviews not only provide responses to predetermined questions on the topic but also offer potentially valuable insights based on the interviewees' knowledge and experience.

4.2.1 Interview questions

As mentioned earlier, the objective of expert interviews is to enhance the case study by offering more extensive information regarding AM. A semi-structured interview is conducted using a prepared list of questions and topics to be discussed, but the specific language and sequence of the questions are not predetermined. (Merriam and Tisdell, 2015) In order to achieve the objective of the expert interview, a comprehensive set of questions was generated by merging information from the literature review and inquiries from the case study. Dursun (2023) states to achieve optimal efficiency throughout the interview and obtain comprehensive and meaningful data, it is imperative for the researcher to carefully design the interview questions and adapt them accordingly throughout the interview process. As a result, the professions to be interviewed were chosen based on the subject matter to be investigated, and the question set was tailored to each interviewee's area of expertise. The planned set of questions for each interviewee is provided in the Appendix section. The semi-structured interview includes a dynamic pattern of questions that evolve during the interview, along with the corresponding responses provided by the interviewees. The transcripts of the interview sequences are also documented in the Appendix section.

4.2.2 Expert selection

Expert interviews necessitate a precise selection of interviewees. It is important to evaluate whether the specialists are working in disciplines that are relevant to the subject and possess sufficient expertise and knowledge to contribute to the research. Relevant experts in the indicated fields were identified and interviewed to address the questions at hand. The main information about these four experts selected from this perspective is shown below in Table 4.3.

Table 4.3 : Main information about experts.

Expert	Professional Background	The technologies s/he is experienced with
A	An industrial designer employed by a 3D printer manufacturer.	FDM
B	A mechanical engineer working for a company that offers prototyping services.	FDM, SLA, DLP, SLS, MJF
C	A mechanical engineer leading R&D at a company that makes levers, classical mixers, and faucets.	FDM, SLA, SLS
D	A designer/owner of a startup company that uses FDM technology in R&D and final-product manufacturing processes.	FDM, SLA

4.2.3 Data analysis

The data noted during the case study were tabulated and compared. The effects of DfAM decisions on the printing process were observed. Moreover, the technical features of the prints were recorded in a table. Since semi-structural expert interviews were conducted, the questions were grouped under certain headings and a more understandable data group was obtained to facilitate analysis. After expert interviews were coded, and the results were divided into subtopics to create the findings subheadings. Additionally, improvements were made to the design decisions by consulting experts during the case study process. The original and translated transcripts of the expert interviews are presented in the Appendix section.

5. FINDINGS

This chapter presents the research study's findings. All data were collected through the case study and expert interviews described in the previous section. The order of the findings is as follows: findings from the case study and expert interviews. The findings of the case study include comparisons of product scope and requirements, design development processes, and layer thickness in terms of time and cost. The data obtained from expert interviews were also separated into common comments and personal comments of the experts.

5.1 Findings from the Case Study

In the 2021/2022 Fall semester, the ITU Computer Engineering Department initiated an interdisciplinary study at the undergraduate level for the first time and collaborated with the ITU Industrial Design Department. Within the scope of the collaboration, one student taking the "BLG 4901E: Computer Engineering Design I" course and eight students from the "EUT 220E: Industrial Design Studio I" course worked together under the supervision of the course instructors (Consent forms of the students participated to the project are given in Appendix I). As part of the pilot study (Figure 5.1), 8 of the projects were selected and developed, and a digital prototype was produced. As a result of these pilot studies, the case study of the thesis was started. The shortcomings of the previous work were identified, and the scope and requirements of the product were determined.

Figure 5.1 : Pilot studies of the project.

5.1.1 Product context and specifics

The industrial design criteria of the air quality measurement device to be used outdoors in smart campuses were determined as follows:

- It will be compatible with its environment and will not disrupt the environmental texture. Color and form preferences will ensure that it blends in with the environment and will not attract attention.
- It can be installed in a structure that is compatible with nature and in a way that does not harm nature.
- It will have a durable connection detail to ensure that the product remains stable.
- The shell material will be resistant to the physical factors listed below:

- climatic conditions such as rain, snow, sun
- to the wind and the storm
- physical blows
- birds and other creatures

- For the sensor to be in contact with the air, the sensor will be placed at the bottom of the product so that it will not be affected by rain. In the shell design, the part where the sensor is located will have a breathable perforated structure. No gaps will be left in the shell other than this perforated surface.
- The following points will be taken into consideration when choosing product materials:
  - environmental friendliness of the material
  - heat resistance of the material
  - impact resistance of the material
  - number of production and costs
  - esthetics of the product
  - water resistance
- It will contain a rechargeable lithium battery. This battery will have as high a capacity as possible but be small. A battery will be preferred according to the product's ideal battery replacement time.
- The product will not be placed within easy reach of people.
- The product will not be placed at points where vehicles may crash.
- The center of gravity of the product will be close to the connection surface.

5.1.2 Main components and tools

The kit consists of 4 fundamental parts: a microcontroller board, a power storage unit, a Bluetooth module, and an air quality sensor (Table 5.1).

Table 5.1 : Component list.

Component	Dimensions (mm)
Microcontroller (Arduino UNO)	66.5x53.4x12.5
Bluetooth Module	26.7x13x3
Air Quality Sensor	32x20x20.1
Power Bank	10.5x65x25

Two 3D printers were purchased within the project's scope. One uses FDM technology, and the other uses SLA technology. Table 5.2 lists the preferred devices and their technical specifications.

Table 5.2 : Comparison between Creality and Anycubic printers.

Criteria	Creality CR-X Pro	Anycubic Photon M3 Plus
Technology	FDM	SLA
Design & Build Volume	270x270x400 mm	245x197x122 mm
Material Options	PLA, ABS, TPU, etc.	Variety of resins
Speed & Economy	Generally, it is faster for larger objects. More economical filament costs.	Slower with intricate designs. Typically, higher material costs.
Surface Finish	High quality but may show layer lines. Post-processing might be required.	Superior finish with finer details and no visible layer lines. Curing and washing are necessary.

As a result of the literature review and expert interviews, one of these two technologies was focused on. FDM was found to be suitable for this study in many respects and was determined as the main production method of the study. FDM is a more suitable production method compared to SLA because it is both easier to produce and results can be obtained faster. In addition, the gas release of the resin in a closed area and the equipment that needs to be used are other issues when choosing FDM. Another issue is the materials to be used in the production process. PLA filaments were used in the creation of the design phases until the final product was created. Once the design had been done, ABS material was used in the final production of 10 units.

5.1.3 Design and printing process

The design process of the product was meticulous and multi-faceted, aiming to efficiently integrate technology and functionality while adhering to the aesthetic and environmental constraints of the university campus. Initially, the essential components, including an Arduino, air quality sensor, Bluetooth card, and power bank, were identified to ensure accurate air quality measurement and seamless data transmission. The arrangement of these components was optimized to achieve the smallest possible size, ensuring minimal intrusion into the campus ambiance. Moreover, a decision was made to utilize AM, as it was found to be a more economical method given the production quantity of ten units. Special attention was paid to the product's durability against external factors like rain and sunlight to guarantee sustainable outdoor use. Finally, a considerate approach was taken to integrate the product within the campus setting, deciding to attach it to existing cylindrical structures like trees and streetlamps. This was done by ensuring no harm to the natural structures, maintaining aesthetic harmony, and ensuring a safe placement away from potential collisions with vehicles or individuals, highlighting a well-rounded design process attentive to technical, economic, environmental, and aesthetic factors. The potential user scenario can be seen in Figure 5.2. In the pilot study, all parts had to be removed to change the battery and components. A design that would provide ease of use was planned. In addition, the product was fixed more securely to objects such as trees or poles.

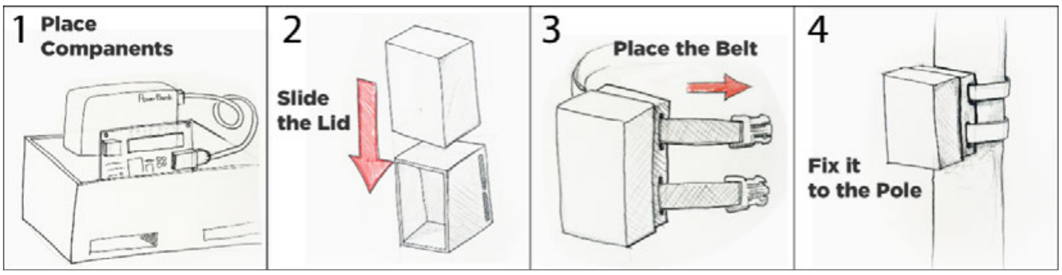

Figure 5.2 : User scenario of the case.

5.1.3.1 Design phases and FDM printing

A preliminary study on the project has been completed. Designing product alternatives and producing prototypes took place in three stages (Figure 5.3).

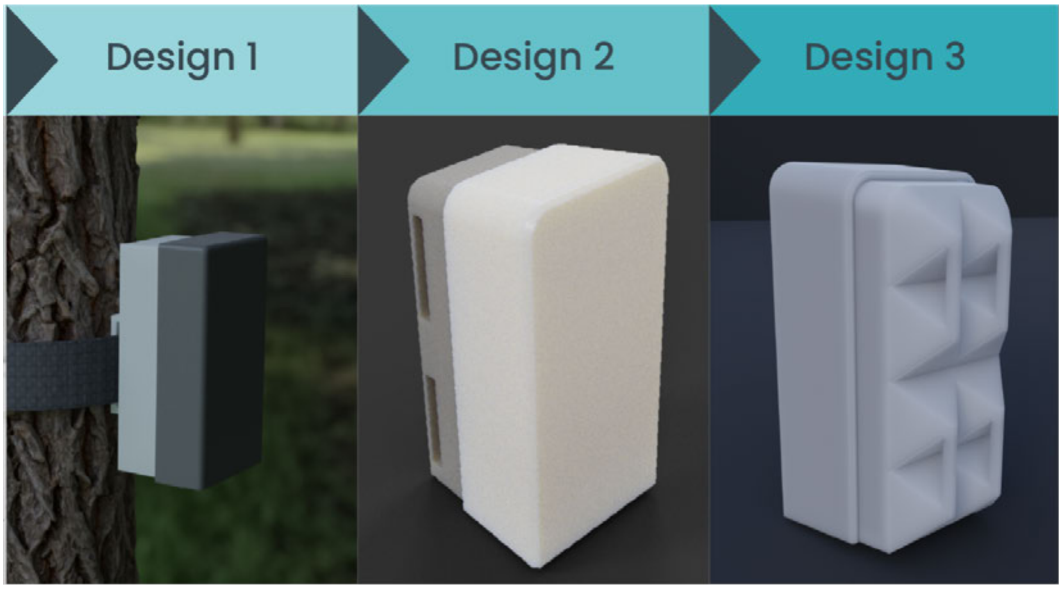

Figure 5.3 : Project phases.

In the first stage, the pilot project and the product criteria listed in the project application form were taken as basis. Unlike the prototype produced in the pilot project, the placement of the charger, Arduino, and sensors within the product has been changed to make it easier for the user to replace the external charger. Additionally, an inner wall has been added, and the Arduino and sensor will be fixed. It is recommended to use an adjustable textile belt instead of plastic clamps to make it easier to hang the product outdoors and remove it when necessary and to make it suitable for hanging in large places such as lighting poles. Initial design images are shown in Figures 5.4-5.7.

Figure 5.4 : V1 CAD render images.

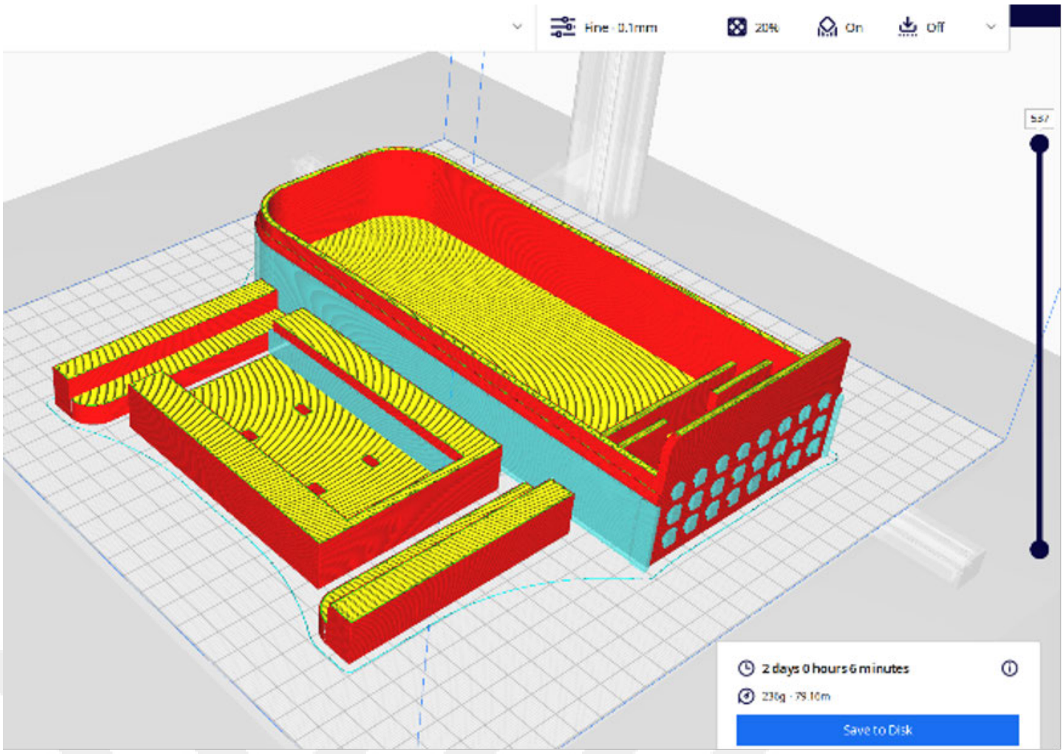

Figure 5.5 : Original printing time and material consumption.

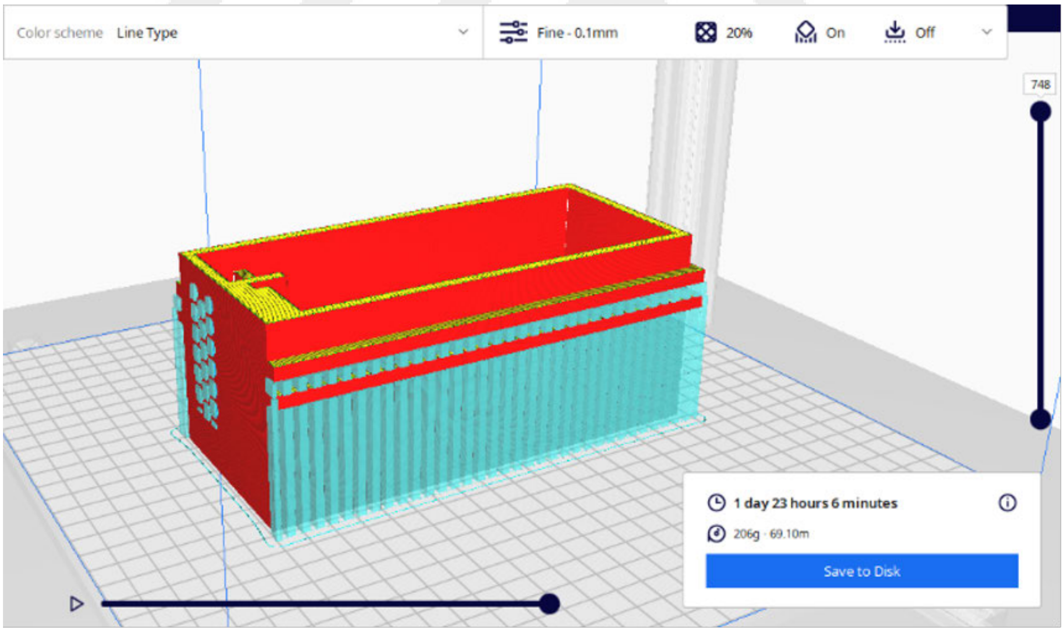

Figure 5.6 : V1 printing time and material consumption.

Figure 5.7 : Design 1 printed model.

The technical details of the 3D printing process of the first prototype are summarized in Table 5.3.

Table 5.3 : Technical details of Design 1 printing.

3D Printer	Creality CR-X	
Slicer	Ultimaker Cura	
Filament	E-SUN PLA, white and blue	
Layer Height	0,4 mm	
Infill and Support	Body:	%15, Octet Support: Touching built plate
	Cover, inner wall, and joint:	%20, Grid Support: Everywhere
Printing time:	Body:	11 hours, 6 minutes
	Cover:	6 hours, 33 minutes
	Inner wall:	1 hour, 25 minutes
	Joint:	1 hour, 26 minutes
	TOTAL	20 hours, 30 minutes

Design changes were made to the first 3D printed prototype in the second stage by evaluating the printing process. All dimensions were reviewed, and the aim was to make the product as small as possible and shorten printing times. Instead of the insertion rails on the cover, the body walls are given an angle that will only open upwards and will not require support during printing. While in Design 1, it was planned to glue the hanger detail to the body, in Design 2, the body and connection section were designed as a single piece, considering the outdoor conditions. In addition, it was decided to use double connecting belts for connection and two spaces were created for this. Images of the digital and final 3D printed model are shown in Figure 5.8 and Figure 5.9.

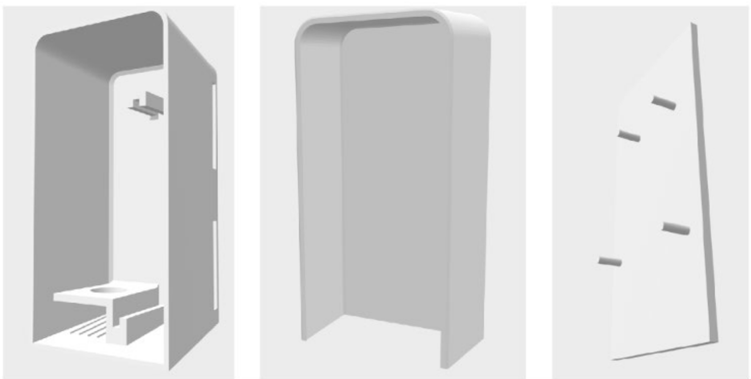

Figure 5.8 : Design 2 digital model.

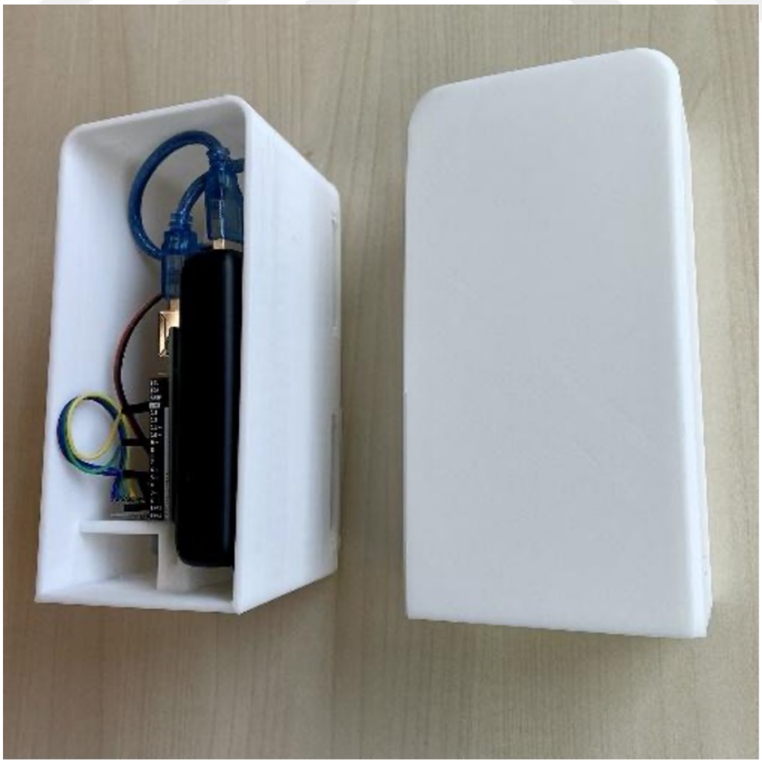

Figure 5.9 : Design 2 printed model.

The technical details of the 3D printing process of the second prototype are summarized in Table 5.4.

Table 5.4 : Technical details of Design 2 printing.

3D Printer	Creality CR-X	
Slicer	Ultimaker Cura	
Filament	E-SUN PLA, white	
Layer Height	0,4 mm (Body and inner wall); 0,3 mm (Cover)	
Infill and Support	Standard infill: %20, Grid Support: Everywhere	
Printing time:	Body:	8 hours
	Cover:	6 hours
	Inner wall:	1 hour
	TOTAL	15 hours

In the second stage, three main problems were encountered: support structure removing and plane surface warping. First, it is the support structure formed in the gaps at the back of the body that allow the two bands to pass through. As seen in Figure 5.10, the surface quality was not very satisfactory after the support was released. Additionally, removing the support structure took a very long time and was difficult.

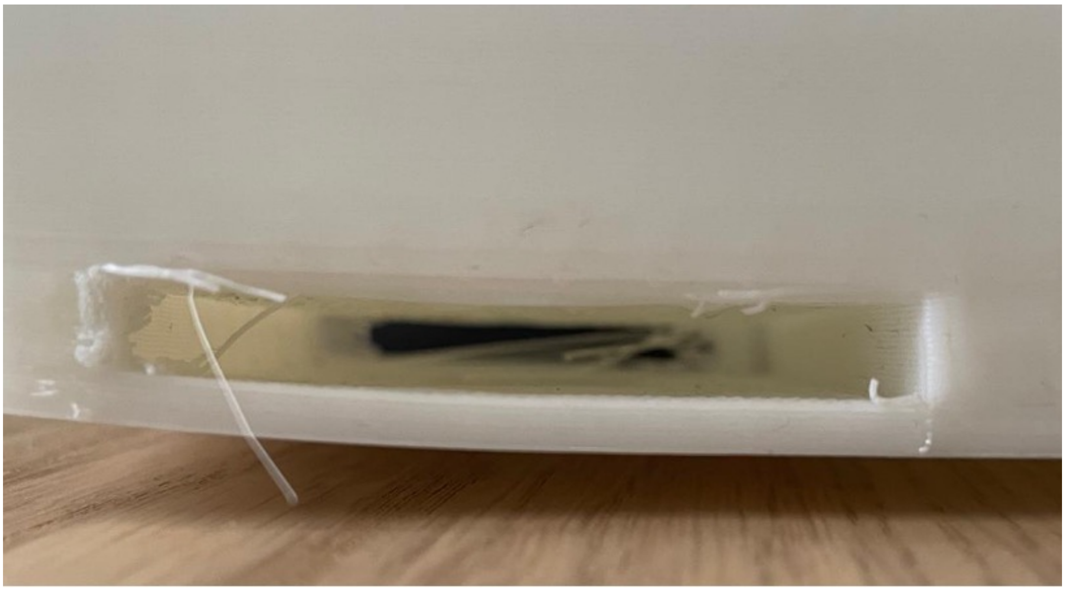

Figure 5.10 : Design 2 support problem.

The second problem is excess in the printing process and material usage. The second problem is the stretching and warping of the surface that occurs when a wide and flat surface is printed on the printing plate (Figure 5.11). To eliminate the warping problem, the methods in Aranda's (2022) study were tried. Below is a list of possible solutions:

- Increasing bed adhesion by adding adhesive to the printing surface and heating the bed.
- Slowing the printing speed and increasing the printing temperature in the first layers.
- Making the room temperature more stable. Closed printers can be much more useful in this respect.

Figure 5.11 : Design 2 warping problem.

In the third stage, the design started by focusing on the two main problems experienced in the previous stage. A new form was tried to solve the problem of the support structure at the back. The triangular and 45-degree angles that created this form enabled the use of support on the back surface to be reduced to zero during printing. Thanks to this pattern seen in Figure 5.12, less material was used, and printing time was reduced. Calculations made with the slicing program appear in Table 5.5. According to this table, while the maximum cost of the first design is 111 units, this amount drops to 72.65 in the third design. While calculating the electricity cost, the technically predicted value of 0.12 kWh consumed per hour by the Creality CR-X pro machine was used. The results show that the energy cost is very low compared to the material cost. However, as time increases, the amount of product produced decreases.

When Expert B examined Design 3, he said that it was similar to the lattice structures used in generative design. Although it has not been studied in this thesis, this subject can be studied in further studies.

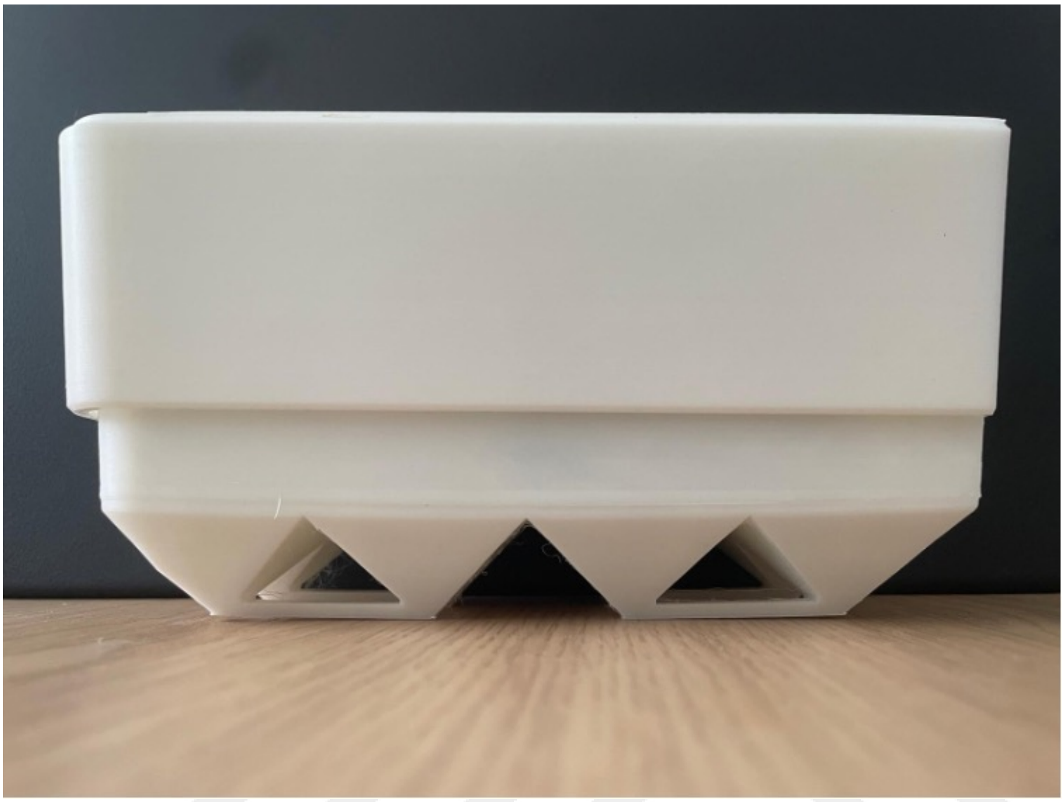

Figure 5.12 : Design 3's rear pattern.

To solve the warping problem, some methods were tried during the slicing stage and the preparation of the printer. Expert A highlighted the importance of a stable printing environment in FDM printing. Accordingly, in the printing process for Design 3, the windows in the room were closed while the print was taking. In the first print, imbalances were observed on the surface due to differences between layers due to the windows being open. Moreover, as mentioned in Singh's (2018) study, increasing adhesion, homogeneity of the process, and structure change are some methods to prevent warping. A smooth glass bed was used to increase adhesion. Additionally, adhesion was increased by applying a PVA-based compound to the bed surface. The technical details of the 3D printing process of the third prototype are summarized in Table 5.6.

Table 5.5 : 3D printing properties of three product designs (Based on the average prices in the Turkish market in Istanbul, May 2024).

Properties	Design		
	1	2	3
Printing time (hour)			
0.1 layer height (lh)	47	37	32
0.2 lh	23.5	18.5	16
0.3 lh	16.5	13	12.5
Material usage (gram)			
0.1 lh	206	170	135
0.2 lh	204	169	135
0.3 lh	211	175	139
Material cost (0.1,0.2,0.3 average)			
ABS	100	82	66
PLA	102	85	68
Electricity Cost			
0.1 lh	9	5.37	4.65
0.2 lh	3.5	2.69	2.32
0.3 lh	2.4	1.89	1.82
Total Cost			
Max	111	87.37	72.65
Min	102.4	83.89	67.82

Table 5.6 : Design 3's technical details.

3D Printer	Creality CR-X	
Slicer	Ultimaker Cura	
Filament	E-SUN PLA, white	
Layer Height	0,4 mm (Body and inner wall); 0,3 mm (Cover)	
Infill and Support	Standard infill: %20, Grid Support: Everywhere	
Printing time:	Body:	12.5 hours
	Cover:	6 hours
	Inner wall:	1 hour
	TOTAL	19.5 hours

5.1.3.2 SLA printing

After FDM printing was completed, a trial was made for SLA printing. The slicing process required for SLA printing was examined and a general comparison was made with the FDM process. Anycubic SLA printers include a USB stick with a test print in their box. How this process progressed was shown step by step (Figure 5.13).

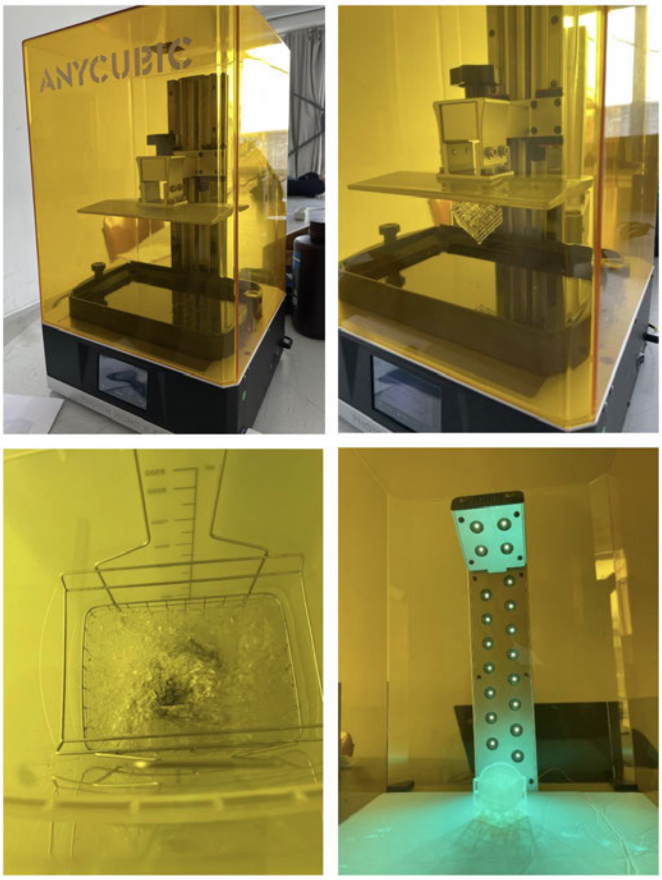

Figure 5.13 : SLA printing steps.

Printer Setup: The resin tank is filled with liquid photopolymer resin, Anycubic's basic transparent one. The build platform is ensured to be clean and properly aligned.

Printing: The build platform is lowered into the resin tank. A UV laser or light projector is used to cure the resin layer by layer, tracing the design. The build platform is gradually raised, allowing each new layer of resin to be exposed and cured.

Post-Processing: The printed object is removed from the build platform. The object is rinsed, in isopropyl alcohol to remove any uncured resin. Anycubic Wash and Cure product that was used for the washing process. This product is a device that can perform both washing and curing processes. It has a special container for washing. Thanks to a vortex at the bottom of this container, the washing process is intended to be more effective. The curing process can also be carried out by removing the container and installing the rotating platform. The object is further cured under UV light to strengthen the material.

Finishing: Any supports that were printed to hold the object in place are removed. The object is sanded, polished, or painted as needed to achieve the desired finish.

Following the completion of the trial render, the final model produced during the design phase was loaded into the Lychee slicer (Figure 5.14) to calculate the printing time and the required amount of material.

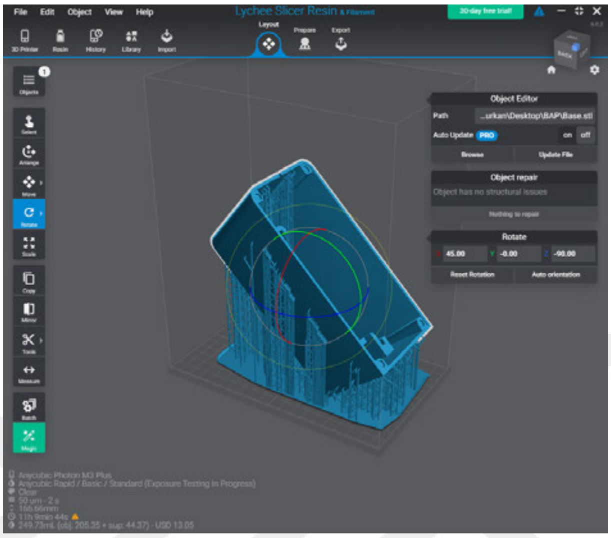

Figure 5.14 : Slicing of design 3.

Some calculations, seen in Table 5.7, were made to compare FDM and SLA printing. SLA printing time and material usage were obtained from the Lychee slicer's interface. Approximately 250 liters will be spent on this print, which costs 124 T according to the current price of the material used in the test print, so it costs almost twice as much as FDM printing. It can be said that their electricity consumption is almost the same. Additionally, Expert D stated that, with the help of post-production methods, FDM printers enable them to achieve a high surface quality equal to that provided by SLA printers. Therefore, surface quality is not a decision maker when preferring SLA over FDM.

Table 5.7 : FDM and SLA comparison. (Based on the average prices in the Turkish market in Istanbul, May 2024).

Machine	FDM (0.3 lh)	SLA
Printing Time	12.5	12
Material Consumption	135 grams	250 liters
Total Cost	67.82	124

In summary, the SLA printing process has more steps and requires more time compared to FDM printing. However, as mentioned in the literature and expert interviews, the surface quality is much better. In FDM printer printing, when the thickness is reduced to 0.1-layer height, the printing takes almost 3 times longer. In addition, even if the layer thickness is 0.1 in the FDM printer, the surface quality as high as in SLA printing cannot be achieved. Since high surface quality is not required for the product to be produced in the case study, it would be more logical to use an FDM printer. It has been noticed that the FDM process is less costly than the SLA process and is also much easier to use.

5.1.4 Evaluation of the case study

The aim of the research was to better understand how AM technologies can be used in projects or businesses that require low-volume production. This research study collected the necessary data through case study and expert interviews. The Scientific Research Projects (BAP) project within ITU was chosen as the case for this study and the study was carried out successfully. In addition, to better understand the research questions, four experts covering different needs were selected and one-on-one interviews were conducted.

The first aim of the case study was to determine which AM technology was suitable for the study. Additionally, it includes research into how the design process can be adapted to print technology. Development of the design focused on material usage and printing time. According to Shewbridge et al. (2014), printing any regular sized object with a contemporary 3D printer frequently takes a long time. It cannot be said that this has changed much in today's conditions. One of the biggest problems experienced in the case study was the excessive printing times. This problem may come to light especially when a product is produced in dozens of units. In addition to the literature review, expert interviews were also conducted to obtain more in-depth information about the 3D printing process.

5.2 Findings from the Expert Interviews

In this section, titles were determined according to the answers obtained from the expert interviews, and the experts' common and personal opinions were classified.

In the last part, the summarized versions of these answers are shown in Table 5.8. The original and translated transcripts of expert interviews are given in Appendix A-H.

5.2.1 Potential uses of 3D printing

Experts agreed that the applications of 3D printing technology are fairly extensive and diverse. All claimed that 3D printing technologies were most commonly used to manufacture the end product in low-volume productions, whereas, in large-scale production by major companies and their R&D teams, 3D printing technologies were used to build test prototypes and models for silicone molds. Expert A stated that some people use 3D printers for personal use as a hobby.

5.2.2 The advantages of 3D printing over conventional production methods

The first advantage, according to experts, is timesaving in prototyping and cost-efficiency in low-volume production. Furthermore, 3D printing offers a greater level of ease in creating complex structures compared to conventional techniques. Experts B, C, and D explained that 3D printers are useful in instances involving the fabrication of parts with complex geometry because conventional methods for generating these detailed, organic shapes are exceedingly time-consuming and costly. Also, Expert B remarked that more organic forms with the same mechanical properties can be achieved in designs improved by topology optimization, which reduces material usage and makes the product lighter. Finally, as Expert B and C both pointed out, 3D printing offers the chance to digitally store items as needed, eliminating the requirement for traditional supply chain management or physical storage.

5.2.3 Potential of 3D printing technology to produce end-user products

All experts agreed that it is an issue involving manufacturing quantity and production time. According to the experts, using molds for high-volume production of end-user items is more cost-effective and timesaving. However, in projects with limited production volumes, the cost of mold manufacture becomes excessive, making 3D printing technology a more favorable option. While Expert B claimed that they prefer technologies with exceptionally high surface quality, such as MCF, for delivering such items, Expert D noted that there is no noticeable distinction between FDM printed and injection molded products after the process of post-production. Moreover, Experts A and D also stated that 3D printing is more convenient for designs that may require revision, as the design must be finalized before molds can be produced.

5.2.4 Limitations of AM

All participants agree that the most significant limitation of 3D printing technology is its inefficiency in terms of speed and cost in large-scale production when compared to conventional techniques. According to Expert C, another challenge in AM is maintaining print quality and tolerances, especially for products with complex geometry. Furthermore, Expert C stated that faults may occur during the development of working prototypes that require features such as waterproofing, whereas Expert D stated that their company was able to resolve such difficulties through post-production processes including painting.

5.2.5 The ways to improve print quality

Expert A mentioned the following things to consider when improving print quality: keep the resolution high, choose the bed in accordance (there are build plates that offer different surface finishes, such as build plates with textured surfaces as seen in Figure 5.15) with the design, and keep the surface cleaned. While agreeing with Expert A, Expert D emphasized the importance of understanding the printer's strengths and weaknesses, as well as calibrating and controlling them in terms of belt tension, nozzle clogging, bed calibration, and so on. Expert D also proposed improving print quality by modifying medium-grade printing machines' extruder and nozzle sizes. Both experts underlined the importance of focusing on the printing process when designing. Optimizing the dimensions not to reduce thickness by 1 mm and carefully coordinating the angles to allow for printing without support structures can improve print quality.

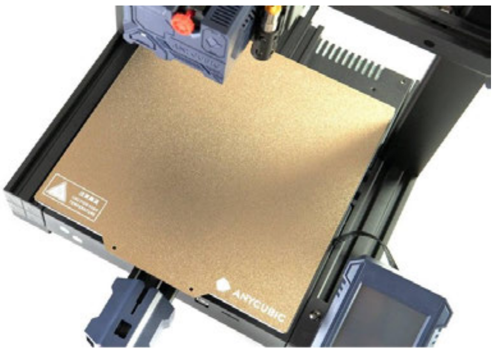

Figure 5.15 : Flexible and textured build plate example (O'Connell, 2022).

5.2.6 Post-production techniques to improve print quality

Although experts said that it is not essential for the device's invisible sections, they agreed that post-production techniques such as sanding, painting, and polishing play a role in parts that require visibility. Expert D also stated that they used the Acetone Vapor Bathing technique to clean the supports postproduction.

5.2.7 The differences between FDM and SLA

Expert A pointed out that because SLA can work at lower microns, it is feasible to create complex surfaces, although it is more expensive than FDM. As a result, Expert A recommended using SLA in projects that require a high level of detail, such as figure manufacturing and jewelry design. Expert C also emphasized the difference, stating that they favor FDM for structurally strong items and SLA for parts with excellent detail. Expert D also stated that they favor FDM since it is chemical-free, has no odor, and the post-processing process is simpler, faster, and more affordable.

5.2.8 The benefits of reducing support usage

Experts A and D stated that the first advantage of eliminating the need for support is to lower material consumption and speed up the production process. Secondly, they stated if the aesthetic appearance of the output is crucial, manufacturing without support is a benefit since the support points may damage the surface of the product.

5.2.9 The ways of reducing support usage

Expert A stated the things that can be done to print without support should be divided into two categories: things that can be done by the user and things that can be done during printer manufacturing. Expert A and D detailed the things can be considered by user is to construct the models and their angles in a way that requires the least amount of support. Expert D also explained a trick they use while printing: to stop the printing at certain stages and place wooden blocks of the same size as the gaps in between instead of printing support. By this technique, Expert D claimed that they ensure that the printing continues without the need for support. On the printer production side, Expert A explained the 3D printers using 5-Axis logic, which have recently begun to be manufactured, allow to produce models without support.

5.2.10 The future of 3D printing

All experts stated they are convinced that the future of AM is quite bright. With constantly advancing technology and materials, they believe 3D printing will be employed in a broader range of sectors and applications. According to experts when this technology becomes more widely adopted, it will speed up industrial change by increasing efficiency and flexibility in manufacturing processes. Expert A pointed out there are also large companies working on this issue. For example, Volkswagen began using 3D printing technology to make some vehicle parts. Similarly, it seems Apple is testing metal 3D printing manufacturing methods for its watches. Expert A added, FDM printer may not satisfy the end user in terms of aesthetic, but as people's cosmetic concerns decline and 3D printing technology advances, the application of these technologies in consumer products will become more common. Expert D also added powder machines will be preferred in the future because there is no support issue, the powder can be reused, and some models can print many materials. He also pointed out that printing devices should be more user-friendly and be able to notify the user of the errors.

Table 5.8 : Findings from the expert interviews.

Topics	Findings
Potential uses of 3D printing	Building test prototypes Creating models for silicone molds Low-volume production Personal use for hobby
The advantages of 3D printing over conventional methods	Cost-efficiency in low-volume production Saving of time in prototyping Ease in creating complex structures. Potential to produce more organic forms with the same mechanical properties. The capability of digital storage
Potential of 3D technology to produce end-use products	Cost-efficiency in low-volume production compared to molding. The capability of digital storage More convenient for designs that may require revision
Limitations of AM	Inefficiency in terms of speed and cost in large-scale production Maintaining print quality and tolerances Potential faults in working prototypes that require features such as waterproofing
The ways to improve print quality	To keep resolution higher To choose the bed in accordance with the design To keep the bed's surface clean To calibrate and to control the belt tension, nozzle clogging, bed calibration. modifying medium-grade printing machines' extruder and nozzle sizes To consider the printing process when designing To reduce thickness by 1 mm To carefully coordinate the angles to enable printing without support
Post-production techniques to improve print quality	Important for visible, aesthetic parts Sanding, painting, and polishing commonly used. Acetone Steam Bath technique to clean the supports
The differences between FDM and SLA	Complexity: SLA can work at lower microns, so it is feasible to create complex surfaces. Affordability: FDM is more affordable than SLA. Detailed surface quality: SLA is more suitable for projects requiring a high level of detail, such as figure manufacturing and jewelry design, while FDM is suitable for structurally strong items. FDM is chemical-free and has no odor. The post-process of FDM is simpler, fast, and more affordable.
The benefits of reducing support usage	Low material consumption Faster production process
The ways of reducing support usage	To construct the models and the angles in a way that requires the least support. To stop the printing at certain stages and place wooden blocks of the same size as the gaps in between instead of printing support The 3D printers using 5-Axis logic
The future of 3D printing	3D printing will be employed in various sectors and applications. 3D printing will speed up industrial change by increasing efficiency and flexibility in manufacturing processes. Powder machines will be preferred in the future. (Expert D)

6. DISCUSSION/CONCLUSIONS

In this section, the answers to the research questions are summarized in line with the results obtained from the literature review and research.

6.1 Discussion

This study highlights the significant benefits that 3D printing technologies provide to small-scale enterprises, particularly in terms of design flexibility and cost-effectiveness for low-volume production. It examines the transformative impact of AM on these manufacturers. The applicability of FDM technology for such manufacturers became evident, as demonstrated by a specific case study. As mentioned in the literature, the appeal of FDM technology lies in its accessibility and low setup costs, making it an ideal choice for companies with limited financial resources and production demands (Kristiawan et al., 2021). Additionally, the advantages of FDM technology were mentioned in expert interviews.

During the design process, deliberate modifications were implemented to enhance product design by prioritizing the reduction of material usage and printing time. This optimization was crucial in improving efficiency, which is essential for small-scale operations that need to maximize resource allocation. The study achieved a more efficient printing process by eliminating the requirement for support structures, reducing material waste and post-processing time (Diegel et al., 2019). The advancements highlight the potential of AM technologies to be customized for the specific requirements of small-scale manufacturers, thereby improving their competitiveness in the market. During the case study, design improvements were attempted to reduce support usage.

The study found that the selection of materials and the specific AM technology significantly impact the operational success of these businesses. To maintain sustainable business practices, it is essential to have materials that are affordable, easily accessible, and compatible with the selected AM technologies (Hozdić and Hozdić, 2023). Furthermore, the utilization of technologies that facilitate the quick creation of prototypes and customization can offer small-scale manufacturers a clear advantage in competition by allowing them to promptly adapt to shifts in the market and meet their customers' preferences.

Various adjustments can be made to enhance printing outcomes. These adjustments encompass machine calibration, choosing suitable printing materials, and optimizing print settings such as resolution and infill (Aranda, 2022). In the case study, some of these adjustments were tried and positive results were obtained. Regular maintenance of the equipment ensures consistent quality and reliability in production outcomes. These adjustments are crucial for optimizing operational efficiency and product quality in AM, especially for businesses seeking to utilize these technologies for commercial prosperity. To summarize, AM offers significant advantages in customization, waste reduction, and operational efficiency, making it a promising option for small-scale manufacturers. The study's findings support the adoption of AM technologies in a deliberate and planned manner, with an emphasis on improving design and production processes to fully exploit the advantages they offer. The ongoing development and adjustment in this domain will probably broaden its practicality and financial gain for small-scale enterprises.

6.2 Answers to Research Questions

The following is the response to the study's primary research questions:

RQ1: What are the advantages of desktop 3d printers for small-scaled manufacturers?

Revised RQ1: What are the important issues while using FDM and SLA printers for low-volume production?

Answer to RQ1: Literature study has shown that AM technologies, namely 3D printers, have many advantages over conventional methods for low-volume production. First of all, expenses in conventional and direct production methods increase significantly. These production methods require extremely expensive and large machines. The use of these devices in closed areas such as homes or small offices is not recommended due to both human health risks and possible fire hazards. Another finding we encounter in conventional production methods is the technical labor requirement required to use this technology. They do not have the ease of use that 3D printers offer. In addition, constant surveillance is needed to check for any dangerous disruptions in the production process. Another issue frequently encountered is design flexibility. AM technologies offer the designer wide freedom. There are no design restrictions encountered in different types of conventional production methods. Complex 3D forms can be produced easily and make the designer's job easier when searching for forms. In addition, it seems that the costs resulting from errors experienced during the product development process have also decreased.

RQ2: Which additive manufacturing technology and materials are more suitable for small-scale companies or individual home fabrication?

Revised RQ2: How to decrease material usage and printing time in FDM?

Answer to RQ2: The literature and expert interviews conclude that FDM, SLA, and SLS technologies are the most suitable for low-volume production. SLS technology offers lower production costs per unit compared to all other AM technologies. However, these printers are not very common among the public, and the machine prices are significantly more expensive (Prusa, 2023). In this respect, FDM and SLA technologies are preferred both for case studies and for such low-volume production.

When comparing FDM and SLA printers, printing plate size, printing detail, printing times and material usage attract attention. One of the greatest conveniences offered by FDM printers is that the printing surface can be very large. In SLA printers, this is at a limited level. On the other hand, print detail quality is much higher on SLA printers compared to FDM.

Another point obtained from the literature and expert interviews is the use of materials. While FDM printers use raw materials called filaments, SLA printers use liquid resins, a type of plastic. Filaments are produced from a variety of thermoplastics such as ABS, PLA and PET and can be used for many different mechanical needs. Resin, on the other hand, offers a more limited mechanical variety. Most users find a filament printer more useful because the raw material is very easy to transport and store, and there is very little waste (Horvath and Cameron, 2020). Additionally, in the case study, a test print was made for the SLA printing process. During this process, a mouth mask, safety glasses and gloves were used to prevent damage that could be caused by the resins. As mentioned in the literature, resins are mostly toxic liquids. It causes the release of poisonous and foul-smelling gas into the air during use. While the test printing was being done, the printing process was carried out in a large room with the windows and door open. Despite all efforts, the strong odor in the room caused a headache. During the process of filtering the resin used after printing and filling it into the resin container for reuse, the resin was scattered around a bit and became difficult to clean. Considering all these, it can be said that it is a more difficult printing process than the FDM process.

RQ3: What are the criteria and strategies of design for AM (DfAM) for desktop 3D printing to optimize printing process?

Revised RQ3: What are the basic printing failures experienced in FDM printing, and how can they be solved?

Answer to RQ3: This question has been approached with more focus on FDM technology. The answer to this question is in 3 parts. It can be explained as pre-printing, during-printing, and post-printing processes. There are CAD and slicing steps before printing. The CAD part starts with designing the 3D model. After the 3D model is prepared, this model is imported for slicing. Modeling in accordance with the preferred AM technology determines both the result and the printing time. A part that is not modeled correctly can also prevent printing from happening. In the literature and case study, the difficulties that the support structure can create have also been observed. The method of reducing the support structure during the design development phase was tried in the case study, and a successful result was obtained. There was a 28% improvement in printing time and a 35% reduction in material usage. In this respect, attention was drawn to the importance of the support structure.

The second part is the adjustments that can be made during printing. It has been observed both in the literature and in the case study that heating the printing plate or coating it with an adhesive prevents the part from lifting off the printing surface during printing. Another point is that the printing environment must have a stable air condition. Variable air temperatures or air flow may cause printing errors.

The post-printing process is the last part that affects the better printing result. Post-processing processes of FDM and SLA printers are included in the literature. From this perspective, while prints made with the SLA method definitely require post-processing, it has been determined that this part is not necessary in any case in FDM technology. However, it has been observed that post-printing processes in the FDM process can achieve better surface quality. Additionally, if there is a support structure, removal of that support also takes place at this stage.

6.3 Suggestions for Desktop 3D Printing

The field of production and design has seen tremendous change since the introduction of AM, or 3D printing. This technology has democratized manufacturing by creating products layer by layer from digital models. It presents unseen options for designers, small-scale producers, and home users. Large-scale manufacturing facilities are no longer necessary for a wide range of users to turn ideas into physical products because of the widespread availability of inexpensive 3D printers and design software. The list of suggestions for designers, producers and home users to optimize 3D printing process is given below.

- To determine the appropriate technology to employ, it is first necessary to ascertain the target. Devices capable of printing with lower microns, such as SLA, DLP, and SLS, may be preferred when high surface quality is desired.
- If rapid production is required and surface quality is not a priority, FDM can be better choice.
- In FDM printing, layer thickness should be made as needed. You can focus surface quality at post-processing. In the case study, reducing layer height from 0.1 to 0.3 reduced print time from 32 to 12.5 hours.
- If a 3D printer is to be utilized for the first time, it may be more convenient and trouble-free to begin with FDM technology. The learning path for SLA and DLP is more challenging due to the pre-production and post-production steps.

- Never contaminate the transparent screen with resin when utilizing SLA or DLP devices. It is critical to use a screen protector whenever possible. Otherwise, the screen may have to be replaced, which can be quite costly.

- FDM printers can last longer than SLA and DLP printers. UV printer projections have a limited lifespan and may degrade print quality over time. FDM printers are less expensive, even if some parts fail over time.

- Exercise extreme caution when working with UV resins. Epoxy resins, in particular, can present problems when utilized in a closed environment for extended periods of time. The surroundings must be constantly ventilated, and a mask should be used. Plant-based resins are a relatively new substance whose development has accelerated. Although the printing quality is lower than epoxy, these materials will be improved in the future.

- If there is an issue with adherence to the plate or warping in FDM printing, it can be resolved by increasing the nozzle temperature of the first four layers by 10 degrees and allowing the cooling fan to operate slower during the first printing process. Slicers like Cura have advanced settings for this.

- Aranda's (2022) book 3D Printing Failures offers a detailed explanation of the problems frequently encountered in FDM printing. It was also frequently used in the case study.

- Print orientation is very important in all 3D printers. In particular, the most optimal printing orientation should be selected before slicing to reduce support use and preserve surface quality.

- If the print contains excessive overhangs or areas that require support, it is advisable to split the product into two parts. After the printing process, two components can be easily bonded. Adding indentations and protrusions at different levels to the surfaces to be bonded can increase the adhesion surface and axis.

- Biobased materials such as PLA should be preferred at home and in narrow indoor spaces.

- In order to reduce the use of support in FDM prints, custom supports can be used by stopping the printing mentioned by Expert D and placing a piece such as wood under the overhang.

- Considering the deformation generated by the support structure on the surface, it may be beneficial to use the points of contact with the support in the least visible sections of the product.

- A textured part on the FDM printing bed can present a better aesthetic appearance.

- Conventional production processes can be used to reproduce 3D printed parts. The surface of the AM-produced master product is smoothed using post-processing processes such as sanding and coating. Molds can be created using the silicon molding method, and production can be done with materials such as polyester, cement, or plaster.

6.4 Limitations of The Study

The main limitation of this study is that AM technologies other than FDM and SLA are not included in the production process in the case study method. According to the conclusion drawn from the literature, FDM is the most preferred and recommended technology for this type of production. However, more definitive conclusions could be reached by clearly demonstrating with numerical data why FDM is the preferred technology.

Another limitation is that design moves to reduce the support structure could have been implemented more stably. Although the design decisions led to reduced support usage, more efficient production could have been achieved by incorporating the generative design concept. This concept uses algorithms to produce several design options optimized for needs and constraints, like weight, durability, and material use (Di Nicolantonio et al., 2019). 3D modeling programs such as Fusion 360 enable this concept to be created (Autodesk, 2018).

6.5 Further Research

In the future, additional research could explore the field of generative design as a crucial next phase in the advancement of AM, specifically for small-scale production. Generative design utilizes sophisticated algorithms to produce optimized structures and shapes that would be challenging or unattainable using conventional design techniques. By combining generative design with AM, manufacturers can investigate a wider range of design options that improve material efficiency and structural integrity.

Future research should prioritize the development of sophisticated algorithms that can better incorporate the limitations and capabilities of AM technologies. These studies have the potential to improve the design process and potentially transform the approach of small-scale manufacturers to product development. By fully utilizing generative design, businesses can attain unparalleled levels of efficiency and innovation, propelling them towards a more sustainable and competitive future in the manufacturing sector.

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APPENDICES

APPENDIX A : Original Transcript of Expert Interview with Expert A

APPENDIX B : Translated Transcript of Expert Interview with Expert A

APPENDIX C : Original Transcript of Expert Interview with Expert B

APPENDIX D : Translated Transcript of Expert Interview with Expert B

APPENDIX E : Original Transcript of Expert Interview with Expert C

APPENDIX F : Original Transcript of Expert Interview with Expert A

APPENDIX G : Original Transcript of Expert Interview with Expert D

APPENDIX H : Translated Transcript of Expert Interview with Expert D

APPENDIX I : Consent Forms of Pilot Study

APPENDIX A : Original Transcript of Expert Interview with Expert A

S1: Daha çok hangi müşteri grupları 3B yazıcıları tercih ediyor?

C1: 3B baskı teknolojilerinin kullanım alanı ve müşteri profili oldukça geniş ve çeşitli. Benim çalıştığım firmada ürettiğimiz yazıcılar için konuşmak gerekirse, daha çok AR-GE ekibi olan firmaların tercih ettiğini söylebilirim. Bu tarz firmalar ürünlerinin tasarım sürecinde protitip denemesi yapma, silikon kalıp için model üretme için kullanılıyor. Bunun dışında hobi amaçlı üretim süreçlerinde 3B yazıcıları tercih eden kullanıcılarımız da var.

S2: Bahsettiğiniz, prototipleme için 3B yazıcıları kullanmayı tercih eden, firmalar genelde startup firmaları mı, yoksa büyük ölçekli şirketlerin AR-GE ekipleri de ürünlerinizi tercih ediyor mu?

C2: Startup firmaları daha uygun fiyatlı firmaları tercih ediyorlar. Bizim firmamızın müşteri portföyü ağırlıklı olarak büyük ölçekli şirketlerin AR-GE ekipleri oluşturuyor diyebilirim.

S3: İlk defa 3B yazıcı kullanacak olan kullanıcılar ne kadar sürede düzgün bir baskı almaya başlıyorlar? Siz müşterilerinize bu konuda nasıl destek oluyorsunuz?

C3: Aslında yazıcıların kurulumunu biz sağlıyoruz, kurulum sonrasında da kullanıcıya yazıcıyla ilgili basit bir eğitim de veriyoruz. Bu basit bir anlatım oluyor ve sonrası kullanıcının seviyesine göre değişebiliyor, kendi araştırmaları sonucunda ve deneme-yanılma yöntemiyle daha efektif sonuçlar elde etmeye başlıyorlar. Kullanıcılar bir sorun yaşadığında yine teknik destek ekibimiz her zaman geri dönüş sağlayıp kullanıcılarımıza yardımcı oluyor.

S4: Firmanızın sektöre girişinden günümüze kadarki süreçte kullanıcı gruplarındaki değişimler nelerdir?

C4: İlk hizmet vermeye başladığımızda yurtiçi. Su an yurtdışına alıştık ve bu kullanıcı kitlemizin değişmesine sebep oldu. Önceden kullanıcı araştırması yaparken target auidence olarak daha geniş bir kitleyi hedef alıyorduk. Şu an, önceden de bahsettiğim gibi, endüstriyel odaklı kullanıma yöneldik ve mühendisler gibi teknik anlamda daha ileri düzey bilgi sahibi kullanıcıları hedef alarak tasarımlarımızı yapıyoruz. Yazıcı fiyatları, teknik servis, malzeme fiyatları üzerindeki yıllar içindeki artıştan dolayı kullanıcı kitlemiz ister istemez daralıyor ve bu işe daha profesyonel yaklaşan, endüstriyel kullanıma odaklanmaya başladık.

S5: Yeni yazıcı teknolojilerini takip ederken nerelerden besleniyorsunuz?

C5: Öncelikle rakiplerimiz ile fiyat, performans anlamında benchmark yapıyoruz ve trendleri takip etmeye çalışıyoruz. Örneğin, son 2 yıldır hızlı baskı trend olmuş durumda ve çoğu marka buna odaklı. Aynı zamanda 3B baskı communitysi çok geniş ve yeni gelişmelerle ilgili haberler çok hızlı yayılıyor. Youtube, Twitter, Reddit, Discord gibi çoğu kanaldan gelişmeleri takip etmek mümkün, aynı zamanda bu alanda paylaşım yapan influencerlar da var. Bunun dışında, 3B baskı alanında içerik üreten basılı ve dijital dergileri ve diğer yayınları takip ediyoruz. Bunun yanında müşterilerle de görüşmeler yapıp onların taleplerine ve önerilerini de değerlendiriyoruz.

S6: Destek kullanımının azaltılmasının avantajları nelerdir? Desteksiz bir şekilde baskı almak için ne gibi yöntemler öneriyorsunuz?

C6: Destek kullanımının azaltılmasının avantajlarından birincisi, malzeme tüketiminin azalması. İkinci olarak, desteğin modele değdiği yerlerde üründe bozulmalar olabiliyor. Eğer estetik olarak ürün görünümünün önemli olduğu bir projeyse desteksiz üretim yapabilmenin bu anlamda da avantaj sağladığını söyleyebilirim. Desteksiz baskı almak için yapılabilecekler de aslında kullanıcı tarafında yapılabilecekler ve yazıcı üretiminde yapılabilecekler olarak ikiye ayrılıyor. Kullanıcı tarafında dikkat edilmesi gerekenin, açılar vb. ayarlanırken 3B yazıcı teknolojisine uygun modeller tasarlamak olduğunu söyleyebilirim. Yüzey kalitesinden beklentinin yüksek olmadığı durumlarda, bazı yamulmalar olmasını göze alarak daha az destek koymak da bir yöntem olabilir. Yazıcı üretimi tarafında ise desteksiz model üretimini kolaylaştıran, 5-Eksen mantığı ile çalışan 3B yazıcılar üretilmeye başlandı. Yazıcılardaki bu gelişme sayesinde de, tablanın ve/veya nozzleın açılı şekilde hareket etmesinden faydalanarak daha az destekle baskı alınabiliyor.

S7: FDM ve SLA üretim yöntemlerinin farklarını siz nasıl özetlersiniz?

C7: Yüzey kalitesi olarak bakıldığında, SLA daha düşük mikronlarda çalışabildiği için daha detaylı yüzeyler elde etmek mümkün ama maliyeti FDM'e göre daha yüksek. Bu sebeple figür üretimi, mücevher tasarımı gibi detayın önemli olduğu üretimlerde SLA tercih edilebilyor.

S8: Baskı kalitesinin arttırılması için tasarım aşamasında nelere dikkat etmek gerekir?

C8: Çözünürlük daha yüksek tutulabilir. Kullanılan tablayı tasarıma uygun seçmek ve tabla yüzeyini temiz tutmak önemli. Ayrıca görünen yüzeyleri tablaya gelecek şekilde yerleştirmek de önemli, bu sayede o yüzey de pürüzsüz çıkmış oluyor. Yazıcının bakımının düzgün yapılması, nozzle temizliği ve değişimi, tabla kalibrasyonu ve temizliği de baskı kalitesini etkileyen unsurlardan.

S9: Dokulu ve pürüzsüz baskı tablası arasındaki farklar nelerdir? Hangi durumlarda tercih edilmesini öneriyorsunuz?

C9: Bu tamamen ürünün estetik görünümüyle ilgili bir tercih. Bizim markamızda iki baskı tablası da mevcut. Dokulu yüzey baskı sonrasında yüzeyin boya tutmasını kolaylaştırıyor. Şu an desenli bazı tablalar da üretiliyor, böylece modeli tablanın desenine göre yerleştirip desenin yüzeye geçmesini sağlayabiliyorsunuz.

S10: Pasif ısıtma teknolojisinin faydaları nelerdir? Bu teknoloji kullanılmadığında yaşanan problemler neler?

C10: Pasif ısıtmada tabla ısıtmalı oluyor, tablanın etrafı kapalı olduğunda tabla ısısının dağılması engellendiğinden kabinin içi ısınmış oluyor. Heated Chamber da ise kabin içine dışarıdan ısı veriliyor ama tabla ısıtmalı olmuyor.

S11: Tam otomatik kalibrasyon sistemi farklı noozle kalınlıklarına göre optimizasyon sağlıyor mu? Ne gibi avantajları var?

C11: Nozzle çapı değiştiğinde nozzle ve tabla arasında mesafenin ayarlanması gerekiyor. Aynı zamanda tabla üzerindeki pürüzlerden kaynaklı da minör yükseklik farkları olabiliyor. Otomatik kalibrasyon sayesinde, printer üzerinde bulunan sensör yardımıyla bu yükseklikleri noktasal olarak optimize ediyor ve baskının düzgün çıkmasını sağlıyor.

S12:Yazıcılarınızın bazı parçalarını, 3B yazılarınızla kendiniz basıyorsunuz. Bu seri üretimde size nasıl avantaj/dezavantaj sağlıyor?

C12:Bu üretim miktarı ve üretim süresi ile bağlantılı bir durum. Kalıp üretimi yapmak çok maliyetli olduğu için revizyon gerektirebilecek parçalarımız için ya da az miktarda üretilecek parçalar için 3B baskı tekniklerini kullanmak bizim için az maliyetli ve daha hızlı oluyor. Aynı zamanda bu üretimi kendi bünyemizde yapabildiğimiz için lojistik maliyeti ve süresinden de avantaj sağlamış oluyoruz.

S13: 3B baskı teknolojilerinin son kullanıcıya yönelik ürün üretiminde kullanılması konusunda gelişmeler hakkında ne düşünüyorsunuz?

C13: Şu an hala estetik kaygı gözetilen ürünlerde, FDM özelinde konuşursak, sonuç ürün kullanıcıyı tatmin etmeyebiliyor ama biz ürün içindeki parçalarda FDM teknolojisini final ürünlerimizde de kullanıyoruz. Bu konuda çalışmalar yapan büyük firmalar da var. Örneğin, Volkswagen araç içindeki bazı parçaları 3B baskı teknolojisiyle üretmeye başladı. Aynı şekilde, Apple'ın saatlerinde metal 3B baskı üretim yöntemlerini kullanmak için testler yaptığını biliyorum. Diğer taraftan, FDM de yüzey kalitesi ve baskı hızı anlamında gelişme gösterdi. Hem insanların kozmetik kaygısının azalmasının, hem 3B baskı teknolojilerinin gelişmesinin birbirini yakalayacağını ve yavaş yavaş son kullanıcıya yönelik ürünlerde bu teknolojilerin kullanılmasının yaygınlaşacağını öngörüyorum.

APPENDIX B : Translated Transcript of Expert Interview with Expert A

Q1: Which customer groups prefer 3D printers the most?

A1:The applications and client profiles for 3D printing technology are fairly broad and diversified. If we talk about the printers we make at the company where I work, I can state that they are chosen by companies with a RD team. During the product design phase, such companies test prototypes and create models for silicone molds. Aside from that, we have users that choose 3D printers in production processes for their hobby.

Q2: Are the firms you stated who prefer to use 3D printers for prototyping typically start-ups, or do RD teams at large corporations also choose your products?

A2: Startup companies prefer more affordable companies. I can say that our company's customer portfolio consists mainly of RD teams of large-scale companies.

Q3: How long does it take for new 3D printer users to get their first proper print? How do you help your customers in this regard?

A3: In fact, we provide the installation of the printers, and after the installation, we also provide the user with simple training about the printer. This is a simple explanation, and the rest may vary depending on the user's level. As a result of their own research and trial-and-error method, they begin to obtain more effective results. When users experience a problem, our technical support team always responds and helps our users.

Q4: What have been the changes in user groups since your company entered the sector?

A4: When we first began delivering services, we sold domestically, but we have since expanded internationally, causing the users we serve to change. We previously conducted user research with the intention of reaching a larger audience. As previously stated, we are currently focusing on industrial applications and developing designs for more technically advanced users such as engineers. The number of our clients is obviously decreasing as printer, technical support, and material prices rise over time, so we have begun to focus on industrial use and handle this business more professionally.

Q5: What are your sources of inspiration for researching new printing technologies?

A5: First of all, we benchmark our competitors in terms of price and performance and try to follow the trends. For example, fast printing has been a trend for the last 2 years and most brands are focused on it. At the same time, the 3D printing community is very large and news about new developments spreads very quickly. It is possible to follow the developments on many channels such as YouTube, Twitter, Reddit, Discord, and there are also influencers who share in this area. Apart from this, we follow print and digital magazines and other publications that produce content in the field of 3D printing. In addition, we also meet with customers and evaluate their demands and suggestions.

Q6: What are the benefits of reducing support usage? What methods would you suggest for printing without support?

A6: The first advantage of eliminating the need for support is lower material consumption. Second, damage to the product may occur where the support touches the model. If the aesthetic appearance of the output is crucial, I believe that being able to manufacture without support is a benefit. The things that can be done to print without assistance are actually divided into two categories: things that can be done by the user and things that can be done during printer manufacturing. Angles and other factors must be considered by the user. I can state that the goal is to create models that are suited for 3D printing technology. In circumstances where the surface quality expectation is low, using less support and risking some warpage may be an option. On the printer production side, 3D printers that use 5-Axis logic and allow for the production of models without support have begun to be manufactured. Printing can now be done with less support because of advancements in printer technology that allow for the angled movement of the table and/or nozzle.

Q7: How would you describe the differences between FDM and SLA production methods?

A7: In terms of surface quality, since SLA can work at lower microns, it is possible to obtain more detailed surfaces, but its cost is higher than FDM. For this reason, SLA can be preferred in productions where detail is important, such as figure production and jewelry design.

Q8: What should be considered during the design process to improve print quality?

A8: The resolution can be kept higher. It is important to choose the table used according to the design and keep the table surface clean. It is also important to place the visible surfaces on the table so that the surface turns out smooth. Proper maintenance of the printer, nozzle cleaning and replacement, table calibration and cleaning are also among the factors that affect print quality.

Q9: What are the differences between textured and smooth beds? In what situations do you recommend it to be preferred?

A9: This is entirely a choice related to the aesthetic appearance of the product. There are also two beds in our brand. The textured surface makes it easier for the surface to retain paint after printing. Currently, some patterned beds are produced, so you can place the model according to the pattern of the bed and ensure that the pattern transfers to the surface.

Q10: What are the advantages of passive heating technology? What concerns arise when this technology is not used?

A10: In passive heating, the bed is heated, and when the area around the bed is closed, the bed's heat is prevented from dissipating, thus warming up the interior of the cabin. In Heated Chamber, heat is supplied to the cabin from outside, but the bed is not heated.

Q11: Does the fully automatic calibration system optimize for varied nozzle thicknesses? What advantages does it offer?

A11: When the nozzle diameter changes, the distance between the nozzle and the bed needs to be adjusted. At the same time, minor height differences may occur due to irregularities on the bed. Thanks to automatic calibration, it optimizes these heights point by point with the help of the sensor on the printer and ensures smooth printing.

Q12: You use 3D printing to produce multiple parts of your printers. What advantage or disadvantage does this provide in mass production?

A12: This is an issue involving manufacturing quantity and production time. Because mold production is extremely expensive, we prefer using the methods of 3D printing for items that may require revision or will be produced in small quantities. At the same time, because we can produce this within our own structure, we reduce both time and money on logistics.

Q13: What are your thoughts on the developments in the usage of 3D printing technology in the manufacturing of end-user products?

A13: Currently, if we focus on FDM products where aesthetic issues are still considered, the final product may not satisfy the user, but we apply FDM technology in both the product's internal parts and the final product. There are also large companies working on this issue. For example, Volkswagen began using 3D printing technology to make some vehicle parts. Similarly, it seems Apple is testing metal 3D printing manufacturing methods for its watches. On the other hand, FDM has moved forward in terms of surface quality and print speed. I believe that as people's cosmetic concerns decline and 3D printing technology advances, the application of these technologies in consumer products will become more common.

APPENDIX C : Original Transcript of Expert Interview with Expert B

S1: 3B baskı teknolojileri kullanılarak son kullanıcıya yönelik ürün üretilebilir mi?

C1: Tabi ki, ama bunun mantıklı olup olmaması projeye göre değişebiliyor. Bizim bunun için kullandığımız bir "üretim maliyeti/ürün adedi" optimizasyonumuz var. Otomotiv firmaları gibi büyük ölçekli iş yapan, yüksek miktarda parça üretilmesi gereken işlerde kalıp üretmek maliyet ve zaman açısından çok daha verimli oluyor. Daha küçük ölçekli firmaların, yine parça adedinin görece fazla olduğu durumlarda silikon kalıp tercih edilebiliyor. Bu durumda 3B teknolojisi silikon kalıbın üretiminde kullanılacak modelin oluşturulması için faydalı bir yöntem ancak silikon kalıpların da belli bir üretim adedinden sonra yenilenmesi gerekiyor. Üretim adedinin düşük ise, doğrudan son kullanıcıya yönelik ürünlerden faydalanıyoruz. Burada ürün son kullanıcıya gideceği multi jet fusion (MJF) gibi yüzey kalitesinin çok yüksek olduğu yöntemleri tercih etmek kritik oluyor. Özetle, 3B baskı teknolojileri son kullanıcıya yönelik ürünlerde kullanılabilir ancak bunun yaygınlaşması için 3B baskı teknolojilerinde bu tarz üretime yönelik iyileştirmeler yapılması gerekli. Kritik olan nokta 3B baskı teknolojisinin sürece bir katma değeri olması. Eğer üretim hızı, malzeme kullanımı vb. konularda verim sağlıyorsa maliyeti düşürdüğü için tercih edilebilir hale geliyor.

S2: 3B baskı yöntemlerinin geleneksel üretim yöntemlerine kıyasla sağladığı avantajlar neler?

C2: Geleneksel üretim yöntemleriyle üretilmesi için çok parçalı kalıplanması gereken kompleks formlar, 3B baskı teknolojileri ile kolayca üretilebiliyor. İkinci olarak, topoloji optimizasyonu ile iyileştirilen tasarımlar aynı mekanik özelliklere sahip daha organik formlar elde edilerek malzeme kullanımını azaltmak ve ürünü daha hafif hale getirmek mümkün. Geleneksel yöntemlerle bu kompleks, organik formları üretmek çok zahmetli ve maliyetli oluyor. En büyük artılarından birisi ise ürünü depolamaya/tedarik süreci ile uğraşmaya gerek kalmaması. Ürünü fiziksel olarak depolamak yerine dijital stokta tutup ihtiyaç duyulduğunda basabiliyor olmak.

S3: FDM baskı teknolojisinde katman kalınlığı farklı yöntemlerdeki kadar hassas olmuyor. Bunun son kullanıcıda etkisi sizce neler ve bu etki nasıl post-process ile nasıl optimize edilebilir?

C3: Katman kalınlığı düşürülebilir ancak bu da üretim süresini arttırdığı için optimize olmuyor. Görselliğin önemli olduğu durumlarda, post-process aşamasında zımpara, boyalar vb. teknikler uygulanarak ürünün estetiği arttırılabiliyor.

S4: MJF, ev tipi kullanım için mantıklı mı?

C4: MJF için masaüstü çalışan, ev tipi yazıcılar bildiğim kadarıyla yok. Yazıcılar endüstriyel kullanıma yönelik üretildiği için boyut olarak evde kurmaya uygun olmayabilir, aynı zamanda maliyeti bu tarz bir kullanım için gereksiz bir maliyet olabilir.

APPENDIX D : Translated Transcript of Expert Interview with Expert B

Q1: Is it possible to manufacture end-user products utilizing 3D printing technologies?

A1: Of course, it is conceivable; however, whether or not this makes sense depends on the project. We utilize an optimization calculation called "production cost/product quantity" for this. As shown here, making molds is far more cost and time effective in large-scale firms such as automobile producers that need to make vast quantities of parts. Silicone molds may be preferred for smaller businesses and circumstances where the number of parts is rather large. In this scenario, 3D technology is a beneficial and practical approach for developing the model used in the manufacture of silicone molds; however, silicone molds must be changed after a specific number of productions. In projects with limited manufacturing volumes, we manufacture products offered directly to the end user. It is crucial to select technologies with extremely high surface quality, such as multi jet fusion (MJF), for delivering the product to the end customer. In summary, 3D printing technologies can be employed in end-user products; however, for this to become more prevalent, advances in 3D printing technologies for this type of production are required. The essential aspect is that 3D printing technology enhances the process. If it improves efficiency in terms of manufacturing speed, material use, etc., it becomes preferable since it saves money.

Q2: What are the advantages of 3D printing over conventional production methods?

A2: Complex structures that need multi-part molding in conventional manufacturing methods can be simply manufactured using 3D printing technology. Second, more organic forms with the same mechanical qualities can be obtained in designs enhanced by topology optimization, reducing material usage and making the product lighter. Conventional methods for producing these intricate, organic shapes are extremely time-consuming and expensive. One of the primary benefits is that there is no need to store the product or deal with the supply chain. Instead of physically storing the product, keep it on digital stock and print it as needed.

Q3: In FDM printing technique, layer thickness is less sensitive than in other technologies. What effect do you believe this has on the end user, and how may this effect be optimized by post-processing?

A3: The layer thickness can be decreased, although this is not ideal because it increases production time. In circumstances when visuality is critical, post-processing techniques like sanding and painting are applied. The aesthetics of the product can be improved by using techniques.

Q4: Does MJF make sense for household use?

A4: As far as I know, there are no desktop or home printers for MJF. Printers are designed for industrial use, thus their size may not be appropriate for installation at home, and their expense may be unneeded.

APPENDIX E : Original Transcript of Expert Interview with Expert C

S1: Temel olarak ne amaçla 3D yazıcıları kullanıyorsunuz?

C1: Ar-Ge merkezi süreçlerimizde 3D yazıcılardan geniş bir yelpazede faydalanılmakta olup halihazırda bünyemizde 3 adet 3D yazıcı bulunmaktadır. Öncelikli olarak, bu yazıcıları seri imalat öncesi armatür parçalarının tasarımlarının değerlendirilmesi ve prototip üretimi için kullanmaktayız. Prototiplerin hızlı ve maliyet etkin bir şekilde üretilmesi, tasarım iterasyonlarının hızlandırılması ve yeni ürünlerin piyasaya sunulma sürecinin hızlandırılması açısından büyük avantaj sağlıyor. Ayrıca, özel parça ve bileşenlerin üretimi için de 3D yazıcıları kullanıyoruz. Bu, özellikle karmaşık geometriye sahip parçaların üretimi veya fonksiyonel prototiplerin üretilmesi gibi durumlarda büyük fayda sağlıyor.

S2: FDM, SLA veya SLS teknolojilerini ürün geliştirme sürecinde kullanıyor musunuz?

C2: Evet, ürün geliştirme sürecimizde FDM, SLA ve SLS gibi farklı 3D baskı teknolojilerini kullanıyoruz. Her bir teknolojinin avantajları ve kullanım alanlarına göre projelerimize uygun olanını seçiyoruz. Örneğin, FDM genellikle yapısal dayanıklılığı olan parçaların üretimi için tercih edilirken, SLA yüksek detay gerektiren parçaların üretimi için daha uygun olmaktadır.

S3: Ne tür parçalar için bu teknolojileri kullanıyorsunuz?

C3: Bu teknolojileri genellikle karmaşık geometriye sahip parçaların üretimi için kullanıyoruz. Özellikle, fonksiyonel prototipler, armatür bileşenleri, özel montaj bileşenleri gibi parçalar için bu teknolojileri kullanıyoruz.

S4: Profesyonel yazıcıları ve masa tipi yazıcıları tercih ederken neye dikkat ediyorsunuz?

C4: Profesyonel yazıcılar genellikle daha büyük baskı hacimlerine, daha yüksek baskı kalitesine ve daha fazla malzeme seçeneğine sahiptir. Bu nedenle, genellikle büyük ölçekli projeler veya karmaşık parçaların üretimi için profesyonel yazıcıları tercih ediyoruz. Ancak, projenin ölçeğine ve gereksinimlerine bağlı olarak masaüstü yazıcılar da kullanılabilir.

S5: Ne sıklıkla bu eklemeli imalat teknolojilerini kullanıyorsunuz? Bu kullanım sıklığı yıllar içinde nasıl değişti?

C5: AR-GE süreçlerimizde 3D baskı teknolojilerini oldukça sık kullanıyoruz. Özellikle son yıllarda, teknolojinin gelişmesi ve maliyetlerin düşmesiyle birlikte kullanım sıklığımız artmıştır. Şu anda Valfsel Ar-Ge Merkezi bünyesinde yeni başlayan ve halihazırda yürüyen her projede 3D baskı teknolojilerinden mutlaka faydalanılmaktadır.

S6: Eklemeli imalatta sizi en çok zorlayan hususlar nelerdir?

C6: Eklemeli imalat sürecinde karşılaştığımız en büyük zorluklardan biri, baskı kalitesi ve toleransların yönetilmesidir. Özellikle karmaşık geometriye sahip parçaların doğru bir şekilde üretilmesi ve istenilen toleranslara uygun olması zor olabilir. Aynı zamanda fonksiyonel prototip üretmek ve prototip içinden su geçirmemiz gereken durumlarda 3D yazıcı ile üretilen parçalarda yer alana katmanlar arasından su sızabilmekte ve yapılan kontrollerin verimliliğini düşürebilmektedir. Ayrıca, baskı malzemelerinin özellikleri ve baskı parametrelerinin doğru bir şekilde ayarlanması gibi konularda da dikkatli olmamız gerekmektedir.

S7: Kullandığınız yazıcılarda ne gibi limitlerle karşılaşıyorsunuz?

C7: Kullandığımız yazıcılarda baskı hacmi, malzeme seçenekleri, baskı hızı ve hassasiyet gibi belirli limitler bulunmaktadır. Özellikle büyük ölçekli parçaların üretimi veya yüksek hassasiyet gerektiren uygulamalar için bu limitlerle karşılaşabiliriz. Bu nedenle, projenin gereksinimlerini dikkate alarak bünyemizde yer alan üç 3D yazıcıdan faydalanamadığımız durumlarda, dışarıdan hizmet almaktayız.

S8: Yazıcıları hangi ekipler, ne amaçlarla kullanıyor?

C8: Yazıcıları genellikle tasarım, mühendislik, üretim ekipleri tarafından kullanılmaktadır. Tasarım ve mühendislik ekipleri prototip üretimi, parça ve bileşen üretimi için kullanırken, üretim ekibi aparat üretimi veya özel parça üretimi için 3D yazıcılardan faydalanmaktadır.

S9: Maliyetler konusunda bir planlamanız var mı? Maliyet konusu yazıcıların kullanılmasını nasıl etkiliyor?

C9: Maliyetler konusunda bir planlama yapıyoruz ve baskı malzemesi, baskı süresi ve işgücü maliyetleri gibi faktörleri dikkate alarak maliyetleri minimize etmeye çalışıyoruz. Maliyetlerin kontrol altında tutulması, 3D yazıcıların daha sık ve verimli bir şekilde kullanılmamızı sağlamaktadır.

S10: 3D yazıcıların AR-GE sürecinde hangi amaçlarla kullanıyorsunuz, süreçte ne gibi avantajlar sağlıyor?

C10: 3D yazıcılar AR-GE süreçlerimizde hızlı prototipleme, iterasyonların hızlıca yapılması, tasarım doğrulaması ve özelleştirilmiş parça üretimi gibi avantajlar sağlamaktadır. Bu sayede ürün geliştirme sürecini hızlandırılıp, maliyet avantajı olan daha rekabetçi ürünlerin pazara sunulmaktadır.

S11:Eklemeli imalat yöntemleriyle prototipleme dışında bir ürün ya da ürün parçası üretiyor musunuz ya da üretmeyi planlıyor musunuz?

C11: Evet, prototipleme dışında özel parçaların üretimi, yedek parça üretimi, özel fonksiyonlara sahip parçaların üretimi gibi farklı uygulamalar için de 3D yazıcıları kullanıyoruz. Ayrıca, ürün geliştirme sürecinde elde edilen bilgileri kullanarak seri üretim için de 3D baskı teknolojilerini kullanmayı planlıyoruz.

S12: Eklemeli imalatın son ürün üretimindeki dezavantajları nelerdir?

C12: Eklemeli imalatın son ürün üretiminde karşılaşılan dezavantajlar arasında baskı kalitesi, üretim hızı, malzeme maliyetleri ve baskı malzemelerinin mekanik özellikleri gibi faktörler bulunmaktadır. Özellikle büyük ölçekli ve yüksek hacimli üretimlerde geleneksel üretim yöntemleri genellikle daha verimli olabilir.

S13: Eklemeli imalatın geleceğini nasıl görüyorsunuz?

C13: Eklemeli imalatın geleceğini oldukça parlak görüyoruz. Sürekli olarak gelişen teknolojiler ve malzemelerle birlikte, 3D baskının daha geniş endüstrilerde ve uygulama alanlarında kullanılacağını düşünüyoruz. Bu teknolojinin daha da yaygınlaşmasıyla birlikte, üretim süreçlerinde büyük verimlilik ve esneklik sağlayarak endüstriyel dönüşümü hızlandıracağını öngörüyoruz.

APPENDIX F : Translated Transcript of Expert Interview with Expert C

Q1: What is your primary purpose of utilizing 3D printers?

A1: A wide range of 3D printers are used in our company R&D center processes, and we currently have three 3D printers. Primarily, we use these printers for the evaluation of designs and prototype production of armature parts before mass production. Producing prototypes quickly and cost-effectively provides a great advantage in accelerating design iterations and accelerating the process of introducing new products to the market. We also use 3D printers for the production of custom parts and components. This is especially beneficial in situations such as the production of parts with complex geometry or the production of functional prototypes.

Q2: Do you use FDM, SLA or SLS technologies in the product development process?

A2: Indeed, our product development process incorporates various 3D printing methods, including FDM, SLA, and SLS. We select the most appropriate technology for our projects based on the benefits and applications of each option. For example, while FDM is generally preferred for the production of parts with structural strength, SLA is more suitable for the production of parts requiring high detail.

Q3: What kind of parts do you use these technologies for?

A3: We often use these technologies for the production of parts with complex geometry. In particular, we use these technologies for parts such as functional prototypes, armature components, and special assembly components.

Q4: When selecting professional printers and desktop printers, what factors do you consider?

A4: Professional printers generally have larger print volumes, higher print quality and more material options. Therefore, we often choose professional printers for large-scale projects or the production of complex parts. However, desktop printers can also be used depending on the scale and requirements of the project.

Q5: How frequently do you use these AM technologies? How has this frequency of use changed over time?

A5: We use 3D printing technologies quite frequently in our R&D processes. Especially in recent years, our frequency of use has increased with the development of technology and decreasing costs. Currently, 3D printing technologies are used in every project that has just started and is currently ongoing within our R&D Center.

Q6: What are the most challenging issues for you in AM?

A6: One of the most challenging difficulties we encounter in AM is maintaining print quality and tolerances. Parts with complicated geometry, in particular, might be challenging to manufacture properly and within the tolerances required. At the same time, in circumstances when we need to produce a working prototype and run water through it, water can leak between the layers of 3D printed parts, reducing the efficiency of the controls. We also need to be careful about issues such as the properties of printing materials and the correct setting of printing parameters.

Q7: What limitations do you experience with the printers you use?

A7: The printers we utilize have limitations, such as printing volume, material options, printing speed, and sensitivity. We may run across these limitations, particularly when producing large-scale parts or applications that require high precision. As a result, based on the project's requirements, we outsource services when we cannot use our three 3D printers in-house.

Q8: Which teams use the printers, and for what purposes?

A8: Printers are generally used by design, engineering and production teams. While design and engineering teams use 3D printers for prototype production, parts and component production, the production team uses 3D printers for apparatus production or special parts production.

Q9: Do you have a cost plan? How does the cost of printers impact their usage?

A9: We create a cost-cutting strategy that considers aspects such as printing material, printing time, and labor costs. Keeping prices low enables us to use 3D printers more frequently and efficiently.

Q10: What are the applications of 3D printers in the R&D process, and what benefits do they provide?

A10: 3D printers improve our R&D processes by enabling rapid prototyping, rapid iterations, design verification, and customized part production. This accelerates the product development process and introduces more competitive, cost-effective items to the market.

Q11: Do you manufacture or intend to produce a product or product part other than prototypes using AM methods?

A11: Yes, in addition to prototyping, we employ 3D printers for a variety of applications, including the manufacturing of specific parts, spare parts, and parts with unique functionalities. We also intend to use 3D printing technology for mass production, utilizing information gathered during the product development process.

Q12: What are the disadvantages of AM in end product production?

A12: Disadvantages encountered in the final product production of AM include factors such as printing quality, production speed, material costs and mechanical properties of printing materials. Conventional production methods can often be more efficient, especially in large-scale and high-volume production.

Q13: How do you envision the future of AM?

A13: We believe the future of AM is quite bright. With constantly advancing technology and materials, we believe 3D printing will be employed in a broader range of sectors and applications. We anticipate that when this technology becomes more widely adopted, it will speed up industrial change by increasing efficiency and flexibility in manufacturing processes.

APPENDIX G : Original Transcript of Expert Interview with Expert D

S1: Projede 3B yazıcıları hangi alanda kullandınız?

C1: Donanım gerektiren girişim projelerinde her zaman ürün için bir kasaya ihtiyaç duyuluyor. Ürünümüzün elektronik tasarım detayları netleştikten sonra ilk işimiz buna uygun bir kasa/kabuk tasarımı yapmak oldu, bu kasayı da 3B baskı yöntemiyle ürettik. O dönem elimizde FDM ve SLA cihazlar vardı. Ürünümüz dış mekânda kullanılacağı için, aynı zamanda kısa sürede ve çok sayıda üretim yapmak istediğimiz için FDM cihazların projemiz için daha avantajlı olacağına karar verdik. Bu sebeple 3B baskı sürecinde FDM cihazlarımızı kullandık. Bunlar Ultimaker S5, Ultimaker 3, Ender gibi standart, bilindik cihazlardı.

S2: 3B yazıcılar sizin projenizde ne gibi avantajlar sağladı? Sizce başka potansiyelleri var mı?

C2: Tasarım sürecimizde 3B tekniği kullanmak bizim için çok önemliydi, çünkü sıfırdan başlanan bir donanım geliştirme projesinde mutlaka POC (Proof of Concept) yapmak gerekiyor. Bu süreçte donanımda çok fazla değişiklik yapılması gerekiyor. Sensör, kart, pil gibi bileşenlerdeki değişikliklerden vb. kaynaklı ürün boyutu değişebiliyor. Dolayısıyla kalıp kullanımı gibi maliyetli bir sürece yatırım yapmadan önce mutlaka ondan çok daha az maliyetle, az adetli 3B denemeleri yapmak maddi anlamda avantaj sağlıyor.

S3: Sizce 3 boyutlu yazıcılar ARGE sürecine ne gibi katkılar sağlıyor?

C3: Bizim projemiz için de bahsettiğim gibi tasarım sürecinde deneme-yanılma aşamasında hazırlanan prototiplerin final ürüne yakın kalitede fiziksel halde denenebilmesi açısından fayda sağlıyor.

S4: Prototipleme dışında 3B teknolojilerinin tercih edildiği üretim aşamaları var mı?

C4: FDM baskı için hizmet verdiğimiz başka firmalar da var. Bu firmalar için dış kabuk tasarımı haricinde, iç mekanizmada kullanılacak parçaları da FDM ile ürettik çünkü bahsettiğim parçalar konvansiyonel yöntemle üretilemeyecek, kompleks yapıda ve kalıptan çıkamayacak tasarımlardı. Böylelikle prototip değil, doğrudan piyasaya sürülecek, bitmiş ürünlerde de FDM parçalar kullanılmış oldu. İç mekanizma parçalarına sonrasında bir işlem uygulamadık. Dış kabuk tasarımında da 3B üretim sonrası yüzeyde oluşan tırtıklı dokuyu pürüzsüzleştirmek için epoksi bazlı boya astarı üzerine boya uyguladık.

S5: 3B baskı teknolojilerini en çok hangi firmalar tercih ediyor?

C5: Özellikle fiziksel ürün üreten firmalar için 3B teknolojilerinin kullanımı çok kritik olmakla birlikte bazı durumlarda sadece yazılım odaklı çalışan şirketlere de fayda sağlayabiliyor. Örneğin, 2018 yılında çalıştığımız bir oyun şirketi ile çalıştık. Bir kick-starter projesi için oyun karakterlerinin figürlerini üretmek istiyorlardı, ancak üretilecek figür miktarı fazla olmadığı için kalıpla üretim çok maliyetli olacaktı. Bu sebeple SLA baskı ile üretimi tercih ettiler.

S6: FDM ve SLA teknolojilerinin farkları nelerdir? FDM teknolojisini kullanarak prototipinizi imal etmenizin sebebi nedir?

C6: FDM tercih ediyoruz çünkü kimyasal olmadığından kokusu yok ve post-process süreci daha zahmetsiz. SLA için gerekli olan alkol banyosu, UV cure süreçlerinde hem uygulama esnasında hem de uygulama sonrası atıkların ortadan kaldırılmasında çok fazla ekipman ve zahmet gerektiriyor. Bu sebeple, FDM çok daha hızlı ve pratik.

S7: Hangi malzemeleri kullanarak prototiplemeyi yaptınız?

C7: Materyal olarak ABS kullanmamızın sebebi de Acetone Vapor-Bathing yapabiliyor ve Surface Finishing verebiliyor olmamız. Böylelikle gözeneksiz bir yapıya getirdiğimiz ürünün su geçirimsizliği ile ilgili şüphemiz kalmıyor. Sonrasında da ürün üzerine boya uygulayarak, ürün yüzeyinde UV hasarı oluşmasının önüne geçtik. Buna alternatif olan PLA materyalinin finishingi etil asetat ile yapmak gerekiyor ve bu asetona göre daha tehlikeli bir kimyasal. Aynı zamanda, PLA materyalinin UV dayanımı düşük olduğu için ABS tercih ettik.

S8: Süreçte ürettiğiniz ürünler ile son ürün arasındaki farklar nelerdir?

C8: Son ürünün daha az parçalı şekilde enjeksiyon kalıptan çıkabilmesi için tasarım detayları değişebiliyor, birtakım optimizasyonlara gidilebiliyor. Bazı uygulamalardan vazgeçilebiliyor, örneğin logonun ürün yüzeyi üzerine 3B baskısını 3B teknolojisi ile kolaylıkla yapabiliyorken kalıpla üretimde bu zorlaştığı için bu detayı kaldırmamız gerekmişti. İkinci olarak, tasarımımız üzerinde değişiklik yapma şansımız neredeyse bitiyor. Çünkü baştan bir kalıp üretimi yapmak mümkün olmuyor. Yüzey kalitesi anlamında ise 3B teknolojisi ile enjeksiyon kalıptan çıkan ürünler arasında gözle görülür bir fark yok.

S9: Ürünün tasarım aşamasında çıktı kalitesini arttırmak için ne gibi yöntemler kullandınız?

C9: Yazıcının güçlü ve zayıf noktalarını bilmek çok önemli. Bunlardan birincisi baskı makinelerini kalibre ve kontrol etmek (Kayış gerginliği, nozzle tıkanmaması, tabla kalibrasyonu vb.) İkincisi, bazı orta kalite baskı makinelerini modifiye ederek daha verimli çalışır hale getirmek (Extruder (filamenti iten parça) değişikliği, nozzle çapı değişikliği vb.) Tasarım yaparken de 1mm daha ince çizmemek, açıları desteksiz baskı alabilecek şekilde planlamak.

C10: Çıktı aldıktan sonra herhangi bir üretim sonrası yöntem kullandınız mı?

S10: Acetone Vapor Bathing denilen bir yöntem var. Asetondan etkilenmeyen bir container içine bir miktar aseton döküyoruz ve hava sirkülasyonu için tercihen bir fan koyuyoruz. Container içine bir tel ızgara ve üzerine de 3B parçayı yerleştiriyoruz. Aseton düşük sıcaklıkta buharlaşabilen bir madde olduğu için kapalı kutu içinde buharlaşıp hava sirkülasyonu sayesinde ABS materyalinin bağlarını koparıp kimyasal olarak yüzeyin çözünmesini sağlıyor. Sonrasında parçayı kutudan çıkardığımızda yüzey havayla temas edip yüzey arası boşluklara dolan aseton buharlaştığında yüzeydeki polimerler tekrar zincir oluşturuyor ve yüzey pürüzsüzleşiyor. Wet Sanding denen bir yöntem de var, PLA için bunu tercih ediyoruz. Parçanın yüzeyini ve zımparayı ıslatarak yüzeye zımparalama yapılıyor. Sonrasında üzerinde cila uyguluyoruz.

S11: Destek kullanımının azaltılmasının avantajları nelerdir? Desteksiz bir şekilde baskı almak için ne gibi yöntemler denenmelidir?

C11: Destek kullanımı azaltmak daha hızlı ve daha az malzemeyle üretim yapabilmek anlamında kritik. Bunun için öncelikle tasarımı yaparken açıları en az destek kullanılabilecek şekilde kurgulamaya özen gösteriyoruz. İkinci olarak belli aşamalarda baskıyı durdurup destek yerine aradaki boşluklarla aynı boyutta ahşap bloklar yerleştirerek baskının desteğe ihtiyaç duymadan devam etmesini sağlıyoruz. Ahşap tercih etmemizin sebebiyle metaller gibi sıcaklıktan etkilenip ısınarak baskıya zarar vermemesi.

APPENDIX H : Translated Transcript of Expert Interview with Expert D

Q1: In what areas did you employ 3D printers in your project?

A1: In hardware-intensive startup companies, a product case is always required. After the electronic design specifics of our device were resolved, our first task was to design an appropriate case/shell, which we produced with 3D printing technology. At the time, we used FDM and SLA devices. Because our product would be utilized outside and we need to produce big quantities quickly, we felt that FDM devices would be better suited to our project. As a result, we utilized our FDM equipment in the 3D printing process. These were standard devices, such as the Ultimaker S5, Ultimaker 3, and Ender.

Q2: What advantages did 3D printers provide for your project? Do you believe they have other potential?

A2: It was critical for us to include 3D techniques in our design process because, in a hardware development project starting from scratch, POC (Proof of Concept) is definitely required. During this process, various hardware modifications are required. The size of the product may vary according to the components used, such as sensors, cards, batteries, and so on. As a result, before engaging in a costly process such as the usage of molds, it is more cost effective to make 3D drafts in small quantities. In addition to 3D printing, ready-made plastic injection (ABS) cases are available. If the size of the internal components of the product are suitable, these scenarios can also be favored. We also used these cases during the project development phase, but in order to fit the electronics inside the box, we designed a shelf system that used FDM printing to attach the electronics to these prefabricated cases.

Q3: What contributions do you think 3D printers offer to the R&D process?

A3: As I mentioned for our project, it is advantageous to be able to physically test prototypes created during the trial-and-error phase of the design process at a quality level close to the final product.

Q4: Are there any production stages where 3D technologies are preferred over prototyping?

A4: There are other companies we serve for FDM printing. Apart from the outer shell design for these companies, we also produced the parts to be used in the internal mechanism with FDM, because the parts I mentioned were designs that could not be produced by conventional methods, had a complex structure and could not be removed from the mould. In this approach, FDM parts were used in final products that were sold directly to the public rather than prototypes. We did not apply any treatment to the internal mechanism parts afterwards. In the outer shell design, we applied paint over epoxy-based paint primer to smooth the jagged texture that formed on the surface after 3D production. At the same time, there were cases where we used the 3D technique to speed up the process on the production line. For example, in PSB production, machine sorting cannot be done in small quantity production and the products are sorted manually. For this, it is necessary to apply metal paste to the products. We produced 3D molded sheets to be used when applying paste and ensured that the process was error-free and quick.

Q5: Which companies prefer 3D printing technologies the most?

A5: Although the utilization of 3D technologies is crucial, particularly for organizations that manufacture tangible products, it can also assist companies that focus primarily on software. For instance, we collaborated with a game firm in 2018. They intended to produce game character figures for a Kickstarter project, but mold production would be extremely expensive due to the small quantity of figures required. As a result, they preferred production using SLA printing.

Q6: What is the difference between FDM and SLA technologies? Why did you use FDM technology to produce your prototype?

A6: We decided on FDM since it is chemical-free, has no smell, and the post-processing process is effortless. The alcohol bath required for SLA necessitates extensive equipment and effort to eliminate waste both during and after application in UV curing processes. As a result, FDM is faster and more efficient.

Q7: Which materials did you use for prototyping?

A7: The reason we chose ABS as a material is to do Acetone Vapor-Bathing and Surface Finishing. As a result, we have no concerns about the water impermeability of our product, which has a non-porous structure. We then painted the product to avoid UV damage to its surface. The alternative, PLA material, must be completed with ethyl acetate, a more dangerous chemical than acetone. At the same time, we used ABS because PLA has limited UV resistance.

Q8: What are the differences between the products you produce in the process and the final product?

A8: In order for the final product to come out of the injection mold with fewer parts, design details can be changed and some optimizations can be made. Some applications can be dispensed with, for example, while we could easily 3D print the logo on the product surface with 3D technology, we had to remove this detail as this became difficult in mold production. Second, we're almost out of chances to make changes to our design. Because it is not possible to produce a mold from scratch. In terms of surface quality, there is no visible difference between 3D technology and injection molded products.

Q9: How did you increase the product's output quality throughout the design phase?

A9: It is crucial to understand the printer's strengths and weaknesses. The initial task is to calibrate and control the printing machines (belt tension, nozzle clogging, table calibration, etc.). The second step is to improve the efficiency of some medium-quality printing machines by changing the extruder (the portion that pushes the filament), nozzle diameter, and so on. When designing, it is important to avoid drawing 1mm thinner and to plan the angles so that the product can be printed without support.

Q10: Did you apply any post-production techniques after printing?

Q10:There is a method known as Acetone Vapor Bathing. We pour some acetone into a container that is unaffected by acetone and, preferably, place a fan for air circulation.

We insert a wire grid into the container and set the 3D part on it. Because acetone can evaporate at low temperatures, it evaporates in the closed box and, due to the flow of air, breaks the bonds of the ABS material, chemically dissolving the surface. When we remove the item from the box, the surface comes into contact with air, and the acetone that fills the gaps between the surface evaporates, causing the polymers on the surface to form chains again and the surface to smooth out. There is also a method called Wet Sanding, we prefer this for PLA. Sanding is done by wetting the part's surface and using sandpaper. Then we put polish on it.

Q11: What are the benefits of lowering support usage? Which methods should be tried for printing without support?

Reducing support is crucial for producing faster and with less material. As such, when designing, we take care to construct the angles in a way that requires the least amount of support. Secondly, we stop the printing at certain stages and place wooden blocks of the same size as the gaps in between instead of support, ensuring that the printing continues without the need for support. We use wood because it is not affected by temperature and can become heated like metals without damaging the print.

Q12: What do you think about the future of 3D printing?

A12: I believe printing devices should be more user-friendly. An investment is made and a printing machine is acquired, however it is not used due to mechanical issues. Devices must be able to notify the user of these issues. SSL powder machines, SLA resin machines, and FDM may represent the future of these technologies, but post-processing steps must be accelerated and simplified. Powder machines will be preferred in the future because there is no support issue, the powder can be reused, and some models can print many materials.

APPENDIX I : Consent Forms of Pilot Study

24.04.2024

ONAM FORMU

İTÜ Endüstriyel Tasarım Bölümünde 2021/2022 Güz Yarıyılında Dr.Öğr.Üyesi Elif Küçüksayraç tarafından yürütülen "EUT220E: Industrial Design Studio I" dersi kapsamında kısa grup projesi ile ilgili aşağıdaki görselin ilgili akademik rapor ve yayınlarda yer almasını kabul ediyorum.

CONSENT FORM

I accept that the following visual regarding the short team project completed within the scope of the "EUT220E: Industrial Design Studio I" course conducted by Asst.Prof.Dr. Lecturer Elif Küçüksayraç in the 2021/2022 Fall Semester at ITU Industrial Design Department, will be included in the relevant academic reports and publications.

Name, Surname:	
Signature:	

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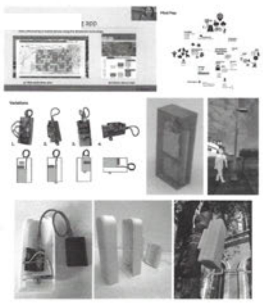

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PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS:

- Taştan,N., Özgen, C., Türkmenoğlu Berkan, S., Erciş, E., Dalyanoğlu, A., Türeyengil,B., Çınar Balcı E., **Keleş, A. F.**, (2023). 5. Uluslararası Afet ve Dirençlilik Kongresi dahilinde "Papers of iDRC 2023" bildiri kitapçığındaki "Deprem sonrası iletişim ve koordinasyon durum tespitine yönelik bir araştırma." 139-143 pp., Kocaeli,Türkiye.Gebze Teknik Üniversitesi,11-13 October 2023, ISBN: 978-605-72775-2-7