Development of a Digital Rapid Training Course for Improving the Additive Manufacturing Adoption Rate - Fused Filament Fabrication

by

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Declaration

By submitting this thesis electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the sole author thereof (save to the extent explicitly otherwise stated), that reproduction and publication thereof by Stellenbosch University will not infringe any third-party rights and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

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Abstract

Additive Manufacturing (AM) technologies, such as Fused Filament Fabrication (FFF), have a slow adoption rate. Training on these AM technologies is typically not included in primary to tertiary education curriculums and studies have shown that the lack of education on it, negatively affects the adoption rate. This issue was addressed in this study by developing a digital rapid training course on FFF.

A literature study was first performed to gain a better understanding of the different AM technologies and the adoption thereof. The focus was then shifted to a set of learning methods and platforms that are used in the educational sphere. After completing the literature study, it was concluded that training users in FFF can help improve the adoption rate of the technology.

The knowledge gained through the literature study was then used to develop a cross-platform digital training course (Web, iOS, and Android), aimed at introducing users to and educating them in FFF. The course consists of teaching sessions, tests, and questionnaires. The course was made available to the general public (free of charge) for a year with no specific target group, allowing users with and without FFF experience to participate. The training course automatically gathered quantitative and qualitative data by recording users' answers during tests and questionnaires respectively. The course was completed by 198 participants.

This data was then analysed to determine whether the training course increased the users' knowledge of, confidence to engage with, and likelihood to adopt the FFF technology. From the group of participants, 87% claimed that their level of knowledge and understanding of FFF increased by participating in the course. The majority (94%) of the participants stated they are more likely to interact with the technology after participating. The users with no prior knowledge/experience with the technology were found to have benefited the most from the course. Such individuals can be targeted during the development and deployment of AM courses to have the biggest impact on the adoption rate.

It was concluded that the training course increased the majority of users' knowledge of, confidence to engage with, and likelihood to adopt the FFF technology.

Opsomming

Additive Manufacturing (AM) tegnologieë, soos Fused Filament Fabrication (FFF), het 'n stadige aannemingstempo. Opleiding oor hierdie AM tegnologieë word tipies nie by primêre tot tersiêre onderwyskurrikulums ingesluit nie. Studies het getoon dat die gebrek aan onderrig oor die onderwerp ‘n negatiewe invloed op die aannemingsyfer het. Dié kwessie is in hierdie studie aangespreek deur 'n digitale opleidingskursus oor FFF te ontwikkel.

'n Literatuurstudie is eers uitgevoer om 'n beter begrip van die verskillende AM-tegnologieë en die aanneming daarvan te verkry. Die fokus is toe verskuif na 'n stel leermetodes en platforms wat in die opvoedkundige sfeer gebruik word. Na voltooiing van die literatuurstudie, is die gevolgtrekking gemaak dat opleiding van gebruikers in FFF kan help om die aannemingstempo van die tegnologie te verbeter.

Die kennis wat deur die literatuurstudie opgedoen is, is toe gebruik om 'n kruis-platform digitale opleidingskursus (Web, iOS en Android) te ontwikkel wat daarop gemik is om gebruikers bekend te stel aan en hulle in FFF op te voed. Die kursus bevat onderrigsessies, toetse en vraelyste. Die kursus is vir 'n jaar beskikbaar gestel aan die algemene publiek (gratis), sonder 'n spesifieke teikengroep. Dit het gebruikers met en sonder FFF-ervaring toegelaat het om deel te neem. Die opleidingskursus het outomaties kwantitatiewe en kwalitatiewe data ingesamel deur gebruikers se antwoorde tydens onderskeidelik toetse en vraelyste aan te teken. Die kursus is deur 198 deelnemers voltooi.

Hierdie data is toe ontleed om te bepaal of die opleidingskursus die gebruikers se kennis van, selfvertroue om die FFF-tegnologie te gebruik, en die waarskynlikheid om dit aan te neem, verhoog het. Uit die groep deelnemers beweer 87% van hulle dat hul vlak van kennis en begrip van FFF toegeneem het sedert hulle die kursus voltooi het. Die meerderheid (94%) van die deelnemers het gesê dat hulle meer geneig is om die tegnologie te gebruik nadat hulle deelgeneem het. Daar is gevind dat die gebruikers, met geen vorige kennis van/ervaring met die tegnologie, die meeste by die kursus baat gevind het. Hulle kan geteiken word tydens die ontwikkeling en ontplooiing van AM-kursusse om die grootste impak op die aannemingstempo te hê.

Daar is tot die gevolgtrekking gekom dat die opleidingskursus die meerderheid van gebruikers se kennis van, selfvertroue om die FFF-tegnologie te gebruik, en die waarskynlikheid om dit aan te neem, verhoog het.

Acknowledgments

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Nomenclature

2D	-	Two Dimensional
3D	-	Three Dimensional
ABS	-	Acrylonitrile Butadiene Styrene
AM	-	Additive Manufacturing
AI	-	Artificial Intelligence
AMF	-	Additive Manufacturing File Format
App	-	Application
ARPANET	-	Advanced Research Projects Agency Network
CAD	-	Computer-Aided Design
CNC	-	Computer Numerical Control
CPDF	-	Cross-Platform Development Framework
CT	-	Computed Tomography
DBMS	-	Database Management System
DED	-	Direct Energy Deposition
DfAM	-	Design For Additive Manufacturing
DLP	-	Digital Light Processing
DNA	-	Deoxyribonucleic Acid
DOI	-	Diffusion Of Innovation
FFF	-	Fused Filament Fabrication
FDM	-	Fused Deposition Modelling
GHC	-	Gartner Hype Cycle
GPS	-	Global Positioning Systems
HTML	-	HyperText Markup Language
HTTP	-	Hypertext Transfer Protocol
I4.0	-	Industry 4.0 (4th industrial revolution)
IP	-	Internetwork Protocol
IT	-	Information Technology
LCD	-	Liquid Crystal Display
MRI	-	Magnetic Resonance Imaging
mSLA	-	Masked Stereolithography
MTA	-	Make-to-Assemble
MTO	-	Make-to-Order
MTS	-	Make-to-Stock
OBJ	-	Object model file
PBF	-	Powder Bed Fusion
PET	-	Positron Emission Tomography
PLA	-	Polylactic Acid
PVA	-	Polyvinyl Alcohol
R&D	-	Research and Development
SL	-	Sheet Lamination
SLA	-	Stereolithography
STL	-	Standard Tessellation Language
SM	-	Subtractive Manufacturing
SME	-	Small and Medium-sized Enterprises
TCP	-	Transfer Control Protocol
URI	-	Uniform Resource Identifier
URL	-	Uniform Resource Locators

UV	-	Ultraviolet
WWW	-	World Wide Web
XML	-	Extensible Markup Language

1. Introduction

In this introductory section, a brief background on the research topic is provided. This is followed by the project's problem statement, research questions and objectives, research methodology, project scope and limitations, and this document's outline.

1.1. Background

Additive manufacturing (AM), commonly referred to as 3D printing, is one of the fastest-growing methods of manufacturing and has lately increased in market size by at least 15% annually [1]. AM emerged commercially in 1987 and the Fused Deposition Modelling (FDM) process was invented in 1988 by Scott Crump and patented in 1989 [2]. He used his experience with low melting plastics and thermofusion control mechanisms to invent this AM technology that doesn't require lasers or materials that are difficult to handle as with stereolithography (patented in 1986 by Charles W. Hull)[3][4].

FDM, also known as Fused Filament Fabrication (FFF), now accounts for almost 50% of the actively used 3D printing technologies, likely due to its affordability and desktop form factor [5]. The main uses for AM are prototyping, production, and proof of concept, which are key stages in product development [6]. AM has much to offer with its range of advantages over traditional manufacturing processes. The adoption of the technology can, however, be hindered by the time and cost of switching to and integrating the new manufacturing process. The individuals who are exposed to and educated in AM throughout their primary to tertiary education are in the minority [7]. The media also tends to portray AM as a magical and futuristic technology that can rapidly produce anything for the consumer [8]. This potentially encourages false expectations of the technology's current capabilities, availability, and affordability.

Materialise, a Belgian AM company, surveyed Chinese manufacturers to hear their thoughts on the adoption of AM, as they are a global leader in manufacturing. The majority of them look forward to the advantages AM has to offer over that of more traditional manufacturing technologies. These include freedom of design, customization, and faster go-to-market, only to name a few. When asked about the perceived limitations of the technology, 41% of the manufacturers believe that the lack of technical expertise is a hurdle to adopting the technology. The limited material availability, machine cost, and material cost were also listed to be hurdles to adopting the technology by 49%, 42%, and 39% of the manufacturers respectively [9]. *Stratasys*, a company co-founded by Scott Crump, also conducted a survey where they reached out to 700 dedicated professionals in the AM industry. The "lack of expertise and/or training among workforce/employees" also surfaced as a challenge of AM that has to be overcome when adopting the technology [10].

A study was performed by Deloitte Insights where extensive interviews were performed with industry experts and academic institutions to identify the current opportunities and issues that are prevalent in raising the next generation of AM professionals. They found that the lack of skill in the workforce is a large hindrance to the adoption rate of AM, effectively forfeiting the potential of AM and its advantages over traditional manufacturing processes. It was concluded in the study that this skill gap and slow adoption rate can be addressed by establishing partnerships between the industry and academia, where the focus is placed on the education and training of individuals [11].

1.2. Problem Statement

Additive manufacturing technologies, such as Fused Filament Fabrication, have a slow adoption rate, even though the technology has been available since 1987. Individuals are not typically trained throughout their primary to tertiary education to successfully engage with AM technologies. Design thinking for conventional manufacturing methods limits the application and true capabilities of additive manufacturing technologies. For the industry to fully utilise the potential of AM, the adoption rate of the technology must be improved.

1.3. Research Questions and Objectives

This research project aims to improve the adoption rate of AM, FFF in particular. There are different ways to incentivise the adoption of a technology. These include explaining the benefits of it to the target group, conducting pilot programs, marketing the technology, or providing potential adopters with the relevant training [12], [13]. It was decided to investigate whether a training course on FFF can help to improve the adoption rate thereof. The training course should ideally be quick to complete to help incentivise the potential adopters to engage with the course.

1.3.1. Research Questions

By answering the following research questions, the problem statement can be investigated and a conclusion can be drawn.

1. Can training be used to improve the adoption rate of AM technologies?
2. Can a digital rapid training course on FFF be developed and successfully deployed?
3. Does the training course increase the users' knowledge of FFF?
4. Does the training course increase the users' confidence to engage with and likelihood to adopt the FFF technology?

1.3.2. Main Research Objectives

To help answer the research questions that were posed, the main objectives of the study were set:

1. Understand the different AM technologies and the adoption thereof.
2. Identify and understand different learning methods and platforms that are used in the education sphere.
3. Develop a digital rapid training course on FFF to educate users on the technology.
4. Evaluate whether the training course can increase the users' knowledge of, confidence to engage with, and likelihood to adopt the FFF technology by analysing the users' performance and feedback.

1.3.3. Specific Research Objectives

The following objectives will not help to answer the research questions, but they will give insight into the users' experience with the training course.

- Investigate the effect of using different teaching methods and elements.
- Investigate whether users have identifiable preferences in engaging with the course.

1.4. Research Methodology

The structure of the research study is broken up into four major stages and presented in Figure 1.1. This is followed by a detailed discussion of each of these stages. The research methodologies that were used to achieve the objectives form part of these detailed discussions.

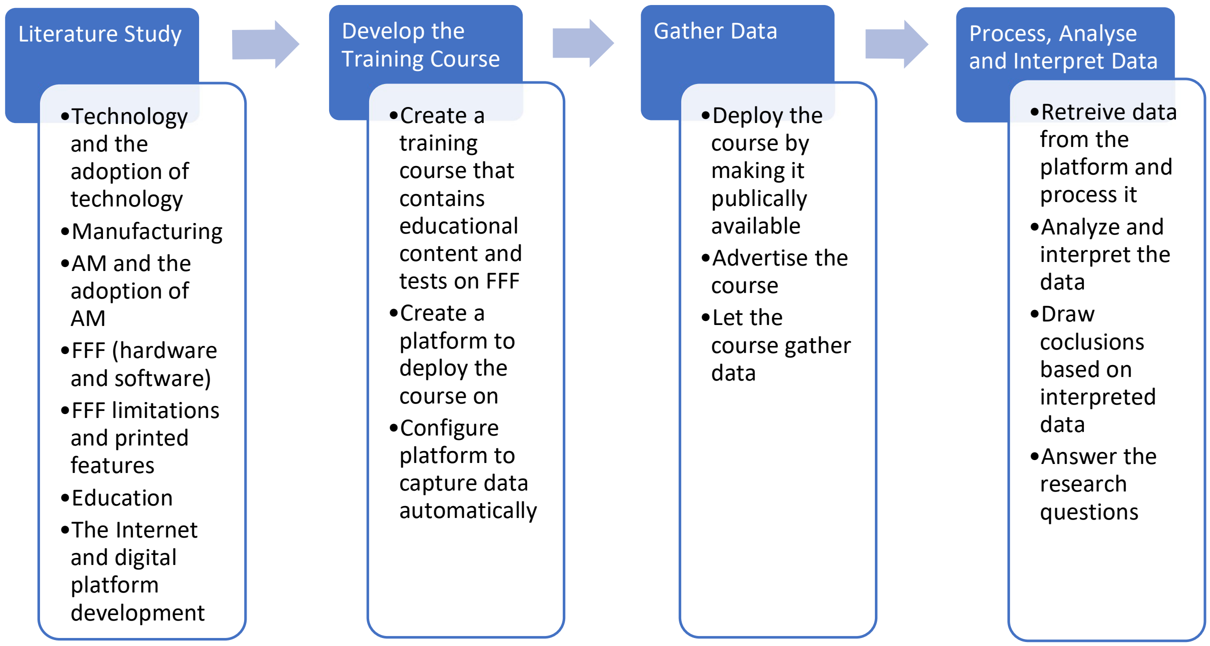


Figure 1.1: Four Major Stages of the Study

Literature Study

The first step to achieving the research objectives was to acquire a better understanding of the FFF technology and how a training course can be developed for it. This was achieved by studying the literature that is available on the different topics. The literature study is structured in such a way as to lead the reader from the basic principles of technology and education to the training of FFF. A brief background on technology, the adoption of technology, and an outline of the different categories of it was given as an introduction.

Manufacturing is one of the categories in technology that led the study to the different means of manufacturing where AM was introduced. After considering the different AM technologies, FFF stood out as the most adopter friendly which led to a detailed literature study of its hardware, software, limitations, and printed features.

After attaining a better understanding of FFF, the focus of the literature study was shifted to education, unique teaching methods and different learning environments. The E-learning environment was identified to have the widest user reach, making it ideal for the FFF training course. Finally, the literature on the different platforms, that E-learning can be distributed on, was studied. The literature study not only helped to develop the training course for FFF but also showed where it fits into society.

Develop the Training Course

The training course can be considered as an experiment and was structured around a mixed-method research methodology where both qualitative and quantitative data were gathered. The quantitative data consists of the users' test results where answers are either correct or incorrect. This data was used to determine whether the course successfully equipped the user with and/or increased their knowledge of FFF. The qualitative data was captured using questionnaires, in which users performed self-evaluations and provided feedback on the course.

Gather Data

The goal was to gather as much data as possible to gain maximum statistical power for the study. After making the course globally available to anyone with Internet access, it was advertised by distributing a flyer (Appendix E) on social media platforms. The AM communities/groups on these platforms were asked to further distribute the flyer within their sphere of influence. The training course was deployed for a year, capturing and storing the data automatically.

Process, Analyse and Interpret Data

After the data was retrieved, processed, analysed, and interpreted, conclusions were drawn. These conclusions were used to answer the research objectives. Based on the literature in Section 2.6, education can increase a user's knowledge, confidence, and experience in a specific field. It was deduced that this effect will lead to an increased adoption rate of a technology since users are more likely to engage with it.

1.5. Scope and Limitations

The scope of the project is defined by stating the inclusions and exclusions of the project. The ethical implications of the project were also considered to understand the project's limitations better.

Inclusions

The research project is based on the structure mentioned in the previous section. The training course was presented on three platforms namely; a website, an Android mobile application (app), and an iOS mobile app. The users were introduced to the FFF technology and trained in the basics with the main foci of the course being the digital model orientation and parameter selection in the slicer environment. The course's test questions were limited to the content provided in the course itself.

Exclusions

The literature study did not go in-depth into the adoption of all types of technology nor the detail of each AM technology that is available. Different training methods were considered, but only those used in the course were included in the literature study. Other AM training courses were researched to ensure that the newly developed course wasn't missing any major elements of FFF training, but the majority of its content was based on the literature study. The course content was not focused on any specific FFF machines (hardware), slicer packages (software), or different printing materials since there are too many combinations of the three, introducing too many variables into the study.

Even though the main focus of the course was on model orientation and parameter selection, it did not cover everything that is available on the topics. These limitations were incorporated due to the study's limited timeframe and to keep the course true to the "rapid" characteristic.

Ethical Implications

Ethical clearance was required for the questionnaires that participants filled out before and after they completed the training course. A new user code was generated for each participant, which means the questionnaire and tests were anonymously completed. The questionnaire and tests were considered to be low-risk since completing them were no different to "daily life". There were no questions that would trigger discomfort for the participant. However, the study was declared as medium-risk since minors could also participate. The participant had to agree to a consent form (Appendix B) to participate in the course. The form clearly states that participation is completely voluntary and that participants could withdraw at any stage of the course. Since minors also had access to the course on the Internet, they had to agree to an assent form and their parent(s)/guardian(s) had to agree to a consent form, permitting the minor to participate. The minor could withdraw from the course at any stage and participation was completely voluntary. In summary, the course was not targeted at a specific group of individuals and none of their personal information was collected or used in the study.

1.6. Document Outline

Please refer to Figure 1.2 for an outline of the thesis to help navigate through the document. A brief description and motivation of each section follows after.

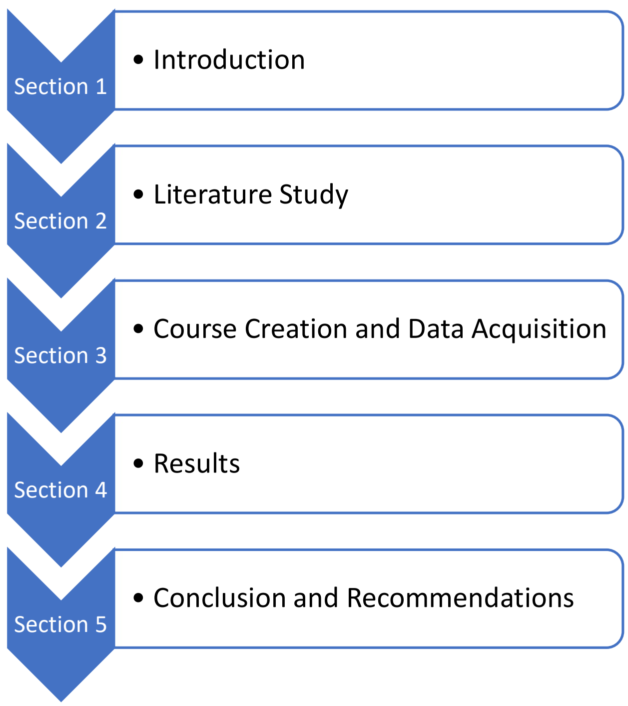


Figure 1.2: Thesis Document Outline

Section 1 - Introduction

This section provides some background to the research topic and presents the problem statement, research questions and objectives, research methodology, project scope and limitations, and finally this document outline. It helps the reader to orient themselves when reading the rest of the content.

Section 2 - Literature Study

The literature study provides the necessary information on the research topic to better understand the relevance and results of the study, enabling readers with no prior knowledge on the topic to also engage with it.

Section 3 - Course Creation and Data Acquisition

The reader is guided through the experiment steps that were taken and how the training course is structured. Examples of the course content are also provided to show how the teaching methods were implemented and the data was gathered.

Section 4 - Results

The quantitative and qualitative data is summarized, interpreted and discussed in the results section. The noticeable trends that were identified in the data are also stated and discussed in this section.

Section 5 - Conclusion and Recommendations

The research questions are answered and proof that the objectives were met, is provided. The final conclusion to the project is drawn and future work for this research topic is recommended.

2. Literature Study

A literature study was performed and is discussed in this section. It provides the reader with background knowledge and insight as to why the research is relevant, where it fits into society, and how it was addressed during the study. Please refer to Section 1.4 for a discussion on the structure and flow of the literature study. The aim of the literature is to achieve the first two research objectives.

2.1. Technology

Technology is defined in the English dictionary as "the branch of knowledge that deals with the creation and use of technical means and their interrelation with life, society, and the environment, drawing upon such subjects as industrial arts, engineering, applied science, and pure science" [14].

History of Technology

The Greek word *technē*, which means *art* or *craft*, and *logos*, translated as *word* or *speech*, were combined to establish the English term, technology. It was coined in the 17th century, but it wasn't used to the full extent as in our modern-day [15]. It was merely used when the concept of *art* was the point of discussion. The art pieces themselves were later referred to as technologies in the 20th century. People started using the term *technology* to also encapsulate ideas, means, and processes that were invented during that time, placing them next to the physical tools and machines. This merger of ideas and physical inventions under a single umbrella term was accompanied by some controversy as it became difficult to distinguish between the means of scientifically studying the world around them and studying the technological activities. When studying the history of technologies, one is limited to the evidence (whether it be man-made physical artefacts that are distinguishable from nature or trustworthy accounts) that is available on the topic. This means that our modern-day historical documentation of technologies is most likely not complete. The two main drivers of technological advancements in these historical civilizations were to reduce or eliminate threats (whether it be environmental or another civilization) and to tend to the needs of the people [16]. Even though the historical evidence may not be complete, one can still acquire a good understanding of the major advancements that were made in technology as they are more likely to have an impact on civilizations and their growth. A civilization's military, manpower, resources, agriculture, medical practices, economic systems, and architecture are some major areas where technology can have a large influence, making them prime fields of study when considering the history of technology [17]. Included is also manufacturing (industrial), communication and transport as they also make up for a large part of a civilization's technology. The general method of studying the technological innovations and the people's interaction with them in history, is to first consider the social construct and conditions of the time in chronological order. Thereafter, the aforementioned list of technological fields can be studied, followed by the final step of studying the sociocultural impact the technologies had. The general structure of this method remains the same when considering different eras and civilizations, but alterations can be made to accommodate new dynamics, resources and innovations [15].

A more challenging part of studying technologies that were introduced throughout history is the transmission (spread/distribution/conveyance/relaying) of them [18]. It became easier to communicate how technology spread and where it originated from since the printing press was commercially introduced in 1450 AD. Ironically, the printing press itself is an example of a powerful technology of which its origin and time of initial invention are unknown. The oldest piece of evidence is a printed book from 868 AD, discovered in Dunhuang, China [19].

Interaction between social and technological systems

As mentioned earlier, the majority of the technology's historical study includes social aspects that need to be considered. This is due to the interaction between technology and humans [20], which ties back into the two main driving factors of technological advancement (reduce/eliminate threats to humans and tend to their needs).

If a new innovation was introduced without the inventor considering the social interaction with it, widespread adoption would be negatively affected. The first of three social factors that the inventor would have to consider is "social need" [15]. They must not only ensure that the invention tends to the practical needs of the adopters, but also want to have/need it. This is an emotional reaction to the invention that needs to be stirred up by the inventor in the potential adopters if they wish to achieve widespread adoption [21]. It has been observed that periods of war drove technological advancement powerfully [22]. If there is a desire to stir technological advancement, improved military-based weaponry can be argued by the governing bodies which can then be supported by the people who now "feel" there is a need for it. For "social need" to be effective in the widespread adoption of new innovations, it is crucial that positive emotional connotation with it has traction and gains momentum amongst the people. An in-depth discussion on the adoption of technology can be found in Section 2.1.1. The social involvement is not limited to the adopters' side, since it also plays a role on the inventors' side. Their involvement is the main driving factor for the new invention to come to fruition. They can, however, be the most determined and ambitious inventor amongst their competitors, but if they do not have the necessary resources at their disposal, the invention will remain an idea. If the inventor does not have the required skills to produce/incorporate their invention themselves, they would have to bring in external workmanship. Skilled labour is a resource, but can also be considered as social involvement [15]. These skills will be lost if they are not transferred to the next generation by teaching and training them. Teaching/learning the use of new technology is further discussed in Section 2.1.3.

2.1.1. Adoption of Technology

New technologies have a wider spread effect on the human race as they are adopted by more people. Unlike the invention of a new technology that is seemingly a single event in time or jump in technological advancement, the adoption of technology is typically a slower and continuous process. It can be noted that different technological inventions have different rates of diffusion and acceptance amongst people [23]. Acceptance is the first step to adopting a new technology and can be described as the individual's attitude towards it. The successful integration and retention of the technology are referred to as the adoption of the new technology [24].

The diffusion of innovation theory

The diffusion of innovation (DOI) refers to the process of products, ideas, practices, etc., being adopted by people to incorporate it into their lives. According to historical records, Gabriel Tarde was the first to discuss the DOI theory in 1903. He was also the first to plot the diffusion S-curve (Figure 2.1) that was later detailed by Ryan and Gross in 1943 who added adopter categories. This helped to create the current DOI theory that was popularized by Everett Rogers. Adopters are categorised into groups of Innovators, Early adopters, Early majority, Late majority, or Laggers (Figure 2.2) [25].

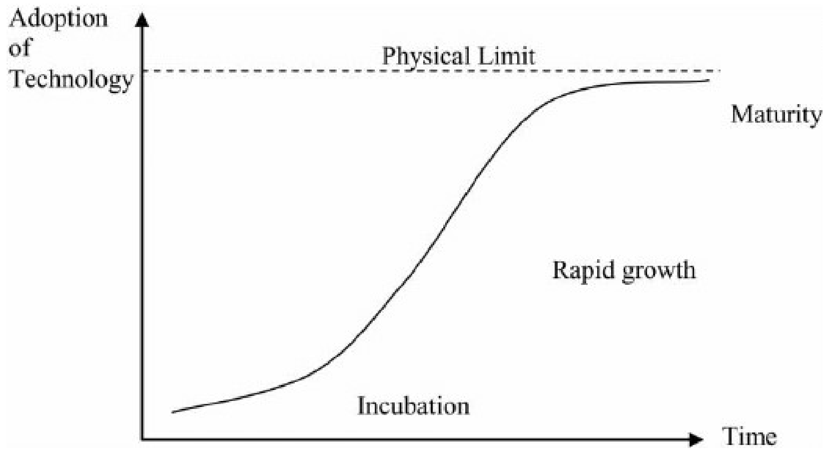


Figure 2.1: Diffusion of Innovation S-Curve [26]

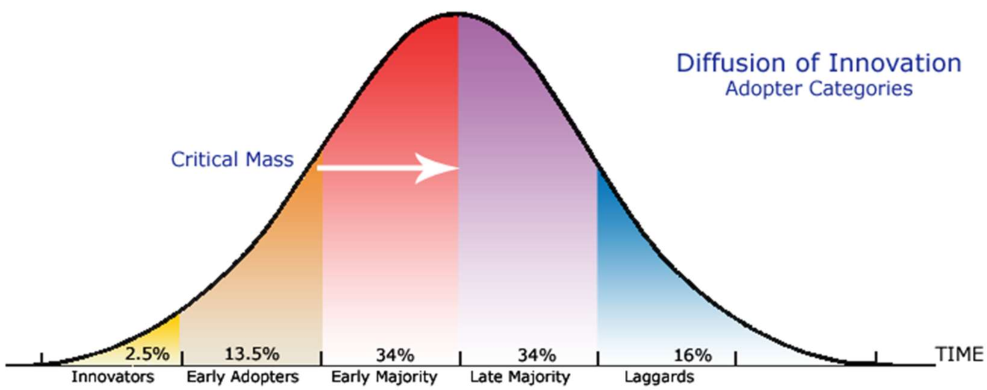


Figure 2.2: Diffusion of Innovation Curve [25]

Innovators are the few (2.5%) who are considered technology enthusiasts. They are willing to take a risk and try something new without the guarantee of the technology being a success. They have a better understanding of the technology's technical side than the general public which enables them to engage with it during its infant stages. Innovators can deal with potential flaws in the technology and adapt to the changes that are implemented by the inventor. These challenges are still worth it for the innovators as they are motivated by the potential they see in the invention and they have an appreciation for it. These innovators act as "gatekeepers" to the technology for the Early Adopters and they can educate their peers on the technology [25].

Early Adopters start engaging with the technology after the Innovators. This group (13.5%) is adventurous and willing to try new things. They may be willing to take the risk and spend more money on new products than the majority and end up being the trendsetters by adopting the technology earlier. They enjoy being first and can be described as visionaries who have a large influence on their peers' opinions. The peers can see the early adopters as role models in engaging with the technology and have a sense of trust in their opinion. The early adopters may have a less biased approach to the new technology than the innovators and are willing to be transparent about their positive and negative experiences with the technology to keep the trust amongst their followers [25].

Early Majority, also referred to as the pragmatist group (34%), are the adopters who are slightly more cautious when it comes to investing their money into a technology that hasn't been proven yet. They try to avoid taking unnecessary risks and adopting complexity. They also prefer to stay within their budget. Similar to Early adopters, they influence their peers, but they are more deliberate about reaching out. The peers trust their judgement as they perceive their careful choices as safer than that of Early Adopters and Innovators. The Early Majority require a more user-friendly introduction to the technology, after which they are confident in the use of it. They also reject frequent and major changes to it [25].

Late Majority refers to the more conservative group (34%) who take more caution when adopting a new technology. They only adopt the technology out of economic necessity and are sensitive to investing money. Consequently, they only prefer to adopt technologies that are well tested and proven over time in the industry. They are more influenced by the scepticism of the Laggers than the confidence of the prior groups, but they can see the need of keeping up with competitors in the industry. They are less confident with new technology and require extensive training in the most mature variant of the technology. A revision in the technology is perceived to be a completely new invention, where a false need of having to abandon all prior knowledge of the current variant. This causes a bad association with the adoption of a new technology [25].

Laggers are the most sceptical group (16%) who tend to isolate themselves from the opinion leaders and just maintain a status quo. They fail to see the potential that a new technology possesses and prefer to stick to the older way of doing things. They have a negative connotation to innovation which is supported by any negative experiences that the Late Majority group has. They will only invest in the technology after careful consideration of all alternatives and are found to be worse. The Laggers remain sceptical of the technology even after adopting it, but in time it becomes their new status quo [25].

The DOI theory can be used as a model to structure innovation in such a way as to better meet the needs of adopters in each of these categories. When considering these categories, it is clear that there is interaction between them and that they influence each other. If an inventor wants their innovation to spread quickly to each of these categories, consequently increasing the adoption rate, it is crucial to have good peer connections and communication established within the community [25]. The gap of accepting and integrating a new technology can potentially be bridged by providing individuals with the necessary training through easily accessible course material.

2.1.2. Technology Life Cycles

The lifecycle of a technology can also be considered from an economic standpoint in conjunction with the adoption stages as discussed in Section 2.1.1. The technology goes through four stages during its life cycle that can be correlated with revenue generated as shown in Figure 2.3.

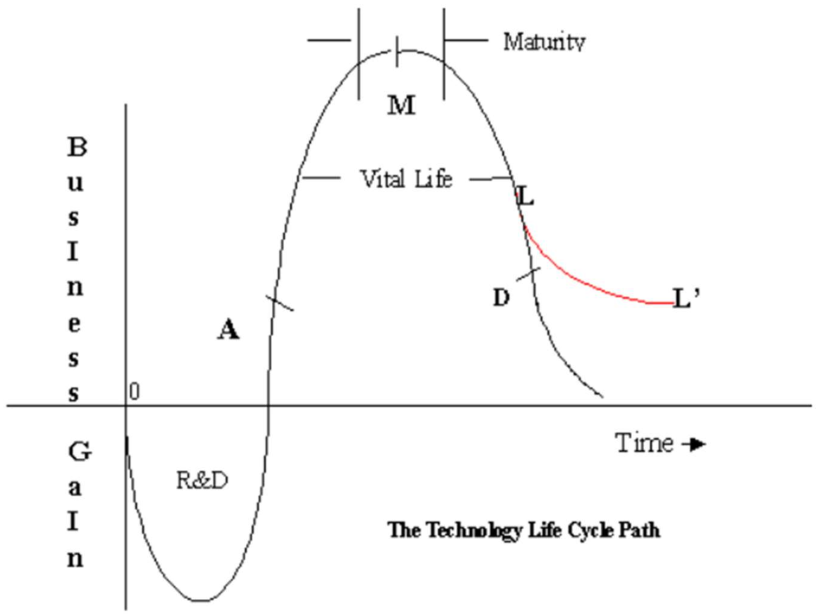


Figure 2.3: Technology Life Cycle vs Revenue Generated [27]

The first stage is Research and Development (R&D), also known as the Innovation stage [28]. As implied by the name, the inventor performs research in the field of their innovation and allocates the necessary resources to the development of it. No revenue is generated during this stage, making it a financial risk for the inventor/investors as there are few to no guarantees that the innovation will progress to the following stages where revenue can be generated.

The inventor has to work efficiently with the available resources and perform enough research to avoid any unnecessary expenses [27]. They can utilize industry standards and expertise as a safe basis for their innovation to be built upon to further minimize the risks [28]. The innovators mentioned in Section 2.1.1 can be approached, as soon as early prototypes are completed, to set the adoption (DOI theory) in motion [25].

As revenue is generated, by selling prototypes or early production units, a break-even point is reached where the cost of R&D is fully recovered. This is the Ascent phase (marked "A" in Figure 2.3) also known as the Syndication stage [28]. The market entry of the new innovation is encapsulated in this phase which means the inventor has to try and gain a competitive edge over those who also innovate in the same field. A large competitive edge is gained by entering the market first so the inventor has to market, hype, and distribute their product as quick and widespread as possible [27]. The early adopters mentioned in Section 2.1.1 are the most involved during this phase of the technology's lifecycle [25].

The early and late majority groups are the main adopters during the Maturity phase (marked "M" in Figure 2.3) of the technology which is also known as the Diffusion stage. The technology has reached a stable point in terms of generating revenue and the high adoption rate starts to plateau. Innovators can continue to make incremental changes and improvements to the technology to keep the adoption rates high for as long as possible before it becomes a common commodity [28]. This turning point in the technology's lifecycle corresponds with the supply surpassing the demand in the market [27].

The final phase of the lifecycle is referred to as the Decline phase (or Substitution stage) where the supply of the technology is reduced to match the demand which is undoubtedly dropping (marked "D" in Figure 2.3). The competitiveness in the market dissolves with the demand. The room for improvements and innovative updates to the technology also reduces and the cost thereof increases drastically. These costs cannot be justified as the revenue generation is dipping. This decline in sales is typically caused by the emergence of a new and efficient/effective (cost and or function) technology. The laggers mentioned in Section 2.1.1 are the only ones who are still adopting the technology. The technology has matured, but the innovators need to move their resources over to a new innovation, typically leaving the laggers without support [28].

Gartner hype cycle

Many trends can be identified in the realm of technology, whether it be within the scope of adoption, distribution, use, decline, refinement, or hype of the technology. A popular trend (not only limited to technology) is the Gartner Hype Cycle (GHC). The GHC profile can be identified in almost every new technology that is released. As the name entails, it has a strong connotation with the hype (or expectation) that surrounds the subject that is being studied over time. Gartner is an advisory firm that was founded in 1979 that helps to equip leaders in industry with the necessary business insight and strategies. Their client base of 14,000+ enterprises stretches across a variety of market sectors and industries in over 100 countries. Their main focus is on: Customer Service and Support, Finance, Human Resources, Information Technology, Legal and Compliance, Marketing and Communication, Product Management, Research and Development, Sale, Strategy, and Supply Chain [29].

The cycle consists of 5 stages namely; Innovation trigger, Peak of inflated expectations, Trough of disillusion, Slope of enlightenment, Plateau of productivity. These stages are indicated in Figure 2.4 and explained thereafter.

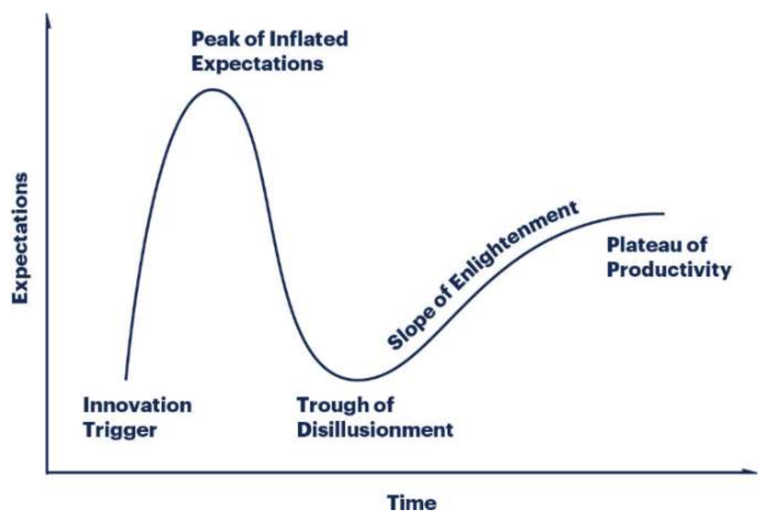


Figure 2.4: Five Phases of the GHC [30]

Innovation trigger

The moment a new technology's innovator decides to make their first idea/prototype public, it triggers the start of the GHC. It has to be noted that the prototypes and proof-of-concept designs have not been refined yet, but potential investors can be drawn in by making the early iterations public. The timeframe between "innovation trigger" and the "peak of inflated expectations" is when the technology is on the rise. The innovator/start-up company focuses on the R&D phase and aims to cater for the early adopters. The media is of such a nature that being the first to report on a new topic carries a lot of value. The innovator also wants to gain as much exposure as possible making it a mutually beneficial situation [31]. As soon as the media catches wind of a potential next hit in the market, they rush to be first in reporting on it. This causes a topic/technology to trend which is another focal point for the media (trending topics), causing it to gain even more publicity. Mass media hype surrounds the technology just before the "peak of inflated expectations" [32], [33].

Peak of inflated expectations

With the rapid increase in publicity and successful prototypes, the hype that surrounds the technology may exceed its actual performance and current success. If the innovator gets caught up in this hype, they may neglect the corrections that are needed during this growing phase. The hype cannot indefinitely continue to grow which means there must be a turning point. This is known as the peak of inflated expectations [32], [34]. Negative press on the technology starts to surface at the peak. People realise that the expectation of the technology exceeded that of the actual performance/capability/ quality/etc. and the media then rushes to report on it. The timeframe where the decline in expectation occurs can be described as "sliding into the trough". The supplier consolidation can start to fail and the innovator has to ensure that their funding doesn't dry up at this stage. They would apply for second and third rounds of venture capital funding and rely on the sales of early iterations as described earlier in this section.

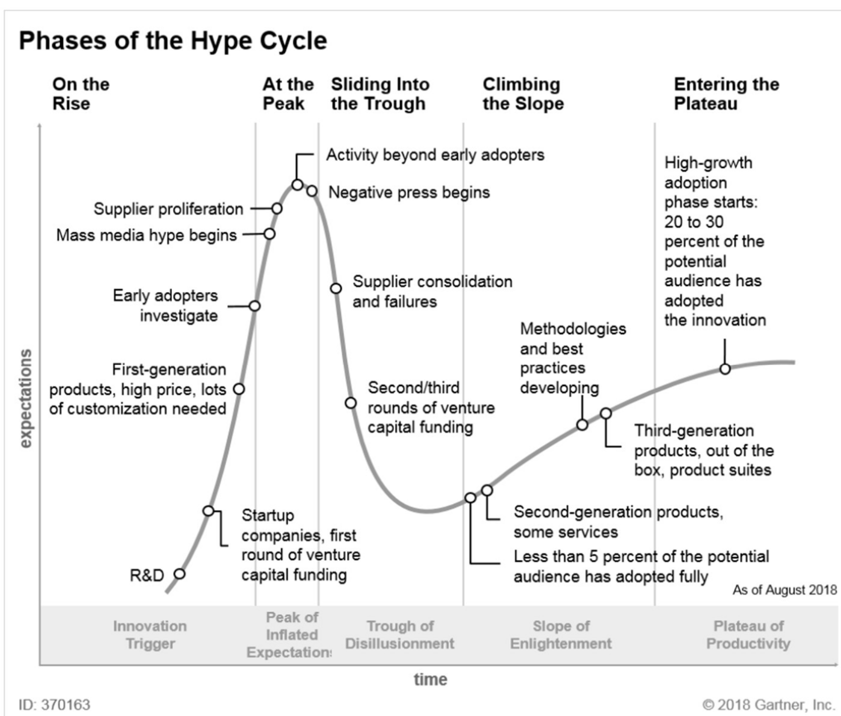


Figure 2.5: Detailed Phases of the GHC [33]

Trough of disillusion

As the hype around the new technology dies down in the media and the minds of investors/early adopters, the innovator has to prove that the technology is valid and can be successful (Figure 2.5). Even if the technology had a steady climb in development, there will typically be a drop in excitement and expectation since it was overinflated [32], [33].

Slope of enlightenment

The continual advancement and maturing of the technology are finally being realised and the public slowly (and steadily this time) gains interest again. Investors have more data to base their investment on as the innovator produces new generations/revisions of the technology and receives more feedback from the early adopters. This feedback is crucial in pointing out the value that the technology provides for the end-user and their experience when interacting with it. The technology's success stories increase [32]–[34].

As the technology "climbs the slope of enlightenment", second and third-generation products and services are released. Only a small percentage (around 5%) of the potential audience has adopted the technology at the start of the climb, but as the methodologies and best practices are refined, the adoption rate also increases (to 20%-30%) (Figure 2.5) [33].

Plateau of productivity

Similar to the hype that cannot continue to grow indefinitely, the technology will also reach a plateau in refinement with only small incremental improvements to follow. This corresponds with the Maturity phase that was discussed earlier. The revenue is steadily being generated as the more conservative investors like the Late majority/Laggers (Section 2.1.1) also commit to adopting the technology. The effort that was put into developing the technology is finally paying off and the value that it adds is widespread known [32], [33].

Components of the hype cycle

It may seem odd that there are two independent ascensions in the expectation that surround the new technology, but that is due to them being driven by two different factors. As seen in Figure 2.6, the first is driven by hype and the second by the continual growth and maturing of the technology.

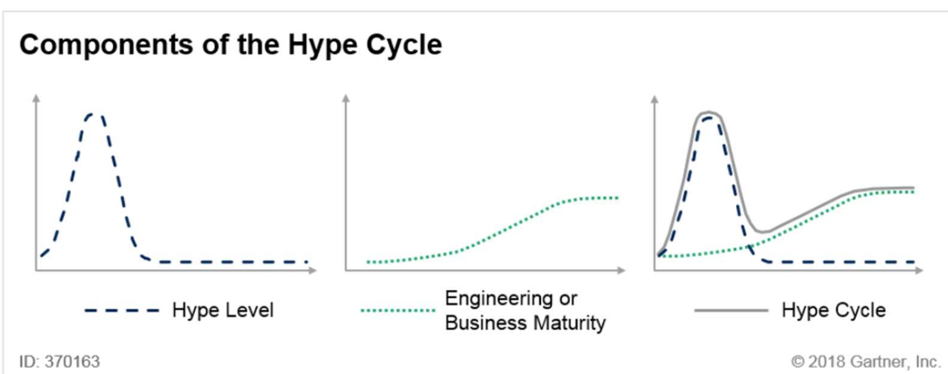


Figure 2.6: Main Contributing Factors of the GHC [33]

The Gartner Hype Cycle can be used to identify generic traps and opportunities connected to the introduction of a new technology. For instance, if a company (we'll refer to as Company X) wants to adopt a new technology to stay ahead of its competition, it can be difficult to distinguish facts about the technology from the hype that surrounds it. The value that the technology can add to the company can also be a bit ambiguous when it is first released. When considering Figure 2.6, it would seem that there is never a good time to adopt a technology, but it merely points out the potential traps that one can step into.

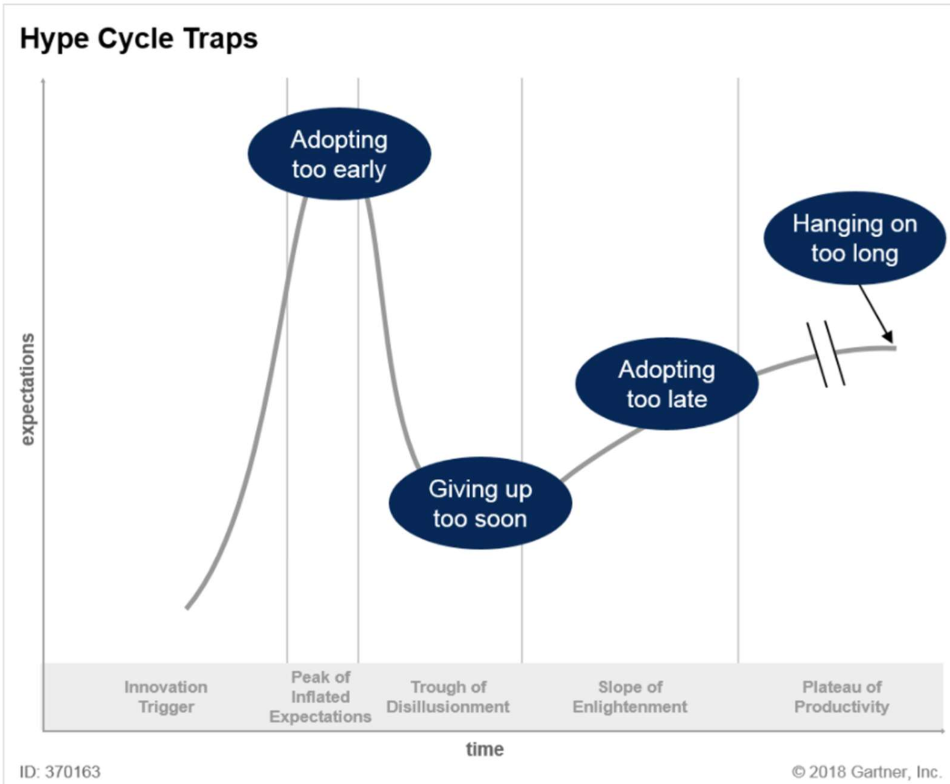


Figure 2.7: Traps Identified Using the GHC [33]

When the expectation/hype of a new technology is at its peak, there may be some exaggerations and unproven claims about the technology's value/capabilities. Sticking with the example of Company X who tries to remain competitive in the market, this peak would be a trap of adopting the technology too early. The trough of disillusion would be the opposite of the aforementioned peak, where the shortfalls and failures of the technology are overexaggerated and can cause Company X to completely give up on the idea of adopting it. When considering Figure 2.7, this is when the technology's maturity and refinement are on the rise which means Company X is giving up too soon. They have to be aware that their competition also considers these new technologies and may have jumped in and adopted the technology by this stage.

That is why Company X runs the risk of losing that competitive edge when only adopting during the slope of enlightenment. If they, at any stage of the GHC decide to adopt the technology, they need to remain competitive by continually considering new technologies and not holding onto the current one for too long (Figure 2.7) [33], [35].

Potential opportunities

If the innovator uses the GHC to track the technology, they can identify in which stage it is and predict when the turning points will happen. By doing so, they can identify the potential opportunities in taking the lead in various aspects (e.g., first to market/leading the mainstream wave) and leveraging their time and resources better than their competitors in each timeframe (e.g., optimization/planning/expanding) (Figure 2.8).

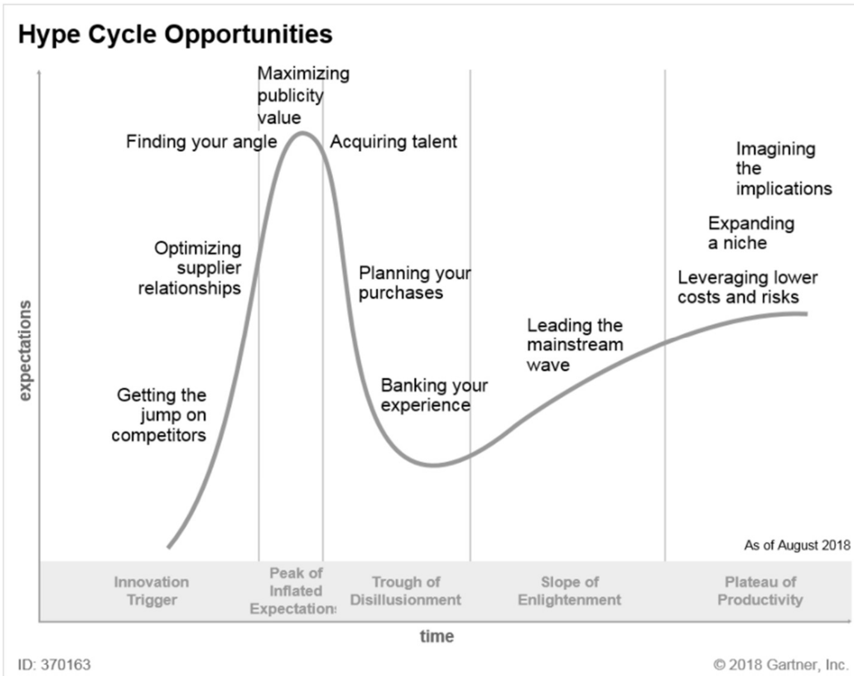


Figure 2.8: Opportunities Identified Using the GHC [33]

Adoption strategies

Company X can follow one of three adoption strategies after they have considered the potential traps and opportunities (identified using the GHC); the aggressive (type A), the majority (type B), and the conservative (type C) (Figure 2.9). There is no general ideal strategy choice since technologies and the companies that acquire them differ vastly. For the company to make the most informed decision when adopting a new technology, they need to have an idea of what value it will add, how well the risks are managed on the developer's side, and where it is currently on the GHC. Each strategy in sequence starts later than the previous on the GHC timeline. The aggressive strategy is high-risk high-reward where a company can gain the competitive edge by adopting the technology early on at the cost of taking the risks associated with an unproven/unrefined technology (Type A, Figure 2.9). The majority will try to strike a balance between the higher risk of adopting early on and not falling behind other companies (Type B, Figure 2.9). These companies must stick to their strategy and be wary of not being caught up in the hype and pressure from other companies, causing them to adopt the technology too soon (Type B Danger Zone, Figure 2.9).

The more conservative adopters are willing to sacrifice the competitive edge for the safety of adopting a more mature and proven technology (Type C, Figure 2.9).

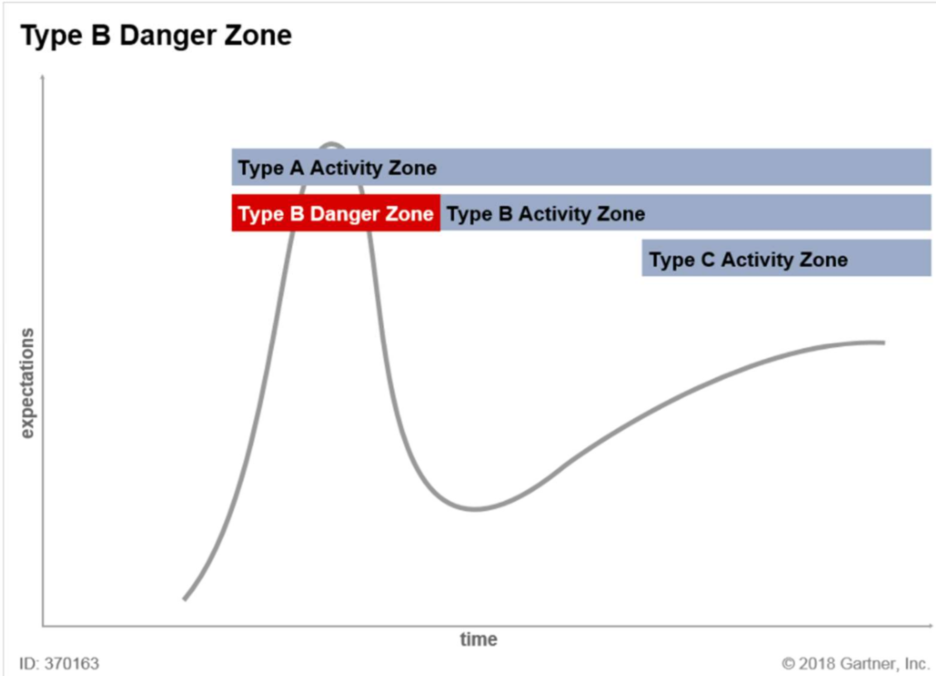


Figure 2.9: Technology Adoption Strategies based on GHC [33]

2.1.3. Teaching/Learning Use of New Technology

The importance and modes of technological transference were briefly mentioned in Section 2.1, but there is a lot more to it. It is not only applicable to the diffusion of the technology within a community (Section 2.1.1) but also the passing down to future generations. They have to be taught how to interact with the technology to successfully engage with it, or even improve it in the future, otherwise, it may be lost. When a new technology has been adopted into a company (as discussed in Section 2.1.1), the employer has to make sure that the potential it has for their company is fully utilized. This is heavily dependent on whether their employees are taught and trained in using the technology optimally. If the technology is used optimally it can lead to cost savings, improved working efficiency, and safety [36], [37]. The employer also has to monitor the changes within the technologies that are currently being used. There may be updates/refreshes that took place since the initial adoption and the training offered to employees may be outdated [38]. The topic of education is further discussed in Section 2.6.

2.1.4. Categories of Technology

There are numerous groups that technology can be categorised under and they are ever-increasing. Whether or not a technology is categorised into a specific group depends on how broad that group's description is and how well a technology line up with it. A discussion of the popularly used categories follows:

Information technologies (IT)

When the term IT is used, the first things that may come to mind are computers and networks. This is understandable as many people were introduced to the term IT when visiting an IT store or dealing with the IT departments in their company, both of which provide computer and network-based services. The IT category includes the software and hardware-based tools that are used for the processing, storing and transferal of information. In addition to computers and networks, IT also deals with; Internet access (Section 2.7), Databases (Section 2.7.4), Data analysis and artificial intelligence (AI), Cybersecurity, Management Information Systems, Quantum computing, etc. [39]–[41].

Communication technology

Communication plays a major role in our modern society as it allows for interaction and exchange of information between individuals and groups in all facets of life, whether it be within business, social, governance, etc. Modern communication technology not only allows humans to communicate quicker and easier, but it also allows for inter-device communication [39]–[41]. The communication data can either be transmitted wirelessly (electromagnetic waves)[42] or wired (e.g. conducting lines and fibre optics)[43]. Examples of communication technologies are telephone, global positioning systems (GPS), Internet, radio, etc. [44].

Electronic technologies

Electronics operate on the basis of electrons flowing either through matter or a vacuum in a controlled manner (using components like transistors, resistors, diodes, etc.) to achieve a desired outcome. It also involves the emitting and storing of those electrons (e.g., batteries and capacitors) in a system that allows it to function. Information and communication technologies heavy rely on electronics to operate which means modern-day society won't be the same without electronics. They are now integrated into almost all devices/systems humans interact with e.g., consumer devices, agricultural systems, production plants, transportation, etc. The design, manufacturing, and testing of these devices also fall under this electronics technology category. [39]–[41].

Mechanical technologies

Mechanical technologies include the design, manufacturing, and testing of functional structures, mechanical motion and or control. Different techniques of assembling/integrating mechanical parts and materials into a system are used in the development, optimization, production, and maintenance of mechanical structures or units (referred to as systems). Engineers also perform analyses before, during, and after (using simulations and measurements) the system has been manufactured/commissioned/in use to ensure optimal performance [39]. Mechanical systems can be static and or dynamic where engineers have to consider the mechanical kinematics-and stresses, energy transfer, fluid dynamics, and the efficiency of different systems [45].

Architectural and structural technologies

Architects primarily focus on the design and layout of buildings while civil engineers design and oversee the construction of buildings, infrastructure (e.g., roads, canals, dams, water and waste, etc.), and static structures in general. Whenever these structures are designed and built, the need, aesthetic, structural performance, cost, and environmental impacts are considered [41], [46], [47].

Material technologies

Materials that are found in nature can be combined (e.g., alloys and composites) and altered (e.g., energy and or atomic addition/removal) to yield a specific set of properties that are then in turn used to achieve a specific goal. Material technology includes the techniques used to test, produce, and implement the materials that are discovered and invented using material science [39], [48].

Medical technologies

The medical industry aims to prevent, monitor, and cure health-related issues (e.g., injuries, infections, etc.). The technology used by doctors to achieve this includes the machines, processes, and facilities. The equipment used in the hospital allows the doctors to perform various scans, take measurements, and operate on patients. Examples of the equipment and technology used are Magnetic Resonance Imaging (MRI), Computed Tomography (CT), X-Ray, Positron Emission Tomography (PET), sphygmomanometer (measure blood pressure), surgical robots, etc. The advancements in medical technology have enabled doctors to make quicker and better choices when treating a patient, improving their chance of recovery [39], [40], [49].

2.1.5. Manufacturing

The word "manufacturing" was coined in the year 1567 with a Latin origin where the two words "manus" and "facere" were combined. They are translated as "hand" and "to make" and refer to the process of making something by hand. A simplified definition of manufacturing, used by DeGarmo, would be [50]:

> "the conversion of stuff into things."

The goal of manufacturing is to add value to raw materials by altering and combining them in a planned manner. The products that are manufactured can be categorised as consumer or producer products. The producer products are those used by other manufactures to produce their own while the consumer products are those purchased/rented and used by the end-user. For a manufacturer to be successful, they have to produce a product cost-effectively for it to generate profit. A more modern definition of manufacturing, used by Scallan, would then be [51]:

> "the making of products from raw materials using various processes,
>
> equipment, operations and manpower according to a detailed plan that
>
> is cost-effective and generates income through sales."

The materials used in manufacturing are selected based on their properties and cost to then produce a product for a target group at a set price [52]. The four most popular categories of materials used in manufacturing are polymers (e.g., rubber, nylon, plastics), metals (e.g., copper, steel, bronze), ceramics (e.g., cement, clay, glass), and composites (e.g., plywood, carbon fibre, concrete). Different manufacturing processes and methods are used depending on the selected materials, the product's design, the production cost, quality, rate and batch size [53]. The different categories of manufacturing are discussed in Section 2.1.6.

2.1.6. Categories of Manufacturing

Manufacturing processes can be categorised by the type of product that is produced or the target market/industry it is used for/in. Some of the most popular manufacturing product/target market categories are listed in Table 1.

Table 1: Manufacturing Categorised by Product/Target Market [54], [55]

Textiles and Apparel	This category is typically defined by the threaded material used to manufacture materials such as fabric, cloth, ropes, etc., that are then combined to produce apparel, upholstery, and any other products that require these materials.
Chemicals, Petroleum, Coal and Plastics	The manufacturers in this category produce chemical, oil and coal-based products for other industries and consumers to use. Some of these elements are put through a polymerisation/polycondensation process to produce plastic and rubber polymers which are widely used in other manufacturing industries.
Electronics, Computers and Transportation	The electronics industry plays a large role in modern-day society and is integrated into most consumer devices. These electronic devices and computers are typically designed to have a human interface at some level and have become a key building block in other manufacturing industries. Modern transportation devices (e.g., ground, water, and air vehicles) also utilize a lot of electronics to improve their usability and performance, whether it be in efficiency, safety, or power output.
Food production	The agricultural industry used to be standalone, but it has become part of the manufacturing industry in the later 1800s to early 1900s. Automated food manufacturing lines produce a higher rate of products than the more traditional organic-style of food production. The food manufacturing process includes the purification, combination, and altering of ingredients to produce the foods that are then packaged and distributed.
Metal	The metal manufacturing industry's target market is typically other manufacturing industries. Metals are refined, combined, and formed to produce metal stock that can either be used in assembly-or machining processes to produce products.
Leather, Paper and Wood	The leather industry supplies the textile and apparel industries with the leather materials that are then used to manufacture products. The leather materials are produced using methods like oiling, tanning, rolling, spraying, etc., to produce different coloured, textured, and priced sheets and strips. The wood manufacturing industry turns raw wood into usable materials (e.g., beams, logs, flooring, laminate, etc.) for the construction and furnishing industries to use. Raw wood pulp is used by the paper industry to produce paper-based products, supplying other manufacturing industries or producing consumables and products directly for the end-user.

Manufacturing processes can also be categorised as high-level (related to the company business model and production flow) or low-level (machinery and hands-on methods) methods. The high-level processes that pertain to the company's business model are listed in Table 2, and those to production flow, in Table 3.

Table 2: Manufacturing Categorised by Business Models (high-level) [56]

Make-to-order (MTO)	Products are manufactured when an order is placed by a customer. After they have placed their custom order (product selection, quantity, quality, etc.) they have to wait for it to be manufactured.
Make-to-stock (MTS)	The manufacturer has to do a market evaluation and predict what product and how much of it will likely sell. They then produce the products (according to these estimates) to then fulfil the role of stock, which means an order hasn't been placed yet. This does however mean the customer can receive the product quicker than with MTO.
Make-to-assemble (MTA)	The MTO and MTS models can be combined to utilize the benefits of each and to counter the drawbacks of the other. This combination yields the make-to-assemble model where some of the product's components are made before the order is placed and then assembled based on the customer's preferences. The manufacturer can effectively reduce the MTO lead time (by having some standardized stock) and reduce the risk of MTS (by not only going based on estimates) when using the MTA model.

Table 3: Manufacturing Categorised by Production Flow (high-level) [57], [58]

Repetitive	If a manufacturer wants to produce a specific set of products with little to no changeover, they can set up a repetitive assembly/production line with a set target production rate. A repetitive production line can be run year-round and the aforementioned production rate can be adjusted to match the customer demand.
Discrete	If a wider range of products need to be produced or the changeover frequency is higher, the manufacturer can set up a discrete assembly/production line. A discrete manufacturing setup is not permanently fixed, allowing employees to rapidly and frequently change it to adapt to the current process. The repetitive setup typically has a higher production rate than the discrete, but it is less flexible and cannot produce as high a variety of products.
Job Shop	Instead of using assembly/production lines like the repetitive and discrete assembly processes, a job shop uses a production area where products are manufactured based on specific orders. This allows for even higher levels of product variants/customizability than discrete setups, but it has a lower production rate. A job shop typically has more manned machines and skilled operators than automated assembly/production lines which can result in a lower setup cost, at the potential cost of predictability (quality and turnover).
Batch	Batch manufacturing processes are similar to job shop and discrete ones where small to medium-sized custom batches can be produced either on a make-to-stock (MTS) or make-to-order (MTO) basis for the customer. The manufacturing setup is limited to a minimum of one batch (dependant on size) before it can be cleaned and altered for a different batch.
Continuous	The continuous manufacturing process is similar to the repetitive process, where high quantities of products are produced at a higher rate than the aforementioned three methods. The difference between repetitive and continuous is that raw materials like liquids, gasses, granules, etc., are typically processed using a continuous line where raw materials are continuously fed into the system.

Some of the popular low-level manufacturing methods that are used to physically perform manufacturing are discussed next.

Machining

Machining, also known as subtractive manufacturing (SM), refers to the process of cutting material away from a workpiece to shape it. The most common material used in machining operations is metal, but the process is not limited to it. Parts can also be machined out of other materials like wood, stone, plastics, etc. Machining is also used to clean up imperfections in parts when formed using the other means of manufacturing (e.g., casting or injection moulding) and to prepare the part for assembly (e.g., drilling and tapping holes). The three most common machining methods are listed and described below [59].

Cutting: A piece of material is cut using a blade, disk, cord, band, or other tools. The process can either be performed manually by a human or an automated machine.

Grinding: The rougher areas of the work part can be smoothed using a variety of grinding operations and machines.

Drilling: A drill bit is used to cut a cylindrical pocket in a part. The drilling operation is performed in one direction and the material that is cut by the tip of the drill bit is evacuated by the spiral body of the drill bit. After a hole has been drilled, boring and tapping operations can be performed where the holes are either enlarged or threaded.

Milling: The milling operation is very similar to that of drilling, but the milling bits are designed to cut in multiple directions, depending on the number of axes the machine can rotate the cutting head/workpiece.

Turning: A workpiece is spun around a single axis, typically on a lathe machine, where cutting tools around it is used to cut material away.

Joining

Joining processes like true bonding, fitting, fastening, or adhesion can be used to assemble different parts. True bonding is where a similar material is used to fuse two pieces of material together e.g., welding. Friction can also be used to fit two parts together, removing the need to add material, fasteners, or adhesives to join the parts together [60]–[62].

Forming

Metal is commonly put through forming processes to achieve the part’s designed properties, shape, and size. The metal can either be formed at room temperature (cold-forming) or heated before and during the process (hot-forming). Metal forming can be categorised as bulk deformation and sheet metal working. Bulk deformation includes rolling, forging, extruding and drawing metal wire/bars. Sheet metal working includes bending, stretching, cup drawing, shearing, and other miscellaneous processes [63].

Casting and moulding

Parts are cast and moulded by having the molten material (e.g., metal or plastics) flow into a negative pattern of a part. After the material has solidified, the mould is opened up, the part is evacuated/removed, and any excess material is cleaned off. When casting a part, gravity is used to fill the pattern until it overflows. When injection moulding a part, pressure is used to force the material into the pattern [64]–[66].

Printing

Unlike the machining processes, printing (AM) is the process of adding material to a print area to form the desired part instead of removing material. The different AM technologies are discussed in depth in Section 0.

The discussion on the different categories and methods of manufacturing set a stage to better understand where AM fits into the manufacturing industry. It also provided insight into the advantages and disadvantages of AM compared to other methods of manufacturing that are discussed in the following section.

2.1.7. Why Additive Manufacturing

AM plays a role in the 4th industrial revolution (I4.0) that is currently ongoing especially within the maintenance industry [67]. The spare part stock count that has to be kept on-hand can be reduced as those parts can be produced on demand using AM. AM technologies are bringing new capabilities to the industrial sector [68], having a range of advantages over that of more traditional means of manufacturing, but they have some disadvantages to also consider.

Advantages

Cost of entry

Some of the AM technologies have a low entry cost and is still falling due to their continued market growth. These low-cost entry-level printers are typically desktop-sized and use affordable materials to produce parts. The printers that are capable of printing metals have a higher entry cost but has to be compared with products that can produce similar (complex) parts. The entry cost of setting up a small to medium production line (print farm) can also be more affordable than that of e.g., injection moulding [69]–[71].

Print-in-place assemblies and complex geometry

The layer-by-layer process used during AM enables the manufacturer to produce complex geometry and print-in-place assemblies that would otherwise be impossible to produce when using other manufacturing methods. Print-in-place assemblies can include interlocking and/or captive parts which reduce the assembly part count and steps in production. [69], [71]–[73]

Material waste and energy

The material waste that is produced when using AM is significantly less than SM processes. Instead of machining the bulk of a material stock away to produce a part using SM, AM only uses the material needed for the part itself (and for support structures in some cases). Large assemblies can also be printed as united parts, reducing the part count which further reduces the manufacturing costs (material and energy consumption) [69]–[71], [74], [75].

Single-step manufacturing

The number of production steps needed to turn a digital part into a physical one can be reduced by using AM (depending on the current manufacturing method) since many of the traditional stages are skipped. Please refer to Figure 2.10 for an illustration of this reduction [71], [76], [77].

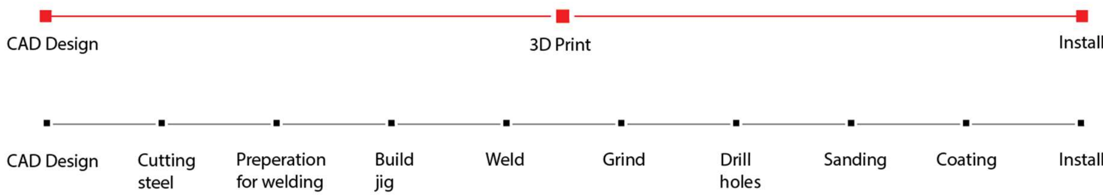


Figure 2.10: Single Step Manufacturing using AM [71]

Low-cost rapid prototyping

AM is an excellent means to perform rapid prototyping. Single-step manufacturing helps creators to go from idea to prototype quicker at a fraction of the cost when compared to injection moulding or some SM processes. AM gives the creator the freedom to alter the design with every print at little to no extra production time or cost (tooling/setup-cost/etc.), reducing the financial risk that is associated with prototyping [69], [71], [75], [78].

Smaller inventory range

The inventory of materials, parts and tools is reduced when using AM since there are little to no tool changes needed during production and the variety of parts used assembly has been decreased. Single-step manufacturing also eliminates inventory related to the additional manufacturing processes [78].

Recreate and optimize legacy parts

AM can be valuable in the industries that produce replacement parts or repair products. It can be difficult to source legacy parts for older machines, but if the digital model (Section 2.3.1) can be acquired/generated, then AM can be used to reproduce or even optimize the part that failed. Specialized high-end tooling can also be repaired using some of the metal AM processes. [69], [70], [79]

Capable of producing sparse infill

The entire part does not have to be solid when using AM. It allows the creator to reduce the part's weight, unlike SM where solid material stock is used. The shell of the part is typically printed solid with a sparse infill pattern. It can also be used to design parts with unique thermal properties. Grid-like and Lattice structure (crystal-structure-like) infill patterns are commonly used in additive manufacturing (Figure 2.11) [69], [80].

Figure 2.11: Lattice Structures Produced Using AM [81]

Little to no tooling cost

When using SM, different sets of tooling (e.g., drill bits, grinding wheels, etc.) need to be procured in addition to the machines themselves. The tooling has a limited use lifespan (after which they have to be replaced) and use cases within a machining job (where they need to be swapped out for the next operation). Most AM machines come preconfigured with a single set of tools (e.g., material deposition nozzle) that can in some cases last the total duration of the machine's lifetime. [72]

Disadvantages

Production rate

AM machines cannot compete with the high production rate of other manufacturing methods like injection moulding or metal casting. If a manufacturer wants to achieve a similar production rate, they would need to increase their AM machine count, effectively creating what is known as a printer farm. The manufacturer has to keep in mind that a printer farm can potentially be more costly to run than fewer injection moulding machines (with a matched production rate) [72], [74].

Surface finish and post-processing

The layer-by-layer characteristic of AM can result in an undesired surface finish on the printed part. They would require post-processing to match the surface finish of parts that were produced using SM and moulding/casting methods, effectively increasing the production time and cost [75], [82].

Dimensional accuracy

Some of the materials that are used in AM shrinks/deforms after it has been applied to the printed part or when the part is "cured" during post-processing. The manufacturer has to account for this to achieve an acceptable dimensional accuracy [72], [73].

Limited to printable materials

AM machines cannot produce parts using all materials that are available in the manufacturing industry. This limits manufacturers to a specific set of materials to choose from, depending on what AM technology and machine they use [75], [83].

Size and support limitations

Some of the AM technologies have practical limits as to how large their print volume can be whereas some other manufacturing methods do not have this limitation. Depending on the AM technology and the printed part's geometry, support structures may have to be included in the build volume to successfully complete the print. The support structures need to be removed after printing which poses a problem if they are captive inside certain part geometries. The manufacturer has to keep these limitations in mind when preparing a print job [72], [75], [84].

Homogeneous material properties

The layer-by-layer process used in AM can produce non-uniform material properties such as directional part strength, cavities within the part (part density), stress concentrations, internal stresses, etc. To accurately predict and calculate the exact properties of a printed part can be difficult since it is subject to the part geometry, repeatability of the machine used, material quality, etc. [75], [85].

2.1.8. Adoption of AM

The adoption of AM can be plotted on the GHC (Section 2.1.1) as seen in Figure 2.12 and Figure 2.13. Gartner generated the graphs in 2015 and 2018 respectively, showing in what phase of the GHC the different elements of AM can be categorised. It can be noted how they shift up (e.g., 3D printing in retail) from 2015 to 2018 and can be expected to shift again from 2018 to 2021. The figures also give an estimate of how many years it would take for a specific element of AM to reach a plateau of productivity.

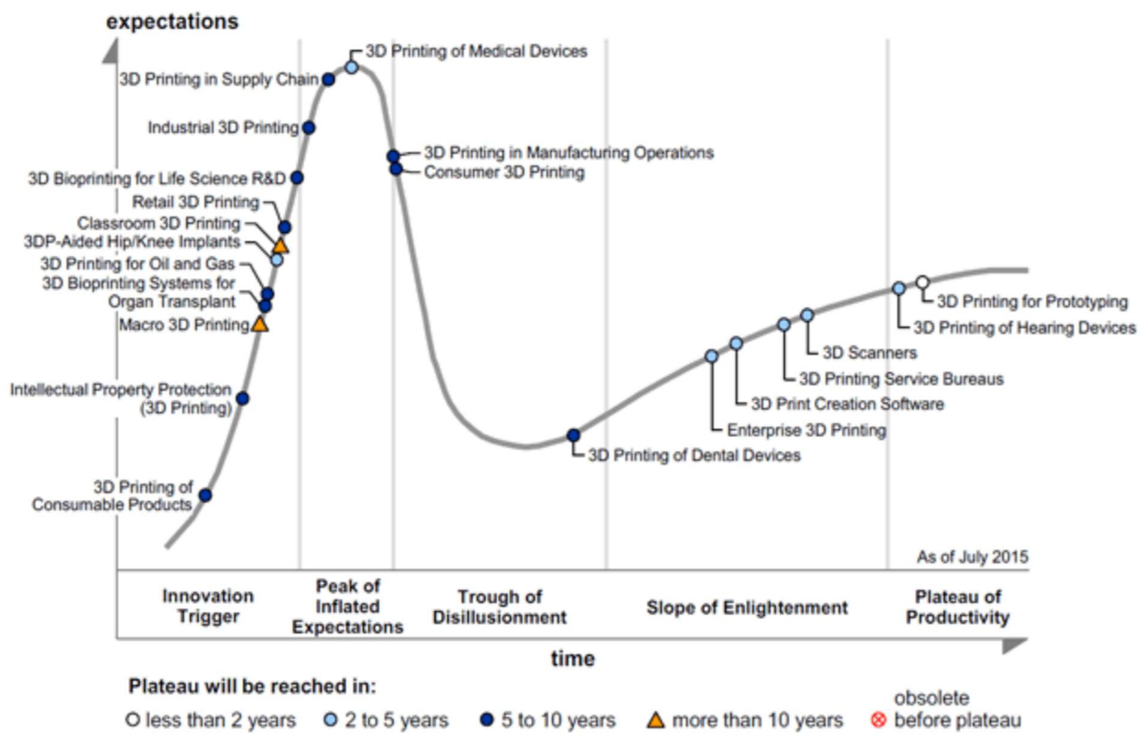


Figure 2.12: AM 2015 GHC [86]

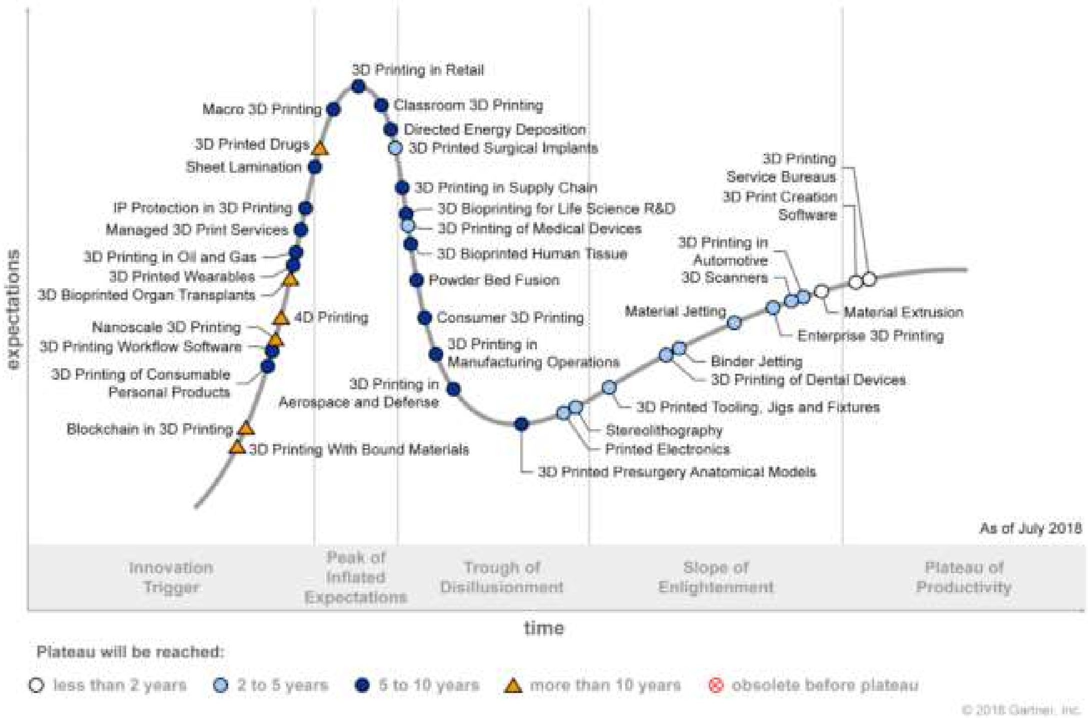


Figure 2.13: AM 2018 GHC [87]

The 2018 GHC is a lot more populated, which is to be expected, as new elements of AM are developed and categorized into the different phases. Not all of the elements on the GHC are applicable to this study, but they help to show that AM is subject to the GHC. The magnitude of the peaks and troughs, as well as the time to reach the plateau of productivity, can potentially be reduced by providing easily accessible training in AM.

Industrial sector

For a company in the industrial sector to adopt AM technologies, a few elements have to be established first. They can be categorised under the business, technical, and social sectors. When considering the DOI theory (Section 2.1.1), it is clear that there needs to be an openness to new innovation if a company wants to remain competitive or take lead on the technological forefront within their industry. The leaders, who typically operate in the business environment, have the greatest influence within a company, making it vital that they are willing to consider new innovations. They can endorse the new innovation in such a way that the company-wide acceptance, of the AM technologies, in this case, is accelerated. They can also address social issues and concerns of AM that can create a negative connotation with it. The company members have to understand that the technology can be used for more ethically correct applications than the minority of malicious intents such as the illegal manufacturing of weapons [88].

With company-wide acceptance, the employees will be more willing to learn how to successfully engage with AM after it has been adopted into the company. Technical aspects such as machine operation/troubleshooting/repairs, understanding and using the materials (and potentially chemicals) correctly, part modelling and editing in the CAD environment, and print preparations on a hardware and software level. These are all required to successfully produce high-quality parts [88], [89].

Small and medium business sector (SMEs)

SMEs fall in a different part of the supply chain and have a more dynamic approach to business than larger companies in the industry. SMEs cannot simply be seen as scaled-down larger companies as they respond differently to changes, have different business models, and serve a different market in the industry. SMEs have to understand and manage the challenges of adopting AM for them the efficiently manage their resources and adapt quickly to remain in a competitive position. The advantages that AM has over traditional means of manufacturing (Section 2.1.7) is a key driving factor for adoption, but SMEs have to overcome the initial investment and upkeep cost of the machines if they choose to do manufacturing in-house. SMEs don't typically have long standing relationships with the AM technology suppliers as the larger companies do. Thus, it can be challenging to negotiate machine, material, and service costs with less bargaining power [90].

The digital models form a large part of AM which allows the technology to be "adopted" by SMEs without having to make the hardware investment. They can achieve this by specializing in the digital designing, optimization and editing of models, followed by outsourcing the print job, and potentially integrating the printed parts in the clients' projects for them. SMEs would however find this challenging if they don't have good inter-organisation communication and information systems to partner and liaise with other companies in the supply chain. Larger companies have more experience in the industry, with matured structures and recognize the value of setting well-defined procedures and standards when adopting a new technology. The SMEs would be able to integrate the technology easily, due to their dynamic and agile approach, but some may find their lack of structure and standards challenging in the long run. This won't necessarily be a barrier to the initial adoption, but it may cause them to have a negative peer influence [91].

As mentioned in Section 2.1.8, there are numerous factors companies have to overcome to fully adopt the technology (hardware and software level), but through a series of case studies, it has been suggested that the lack of skilled employees and the cost of adoption are the two main barriers for SMEs [92], [93].

2.1.9. Categories of AM (ASTM F42)

The ASTM F42 is a committee, established in 2009, where the main focus is on the standards of AM technologies with the members gathering twice a year [94]. By developing the standards, they aim to stimulate the implementation, research of AM, and to further the knowledge in the field. Please refer to Figure 2.14 for the different classifications of AM.

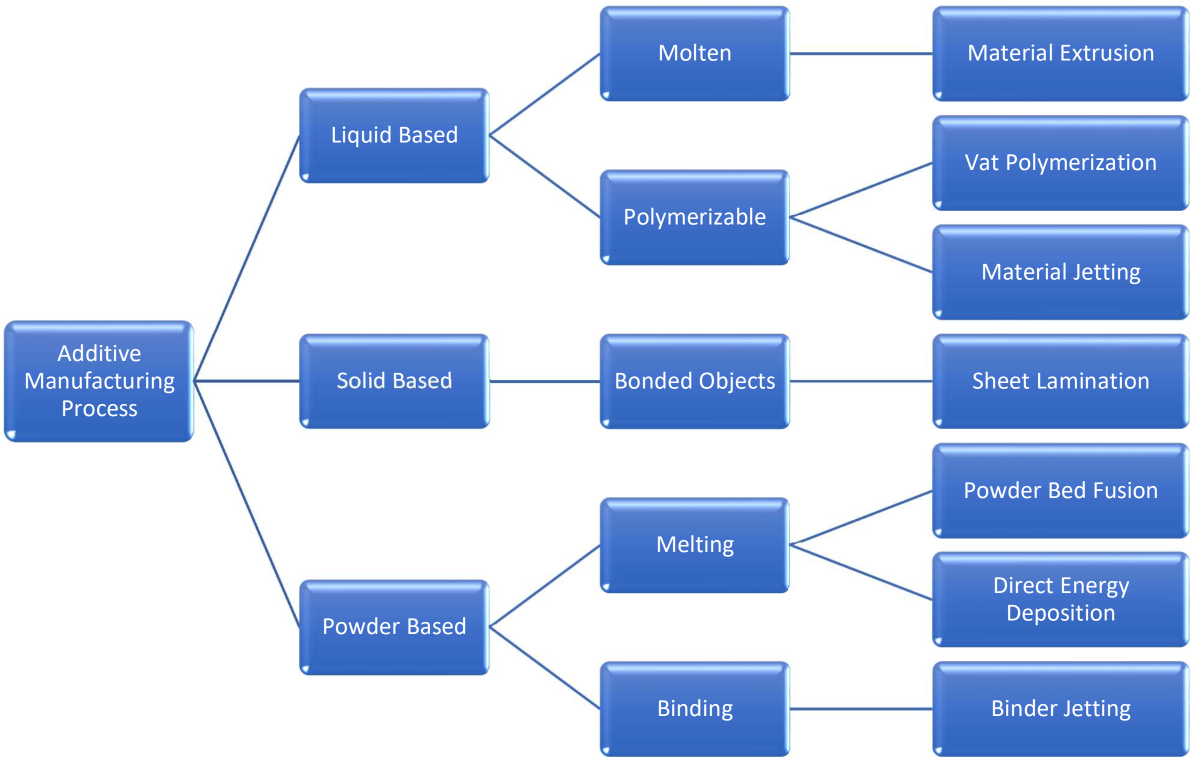


Figure 2.14: ASTM F42 Classification [95]

The three main branches of AM are liquid-based, solid-based, or powder-based. Liquid-based printing has two sub-categories namely polymerization and molten. The polymerization technologies work on the premise of curing liquid resin using ultraviolet (UV) light. Two examples of technologies that utilize this technique are material jetting and vat polymerization [75], [96].

Material jetting technology is very similar to that of an inkjet paper printer, but instead of ink, it deposits resin onto a build plate and cures it using a UV light. Material jetting is considered one of the fastest and most accurate printing technologies, thanks to the line-wise printing method and fine spray resolution it uses. Instead of depositing an entire layer before it is cured, the printer deposits and cures the resin with every line-wise pass it makes (Figure 2.15). The high-resolution printing produces smooth surfaces that are ideal for small detailed parts, investment metal casting, etc. Another benefit of this technology, similar to ink jetting, is that the printer can easily be configured to print using different colours. A wide range of polymer resins, each with different characteristics, is available to print with which means the user is not limited to only different colours when using material jetting, but also has the choice of using different materials in the same print [75], [97], [98].

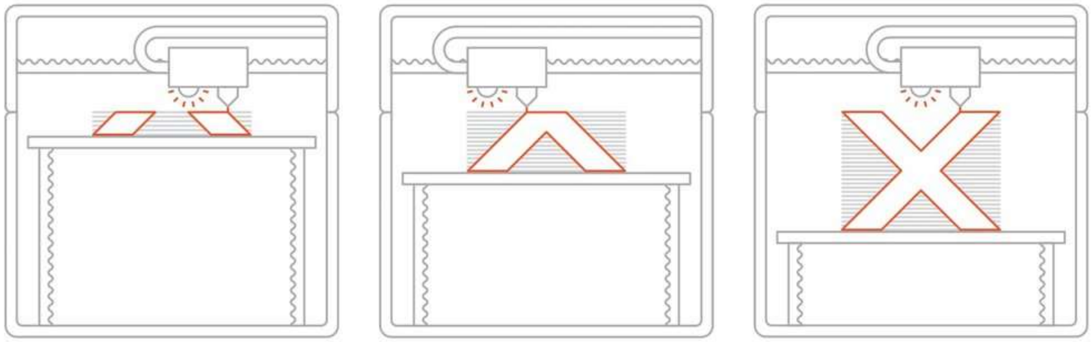


Figure 2.15: Material Jetting Process [98]

There is a range of sub-categories (Figure 2.16) of the vat polymerization technology with the main ones being stereolithography (SLA), masked stereolithography (mSLA), and digital light processing (DLP). They all work on the premise of curing thin layers within a bath of resin. The cured layer sticks to the build plate and as the build plate moves away from the curing zone, new resin from the bath fills the void. The printed part can either be pulled out of the vat with the curing zone at the bottom (between a transparent film and the build plate) or lowered into the vat with the curing zone at the top (between the top surface of the resin and the build plate) as seen in Figure 2.16. [99]–[102].

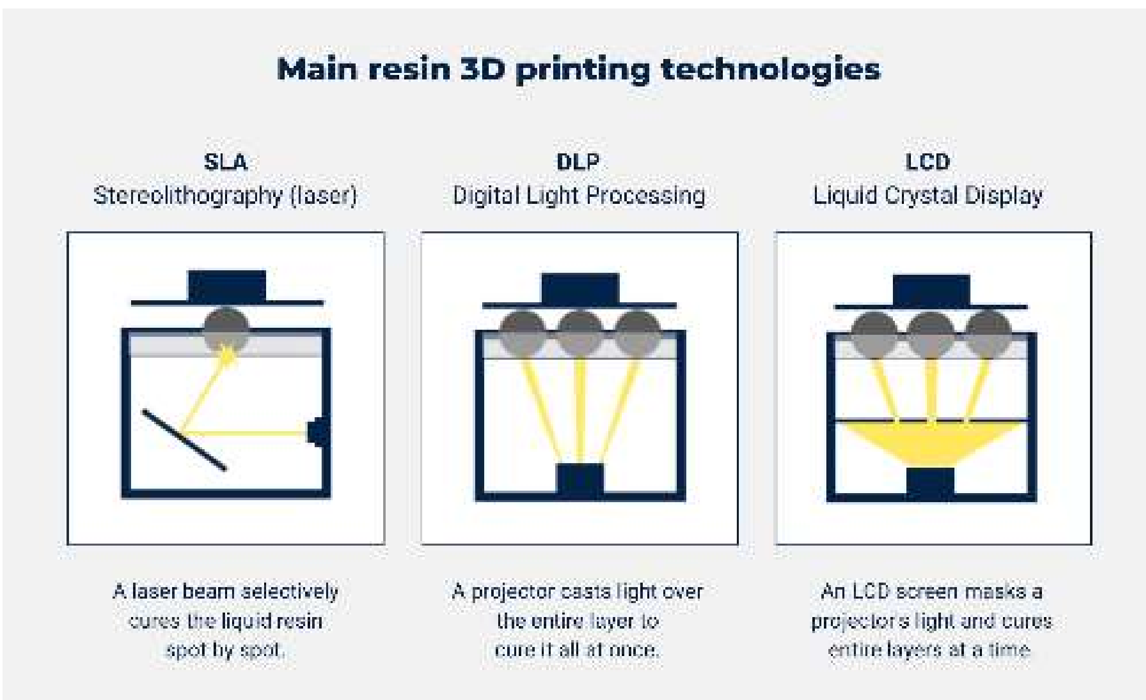


Figure 2.16: Vat Polymerization Technologies [101]

SLA uses a laser and mirrors to selectively cure the resin layer by layer (Figure 2.16). Higher quality SLA printers (typically with larger print volumes) use multiple lasers and mirrors. This is to combat the reduction in print resolution near the edges of the build plate where the laser dot is projected at an angle. The dot effectively grows as it moves further away from projecting perpendicularly on the build plate.

Some SLA printers have the laser mounted on a gantry that moves in the horizontal plane under the transparent film (Figure 2.17) [75], [99]–[102].

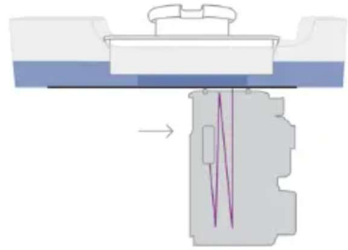


Figure 2.17: SLA Machine with Laser Mounted on Gantry [102]

The mSLA technology uses a liquid crystal display (LCD) to mask the UV lamp, only allowing light through in the areas where the resin needs to be cured (Figure 2.16). Printers that use the mSLA technology can be very compact and affordable since there are few moving and inexpensive parts [100]. DLP printers use a UV light projector to emit a matrix of beams to selectively cure the resin (Figure 2.16). DLP printers cure an entire layer all at once similar to a mSLA printer. The projector has a longer lifetime than the LCD film used in mSLA printers but is more expensive and less compact [100], [103], [104].

Another liquid-based AM technology is Material Extrusion where a solid material (plastic being the most common) is melted and then deposited onto a build plate layer by layer. FFF technology is based on the material extrusion technology and is discussed in greater depth in Section 2.1.10.

The second high-level AM category is solid-based printing where solid material layers are stacked and joined together (using heat, pressure, adhesive, etc.) to form the 3D object. This printing technology is known as Sheet Lamination (SL). Two characteristics that set the different SL printers apart are the materials used and the process of cutting and bonding the layers together. The four most popular materials used are plastics, papers, woven fibre composites, and metal compounds like alumina (aluminium oxide). The material used can influence the order in which it is cut and bonded to the previous layer. In some cases, the material shape is first cut out of a sheet and then bonded to the stack, while in other cases, the shape is cut after it has been bonded (Figure 2.18). The printers typically use a milling bit (Section 2.1.6), sharp cutting tool, or laser to cut the material. SL printers can have large printing areas and different (compatible) materials/colours can be used in the same print to produce unique part properties [75], [105]–[108].

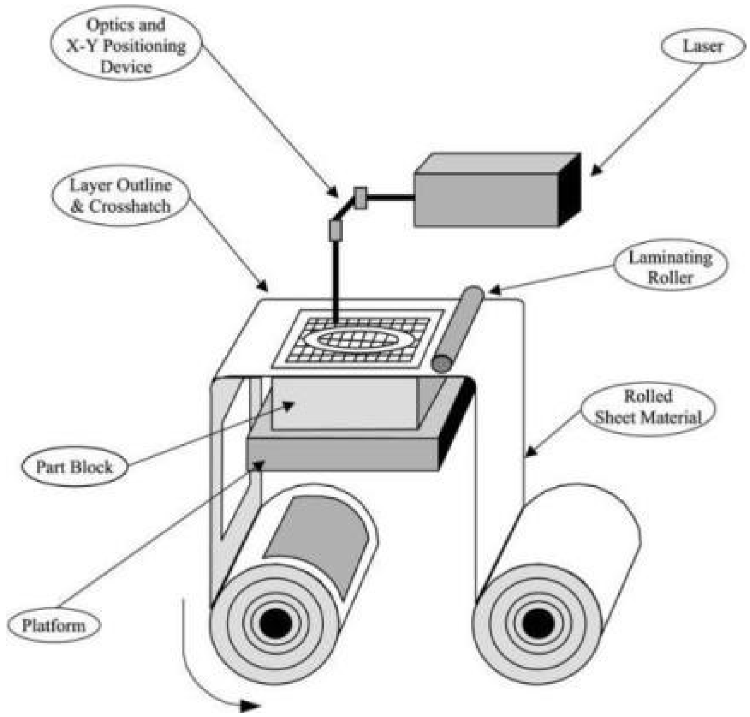


Figure 2.18: Sheet Lamination Process [105]

The third high-level AM category is powder-based printing where a layer of powder is distributed in the printing area or deposited onto a part after which it is selectively bonded or melted together. The powder-based printing technologies that selectively melt the powder can be categorised as powder bed fusion (PBF) or directed energy deposition (DED). The DED technology is typically used to repair existing parts with metals as the most common material used. The material is either deposited as a powder or wire onto the print bed/part after which it is melted using an energy source (laser/electron beam/plasma/electric arc). The deposition nozzle and energy source can be mounted on a multi-axis robotic arm to help navigate around the part and deposit/melt the material at different angles (Figure 2.19)[109].

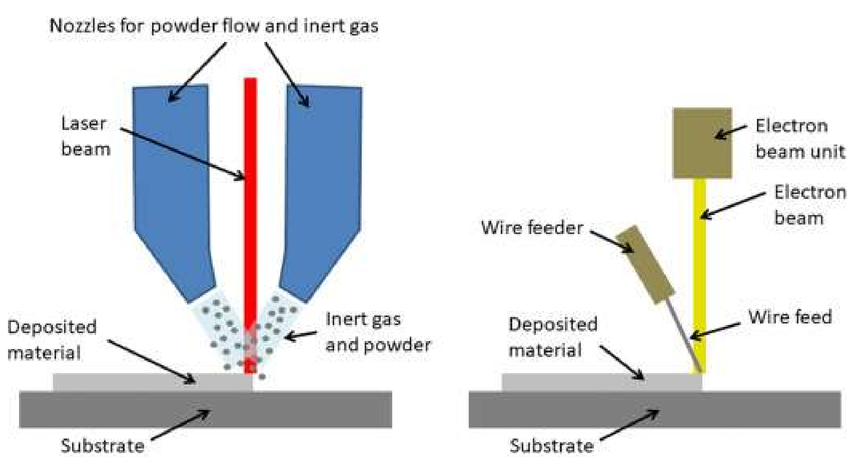


Figure 2.19: Directed Energy Deposition Process [110]

The PBF operates on a more traditional AM basis (compared to DED) where a 2D layer of powder is spread onto the printing area after which it is selectively melted using a laser or electron beam (Figure 2.20)[111]. Another powder-based print technology, that binds the powder using an adhesive/binder (instead of melting the powder), is known as binder jetting. It can easily be confused with the material jetting technology mentioned earlier. The main difference between the two is that the print head of a printer that uses material jetting, deposits both the material and the binder. The binder jetting printers' print head only deposits the binder after which a fresh layer of powder is spread across the entire print surface again using a powder coater of some sort (Figure 2.20) [112]–[114].

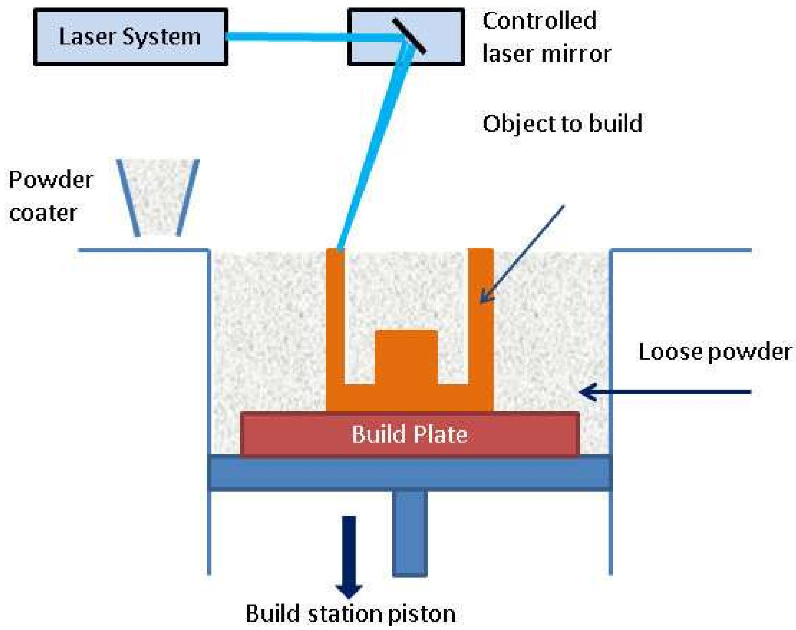


Figure 2.20: Powder Bed Fusion Process [115]

2.1.10. Fused Filament Fabrication

A more detailed literature study was performed on FFF to gain a better understanding of the technology and potentially identify aspects that inhibit its adoption. The majority of the training course content was also based on this detailed literature study. As mentioned in Section 0, FFF is categorised as a liquid-based, molten-material technology. The material (plastics/plastic composite) is fed from a filament spool and pushed through the print head of the FFF printer. The print head's heated nozzle melts the material after which it is deposited in the build volume, layer-by-layer as the previous solidifies as seen in Figure 2.21.

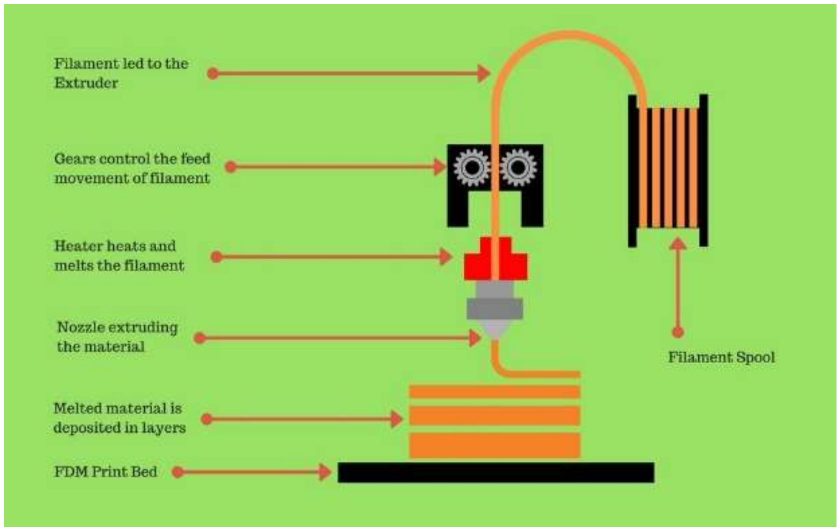


Figure 2.21: Fused Filament Fabrication Hardware [116]

FFF can be very attractive for individuals/companies who want to adopt an AM technology. A list of advantages that FFF has over other AM technologies follows:

- **Cost and ease of access**: As mentioned in Section 1.1, FFF accounts for almost 50% of the AM market, which means there is plenty of competition within the FFF printer market. This leads to a drop in printer prices and an increase in feature sets. The cost to print volume ratio of FFF printers is also very competitive when considering other AM technologies. The basic materials FFF printers use is inexpensive and commonly available at AM and hobby shops. The community-based support has also grown with the technology, making it more accessible to new adopters [117]–[119].
- **Safe to use**: The filament used for printing is safe (except for some fumes released by select materials during printing), easy, and clean to handle as opposed to AM technologies that use powder or toxic resins. The desktop-size (hobby-grade) FFF printers typically don't have very powerful motors, making them unlikely to cause severe pinch related injuries [120], [121].
- **Desktop form factor and scalability**: FFF printers can be used in the classroom/office environment due to their manageable desktop form factor and aforementioned safe operation. They are not as limited as other AM technologies when considering scaling the machines up or down [117], [118]. FFF printers can range from a few centimetres in build volume (Figure 2.22a) to an entire warehouse where, as illustrated in Figure 2.22b, a full-size boat haul can be printed.

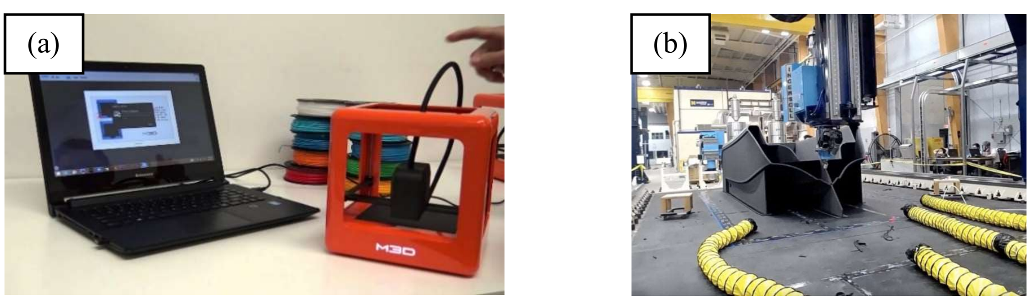


Figure 2.22: Examples of FFF Printer Scalability [122], [123]

The potential adopters of the FFF also have to be aware of the disadvantages that are associated with FFF. They are listed below.

- **Material properties**: The material properties of the filaments FFF printers can print with may not be as versatile/strong as some of the other AM technologies like the metal-based printers. Some of the FFF materials suffer from severe warpage when cooling (Section 2.5.1) which reduces the dimensional accuracy of the part [124].
- **Print speed**: The printing speed of a FFF printer is not as quick relative to some of the other AM technologies like mSLA that can complete an entire layer at a time [124].
- **Hazards:** The user has to take precautions when they work near the heated elements like the hot-end and heated bed (Section 2.2) as they can cause burn injuries. They also have to take precautions when using sharp tools to remove the printed parts [121], [125].

Some of the most popular materials used for FFF are listed in Table 4. The FFF training course does not cover the different materials that are available as stated in Section 1.5. They were, however, included in the literature study to provide insight into the FFF technology and what the material properties the printed models can have and some of the materials are also referenced in the study.

Table 4: Commonly Used Materials for FFF [126]–[128]

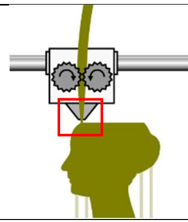
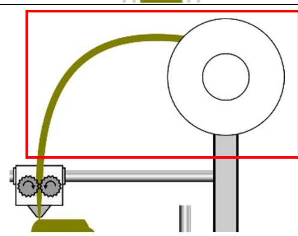
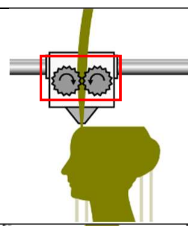
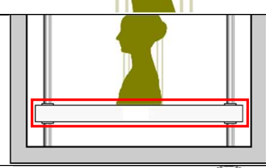
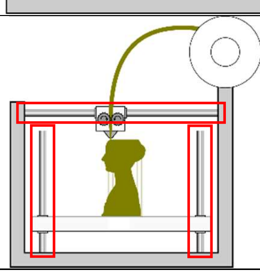
Material	Description	Pros	Cons
Polylactic Acid (PLA)	PLA is a biodegradable thermoplastic that is the most common material used for FFF.	Easy to print with good dimensional accuracy. Can be printed fast at relatively low temperatures with little shrinkage.	Printed parts are not very durable. Not very heat resistant (softening at as low a temperature as 60 °C). The filament can absorb moisture, causing nozzle clogs, poor layer/bed adhesion, and poor surface finish.
Acrylonitrile butadiene styrene (ABS)	ABS is an amorphous polymer that is very commonly used in the manufacturing industry and FFF in particular.	Printed parts are stiff, durable, and recyclable. ABS can withstand high temperatures (100 °C) before softening and can easily be painted and post-processed using chemicals (e.g., acetone) or SM (Section 2.1.6).	High printing temperatures are needed and the material shrinks more than other materials. Odours and harmful gasses are emitted when the plastic is melted. ABS easily absorb moisture causing nozzle clogs, poor layer/bed adhesion, and poor surface finish.
Polyethylene terephthalate (PET)	PET is a semi-transparent thermoplastic used for a wide range of products as it is part of the polyester group.	PET is moister resistant, recyclable, food-safe, partially flexible, and durable. The material is not too difficult to print with and has a melting temperature between ABS and PLA.	PET parts are somewhat heat resistant, but they become brittle if printed at too high a temperature. The material can lose its transparency after being printed.

Material	Description	Pros	Cons
PETG	PETG is PET with Glycol added.	Same material properties as PET, but stronger, more durable, and slightly more heat resistant.	Same material properties as PET, but also UV light sensitive.
Thermoplastic Polyurethane (TPU)	TPU is a semi-flexible material that can be likened to rubber.	TPU parts are flexible, water/oil/grease resistant, and has high strength. The material does not shrink as much when printed and is moderately heat resistant (80 °C).	Difficult to print with and has a high melting temperature. It can be difficult to pros-process or glue TPU parts.
Nylon	Nylon can be created using a variety of polyamides to yield different strengths.	Nylon parts have very high durability, tensile strength, and impact resistance. The material can be used to produce thin and flexible parts with good heat resistance.	Difficult to print with and requires high melting temperatures. Nylon filament easily absorbs moisture causing nozzle clogs, poor layer/bed adhesion, and poor surface finish. The material emits bad odours when printed.
Composites (carbon fibre, wood, etc)	There is a wide range of composite materials available for FFF e.g., carbon fibres or wood particles can be mixed with polymers to produce a printable composite.	Gives parts unique properties e.g., high tensile strength using carbon fibre particles or a wooden aesthetic.	These composites are typically very abrasive to print and can cause wear on the printing nozzle/cause clogs. These composites are more expensive than the more common PLA and ABS materials.
Polyvinyl Alcohol (PVA)	PVA is a dissolvable material, typically used to print support structures that can easily be removed by exposing the printed part to moisture.	Reduces the post-processing time and does not require any specialized tools or solvents, only water.	PVA is expensive and can practically only be used in FFF printers that can print multiple materials within a single print. The PVA is highly sensitive to moisture which makes storing the material more complex.

2.2. FFF Hardware

The hardware components of a generic FFF printer are listed in Table 5, paired with their operational function. The FFF hardware content in the training course was limited to these elements, providing the user with basic insight into how a FFF machine works. It was included in the literature study as background since some of these hardware elements are referenced in the following sections.

Table 5: FFF Hardware Elements [129][130]

Nozzle		The nozzle (heated to the melting temperature of the printing material) deposits the molten material.
Printing material		The printing material (typically a plastic/composite) is pushed through the nozzle by the extruder assembly. The material is purchased in spools of filament (common diameter of 1.75 mm or 3 mm) or pellets (typically ABS).
Extruder assembly		The extruder assembly consists of a motor that drives a feeding system that pushes the material through the nozzle.
Print bed/build plate		The model is built on a print bed by depositing the molten material onto it. In some cases, the build plate is heated for better adhesion.
XYZ axis movement		The material is deposited in a stack (Z-axis) of 2D layers (XY-plane) by either moving the print head or print bed to the desired XYZ coordinate.

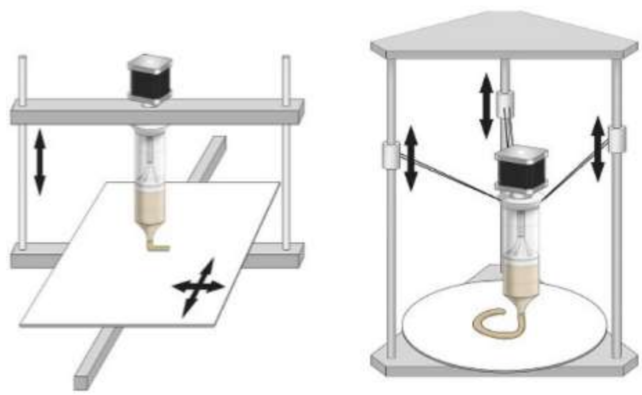
All FFF printers contain these hardware elements, but they may have different kinematic models and extruder assemblies. The five most common kinematic models that are used in FFF printers are discussed in the following section, followed by the three most common extruder assemblies.

2.2.1. Printer Kinematics Models

A kinematic model is a mathematical description of the motion of a physical/virtual model (FFF printer in this case) and the geometric relationship of its segments. The five most popular kinematic models used for FFF printers are cartesian, delta, polar, robotic arm and scara, and the infinite-Z conveyor. These kinematic models will not be presented in the training course, but they are included in the study as background and to ensure that the educational content was valid for all of them.

Cartesian

The most common FFF printer style on the market is cartesian (Figure 2.23a). This mathematical coordinate system is the most basic of the kinematic models where either the print head, print bed, or a combination of the two moves linearly to the desired XYZ coordinate. Movement in the XY plane is quicker than the Z-axis with rapid changes in direction. The mass of the print head of a FFF printer is typically less than that of the print bed and printed model combined. Ideally, the component that has to rapidly change direction and speed, should be the lightest possible (Newton's 2nd law) which is the print head in this case. The print bed is sometimes placed on a moving axis to simplify the printer's design. The linear XYZ-axis movement of a cartesian printer yields a cube-shaped print area [131].



(a) Cartesian (b) Delta

Figure 2.23: Cartesian- and Delta Kinematics [132]

Delta

The delta model also uses the cartesian coordinate system, but the driven movement is vastly different from that of a cartesian printer (Figure 2.23b). The print head is suspended by three arms that are fixed to vertical articulating points. The vertical movement of the three points triangulates to a horizontal movement plane for the print head. Delta printers are considered faster than cartesian ones, potentially at the cost of print accuracy [131]. A delta printer has a static round build plate with a cylindrical print volume and coned top (cylindroconical) as the range of motion on the 3 arms become limited (Figure 2.24).

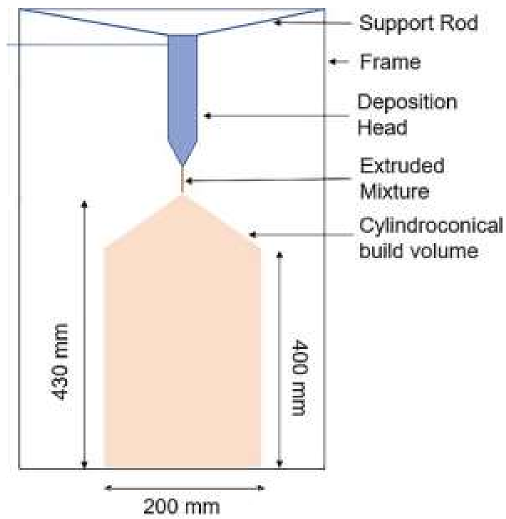
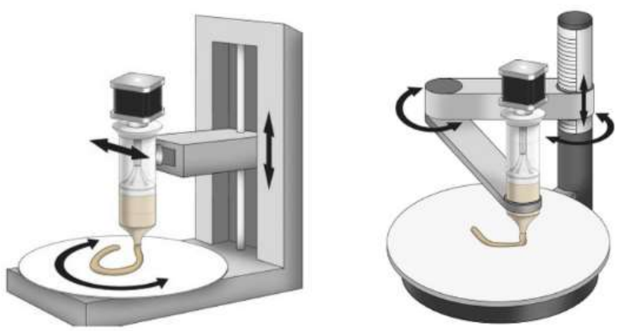


Figure 2.24: Delta Print Volume [133]

Polar

A polar-based printer has a print head that moves vertically (Z-axis) with a rotating (around the vertical axis) and sliding (Y-axis) print bed (Figure 2.25a). The horizontal kinematics is not based on XY coordinates, but on an angle and length. This gives the polar printer a cylindrical print area with a round print bed [131].



(a) Polar (b) Scara

Figure 2.25: Polar- and Scara Kinematics [132]

Robotic arm and Scara

The printhead is mounted on a robotic arm that articulates in the XYZ space and deposits the material on a static print bed. Additional axes of movement can be added to the print head to allow for additional layer directions other than vertically.

Scara printers have a robotic arm that only articulates in the XY-plane with the print bed moving vertically (Z-axis) (Figure 2.25b). The printing area of robotic arm-based printed is determined by the range of movement of the arm itself.

Conveyer (infinite Z-axis)

These printers are based on the cartesian-style printers, but it has the XY-plane of movement tiled to 45 degrees (along which the printhead moves) and the build plate is replaced by a conveyer belt that horizontally shifts the part out of the printer (Figure 2.26). This removes one of the build volume's limits, allowing the printer to theoretically produce "infinitely" long parts. The printed layers are built up diagonally instead of vertically like the other kinematic models [134].

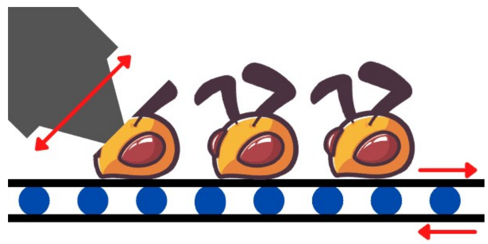


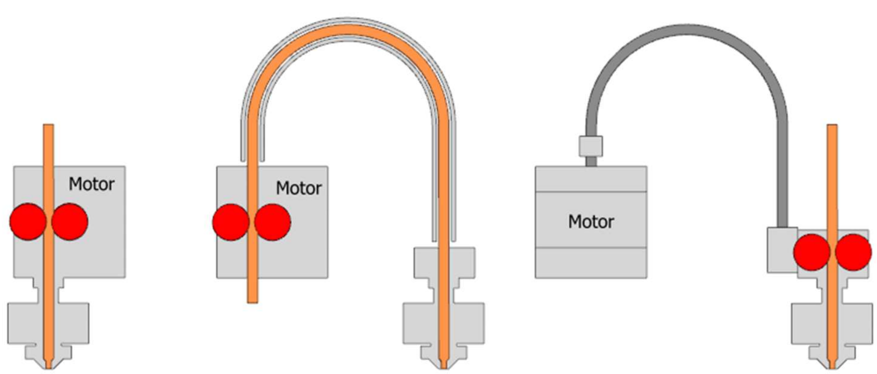
Figure 2.26: FFF Conveyer Printer Illustration [134]

2.2.2. Extruder Assemblies

The extruder assembly is responsible for feeding the material through the heated nozzle as noted in Table 5. The three main extruder assembly types are direct drive, bowden drive, and remote drive. The different extruder assemblies are not taught in the training course, but they are included in the study as background on the FFF technology and to ensure that the teachings are valid for each extruder type.

Direct drive

With direct drive, the entire extrusion assembly is mounted on the print head (Figure 2.27a). The advantage of direct drive systems is the short distance between the feeding mechanism and the print nozzle. The shorter distance reduces inaccuracies that are introduced between the two, allowing for higher control over the printer's flow rate during printing.



(a) Direct Drive (b) Bowden (c) Remote Motor

Figure 2.27: Direct Drive vs Bowden vs Remote Motor [135]

By mounting the extruder assembly to the print head, the mass of this rapid-moving component is increased which can cause inaccuracy in the plane of movement (ripples are visible on printed surfaces as the print head changed direction) [135]. Ideally, printers that use pellets as printing material, should use direct drive systems since it would be difficult to push the pellets/molten plastic accurately over long distances.

Bowden drive

The extrusion assembly is mounted to the frame of the printer, feeding the material to the print nozzle through a tube (Figure 2.27b). Irregularities in flowrate can be introduced in a tube with loose tolerances, especially when using flexible filament that can compress easily. The advantage of using a Bowden style extruder is the reduced weight of the print head, resulting in more accurate movements [135].

Remote drive

The remote drive system is a hybrid of the Direct- and Bowden drive systems (Figure 2.27c). The heaviest part of the extruder assembly (the motor) is mounted to the frame of the printer and drives the feeding mechanism (mounted to the print head) remotely by a semi-rigid shaft. This yields a lightweight print head with accurate control over the material flow rate [135].

2.2.3. Controller Board

The majority of the training course content was based on the slicer software used for FFF. The link between the slicer software and the hardware that performs the printing process is the control system. Most FFF printers have a controller board that processes a set of instructions (typically G-Code) and powers/controls the printer's motors, heating elements, and any sensors. Some controller boards have onboard storage/removable storage where the user saves the instruction set and the printer reads it from, while others have the instruction set streamed to it via a data/network cable from a computer. The user has to ensure that the data stream is not interrupted or terminated during printing since it can cause the print to fail [136]. The firmware that runs on the controller board is discussed in Section 2.3.4.

2.2.4. Open- and Closed-Loop Control Systems

FFF controller boards either operate on an open- or closed-loop control system. These two control systems are summarised in Table 6.

Table 6: Open- and Closed Loop Control Systems [137]

Control System	Operation	Pros	Cons
Open-loop	The output of the system has no effect on the system's operations/actions that are executed.	Simple to implement. Cost-effective. Stable and constant internal processes.	It does not adapt to external changes. Requires external supervision and correction. Less accurate in non-linear environments.
Closed-loop	Closed-loop systems typically have sensors that can measure the output of the system and adjust the operations/actions accordingly.	Adapts to external changes. Requires no external supervision or correction. More accurate in non-linear environments.	Costly and complex to implement and tune. Less stable operation. Feedback can cause runaway if processes are not limited.

The majority of FFF printers have open-loop control systems. The lower cost and level of complexity makes it suitable for the lower-end printers that are currently filling the market. This can come at the cost of failed prints, wasted material, time, and power if an error occurred during printing. Some errors can be detected using sensors and corrected during printing, but others require the object(s) to be printed again. In some cases, the error cannot be corrected during printing, but material, time, and power can be saved by cancelling the print and notifying the user. Below are a few examples of errors that can occur during printing, sensors used to detect those errors, and how one can be corrected during printing.

Table 7: Correction after Sensor Detected Error During FFF Print [138]–[140]

Error	Sensor	Correction during printing
Loaded material depletion	Optical/tactile switch	Halt/terminate print
Stepper motor skipped steps	Motor current detection	Halt/terminate print
	Motor encoder	Correct step count and continue printing
Clogged nozzle	Motor current detection	Halt/terminate print
	Camera & Image recognition	Halt/terminate print
Failed print (bed adhesion, layer adhesion, object features, etc.)	Camera & Image recognition	Halt/terminate print

It is clear from Table 7, that in most cases, the only correction that can be made during printing is halting/terminating the print. An entry-level FFF printer like the popular Creality Ender 3 (without motor stall detection) is sold at 189 USD and the stepper motor drivers that can detect motor stall cost approximately 12 USD (6.3 % of the printer's cost) [141], [142].

The mass-produced entry-level FFF printers typically have a small profit margin, so the manufacturer (e.g., Creality) has to consider whether this corrective action is worth the cost of integrating sensors into the control system.

2.3. Software for FFF

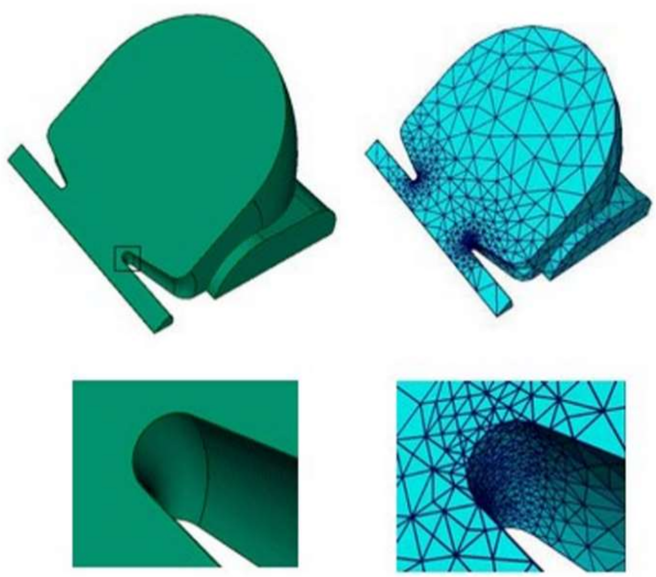
Three major software components form part of FFF; the software used to create a 3D digital model, the software used to slice the model into layers and create an instruction set, and finally the firmware (running on the printer's controller board) which processes and executes the instruction set. A 3D digital model is a virtual representation of a surface or object.

2.3.1. Digital Model

Users can either acquire digital models on the Internet or they can create them themselves using computer-aided design (CAD) or mesh modelling software. Both CAD and mesh models can be 3D printed and a brief discussion on both follows:

CAD model

CAD models are typically solid bodies (with some software packages also capable of surface/mesh modelling) where features are distinguished from each other by accurate continuous lines (Figure 2.28a). Models are either saved as suite-specific or *generic solid* bodies. Suite-specific models can be easily edited using their corresponding software package, but not as easily shared with other editors since they require the same software. *Generic solid* models are universally more compatible with different software packages, but they cannot be edited as easily. Some CAD software packages can convert them back and forth between the two, but suite-specific data can be lost [143].



(a) Solid-body (b) Mesh Model

Figure 2.28: Solid-body vs Mesh model [144]

Mesh model

Mesh models, also known as polygonal models, consist of a collection of data points in the Cartesian coordinate system (X, Y, and Z) connected in triangular patterns that never intersect one another (Figure 2.28b). This collection is referred to as a point cloud, with each point serving as a vertex and the connecting lines as edges. This means mesh models do not have distinguished features (holes and faces separated by continuous lines) as CAD models do which makes them harder to edit. A 3D scanner can be used to capture the shape of an object in a point cloud, producing a mesh that can be edited and printed. Some scanners project lines (using lasers) onto an object and then capture multiple images of it at various angles. An example of such a 3D scanner is provided in Figure 2.29, where a 3D model of a pig is being captured by rotating and capturing images of the contour (of the projected line) at different angles. The lines in the images are then analysed and compared to generate the point cloud that represents the object's surface [145], [146].

Figure 2.29: 3D Laser Scanning [147]

2.3.2. Slicer

The software that is used to prepare a digital model for 3D printing is known as a slicer. The software is used to slice 3D digital models into 2D layers. It then outputs an instruction set for the printer to execute. Some of the most popular slicer software packages were studied to generate a generic user interface that is used in the training course to introduce the user to the slicer environment, enabling them to engage quicker/easier with it.

Popular software packages

There are a wide variety of slicers available on the market at different prices, features set, print quality, user interfaces, and performance. When searching the Internet, users can typically find websites rating the slicer software packages (based on the aforementioned qualities) and ranking them e.g., *top 10 slicers on the market.* The top-rated slicers in Table 8 are based on the weighted average ranking (Appendix C) on the first 6 web search results for "top slicer software".

Table 8: Popular Slicer Software Packages [148]–[153]

Software Package	Score out of 100
Cura	100
Simplify3D	82
Slic3r	75
OctoPrint	63
KISSlicer	57
Repetier	48
AstroPrint	36
PrusaSlicer	22
Netfabb Standard	18
MatterControl	18
ideaMaker	18

User interface

A generic user interface, based on the software packages mentioned in Table 8, is presented in Figure 2.30. Note that the coloured borders are for reference purposes only.

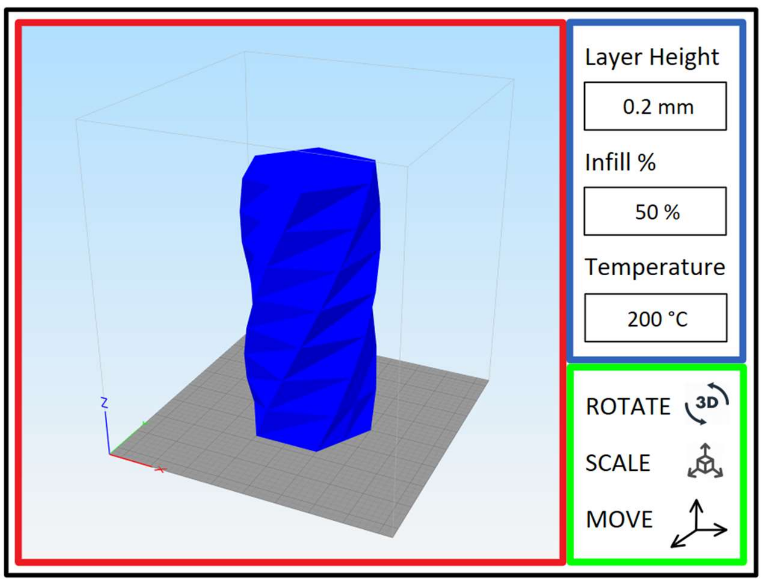


Figure 2.30: Generic Slicer Software User Interface

Red - Model viewing window

The user is given a preview of the digital models, their orientation, size, and position in the virtual print area of the FFF printer that will be used. Some slicer software also allows the user to view the individual layers after the model has been sliced.

Blue - Printing parameters

A varying range of printing parameters is presented to the user. The printed model's physical properties (dimensional accuracy, strength, weight, etc.), printing time, and material usage is determined by the combination of printing parameters selected.

Green - Model manipulation controls

The user can typically translate (move), rotate, and scale the digital model using the controls. Additionally, models can be duplicated and arranged on the build surface using the controls in some slicers.

2.3.3. Model File

The most common model file format used in the slicer environment is Standard Tessellation Language (STL) which is a mesh model (Section 2.3.1) that has a single colour property. A new format known as the Additive Manufacturing File Format (AMF) has been introduced and is based on the Extensible Markup Language (XML) standard. It can contain multiple colour properties and can be compressed to roughly half the size of an STL file [154]. Some also use Wavefront's 3D model format (OBJ) if the model has to possess material and colour properties [155].

The instruction set mentioned in Section 2.2.3 is typically based on the G-Code standard which is popular in the Computer Numerical Control (CNC) based industry. It contains the layer-based route that the print head has to follow (relative to the build surface) and other instructions like material flow rate, temperature setting, etc. [154].

2.3.4. Printer Firmware

Firmware is the interface between software and hardware. It translates the instruction set into electrical signals that can be *interpreted* by the printer's hardware. Most pre-built printers come pre-installed with firmware, but it might be up to the user to install it themselves when assembling a printer kit or upgrading to newer firmware. They have to however ensure that the firmware is compatible with the controller board's hardware. Different firmware packages offer different feature sets at different performance levels, making some more popular than others (with the most popular ones being: Marlin, Repetier, RepRap, Smoothieware, Teacup, Klipper, and Redeem). Some controller boards don't have the option to upgrade or change the firmware running on them [156].

2.4. Limitations of FFF

The general disadvantages of FFF were touched on in Section 2.1.10, but there are some limitations to the printed part geometry as well. These were included in the training course content to ensure that the user was made aware of the technology's limitations. Design for Additive Manufacturing (DfAM) is a design thinking method where the benefits and limitations of AM are kept in mind during the design phase of a model that is to be printed to increase the likelihood of a successful print.

2.4.1. Supported Printing

As discussed in Section 2.2, the latest layer of a FFF print has to be deposited on top of a previously solidified layer or support material. The extruded plastic can typically not cool down and solidify quick enough to be printed unsupported in mid-air. This introduces some limitations to unsupported model geometries namely; overhangs and bridges [157].

2.4.2. Overhangs

Overhangs are printed features that can be categorised as any segment of geometry that, when sliced, results in a newly printed layer extending outwardly past the previous layer. This can result in a partially supported layer, referred to as an angle (Figure 2.31a), or a completely unsupported cantilever layer (Figure 2.31b).

(a) Overhang Angle (b) Cantilever

Figure 2.31: Overhang Angle vs Cantilever

A typical FFF printer is capable of printing a maximum unsupported (without removable support structures) overhang angle of 45° (from the vertical axis) after which the dimensional accuracy of the slope degrades [158]. In-depth studies on the effect printing temperature, printing speed, material, model cooling, overhang geometry, etc., have on the overhang printing performance, using different FFF printers, have been conducted in the past. Unfortunately, their results are localized to those specific conditions, print settings, printer hardware, and material used, making it difficult to generalize any further than the widely accepted unsupported angle of 45° being printable in most situations.

2.4.3. Bridging

A bridge is an unsupported printed layer, suspended between two segments of the printed model. As the unsupported gap between the two segments is increased, the dimensional accuracy of the suspended layer decreases, with the material strands sagging and not boding well together (Figure 2.32). The model cooling, sprinting speed, printing temperature and material flowrate all have an impact on the bridging performance during a print [159].

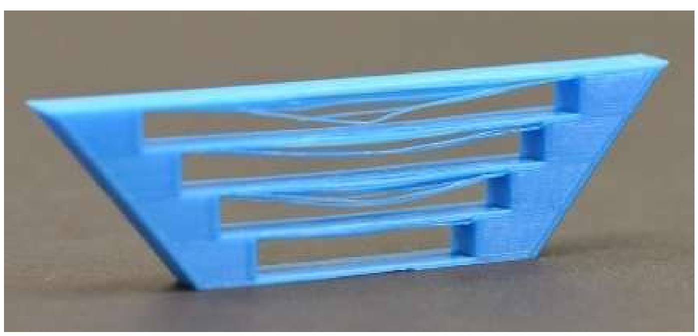


Figure 2.32: FFF Bridging [160]

2.4.4. Printing Area

A FFF printer only has a limited range of motion, with its outer limits encapsulating the available print area. Printed models have to be equal to or smaller than the print area, otherwise, the firmware will implement its soft printing limits (halt movement in the limited direction before a hardware collision occurs) by drawing a straight line along the limited perimeter to where the printed model continues within the printing area [161]. The printer's kinematics also has an influence on the shape of the printing area as mentioned in Section 0.

2.5. FFF Printed Features

Some of the printed features and elements of FFF parts have to be considered when using this manufacturing method. The printed part's first layer, functionality, dimensional accuracy, and the supports required for printing are discussed in this section. All of these features were taught in the training course.

2.5.1. First Layer

As discussed in Section 0, a lot of FFF printers cannot detect whether the first layer of a print was successful and stable. If the first layer is not stable/successful, then the remaining layers can fail as they are all dependent on the previous. If the material warps or the nozzle oozes material, it can result in an uneven new top layer. The printhead can potentially crash into these uneven layers, either damaging the print/printer or knocking the print loose from the build plate [162]. If the model has a secure first layer and stable geometry (large base) the print has a better chance of continuing/recovering after a collision. Some FFF printers have the build plate set up on axes of movement which can potentially shake unstable prints loose, also resulting in a failed print. Thus, it is important that the user understands how to orient the parts correctly for the parts to have the maximum contact surface area, as it influences the stability and bed adhesion of the part's first layer [163].

The user has to ensure that the printhead is offset at the correct height from the build plate for the first layer. If it is too far away, the material won't adhere to the build plate, but if it is too near, the nozzle won't be able to extrude the material correctly (Figure 2.33). This means the build plate must be level to ensure a constant first layer height. The bed adhesion is not only a product of the part's orientation but also of how well the material adheres to the build surface (regardless of the print height). The user has to ensure that their printer's build surface material would provide adequate adhesion for the material that they plan on using [164].

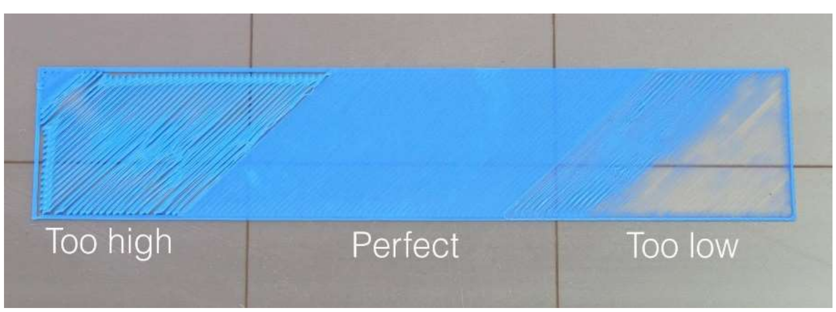


Figure 2.33: Perfect First Layer Height for FFF Print [165]

Material warping

As a printed layer of a model cools down, the material shrinks slightly. The shrinking force acts in both horizontal and vertical directions with a net force towards the upper centre of the part as shown in Figure 2.34. This typically results in the corners of the model warping upward, reducing the bed adhesion during printing and the final dimensional accuracy [166].

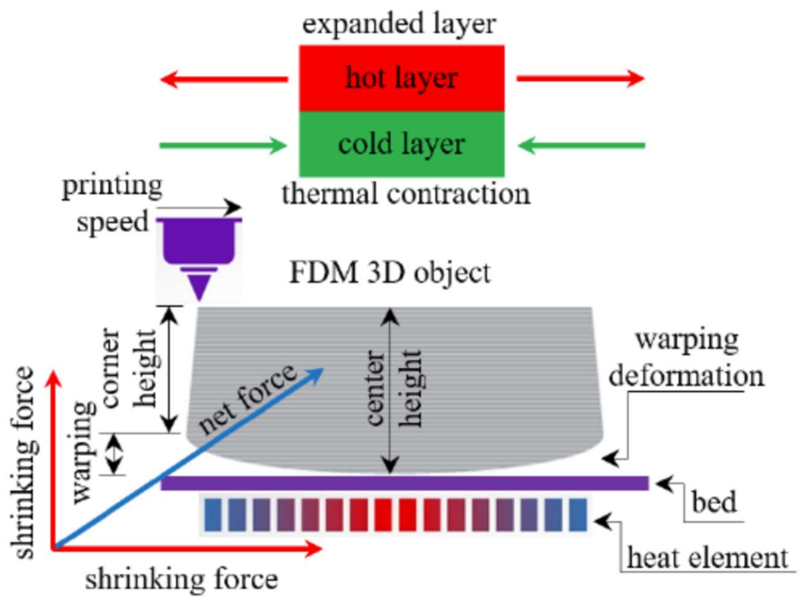


Figure 2.34: Net Shrinkage Force in FFF (FDM) Print [24]

Warping can be reduced by limiting the difference in temperature between the cooled (previous) layer and the hot newly printed layer. The printed layers can be kept warm using conduction (air surrounding model)-or radiation heat (heating bulbs aimed at the model). Convection heat transfer is more effective than conduction, thus any cool air blowing across the model (e.g., the model cooling fan) can aggravate warping. By enclosing the printer, capturing the heat produced by the build plate (if installed), and limiting cool airflow from the printing environment and model cooling fans, warping deformation can be reduced.

Some model geometries are more susceptible to warping deformation due to the net shrinking force overcoming the adhesion force effectively. Thin and long geometries with sloped sides (Figure 2.35a) are more prone to warping [167].

(a) Geometry Prone to Warping [167] (b) Brim [168] (c) Raft [169]

Figure 2.35: Model Geometry that is Prone to Warping and FFF Bed Adhesion

Warping typically starts at the model's corners since the shrinking force of two sides both act out on one point. Warping deformation can be reduced by rounding the model's corners, orientating the model with larger surfaces touching the build plate, and increasing bed adhesion using a brim/raft (Figure 2.35b and Figure 2.35c) to increase the surface contact area or using a different build surface material. The user can also use a different build surface material to achieve better adhesion for the first layer [163].

2.5.2. Functional Models

Some models are printed as functional/replacement parts that have to endure/withstand the environment it is used in [170]. An appropriate printing material, model orientation, and print settings have to be used based on the model's application (impact, bending, compression, tension, torsional forces or model opacity, buoyancy, weight, dimensional accuracy, etc.).

Directional strength

FFF models are anisotropic which means they are stronger in certain directions than others. The layer adhesion of a FFF model is up to 55% (tensile strength) weaker than the in-line material strands which mean models can withstand higher loads with their layer lines oriented parallel to the tensile force (stronger in X and Y directions than Z when pulled apart)(Figure 2.36)[171]. Layer adhesion can be altered by using a different printing material, layer height, extrusion width, model cooling setting, and layer density (shell thickness and infill percentage) [172].

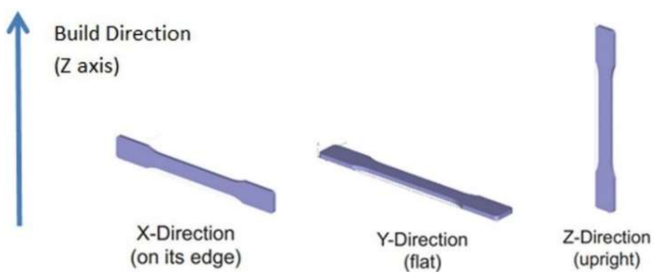
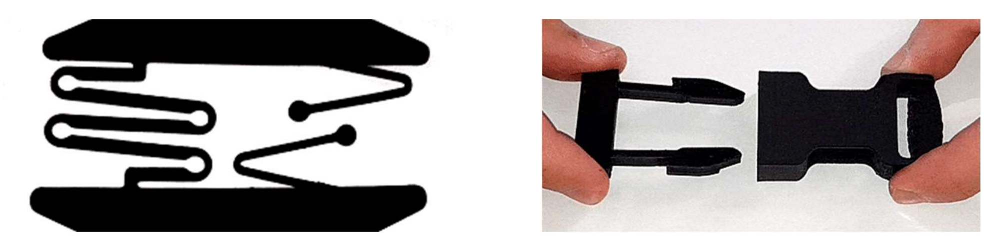


Figure 2.36: Using Print Orientations for Directional Strength on FFF Printed Models [173]

Compliant material

Most of the FFF printing material has compliant properties, which means the material can recover to its original shape after being deformed if plastic deformation hasn't occurred yet [174]. This allows for clipping- (Figure 2.37b), spring- (Figure 2.37a), locking- and switching mechanisms to be integrated into FFF models. The layer lines have to run parallel to the bending direction to achieve the most durable mechanism.



(a) Spring Mechanism (b) Clipping Mechanism

Figure 2.37: Compliant Materials

2.5.3. Dimensional Accuracy

The dimensional accuracy of a FFF model can be crucial depending on its application. The user can perform test prints on their FFF machine and tune a variety of slicer settings or change hardware components to improve dimensional accuracy. The dimensional accuracy can be categorised into two main parameters namely vertical- and horizontal measurements [175].

Vertical

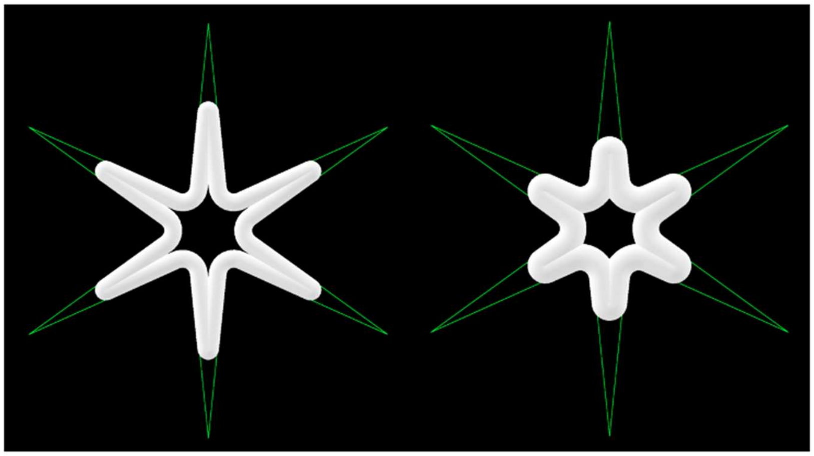
When a model's sloped/rounded surface is sliced and printed on a FFF printer, a stepped surface is produced by the layers (Figure 2.38). If the layer height is increased, the step size increases which results in less dimensional accurate sloped/rounded surfaces (Figure 2.38b). The opposite is true when the layer height is decreased, but the higher dimensional accuracy comes at the cost of extended print times since more layers have to be printed (Figure 2.38c). The total (printed) vertical height of the model can also be influenced by the division of the (digital) model's height by the layer height e.g., printing a 10 mm high model using a layer height of 0.3mm would result in a 9.9 mm or 10.2 mm high model dependant on whether the slicing software rounded the layer count up or down.

(a) Digital 3D Model (b) 0.3 mm Printed Layer Height (c) 0.1 mm Printed Layer Height

Figure 2.38: Vertical Resolution (viewed from the side)

Horizontal

When a model is sliced in the slicer software, the outer-most printed perimeter may not exceed the boundary of the digital model's outer surfaces. An example of printing a star shape slice is provided in Figure 2.39. If the model has geometric features that are thinner than the printer's nozzle, it will only print up to the point where the nozzle fits within the lines. If a smaller diameter nozzle is installed, the slicer software allows for more of the feature to be printed since it can still travel within the boundaries (Figure 2.39a), but the printing time is increased due to a lower rate of material deposition. The opposite is true when using a larger diameter nozzle, as more material can be extruded per time interval, but the printed geometry will be limited more by the digital model's outlines (Figure 2.39b).

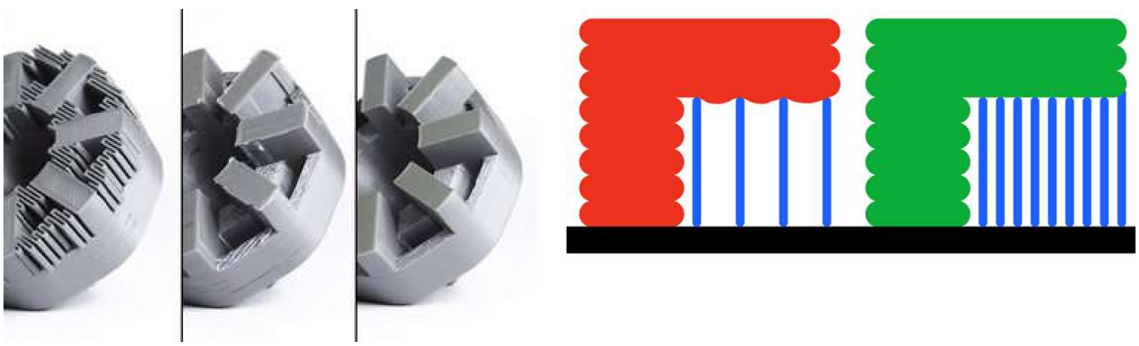


(a) 0.4 mm Nozzle (b) 0.6 mm Nozzle

Figure 2.39: Horizontal Resolution (viewed from above)

2.5.4. Support Structures

Support structures are pillar-like structures that are printed with the model to support overhanging surfaces (Section 2.4.2). Supports are typically printed in a zig-zig pattern and not 100% solid. These structures are removed after printing and discarded (Figure 2.40a).



(a) Zig-Zag Support Structure [144] (b) Support Structure Density

Figure 2.40: FFF Support Structures

By adding supports to a model result in more material cost, printing time, and post-processing. It does, however, enable some features to be printed that otherwise could not, even when reoriented. Most slicer software packages have the option to generate support structures where needed, but the user has to ensure that they are reachable for removal. If the support density is too low, the supported material strands can sag between the pillar lines and bond with the supports (Figure 2.40b). By increasing the density of the supports' interface layers with the model and offsetting the supports (horizontally and vertically) from the model, the adhesion between the two is reduced, making removal easier for the user during post-processing. The effectiveness of the support structure is reduced if the part is offset too much since the material strands will start sagging as with no supports.

Some FFF printers can print using two different types of filaments (either using two nozzles or backing one filament up for the other to flow through). Dissolvable filaments like PVA can be used to print the support structures (Figure 2.41). This allows the user to place support structures where they cannot be reached using tools (for removal) but accessible by water [153].

Figure 2.41: PVA Dissolvable Support Structure [128]

2.6. Education

After gaining a better understanding of technology, AM, and FFF in particular, the focus of the literature study was shifted to education. This section provides background on education and helped to develop the training course. The E-learning platform (that the course was based on) and the different teaching methods and elements (that was used to develop the course) are discussed in this section.

Education refers to a formalized transmission of knowledge from an educator to a learner. It is a discipline that is conducted within education environments where the educator directly/indirectly spends time, using different teaching methods, to transfer a specific set of values/information to a student [176].

2.6.1. Learning Environments and Students' Experience

When using the term "education environment", it can refer to the physical environment that is used for the discipline or the learning atmosphere that the educator creates [177]. Education can be performed face-to-face, remotely, or as a hybrid of the two. The educator can establish a positive educational atmosphere by addressing the student's needs, providing them with a balance of positive and critical feedback, and ensuring they feel physically and mentally safe/supported [178].

The aim of the FFF training course was to increase the adoption rate of the technology by equipping the students with knowledge on it and to increase their confidence to engage with it. A brief discussion on knowledge retention methods and student confidence follows:

Knowledge retention

There are numerous methods to help improve knowledge retention during education. A few of these methods are listed in Table 9. They were used in the training course to help make the course more effective in educating the user in FFF.

Table 9: Boost Knowledge Retention during Education [179]

Introduce small tests/quizzes	When small low-risk tests are introduced in between the teaching sessions, the students are required to recall the information they just learned. These tests also help retain the students' attention and can be considered as a gamification element (Section 2.6.4)
Combine topics	By combining the different education topics that are relevant to one another, the students are required to recall and apply different sets of knowledge to the new situation.
Encourage students to use new information/skills	Give an opportunity for the students to use the new skill/knowledge that they acquired. The quizzes are an example of this, where students are encouraged to pay attention during the teaching as they will soon have to use the knowledge/skill.
Utilize scenarios	The students' long-term memory is utilized when real-world scenarios are connected to the educational content. It also encourages them on the relevance of the teaching as it has real-world implications.

A discussion of how each method was used in the FFF training course is provided in Section 3.3.

Student confidence

Education not only helps to increase the student's knowledge, but can also boost their confidence by improving their skills in communication, critical thinking, problem-solving, and their future prospects [180]. Educators also utilize practical- and written tests to help further the student's experience in a specific field of expertise [181]. An individual with knowledge, confidence and experience has very little hindrance to engaging with the corresponding field of expertise. Thus, if users receive training in FFF, they will be more confident in engaging/adopting the technology which will help address the problem statement of this research study.

2.6.2. Teaching vs Training

The terms teaching and training are often used interchangeably, but they are not exactly the same. Teaching refers to the theoretical impartation of knowledge on a certain subject, from a teacher to student(s). A base and an in-depth understanding can be transferred through teaching, allowing the student to study the subject further or even equip others with the knowledge.

The entire process of teaching can happen without direct interaction with the subject. A wider range of subjects can be covered during a teaching session than that of training. Teachers have, however, discovered the value of the aforementioned interaction for an improved understanding and knowledge retention amongst students. Teaching is still primarily knowledge-and understanding-based [182].

Training, on the other hand, takes place between a trainer and trainees, where skills are imparted through exercises and abilities are refined. A training session typically only focuses on one subject at a time to ensure that the skill is successfully established. Training can greatly benefit from the trainees having a good understanding of the subject, imparted through teaching [182].

The term “training course” is defined in the Cambridge Dictionary [183] as:

“a series of lessons to teach the skills and knowledge for a particular job or activity”

It makes sense that the two terms are used interchangeably as we see how much the two categories overlap and complement one another.

2.6.3. E-Learning

E-learning is an educational environment that is accessed via digital devices on local or international networks (periodic updates can also be made to offline digital devices). A large advantage of this environment is that the students and teacher do not have to be present at the same location or time. This means synchronous and asynchronous learning can take place at the click of a button. Synchronous e-learning allows for live engagement (questions and answers, discussions, etc.) between the students and the teacher e.g., a webinar. Pre-recorded video/audio teachings paired with the educational content (slides, textbooks, etc.) are examples of asynchronous teaching where the students can engage with the teaching at their own pace and time [184]. Digital tests with definitive answers can also be graded automatically and give students instant feedback on their performance. In addition to providing them with rapid feedback, the teacher/digital course can also provide the students with the applicable resources to improve on their mistakes [185].

Access to e-learning

As mentioned in Section 2.6.3, students require digital devices to access the educational content. The adoption of digital devices (personal computers, smartphones, etc.) has drastically increased over the last decade with the mobile industry giving 3.5 billion people (47% of the global population as of 2019) access to the Internet. An estimated 90% of the global population is covered with broadband mobile networks, but 48% of them do not use these networks which means the Internet user base (e-learning included) has great potential for expansion in the future [186].

2.6.4. Teaching Methods

The two main teaching methods that were used in the FFF training course are gamification and trial-and-error-feedback. These methods are discussed in further detail in this section.

Gamification

Gamification was described by a training institute (Training Industry) as “the process of applying gaming designs and concepts to learning or training scenarios to make them more engaging and entertaining for the learner” [187]. The gamification of educational content and training courses are categorised as “serious” gaming, while “recreational” gaming i.e., video games are purely for entertainment purposes. By implementing a combination of competitive and reward-based activities, a more enjoyable experience can be created for the learner while increasing their knowledge retention and skill development [187], [188]. Generation Y, also known as the millennial generation, describes a person born between 1980 and 1999 and is known for being technologically savvy and enjoys personalization [189]. The majority of generation Y grew up playing video games and tend to seek out gaming mechanics in the environment around them i.e., playing stock exchange simulation games, creating virtual teams for popular sports, etc. This makes game-based education and training more attractive and engaging for generation Y learners than traditional methods [188].

A set of best practices for the development and gamification of training courses in the industry was developed by Training Industry [187]. It can also be used in higher educational institutes to form part of the preparation for the manufacturing industry. These best practices are as follows:

Identify business objectives:

The company should first identify their business needs and objectives to make sure that gaming would be beneficial for their training. Even though gamification has proven to be very effective in certain applications, non-gaming activities such as customer service, market research, and product support would not benefit from gamification as a method of teaching or training.

Partner for performance:

The company can communicate their business objectives and purpose for training better if a close partnership has been established with the game developer. The performance and efficiency of the training might be non-optimal if the game developer has to fill in any areas that weren't properly communicated by the company.

Plan, model, and test:

The player experience and the success of a game are dependent on how well the development was planned, executed, and refined. The developers can base their planning on the company's objectives and have sample groups of students test the game after development for feedback and final refinement.

Design for engagement:

A game is successful if the players engage with it. Interest in the game can decrease if the game is based more on viewership than engagement. If the player can visibly link their achievements to their actions, typically through dashboards, they can track their progress. The competitive aspect of gaming can be implemented using leader boards which also boosts engagement.

Consistency is key:

The game developers might use different game mechanics, methods of training, and means of delivering information to the student. However, the game should be relatively consistent throughout since the learner might be unfamiliar with game-based learning. Inconsistency in the game can break the student's engagement with the game.

Refresh the information:

The training course content has to be updated for it to remain relevant in the ever-developing industry. This is only valid for training courses that will continually be used in the future.

Sustain training impact:

Small game-based activities can be integrated into the less exciting teaching or training elements to maximize the impact on the learner.

Vary the program:

The player behaviour can be controlled using customizable plug-ins and reward systems so that the company's desired result can be achieved.

Trial-and-error-feedback

The subconscious plays a large role in the learning process and is considered to be an efficient and powerful part of our brain [190]. Dr David Eagleman investigated how great a role our subconscious plays in our daily lives and noted that “there is a chasm between what the brain knows and what our minds can fathom”.

He uses examples like the act of breathing, analysing finger movement while playing the piano, or your swing during a golf game to show how poor our conscious thinking would be at performing the subconscious’s job. David Eagleman stated that “you are not consciously aware of the vast majority of your brain's ongoing activities, nor would you want to be - it would interfere with the brain's well-oiled processes” [191]. A form of implicit memory is used to remember motor acts as riding a bicycle, treading water to stay afloat, or simply breathing where the person doesn’t have to and sometimes cannot access that knowledge with their mind. A skill or expertise can also reside in the same implicit memory. The question is how can someone train another in, or personally learn a new skill that cannot be accessed by the mind.

Edward Lee Thorndike stated in some of his theories on learning (1913), Bond Theory of Learning in particular, that connections are formed between responses and stimuli within the nervous system. He referred to these connections as bonds, hence the name of his theory. He tried multiple solutions to a problem in a “random” manner and ignored the irrelevant responses. Gautam noted that some refer to it as “learning by selection of the successful variant” [192]. He also noted that the solutions are not picked completely at random, but that the trial-and-error-feedback method involves systematic/relevant responses. He described the stages that a learner has to pass through when answering questions as “goal, block (hindrances), random movements or multiple responses, chance success, selection and fixation.” which then helps to shape future responses. [192]. Thorndike propounded what is known as the laws of learning. There are three basic ones he put forth and five subordinate ones he referred to (Table 10)[193], [194]. A recent study on trial-and-error learning shows that the task of learning goes beyond merely associating stimuli and responses via incremental reinforcement. Specifically, during initial learning, high-level cognitive processes support sophisticated learning strategies that increase learning efficiency while keeping memory demands and computational efforts bounded” [195].

The Japanese used a similar training method in the early 1930s. It was used by professional chicken hatchling sexers to train students in identifying the gender of a young chick, which is notoriously difficult since the male and female chicks look virtually the same. The professionals can identify the gender based on very subtle cues, but they couldn’t train the students in what the cues are since they didn’t know them themselves. Instead, the students tried to identify the gender under the professional’s supervision. The student is given a “yes/no” feedback on their guess, which over time improved the success rate of their guesses. The students are also unable to explain the visual cues that they based their decisions on, but they are now equipped with a new subconscious skill. The British used a similar method in World War II to train their spotters in quickly and accurately identifying incoming planes like the British returning or German bombers attacking [191].

Table 10: Laws of Learning [193], [194]

	Law	**Description (partially quoting Manisha Naithani)**
Thorndike's Basic laws	Readiness	Learning takes place when an action tendency is aroused.
	Exercise	Practice helps in increasing the efficiency and durability of learning.
	Effect	Any behaviour that is followed by pleasant consequences is likely to be repeated.
Subordinate laws	Multiple Response	A change or variation in response till an appropriate behaviour is arrived at.
	Set or Attitude	Learning is affected more in the individual if they are set to learn more or to excel.
	Pre-potency of Elements	The learner would react selectively to the important features in the situation neglecting the non-essential ones, thus leading to analytical and insightful learning.
	Law of Response by Analogy	Utilising old experiences in a new situation.
	Law of Associative Shifting	Teachers may get a response from learners with other situations to which they are sensitive.

Dirk C. Prather compared trial-and-error training (with no feedback) to an errorless training method. The students were left alone to re-answer the same question until they got it right in the trial-and-error method, while the errorless method is based on helping or prompting the student to answer the questions correctly. The two methods yielded similar results, but it was found that the errorless method is based on a feedback system. This shows that trial-and-error with no feedback, in itself is a powerful method of learning and that a feedback system helps students to perform better [196].

2.6.5. Bloom's Taxonomy

Bloom's taxonomy is a framework that has been used by many K-12 educational instructors (teachers and lecturers) for generations now, to categorize their educational goals. Benjamin Bloom, in collaboration with four other individuals, established the six categories as knowledge, comprehension, application, analysis, synthesis, and evaluation and published the framework in 1956. It is known as The Original Taxonomy with The Revised Taxonomy published in 2001 by a group of specialists in the field.

The new framework recategorised the 6 processes as remember, understand, apply, analyse, evaluate, and create, with knowledge being the basis for them all (Figure 2.42). The framework helps educators to establish and organise their learning objectives, which then aids them in planning, designing, and executing their assessment tasks [197].

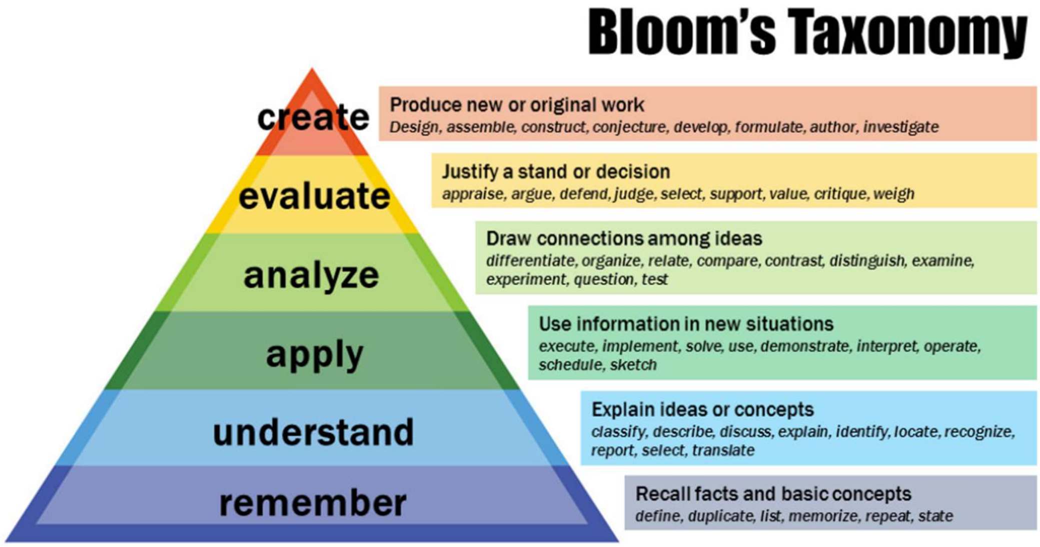


Figure 2.42: Revised Taxonomy [197]

This framework was used to develop the FFF training course structure and content. A discussion on how it was used is provided in Section 3.3.

2.6.6. Visual Aids

During a teaching session, the teacher has to ensure that the knowledge transfer to the student is successful. A good teacher can identify when the students no longer follow their explanation or lose interest/not paying attention anymore [198]. This disconnect can occur when the content is not structured to be engaging and when knowledge is being dumped on the student by merely using written and spoken words. If the student has to understand a concept that is being taught (and not merely memorize the knowledge), they need to constantly convert the words they hear/read into imagery, concepts, or just their own words to better grasp and retain the knowledge [199], [200]. This can become tiring and the flow of effective teaching can be interrupted every time a concept is too abstract for the student to quickly convert. The contribution of human senses to the learning process has been estimated as follows (Table 11).

Table 11: Contribution of human senses to learning [201]

Human sense	Estimated % Contributed to Learning
Taste	1
Touch	1.5
Smell	3.5
Hearing	11
Sight	83

Sight has the biggest influence on the learning experience, making a tool like visual aids extremely useful. “Visual aid” is defined in the Oxford dictionary as [202]:

“a picture, video, etc. used in teaching to help people to learn or understand something”

By introducing visual elements like images, videos, charts, maps, etc., the student can easily and quickly engage with the content. The visual representation of the concept that is being taught reduces the need for a detailed description (using words) to encapsulate the entire concept. Instead, the visual aid summarizes/simplifies it, while retaining the attention of the student by using different colours, shapes, sizes, formats, etc. Studies have shown that the use of visual aids can elevate the effectiveness of the teaching process [201], [203]. The findings of one of these studies, with a sample size of 200 individuals, are summarized in Table 12.

Table 12: Study on Visual Aids [201]

A statement that visual aids . . .	Percentage of students and teachers within the test group who agree with the statement
Help to motivate students and teachers	70%
Help to clarify the learning content	75%
Help to expand the learner and teacher's vocabulary	68%
Help to save time during the learning process	82%
Help to avoid dullness during the learning process	71%
Help to improve the direct learning experience	92%

The study has found that the students develop a personal understanding in a pleasant learning environment, established when using visual aids. The use of visual aids also stimulated thinking and can substitute monotonous learning environments if used correctly [201]. The younger generations of students have indicated a preference for the use of more visual aids during teaching [204], [205]. There is also increased use of visual aids in online teaching platforms (Section 2.6.3), following in the footsteps of large social media platforms who retain the user's attention better by limiting the amount of written content and prioritizing the visual content [205], [206]. Visual aids form a major part of the FFF training course content and are discussed in Section 3.3.

2.7. Online Platform Development and Hosting

This section provides background on the online platforms and tools that were used to develop the online FFF training course. A brief discussion of the Internet was provided first as it plays a crucial role in these platforms, after which web and app development, development languages and frameworks, databases, and hosting servers are discussed.

2.7.1. The Internet

The Internet was created in the 1960s to connect the large computers of the time, enabling the exchange of data and removing the need for users to go to different computers to access the locally stored data. It was primarily used by governmental researchers, with an increased use during the Cold War. The United States Defence Department wanted to establish means to exchange information in the event of a nuclear attack (around the time when the Soviet Union launched the Sputnik satellite) [207], [208]. This need was fulfilled by the Advanced Research Projects Agency Network (ARPANET) that was developed, but it wasn't available for public use. ARPANET was however a stepping stone to the development of the Internet (1983), a standardised means of communication between computers. The Transfer Control Protocol/Internetwork Protocol (TCP/IP) was developed thereafter which allowed inter-network communication and was not limited to computers having to be of the same brand or model for communications to occur [207]–[209].

The World Wide Web (WWW) as we know it today is a hypertext project, developed by Tim Berners-Lee in 1989. His vision was to create an interlinked "web" of hypertext-based documents, better known as web pages that can then be accessed by users using an application/program known as a "browser" [210]. In 1990, Tim released three new technologies, each with a different function (Table 13)[211], [212].

Table 13: Three technologies developed by Tim Berners-Lee [211]

Name	Abbreviation	Use
Hypertext Transfer Protocol	HTTP	Used to retrieve other web pages and resources across the WWW.
Uniform Resource Identifier/Locators	URI (URL)	Used to identify a webpage or the resources in it by using a unique address.
HyperText Markup Language	HTML	Used to do the visual structuring/formatting/markup of the web page.

The WWW went through multiple revisions, with the first (Web 1.0) being very slow and the web pages did not update automatically when altered by the owner. The pages had to be refreshed regularly and only the owner could make changes/add information to it. The second revision (Web 2.0) allowed for bi-directional user interaction, where they can upload and download content to and from web pages. Communities were enabled to interact socially using the WWW when this bi-directional functionality was introduced. The third and current revision of the WWW (Web 3.0) introduced executable web apps where users can interact with dynamic pages (contact forms, payment portals, etc.). The WWW itself became a large database that can easily be navigated with quicker/more "intelligent" search results [212]. Digital devices are also enabled to communicate and exchange data with each other without human intervention. This plays a large role in the 4th industrial revolution mentioned in Section 2.1.7. With the increased use of mobile personal computers (PC), smartphones, and other "smart" devices (Section 2.6.3), users can quickly and easily access the Internet (if a wired/wireless connection is available).

2.7.2. Web and App Development

A web developer is someone who creates web pages or elements for it. They also perform maintenance and upgrades on existing pages [213]. The developers have a range of web developing workflows and coding languages at their disposal. Many of the web development elements are also used to develop mobile apps for smartphones. A generic web and app development workflow is presented in Figure 2.43.

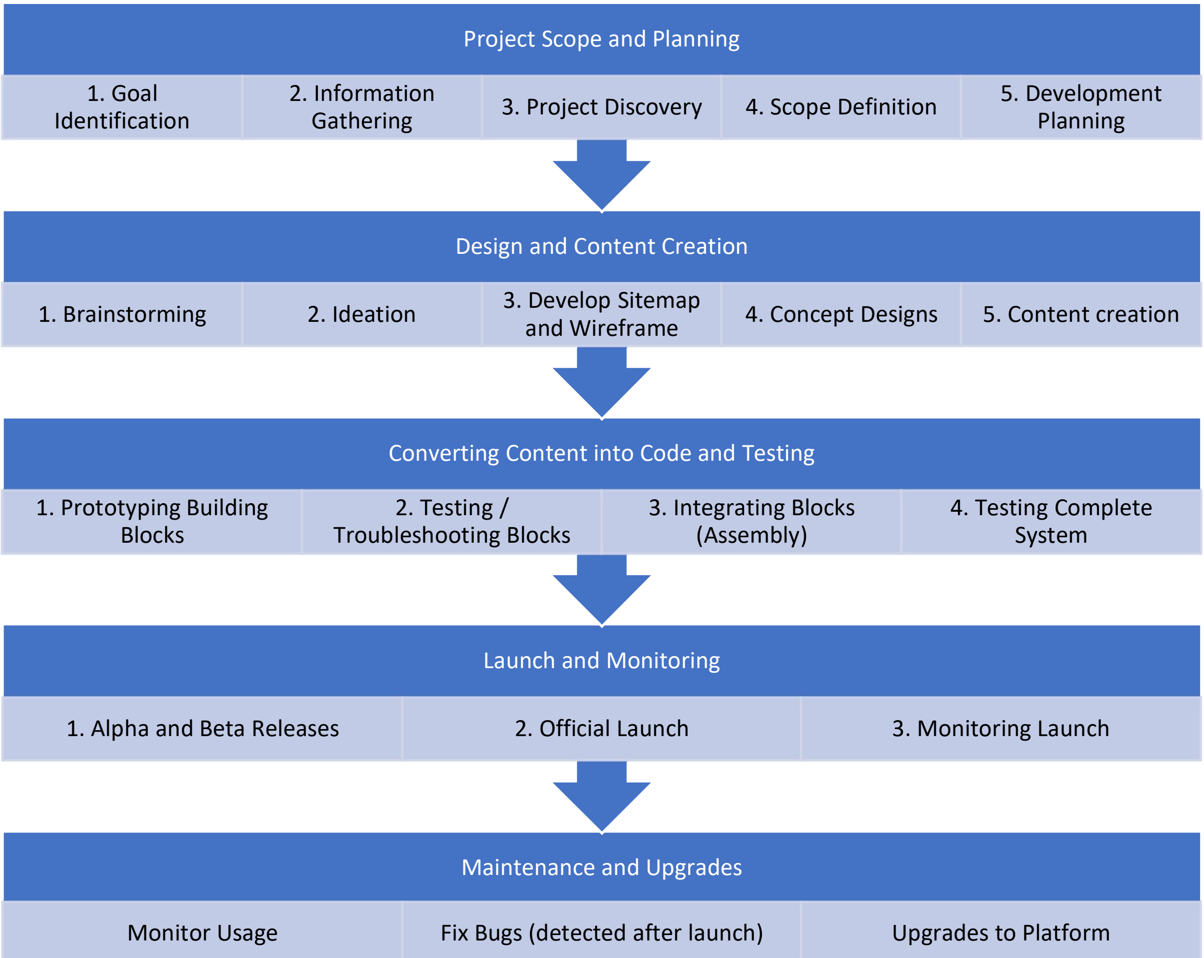


Figure 2.43: Generic Web/App development Workflow [214]–[217]

A short description of each step in the development process follows. When the term "developer" is used in this case, it refers to the entity (individual, company, group, etc.) that is responsible for completing the development process. The webpage/app is referred to as the "platform".

<u>Project Scope and Planning</u>

1. **Goal identification:** The developer allocates time to establish what the client's needs are or to formulate their own goals for the project.
2. **Information gathering:** Research the target market for the platform and requirements of developing a platform in the desired sphere/industry where competitors may be at play.
3. **Project discovery:** More goals can be identified during the research phase that can lead to additional research. The developer "discovers" more of the project as they lay down the foundations for developing the platform.
4. **Scope definition:** After gaining a better understanding of the project, the developer can define the project scope. This provides a reference point to help ensure that the project does not deviate from the original goals that were set out.
5. **Development planning:** The project scope is considered to help plan and establish the project's timeline, costing, deliverables, etc. These elements can be used to measure the performance of development during the process.

Design and Content Creation

1. **Brainstorming:** The developer starts laying down their thoughts (whatever comes to mind) for the content creation to kick off.
2. **Ideation:** The raw ideas from the brainstorming session are then categorised/packaged/refined to produce standalone ideas that can be further developed.
3. **Develop sitemap/wireframe:** A general project structure/sitemap is laid out as a wireframe that can be filled in. The sitemap becomes more detailed/fleshed out as the different ideas and preliminary content (generated in prior steps) are integrated.
4. **Concept designs:** Concept designs can be generated using the fleshed-out wireframe. The developer can perform a trade-off study if they opted to generate more than one concept design (by comparing the pros and cons of each).
5. **Content creation:** The actual content creation can commence and be based on a concept design or a combination of concept designs. The flow/user experience of the platform will be considered and the layout of the different elements will be finalized.

Converting Content into Code and Testing

1. **Prototyping building blocks:** Developers can split the task of coding an entire platform into smaller manageable "blocks" of code (typically split by feature/function type). Some elements, layouts, and code snippets can be duplicated and reused/edited multiple times to standardize the code and reduce the development time.
2. **Testing/troubleshooting blocks:** By splitting the bulk code of the platform up into smaller blocks (that can be assembled later), enables the developer to troubleshoot issues easier as they are contained within each block.
3. **Integrating blocks (assembly):** The code blocks are finally assembled according to the wireframe structure. Additional code may be necessary to have the blocks of code work together correctly.
4. **Testing complete system:** The individual blocks of code may function correctly in a standalone setup, but the developer has to test the platform's code in its assembled state. Coding errors (also known as "bugs") may have been introduced by the new code that was written for the assembly or in the interaction between blocks.

Launch and Monitoring

1. **Alpha and Beta releases:** The developer can make the platform available for the public/client to test in its preliminary (Alpha) or more refined development state (Beta). The developer clearly states to the early adopters that the platform is not in its final form and is still undergoing development and changes.
2. **Official launch:** After receiving internal and/or external feedback on the Alpha and Beta releases of the platform and making the required changes, the developer can officially launch the platform for the public/client.
3. **Monitoring launch:** There may be more user traffic during the official launch of the platform. The developer should be able to monitor the performance and statistics of the platform launch to ensure everything is working as intended.

Maintenance and Upgrades

- **Monitor usage:** The platform use can typically be monitored to gather data for internal performance statistics. The data can also be used to identify areas that can be optimized.
- **Fix bugs (detected after launch):** Any bugs that were detected after the official launch (or introduced by revisions/upgrades to the platform) are fixed through incremental updates.
- **Upgrades to Platform:** The developer can upgrade the platform by improving its performance or adding additional functionality.

The "Maintenance and Upgrades" phase can continue for the lifespan of the platform or until the developer decides to do a large revision of it. The development can be categorised as either back-end or front-end and is an important aspect to understand when engaging with the process.

Back-end vs Front-end Development

The front-end refers to the visual elements/content and client-side interaction. These include media (images, videos, animations, etc.), buttons, forms, lists, navigation, user menus, general layout structure, etc. The front-end would not be able to function properly without the back-end since the back-end is where the functionality of the website is coded and is not visible for the end-user. The back-end developers have to keep the architecture/structure of their code, security, the interface with the front-end, databases, servers and with other web pages in mind when developing the platform [218], [219].

2.7.3. Development Languages and Frameworks

There are hundreds of free open-source programming languages and frameworks that developers can choose from. A language can be selected based either on its strong suits, the experience the developer has with it, preferences of the development group, community size, resources that are compatible/available for it, or a combination of these factors. A coding language refers to the grammar and syntax that is used during the development while frameworks are used to simplify the process by providing a set of libraries for the developer to use [220], [221].

Languages that are commonly used/popular among developers for back-end development are Python, PHP, Java, and C# to name a few. Javascript, React, Angular, VueJS, are some of the popular languages used for front-end development and can be used with markup tools like HTML and CSS [222]–[224]. The developer uses text-based editors (Visual Studio Code, Atom, Notepad++, etc.) to write the webpage/mobile app code. Frameworks like PhoneGap, Ionic, React Native, Flutter, and Xamarin allow developers to develop apps for multiple platforms (e.g., Android, iOS, Web) at once which can help cut down on development time when catering for a larger audience of users [225].

2.7.4. Databases and Hosting Servers

A database is a predefined structure (typically a grid of rows and columns) used to organize data or files that contain information (records, documents, media, etc.). Digital databases are managed/controlled using a database management system (DBMS) and allow the user to view and edit the data [226], [227]. Digital databases can be stored on local devices (desktop computer, smartphone, etc.), local storage devices (compact disc, flash drive, storage array, etc.), or on remote storage arrays (commonly referred to as the "cloud").

Large technology companies like Google, Microsoft, Apple, etc., provide remote storage for their users that can be accessed over the Internet [228]. Other companies like Wix, Squarespace, WordPress specialize in hosting web pages on their storage arrays (also referred to as servers) and even provide user-friendly tools to build one without knowing any coding languages [229]. The companies that develop operating systems for smartphones (e.g., Google and Apple) also have online app stores where a collection of compatible apps is listed. The developers of the mobile applications upload their app to the company's storage server after which the smartphone users can download it from the app stores [230], [231].

2.8. Existing Digital FFF Training Courses

A study was performed on existing digital FFF training courses and discussed in this section. The training course that was developed during this study is referred to as the "new course" in this section.

The existing courses were studied to ensure that all of the foundational elements of FFF were included in the new course. Only the ones that are free of charge were evaluated to keep the project's expenses low and to match the "new course" since it was made publicly available free of charge. The majority of free training courses were found on the YouTube platform and can be categorised by their "time to complete" and "educational content detail level". The courses that go into less detail on FFF require less time to complete, with the opposite being true for more detailed courses. The training courses that were evaluated in the study are categorised in Table 14.

Table 14: Existing FFF Training Courses Educational Content Detail Level and Time Required to Complete

Educational Content Detail	Introductory	Basic	Detailed
Course Time to Complete	Short (< 1 hour)	Medium (1 to 4 hours)	Long (> a day)
Training Course References	[232]–[235]	[236], [237]	[238]–[240]

The time required to complete the new course was compared to that of courses with a similar level of content detail to qualitatively determine whether the new course can be described as a rapid training course. The new course's content can be considered to provide a basic level of detail so the benchmark was to have users complete it in under an hour. A discussion on this is provided in Section 0.

2.9. Literature Study Summary

A literature study on the various topics linked to a digital FFF training course has been successfully completed and the first two research objectives have been achieved by doing so. As a reminder, the objectives were to:

1. Understand the different AM technologies and the adoption thereof.
2. Identify and understand different learning methods and platforms that are used in the education sphere.

The literature study provided insight as to what AM is, the adoption of technology (AM in particular), and why the focus of this study was placed on FFF. It also showed how different learning methods and platforms can be used for the FFF course and that training on a certain subject can increase a user's knowledge and confidence to engage with it. The remainder of the research objectives is addressed in the following sections.

3. Course Creation and Data Acquisition

The third research objective was to develop a digital rapid training course on FFF to educate users on the technology. This section is used to show how this objective was successfully achieved using the knowledge gained through the literature study. To reiterate the research methodology on the development of the course; both qualitative and quantitative data were gathered using questionnaires and tests respectively. The training course was broken up into three sequential stages to both gather data and equip the user with knowledge of FFF. The course structure and content, teaching methods and elements, questionnaires, and platforms that were used, are also discussed in further detail in this section.

3.1. Training Course Stages

The course was structured to address the final research objective which is to evaluate whether the course increased the users' knowledge of, confidence to engage with, and likelihood to adopt the FFF technology. The users can self-report on whether their confidence and likelihood to adopt the FFF technology increased (qualitative data), but an actual increase in knowledge can only be detected by determining it before and after the users received training (quantitative data). Table 15 helps to illustrate how this was achieved.

Table 15: Determining users' knowledge level before and after training

	Knowledge level before training		Knowledge level after training
Users who indicated they have no prior knowledge of FFF	None	Users receive training →	Determined by having users complete tests on FFF.
Users who indicated they have prior knowledge of FFF	Determined by having users complete a background test on FFF.		Determined by having users complete tests on FFF. These tests include similar questions to those in the background test.

The training course was divided into three stages. These stages are listed below:

1. **Pre-training:** The users reported their prior knowledge of and likelihood to adopt the FFF technology by completing a questionnaire before they received training. The users who indicated they have prior knowledge of FFF had to complete an additional background test.
2. **Training:** The users then go through educational content on FFF and completed a series of tests that were based on the content.
3. **Post-training:** Finally, the users evaluated and self-reported their perceived new level of knowledge of, confidence to engage with, and likelihood to adopt the FFF technology.

3.2. Structure and Course Content

The three stages of the training course are discussed in further detail in this section, and examples of the training course content are provided. The course content was identical on the website and mobile app platforms with the only difference being the scaling. This allowed the content to properly fit on the different screen sizes of digital devices. The course content was presented in a sequential series of pages. The users were routed to the next page after reading the content and answering the questions on the current one. An illustration of the overarching structure is provided in Figure 3.1.

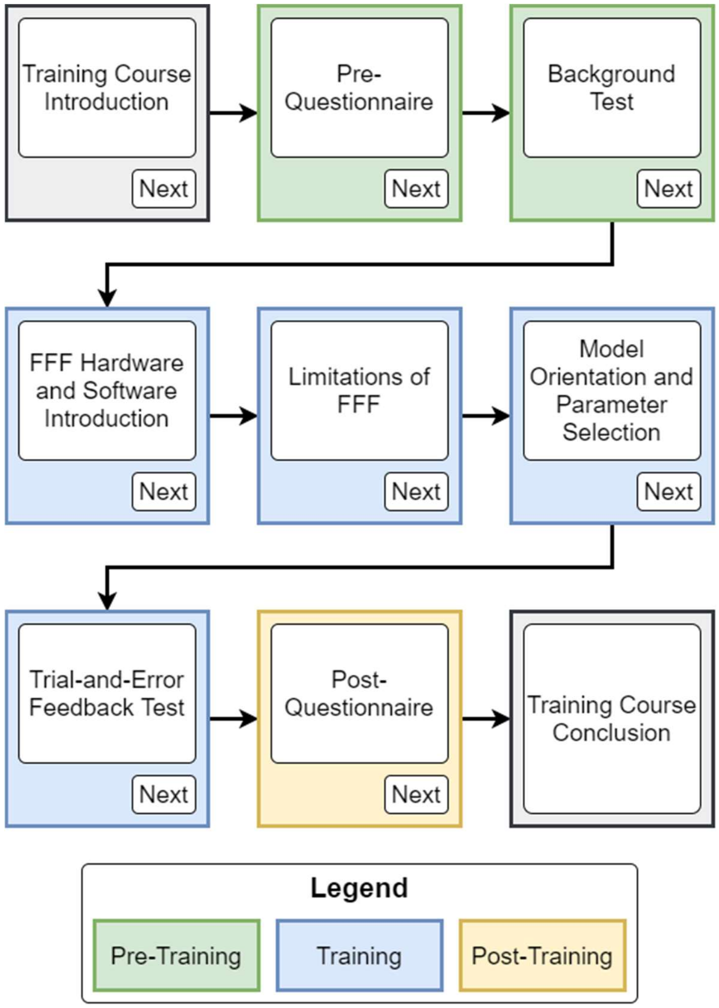


Figure 3.1: FFF Training Course Structure

All of the knowledge retention methods (discussed in Section 2.6.1) were used to help structure the training course and develop the content. The users were provided with an opportunity to immediately use the knowledge they received. This was achieved by introducing small quizzes within the training stage in addition to the large test at the end. These quizzes divided the educational content up and provide the user with real-world scenarios that draw on the knowledge provided up to that point in training. Screenshots of the pre-questionnaire (Figure 3.2a), background test (Figure 3.2b), educational content (Figure 3.2c), quizzes (Figure 3.2d), and trial-and-error-feedback tests (Figure 3.2e&f) are provided to give insight as to what the training course content looks like.

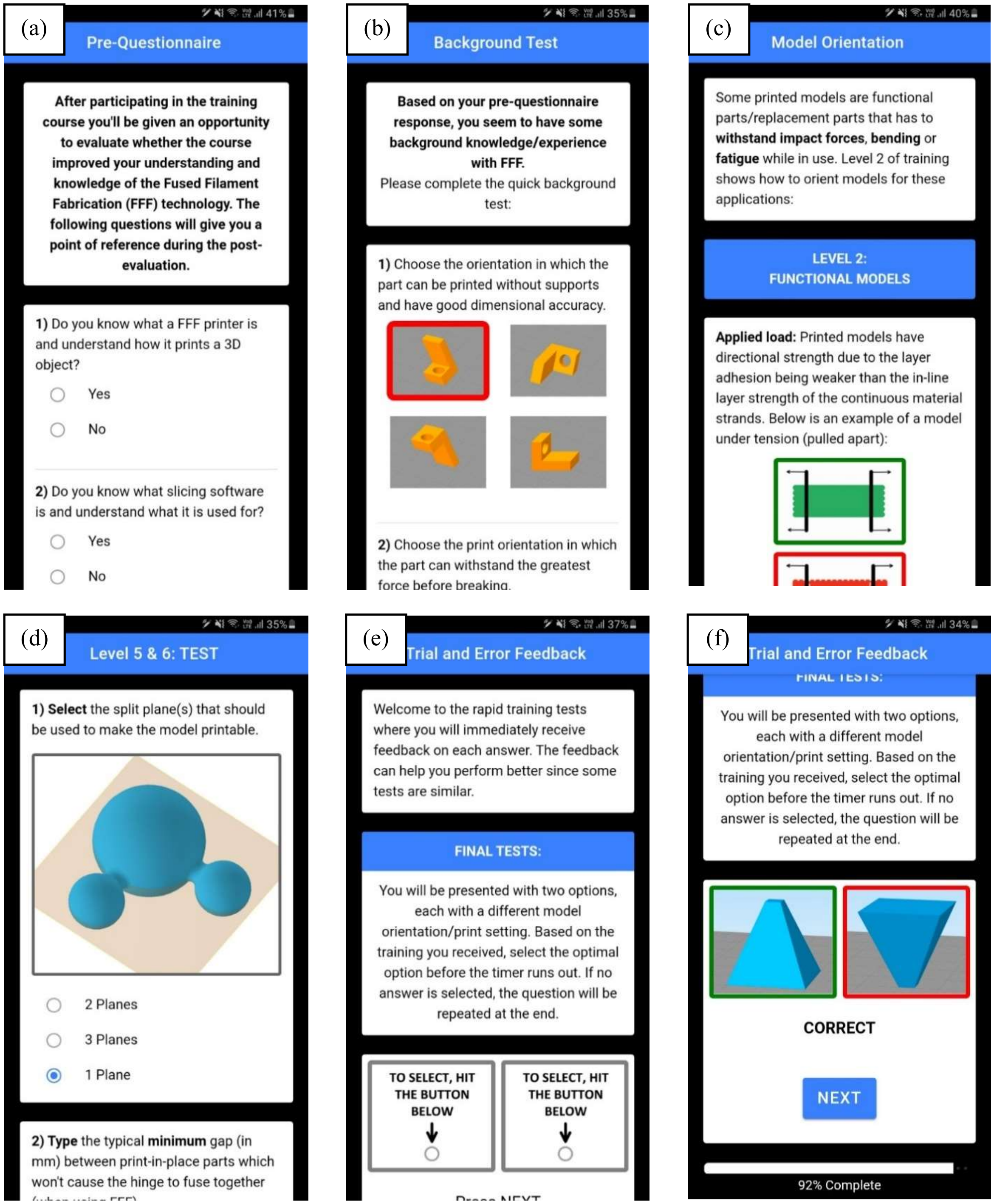


Figure 3.2: Screenshots as Examples of the Training Course Content

The teaching methods and elements that were used in the training course are discussed in the following section.

3.3. Teaching Methods and Elements Used

This section discusses how and why the teaching methods and elements (that were investigated in the literature study) were used to develop the training course. These include Bloom's taxonomy, gamification, trial-and-error-feedback, and visual aids.

Bloom's taxonomy

Since Bloom's taxonomy is a proven framework (Section 2.6.5), it was considered during the structuring and content creation of the training course. A breakdown of how the original taxonomy was used is provided in Table 16. The practical elements of FFF training (e.g., preparing a model in a real slicer environment, printing it using a FFF machine, and evaluate the printed model) was not included in the training course. They were excluded because not all users have access to a FFF machine nor will they all be using the same slicer software.

Table 16: Structure Based on Original Taxonomy

	Original taxonomy categories	**Elements of the training course that were inspired by Bloom's taxonomy**
Included in the training course.	Knowledge	The users were equipped with knowledge of the FFF technology by providing them with educational content.
	Comprehension	Visual aids and examples were used in the training course to better convey the educational content.
	Application	The users were given an opportunity to apply their knowledge of FFF during the tests that form part of the course.
	Analysis	During the trial-and-error-feedback training, the users were given an opportunity to analyse the correct answer to the questions.
Not included in the training course.	Synthesis	Users prepare a part in a slicer environment and print it using a FFF machine.
	Evaluation	Users evaluate the printed part and compare their findings with the content taught during training.

Gamification

If a course spans multiple days, weeks, or months, it becomes crucial to keep the user engaged. With a shorter course, it is easier to keep the attention of the user. Consequently, very few gamification elements were included in the course content. This was also done to conserve time during app development since the implementation of greater features would have required too much time investment when considering the timeline of the project. Gamification elements like the small tests in-between the educational sessions and the game-like progress bar (Figure 3.3) were included to make the course more fun to interact with. After a training stage was completed, it became a clickable button that could be used to navigate back if the user wanted to revisit a portion of the content. They were limited to only viewing the educational content and couldn't reattempt the quizzes.

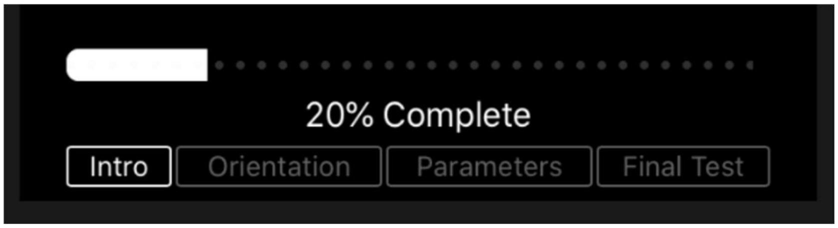


Figure 3.3: Training Course Progress and Navigation Bar

After dividing the educational content (model orientation and parameter selection) up into smaller sessions using quizzes, they were arranged from basic information to complex information. This was done to first introduce the user to the basics of each, after which the content becomes progressively more complex/difficult to understand. These sessions were labelled as "Levels", providing the user with a sense of achievement as they work through the content and progress through the game-like levels (Figure 3.2c&d).

Trial-and-error-feedback

Some digital models can be printed successfully in various orientations, which makes it difficult to teach students which ones are correct and incorrect. Model orientation can be considered a skill that a user develops as they gain experience by practising model orientation. The goal was to utilise the users' implicit memory to rapidly supply them with model orientation experience. An attempt was made to do so by using the trial-and-error-feedback teaching method (Section 2.6.4) tests at the end of the course (example in Figure 3.4).

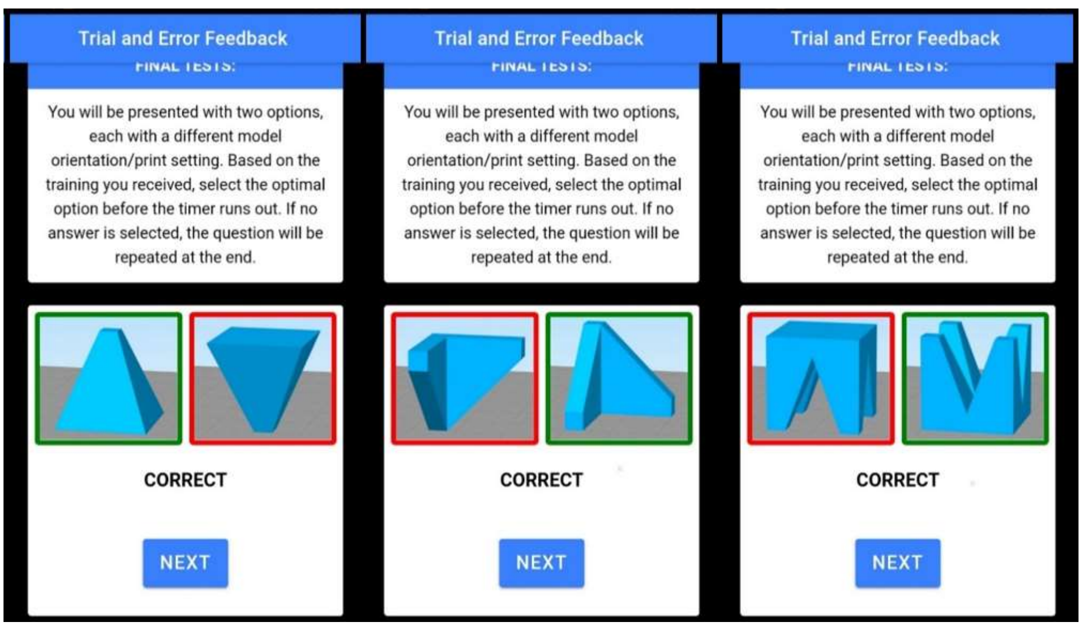


Figure 3.4: Similar Questions During the Trial-and-Error-Feedback Training

This was achieved by having the users complete a series of similar questions and immediately providing them with feedback on their latest answer by revealing the correct one (Figure 3.2f). The digital models that require similar orientations also had the same colour in an attempt to reinforce the correlation between selecting the correct answer and the orientation of a similar model (Figure 3.4).

Visual aids

The literature study on visual aids clearly indicated their value in the educational process which is why they were used in the training course. The two main visual aids that were used in the course are images and animated images (Graphics Interchange Format (GIF)). A collection of these was also used during the quizzes in the first half of the course, while none were used during the second. This was done to investigate whether users performed better with/without visual aids.

3.4. Questionnaires

The pre-and post-questionnaire questions used in the training course are presented in Table 17. **Pre-Questionnaire:** If a user indicates that they have prior knowledge of FFF, by answering yes to any of the first four questions, they were routed to the background test. The rest of the questions provide the user with a point of reference for when they complete the post-questionnaire. **Post-Questionnaire:** Note that the users are not asked about their current state of knowledge/confidence/willingness, but rather to evaluate their own progression in these areas. A user's answer to the question on their likelihood to purchase a FFF machine can be compared to the pre-questionnaire to determine whether the training course made them willing to invest more in the technology.

Table 17: Pre- and Post-Questionnaire Questions

<table>
<tr><th colspan="2">Pre-Questionnaire</th><th colspan="2">Post-Questionnaire</th></tr>
<tr><th>Question</th><th>Answers</th><th>Question</th><th>Answers</th></tr>
<tr><td rowspan="2">Do you know what a FFF printer is and understand how it prints a 3D object?</td><td>Yes</td><td rowspan="2">Did your level of knowledge and understanding of FFF printing increase?</td><td>Yes</td></tr>
<tr><td>No</td><td>No</td></tr>
<tr><td rowspan="2">Do you know what slicing software is and understand what it is used for?</td><td>Yes</td><td rowspan="3">Would you be more confident in using a FFF printer?</td><td>Yes</td></tr>
<tr><td>No</td><td>No</td></tr>
<tr><td rowspan="2">Have you ever used a FFF printer?</td><td>Yes</td><td>I'm already using one</td></tr>
<tr><td>No</td><td rowspan="2">Did your confidence in using slicing software increase?</td><td>Yes</td></tr>
<tr><td rowspan="2">Have you ever used slicing software?</td><td>Yes</td><td>No</td></tr>
<tr><td>No</td><td rowspan="2">Did your level of knowledge and understanding of designing parts for FFF printing increase?</td><td>Yes</td></tr>
<tr><td rowspan="2">Do you have any experience in troubleshooting failed FFF prints?</td><td>Yes</td><td>No</td></tr>
<tr><td>No</td><td></td><td>Yes</td></tr>
</table>

Have you ever used CAD software?	Yes	Are you more likely to use the technology if it is available to you?	No
	No	How likely are you to purchase a FFF printer?	Not likely
Have you designed an object specifically to be printed using a FFF printer?	Yes		I'm thinking of buying one
	No		I'm buying one in the future
How likely are you to purchase a FFF printer?	Not likely		I own on
	I'm thinking of buying one		
	I'm buying one in the future		
	I own on		
End of Pre-Questionnaire		End of Post-Questionnaire	

These questionnaires produced the qualitative data that is evaluated and discussed in section 4.

3.5. Training Course Platform

The goal was to gather as much data as possible to gain maximum statistical power. The general rule of thumb for the minimum data points needed for statistical significance is 30 [241]. An E-learning platform was used since it has a global reach to potential users across the Internet.

Cross-platform access

Digital consumer devices that can access web pages and mobile apps have drastically increased in the last decade as mentioned in Section 2.6.3. The Apple iOS and Google Android platforms are currently the most popular mobile phone platforms [242]. To make the course accessible to as many users as possible, the training course was presented through a website as well as iOS and Android apps. Access to both the website and mobile app were free of charge since a fee can potentially deter potential users from engaging with the experiment, effectively reducing the potential data pool size.

Web and App development platform

The training course was created using a cross-platform development framework (CPDF) so that time isn't wasted on developing and updating apps that were developed for native platforms. The author had no prior experience with web and app development and first had to learn how to engage with it. The goal was to find educational content for an easy-to-learn CPDF that has the necessary functionality to deliver the training course. The emphasis of the research study is not on web and app development, as it was merely a means of gathering the data.

Thus, the time spent on developing the platform has to be minimal. Four cross-platform development frameworks were considered namely; Flutter, React Native, NativeScript, Ionic (Figure 3.5).

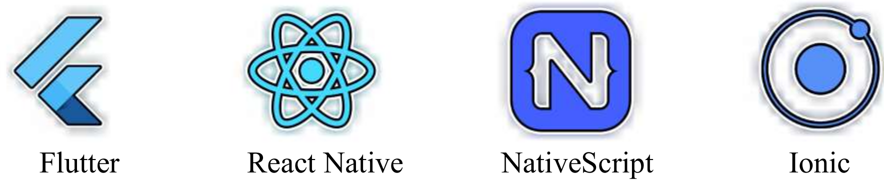


Figure 3.5: Cross-Platform Coding Frameworks [243]

Maximilian Schwarzmüller, a top educator on the Udemy platform, compared the four using scales of usability (Java and Swift were also included in the comparison) (Figure 3.6) [243].

Figure 3.6: Maximilian Schwarzmüller Comparison [243]

The Ionic framework was selected after considering Maximilian's comparison. Ionic accelerates the development process since code can be reused multiple times and there are plenty of third-party libraries that can be used. It also has rich pre-styled component libraries that can be used to create a good-looking platform in a limited timeframe.

The Ionic framework wraps a webpage into a mobile app which saves development time at the cost of app performance (responsiveness). This trade-off was made since the training course was very basic when considering the feature-sets and performance that are available with these frameworks [243]. Maximilian also provides an affordable and comprehensive educational course online (Udemy) on Ionic that the author utilized. Maximilian used Angular (back-end), HTML and CSS (front-end) with the Ionic framework (Section 2.7.3).

Data storage

The data that was produced by the training course consists of the users' answers. It was temporarily stored locally on their devices and automatically uploaded to an online database (as soon as the course has been completed) where it could be retrieved for processing and analysis. Maximilian used Firebase, a Google database, during his educational course. It is free to use, secure, and easily integrable with Ionic-Angular. The author decided to also use it for the training course since it meets the requirements for storing the course data and it was included in Maximilian's educational course. If the users terminate their training session (close the webpage or mobile app) before finishing, their data will not be submitted. The partial data sets would have been of little value for the project since all the steps were required.

3.6. Data Acquisition Summary

The process of developing a digital rapid training course on FFF was discussed in this section and serves as proof of the third research objective being completed. As a reminder, the objective was to:

- Develop a digital rapid training course on FFF to educate users on the technology.

The training course was made available for global participation by deploying it on the website and mobile apps on the Internet. The course was advertised as described in Section 1.4 and left to accumulate data automatically for approximately a year. The data was then retrieved from the Firebase database (where it was automatically stored by the website and mobile apps) by downloading it to a local PC. The data was processed using custom VBA scripts in Microsoft Excel (that the author developed for the research project) and then finally analysed. The processed data is presented and discussed in the following section.

4. Results

A detailed discussion on the data analyses that were performed is presented in this section. The goal is to achieve the final research objective. As a reminder, the objective was to evaluate whether the training course can increase the users' knowledge of, confidence to engage with, and likelihood to adopt the FFF technology by analysing the users' performance and feedback. A total of 198 users participated in the training course which means the data carries significant statistical power (Section 3.5). The users' performance, feedback, and the correlation between the two are considered in this section, followed by a few general observations that were made. The terms "users" and "participants" are used interchangeably during the discussions in this section.

4.1. User Performance

Quantitative data, gathered by having the users complete tests on FFF, was used to determine the users' course performance. The course difficulty was validated after which the users' knowledge levels before and after training were evaluated by using the method described in Section 3.1.

4.1.1. Course Difficulty

All the participants' average scores were above 50% with a general average of 73%. Users with no prior knowledge of or experience with FFF, scored an average of 69%, with 27% of them scoring above 80%. Three of these users, scoring 97%, 97%, and 95% respectively, provided additional feedback after participating in the course, stating that they scored well by thoroughly reading the content and not rushing through it. This indicates that the tests' difficulty was on par with the training content that was provided.

4.1.2. Duplicate Questions

As mentioned in Section 3.1, the background test indicates the users' current level of knowledge and understanding of the FFF technology. Similar questions, to those in the background test, were included in the main course's content and are referred to as "duplicate questions". By comparing the results of the duplicate questions, one can statistically evaluate whether the course improved the user's understanding of FFF. The result pairs are categorised into four groups as seen in Table 18. If the user has no prior knowledge or understanding of FFF, they are allocated an "INCORRECT" for the background questions.

Table 18: Duplicate Question Grouping

	Group 1	Group 2	Group 3	Group 4
Background question	CORRECT	INCORRECT	INCORRECT	CORRECT
Duplicate question	CORRECT	CORRECT	INCORRECT	INCORRECT
Description	The user is well acquainted with FFF or got lucky.	The user's understanding of FFF improved by participating in the course.	The user's understanding of FFF did not improve by participating in the course.	The user either made guesses, didn't concentrate during participation, or was confused by the course content.

Five duplicate questions were included in the training course. These questions were answered by 198 users which equates to 990 data points. The categorised group percentages are presented in Table 19. Of the 990 data points, 24% is categorised in Group 1, 60% in Group 2, 13% in Group 3, and 3% in Group 4.

Table 19: Duplicate Question Group Percentages

	Group 1	Group 2	Group 3	Group 4
Group percentage	24%	60%	13%	3%

No improvement can be detected in Group 1 so Group 2 will only be compared with 3 and 4. Of the new data pool, users improved on similar questions in 79% of the questions after they received training as shown in Table 20.

Table 20: New Data Pool of Duplicate Question Group Percentages

	Group 2	Group 3	Group 4
Group percentage	79%	17%	4%

This data serves as statistical evidence that the training course successfully increased the greater majority of the user group's knowledge of FFF.

4.2. User Feedback

The feedback that the users provided in the post-questionnaire after receiving training on FFF was evaluated. The first three questions of the post-questionnaire required the users to evaluate whether they believe their knowledge and understanding of FFF increased, they feel more confident to use a FFF printer, and whether they feel more confident to use slicer software. Of the 198 users, 95% believe that the training course increased their knowledge and understanding of FFF, while 79% and 88% of them feel more confident to use a FFF printer and slicer software respectively (Table 21). The three data sets were combined to produce an average increase in knowledge and confidence score. An average of 87% of users felt they have more knowledge of and are more confident to engage with FFF after participating in the course.

Table 21: Feedback on Q1-Q3 of Post-Questionnaire

	Knowledge and understanding of FFF increased	**Increase in confidence to use a FFF printer**	**Increase in confidence to use slicer software**	**Average increase from self-assessment**
Score percentage	95%	79%	88%	87%

Apart from just engaging with FFF, the users were also asked whether they are more likely to interact with the technology after participating in the training course. Of the 198 users, 95% feel their knowledge and understanding of DfAM increased and 93% are more likely to use FFF after participating in the course if it is available to them (Table 22).

The two data sets were combined to produce an average increase in likeliness to interact with the FFF technology. An average of 94% of users is more likely to interact with the FFF technology after participating in the training course. The course also made 24% of the 198 users willing to invest more money into the FFF technology than prior to participating.

Table 22: Feedback on Q4-Q6 in Post-Questionnaire

	Knowledge and understanding of DfAM increased	More likely to use FFF if available	Average increase in likeliness to interact with FFF	Increase in likeliness to invest in FFF
Score percentage	95%	93%	94%	24%

4.3. Correlation Between Performance and Feedback

The quantitative and qualitative data were evaluated together to investigate whether there are any noticeable correlations between the two. The users have been grouped into one of 6 categories based on their course score (Low/Medium/High) and whether they have background knowledge of FFF or not (1 or 0). The groupings are depicted in Table 23. Each group is given a code that helps to reference them in the rest of the section.

Table 23: User Background-Performance Grouping Codes

Background	No			Yes		
Course Score	40%-60%	61%-80%	81%-100%	40%-60%	61%-80%	81%-100%
Group Code	L0	M0	H0	L1	M1	H1

4.3.1. Willingness to Invest

The users were asked during the pre- and post-questionnaire how willing they are to invest in the FFF technology at that stage. If they are more willing to invest after completing the course (by selecting a higher option in the post-questionnaire than in the pre-questionnaire), they were given a score of “1” and if not, a “0”. The users who are willing to invest more, after participating in the course, are shown on the right-hand side of Figure 4.1. Users with no background knowledge of and experience with FFF (L0, M0, H0) are willing to invest more, after completing the training course, than those with (L1, M1, H1). This shows that the greatest investment spike into FFF can potentially be achieved by targeting the users who are unfamiliar with FFF, when developing and distributing FFF training courses.

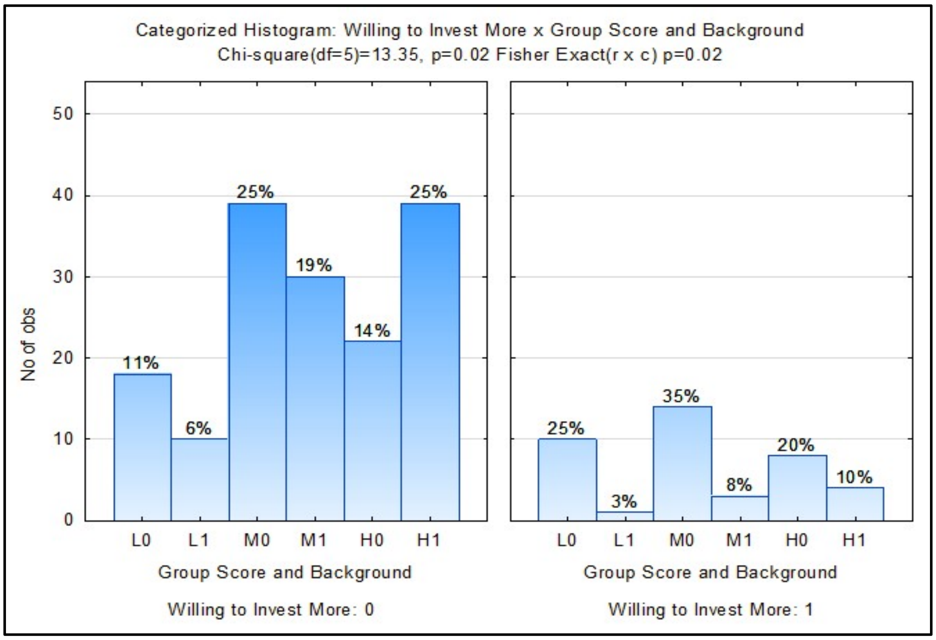


Figure 4.1: Performance Groups - Willingness to Invest More

4.3.2. Self-assessment After Participation

The users' average "self-assessment" score (Section 4.2) was analysed within the groupings stated in Table 23. As seen in Figure 4.2, the data is normally distributed with a P-value < 0.01. This means the null hypothesis, that there is no relationship between the data groups, can be rejected.

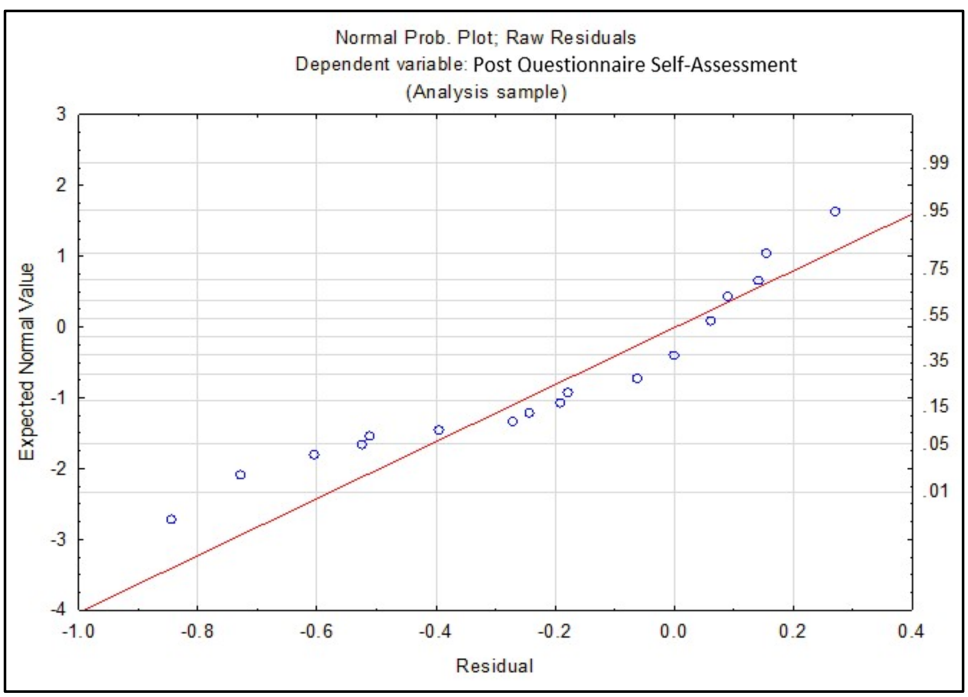


Figure 4.2: Normality of Post-Questionnaire "Self-Assessment" Data (Q1-Q3)

Users with background knowledge and experience who scored medium to well in the course (M1 and H1) potentially do not feel that that the course added as much to their knowledge and understanding of FFF as it did for the others as seen in Figure 4.3. This is to be expected since the course does not offer in-depth training in FFF, but rather on content that the M1 and H1 groups are already familiar with. The L0 group also had a slightly lower score which could be a result of having a negative experience of the course as they potentially did not understand the content, when considering their course score. The other groups found the course useful, especially the ones with no background in FFF and that scored well in the course (H0). This shows that the greatest spike in knowledge and confidence can be achieved within the user group who was unfamiliar with FFF. This group can be targeted when developing and distributing FFF training courses. The training course can also be simplified and explained even further to accommodate the users who may have found it to be too complex. This can potentially include them in this spike of knowledge and confidence.

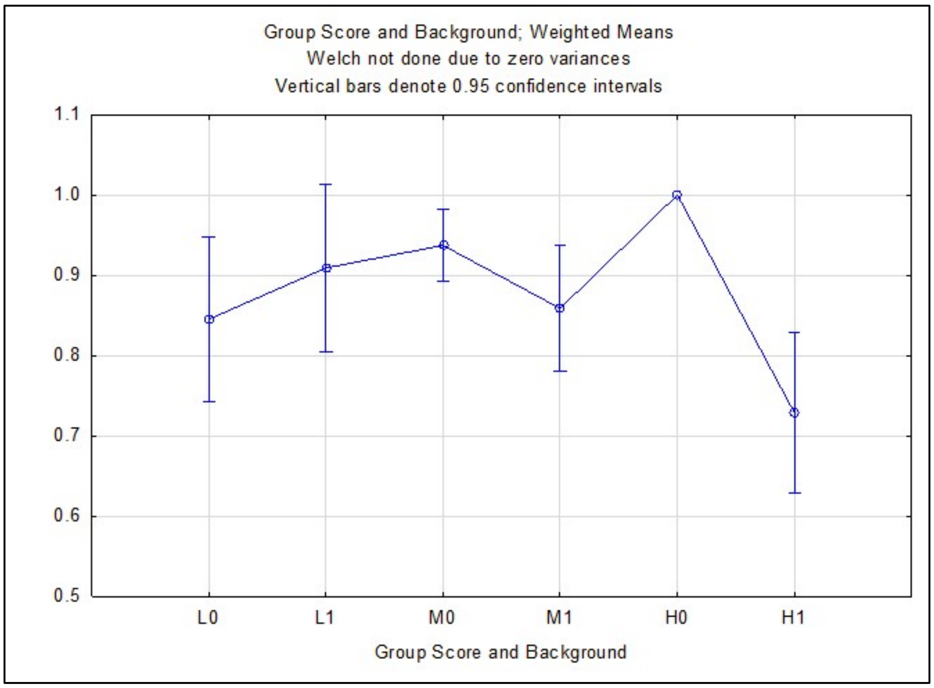


Figure 4.3: Weighted Means of Post-Questionnaire "Self-Assessment" within Performance Groups

4.3.3. Willingness to Interact with FFF

The users' "willingness to interact with FFF" score (Section 4.2), was analysed within the groupings stated in Table 23. As seen in Figure 4.4, the data is normally distributed with a P-value = 0.02. This means the null hypothesis, that there is no relationship between the data groups, can be rejected.

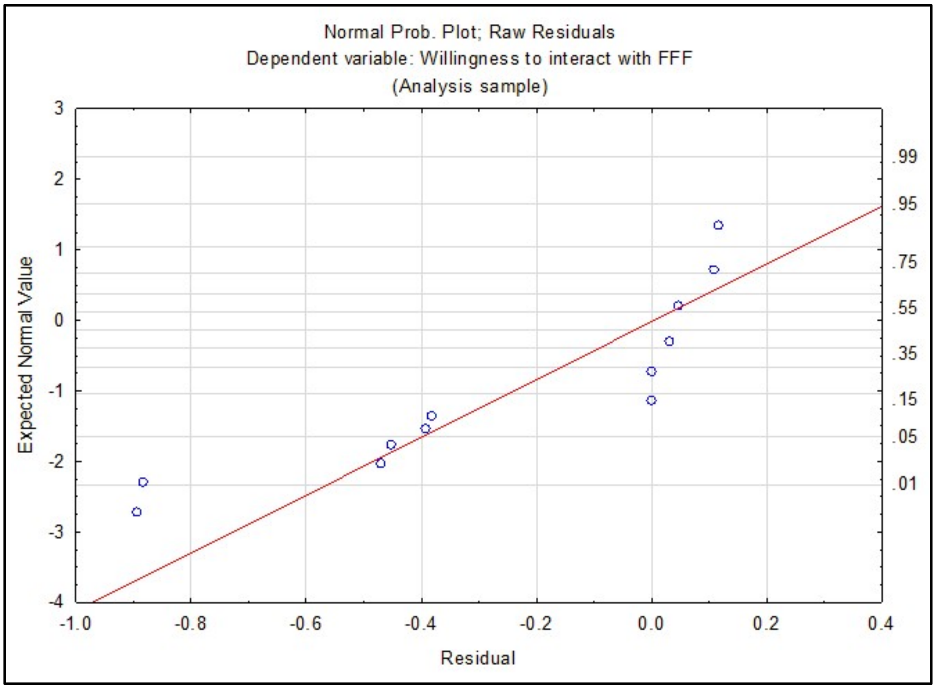


Figure 4.4: Normality of Post-Questionnaire "Willingness to Interact with FFF" Data (Q4-Q5)

Users with background knowledge and experience who scored well in the course (H1) are not more willing to interact with FFF after participating in the course (Figure 4.5). This is to be expected since the H1 group is already familiar with the technology, with little to no content in the course that would motivate them to be more willing than they currently are. The L0 group also had a slightly lower score which could be a result of having a negative experience of the course as they potentially did not understand the content, when considering their course score. The other groups are more willing to adopt the FFF technology after participating in the course. The training course can be simplified and explained even further to accommodate the users who may have found it to be too complex. It would then cause the greatest spike of willingness to interact with FFF among potential adopters.

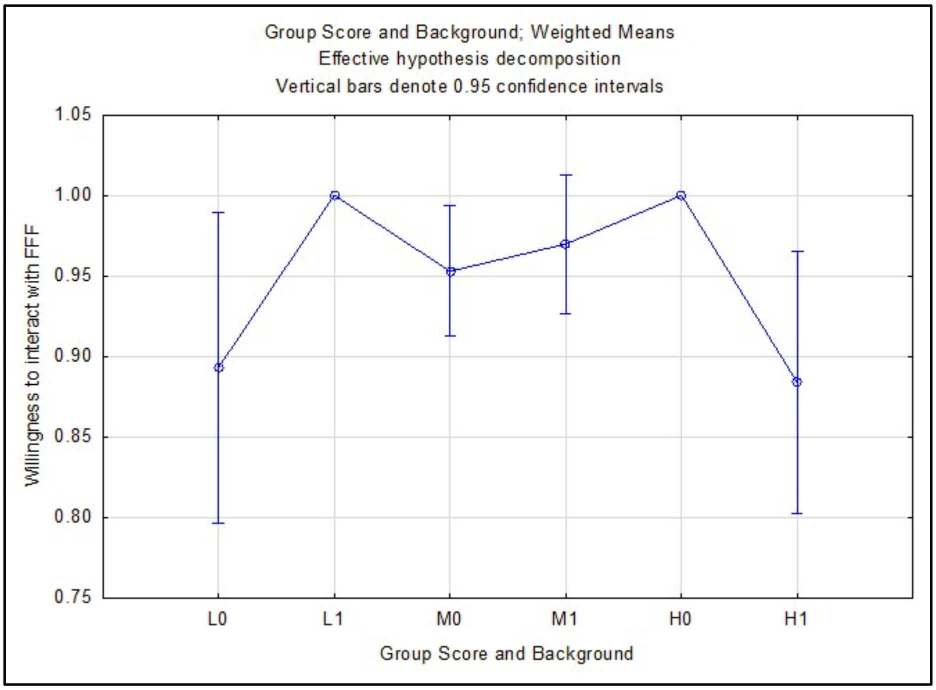


Figure 4.5: Weighted Means of Post-Questionnaire "Willingness to Interact with FFF" within Performance Groups

4.4. General Observations

A few general observations were made during the analysis of the processed data. These observations are used to address the specific research objectives that were set in Section 1.3.3. As a reminder, the specific objectives are to:

- Investigate the effect of using different teaching methods and elements.
- Investigate whether users have identifiable preferences in engaging with the course.

4.4.1. Traditional Tests vs Trial-and-Error-Feedback

The small quizzes throughout the training course are considered traditional-styled tests compared to the unique trial-and-error-feedback tests. It was observed that participants scored better during the trial-and-error-feedback tests, with an average of 80%, than during the more traditional tests (that were also based on model orientation), averaging at 68%. It has to be noted that if participants chose answers at random, they statistically have a larger chance of scoring higher (on average) during the trial-and-error-feedback test than the traditional. This is because the trial-and-error-feedback tests consist of only two possible answers compared to the two or more in the traditional tests. The assumption was made that the participants did not select answers at random. It can be concluded that the trial-and-error-feedback teaching method was more effective for training individuals in digital model orientation for AM.

4.4.2. Visuals vs No-Visuals

As mentioned in Section 3.3, the first half of the course's quizzes had visual aids while the second didn't. When comparing the results, it can be noted that the users scored slightly better in the quizzes that had visual aids (average of 71%) compared to those with non (average of 69%). The difference between the two was less than expected after considering the results of the case studies that were discussed in the literature study (Section 2.6.6). The higher average of 71% does, however, support the case studies' findings, that visual aids are effective tools for transferring information.

4.4.3. Learning Platform Preference

The course was made available on mobile platforms (Android & iOS) and as a website. Of the 198 users who participated in the training course, 68% preferred using the website platform instead of the mobile apps, effectively streaming the content from the Internet during training (Table 24). Only 32% of users preferred to download all of the content onto their mobile device as an app before engaging with the content. This can potentially be attributed to users not wanting to wait for the entire download to finish before starting the course. It can also be attributed to the fact that more digital devices can access a website than a mobile app. A wider group of potential AM adopters can be reached if a training course is distributed as a website instead of mobile apps.

Table 24: Download vs Stream Shor E-Learning Course Content

	Android	iOS	Web
User percentage	14%	18%	68%
Download vs Stream	32%		68%

4.5. Results Summary

The data that was gathered by the digital FFF training course, was analysed and interpreted in this section. The final research objective was achieved by doing so. As a reminder the objective was to:

- Evaluate whether the course can increase the users' knowledge of, confidence to engage with, and likelihood to adopt the FFF technology by analysing the users' performance and feedback.

Both quantitative and qualitative evidence was provided that the training course increased the majority of the users' knowledge of FFF with 87% and 94% of them claiming to be more confident and willing respectively, to engage with it. Based on the literature on knowledge and confidence in the educational sphere (Section 2.6.1), it can be deduced that the majority of users are more likely to adopt the FFF technology after they have received training.

Strong correlations between the users' performance and feedback were also identified in this section. It revealed how the biggest increase in FFF adoption rate can be achieved by targeting the individuals with no prior knowledge of the technology, during the development and distribution of the training course. The users with no prior knowledge of FFF and with a low test scores indicated that the course did not increase their knowledge, nor their willingness to engage with FFF as much as the others. The aforementioned target group can potentially be enlarged by providing additional simplified explanations on the content to accommodate these users as they may have been discouraged by the fact that they do not understand FFF much better after receiving training. It can be noted that the course was not as valuable for the users with prior knowledge and a high test score. This was attributed to the fact that the course didn't provide them with a lot of additional insight into the technology.

The two specific research objectives were also achieved in this section. As a reminder they were to:

- Investigate the effect of using different teaching methods and elements.
- Investigate whether users have identifiable preferences in engaging with the course.

It was concluded that the trial-and-error-feedback teaching method was more effective for training users in digital model orientation than a traditional teaching style. The users also performed slightly better in the quiz tests that utilized visual aids than in those with non. One noticeable user preference was identified during the data analysis. It was found that more users preferred using the website platform over downloading the mobile app. The assumption was made that most participants had access to both platforms when considering the popularity of iOS and Android devices.

Some of the participants were asked how long the course took them to complete with an average response of 45 min to 1 hour. The benchmark of >1 hour that was set in Section 2.8 was achieved. Thus, the course can be qualitatively considered as a rapid training course after studying other free FFF training courses that are available. It can be noted that the newly developed training course also provided the users with an opportunity (within the same session) to test their understanding of FFF, unlike the existing ones that were studied. It can be concluded that the new course likely offered the users' more value within a similar period of time than the existing ones.

The following section provides a discussion on the project and the final conclusion is drawn. Future work on this research is also recommended.

5. Conclusion and Recommendations

In this section, a general conclusion to the study is drawn and a discussion on how the research problem statement was successfully addressed is provided. Future work that can add to the study, is also recommended.

5.1. General Conclusion

The aim of the study was to improve the adoption rate of AM, FFF in particular, to address the problem statement. As a reminder, the problem statement is as follows:

Additive manufacturing technologies, such as Fused Filament Fabrication, have a slow adoption rate, even though the technology has been available since 1987. Individuals are not typically trained throughout their primary to tertiary education to successfully engage with AM technologies. Design thinking for conventional manufacturing methods limits the application and true capabilities of additive manufacturing technologies. For the industry to fully utilise the potential of AM, the adoption rate of the technology must be improved.

It was determined, by means of a literature study, that training can improve the adoption rate of a technology. According to the study, the trainee is more confident and likely to engage with/adopt a technology if they are provided with knowledge of and experience with it. The literature study also aided in the successful development of a digital rapid training course in FFF, which was deployed as a website and mobile apps. During the timeframe that the training course was made available publicly, 198 individuals participated in it. The data consists of the users' performance scores and feedback and was automatically gathered by the training course. The data was then retrieved, processed, analysed, interpreted, and reported on in this document. It was concluded that the course increased the users' knowledge of, willingness to interact with and likelihood to adopt the FFF technology and ability to interact with FFF. The final conclusion is drawn that the digital rapid training course on FFF can help increase the adoption rate of the technology.

By answering the research questions in the following section, servers as proof that the problem statement was successfully addressed.

5.2. Project Discussion

A discussion on the approach that was taken during the research study is provided in this section. The approach consists of seven steps which are listed below. The first five steps have been completed in previous sections and are included in the list. A summary of these steps is provided in Figure 5.1. The final two are completed at the end of this section.

1. Define a research problem statement that will be addressed (Section 1.2).
2. Define research questions that, when answered, will help prove that the problem statement has been addressed (Section 1.3.1).
3. Define research objectives that, when completed, will help answer the research questions (Section 1.3.2).
4. Define a research methodology (Section 1.4).
5. Use the research methodology to achieve the research objectives (Table 25).
6. After achieving the research objectives, the research questions can be properly answered.
7. By answering the research questions, proof has been provided that the problem statement has been successfully addressed.

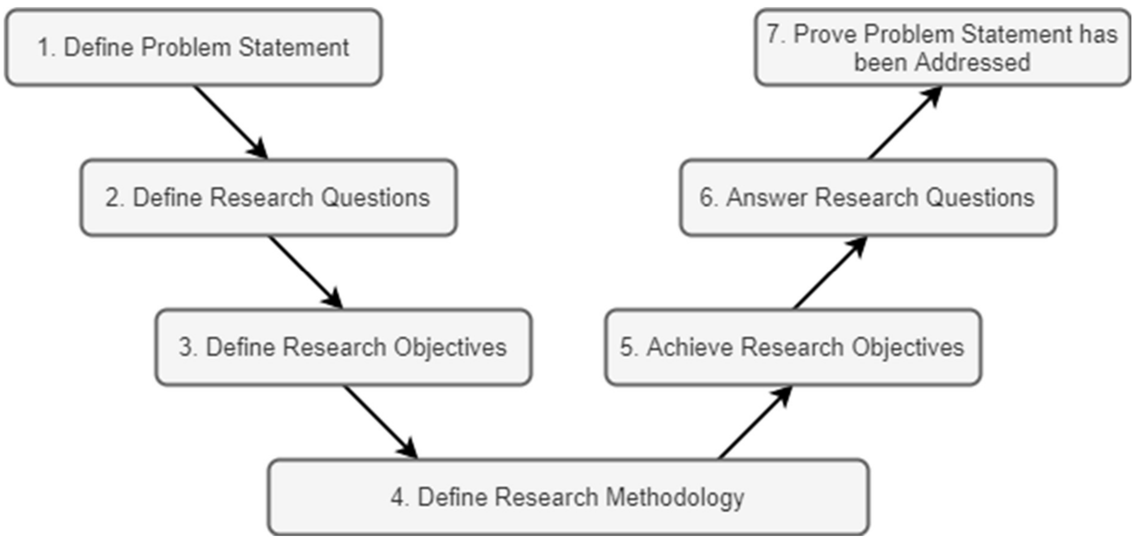


Figure 5.1: Research Approach Taken During the Study

A summary of where each of the research objectives was achieved is provided in Table 25.

Table 25: Research Objectives Achieved in Respective Sections

Main Research Objectives	1. Understand the different AM technologies and the adoption thereof.	A literature study was performed on technology, the adoption of technology, manufacturing, AM technologies, and the adoption thereof (Section 2.1).
	2. Identify and understand different learning methods and platforms that are used in the education sphere.	A literature study was performed on the trial-and-error-feedback and gamification learning methods. Bloom's taxonomy and the use of visual aids were also considered to aid in the development and structuring of the training course (Section 2.6).
	3. Use the knowledge to develop a rapid training course in FFF to educate the users on the technology.	A digital rapid training course on FFF was successfully developed and deployed. The course automatically gathered data and stored it on an online database (Section 3.6).
	4. Evaluate whether the course can help accelerate the adoption rate of the technology by analysing the users' performance and feedback.	The data (users' test results and feedback) was processed, analysed, and interpreted. It was determined that the training course can help accelerate the adoption rate of FFF (Section 4).
Specific Research Objectives	Investigate the effect of using different teaching methods and elements.	It was determined that the trial-and-error-feedback method was more effective to train individuals in digital model orientation (Section 4.4.1). Users also performed better in tests that contained visual aids than in those without (Section 4.4.2).
	Investigate whether users have identifiable preferences in engaging with the course.	It was determined that most users preferred to use the website instead of the mobile app. This may be due to more users having access to the website or they preferred to not wait for an app to first download before starting (Section 4.4.3).

The research questions stated in Section 1.3.1 can be properly answered now after the research objectives have been completed. As a reminder, the questions are as follows:

1. Can training be used to improve the adoption rate of AM technologies?
2. Can a digital rapid training course on FFF be developed and successfully deployed?
3. Does the training course increase the users' knowledge of FFF?
4. Does the training course increase the users' confidence to engage with and likelihood to adopt the FFF technology?

The first question can be answered in the affirmative based on the literature study that was performed (research objective 1 and 2). Training can be used to improve the adoption rate of AM technologies (FFF in particular). The second question can also be answered in the affirmative as a digital training course on FFF has been successfully developed and deployed (research objective 3). Finally, the third and fourth research can be answered in the affirmative based on the results of the data analyses (research objective 4). The training course increased the users' level of knowledge of FFF, confidence to engage with it, and likelihood to adopt the technology.

5.3. Recommended Future Work

The recommended alterations and additions that can be made to the study are discussed in this section. It can be noted that a similar training course can be developed for other applications.

5.3.1. Alterations to the Current Study

The effectiveness of the trial-and-error-feedback teaching method could not be validated during the study since there were only on average 3 (with a maximum of 5) consecutive questions that were similar (on each topic). Based on the literature study, students are expected to perform better near the end of a series of trial-and-error-feedback tests (Section 2.6.4), but there was no observable trend in the test results. The effect of this teaching method can be investigated by including a large series of similar trial-and-error-feedback questions in the training course.

5.3.2. Additions to the Current Study

The following features can be added to the training course:

- Measure the user's time spent on the course to acquire additional insight into their experience and to identify potential areas where users struggle to comprehend the course content. The user can be notified about the timer so that they pay full attention during participation, but this has the potential of inducing stress.
- Investigate possible social factors that are at play during participation e.g., users don't take the course seriously since it was free of charge, anonymous participation that cause users to be overconfident/brave during the questionnaires, course duration affecting user performance, the reputability of the course/creator affecting how much the participants value the course, etc.
- Include additional rapid training courses that focus on the hardware of popular FFF printers and the use of popular materials (e.g., Creality Ender 3 using PLA filament).
- Additional training methods and mediums can be used e.g., gamification, augmented reality, virtual reality, etc.

5.3.3. Additional Fields of Application

A similar course can be developed for different means of manufacturing and potentially other areas of education. The effectiveness of the current and future formats of the course can be investigated within the different fields of education.

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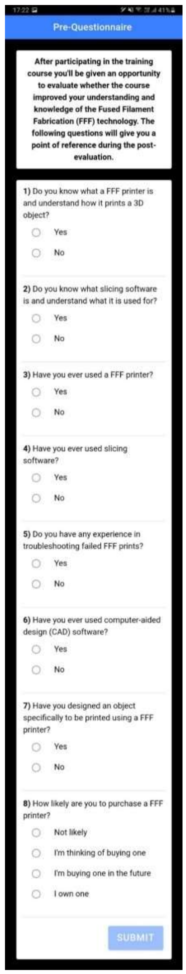
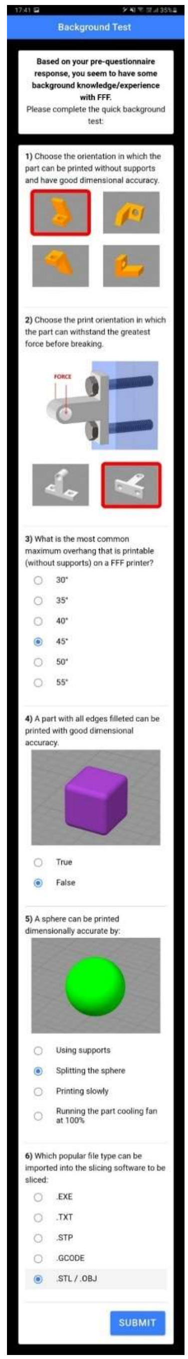
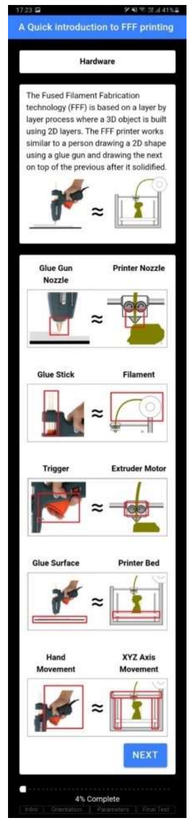
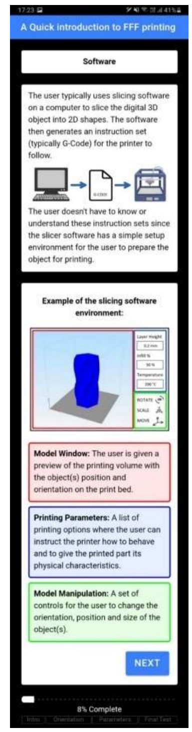
Appendix A Course Content

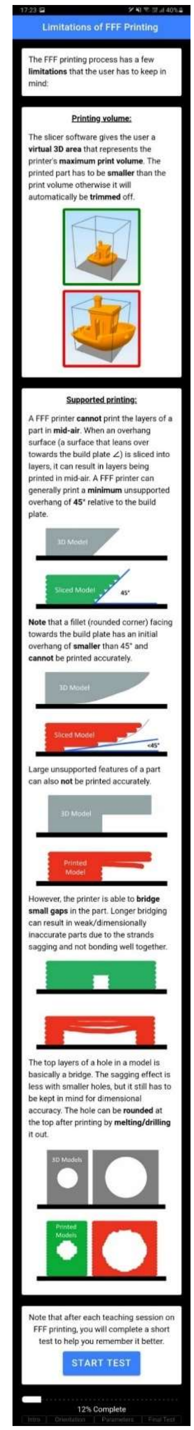
Table 26: Course Content

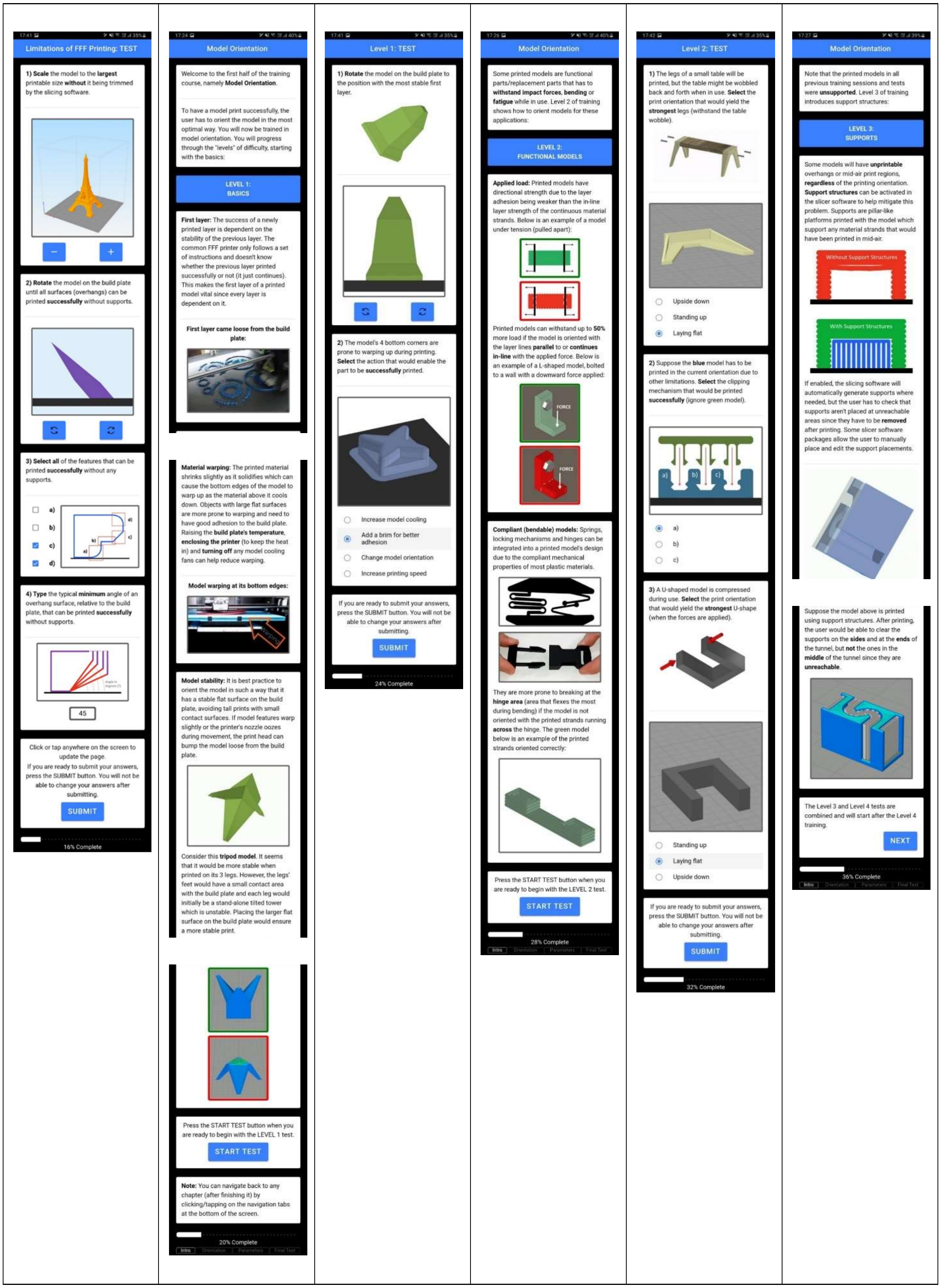


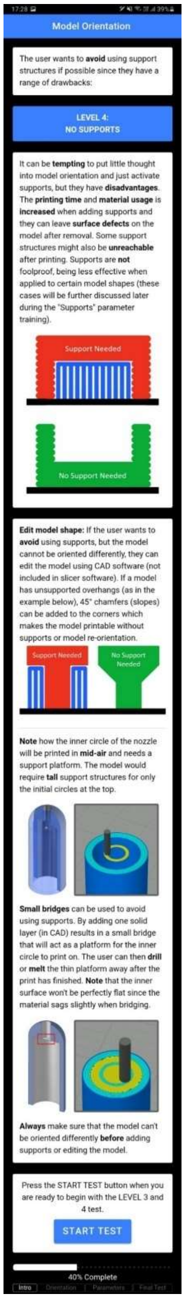




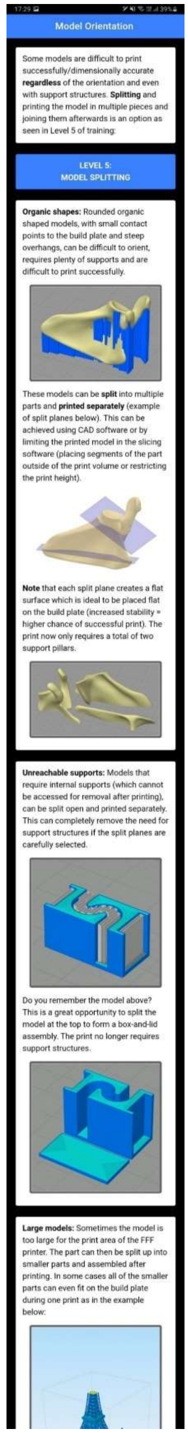


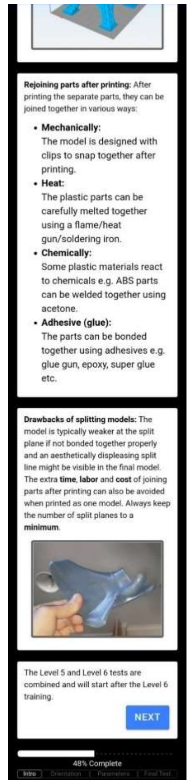


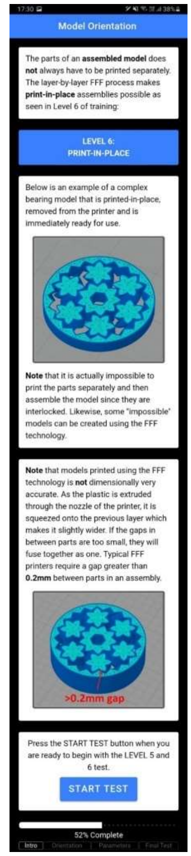

Limitations of FFF Printing: TEST
1) Scale the model to the largest printable size without it being trimmed by the slicing software.
2) Rotate the model on the build plate until all surfaces (overhangs) can be printed successfully without supports.
3) Select all of the features that can be printed successfully without any supports.
a)
b)
c)
d)
4) Type the typical minimum angle of an overhang surface, relative to the build plate, that can be printed successfully without supports.
45
Click or tap anywhere on the screen to update the page.
If you are ready to submit your answers, press the SUBMIT button. You will not be able to change your answers after submitting.
SUBMIT
16% Complete
Model Orientation
Welcome to the first half of the training course, namely Model Orientation.
To have a model print successfully, the user has to orient the model in the most optimal way. You will now be trained in model orientation. You will progress through the "levels" of difficulty, starting with the basics:
LEVEL 1: BASICS
First layer: The success of a newly printed layer is dependent on the stability of the previous layer. The common FFF printer only follows a set of instructions and doesn't know whether the previous layer printed successfully or not (it just continues). This makes the first layer of a printed model vital since every layer is dependent on it.
First layer came loose from the build plate:
Material warping: The printed material shrinks slightly as it solidifies which can cause the bottom edges of the model to warp up as the material above it cools down. Objects with large flat surfaces are more prone to warping and need to have good adhesion to the build plate. Raising the build plate's temperature, enclosing the printer (to keep the heat in) and turning off any model cooling fans can help reduce warping.
Model warping at its bottom edges:
Model stability: It is best practice to orient the model in such a way that it has a stable flat surface on the build plate, avoiding tall prints with small contact surfaces. If model features warp slightly or the printer's nozzle oozes during movement, the print head can bump the model loose from the build plate.
Consider this tripod model. It seems that it would be more stable when printed on its 3 legs. However, the legs' feet would have a small contact area with the build plate and each leg would initially be a stand-alone tilted tower which is unstable. Placing the larger flat surface on the build plate would ensure a more stable print.
Press the START TEST button when you are ready to begin with the LEVEL 1 test.
START TEST
Note: You can navigate back to any chapter (after finishing it) by clicking/tapping on the navigation tabs at the bottom of the screen.
20% Complete
Level 1: TEST
1) Rotate the model on the build plate to the position with the most stable first layer.
2) The model's 4 bottom corners are prone to warping up during printing. Select the action that would enable the part to be successfully printed.
Increase model cooling
Add a brim for better adhesion
Change model orientation
Increase printing speed
If you are ready to submit your answers, press the SUBMIT button. You will not be able to change your answers after submitting.
SUBMIT
24% Complete
Model Orientation
Some printed models are functional parts/replacement parts that has to withstand impact forces, bending or fatigue while in use. Level 2 of training shows how to orient models for these applications:
LEVEL 2: FUNCTIONAL MODELS
Applied load: Printed models have directional strength due to the layer adhesion being weaker than the in-line layer strength of the continuous material strands. Below is an example of a model under tension (pulled apart):
Printed models can withstand up to 50% more load if the model is oriented with the layer lines parallel to or continues in-line with the applied force. Below is an example of a L-shaped model, bolted to a wall with a downward force applied:
FORCE
FORCE
Compliant (bendable) models: Springs, locking mechanisms and hinges can be integrated into a printed model's design due to the compliant mechanical properties of most plastic materials.
They are more prone to breaking at the hinge area (area that flexes the most during bending) if the model is not oriented with the printed strands running across the hinge. The green model below is an example of the printed strands oriented correctly:
Press the START TEST button when you are ready to begin with the LEVEL 2 test.
START TEST
28% Complete
Level 2: TEST
1) The legs of a small table will be printed, but the table might be wobbled back and forth when in use. Select the print orientation that would yield the strongest legs (withstand the table wobble).
Upside down
Standing up
Laying flat
2) Suppose the blue model has to be printed in the current orientation due to other limitations. Select the clipping mechanism that would be printed successfully (ignore green model).
a)
b)
c)
3) A U-shaped model is compressed during use. Select the print orientation that would yield the strongest U-shape (when the forces are applied).
Standing up
Laying flat
Upside down
If you are ready to submit your answers, press the SUBMIT button. You will not be able to change your answers after submitting.
SUBMIT
32% Complete
Model Orientation
Note that the printed models in all previous training sessions and tests were unsupported. Level 3 of training introduces support structures:
LEVEL 3: SUPPORTS
Some models will have unprintable overhangs or mid-air print regions, regardless of the printing orientation. Support structures can be activated in the slicer software to help mitigate this problem. Supports are pillar-like platforms printed with the model which support any material strands that would have been printed in mid-air.
Without Support Structures
With Support Structures
If enabled, the slicing software will automatically generate supports where needed, but the user has to check that supports aren't placed at unreachable areas since they have to be removed after printing. Some slicer software packages allow the user to manually place and edit the support placements.
Suppose the model above is printed using support structures. After printing, the user would be able to clear the supports on the sides and at the ends of the tunnel, but not the ones in the middle of the tunnel since they are unreachable.
The Level 3 and Level 4 tests are combined and will start after the Level 4 training.
NEXT
36% Complete

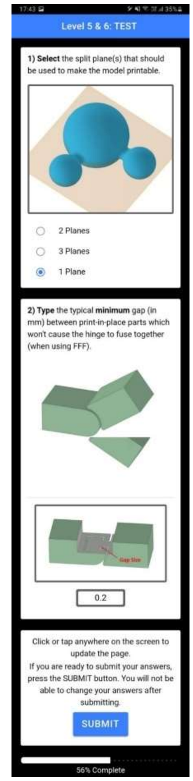

Model Orientation
The user wants to avoid using support structures if possible since they have a range of drawbacks:
LEVEL 4:
NO SUPPORTS
It can be tempting to put little thought into model orientation and just activate supports, but they have disadvantages. The printing time and material usage is increased when adding supports and they can leave surface defects on the model after removal. Some support structures might also be unreachable after printing. Supports are not foolproof, being less effective when applied to certain model shapes (these cases will be further discussed later during the "Supports" parameter training).
Support Needed
No Support Needed
Edit model shape: If the user wants to avoid using supports, but the model cannot be oriented differently, they can edit the model using CAD software (not included in slicer software). If a model has unsupported overhangs (as in the example below), 45° chamfers (slopes) can be added to the corners which makes the model printable without supports or model re-orientation.
Support Needed
No Support Needed
Note how the inner circle of the nozzle will be printed in mid-air and needs a support platform. The model would require tall support structures for only the initial circles at the top.
Small bridges can be used to avoid using supports. By adding one solid layer (in CAD) results in a small bridge that will act as a platform for the inner circle to print on. The user can then drill or melt the thin platform away after the print has finished. Note that the inner surface won't be perfectly flat since the material sags slightly when bridging.
Always make sure that the model can't be oriented differently before adding supports or editing the model.
Press the START TEST button when you are ready to begin with the LEVEL 3 and 4 test.
START TEST
40% Complete

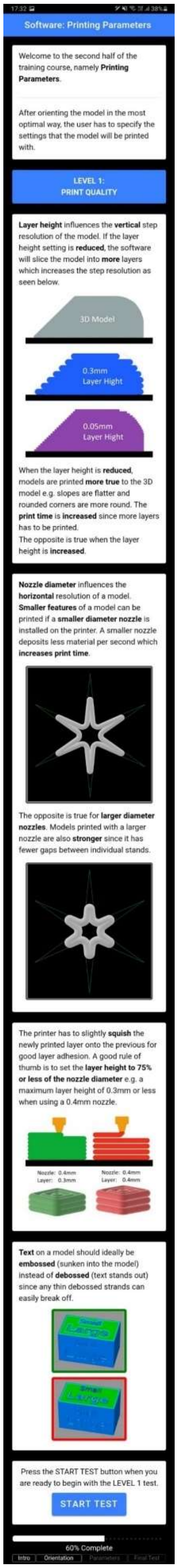

Level 3 & 4: TEST
1) The wheel model will be mounted on a shaft which means the inner hole has to be perfectly round for the shaft to fit properly. The flat surfaces touching the blue surfaces of the shaft has to be as flat as possible. Select the best means of printing the model successfully.
Add a membrane
Change model orientation
Add support structures
2) Select the best means of printing the pipe clamp model successfully.
Add 45° slope to each overhang using CAD
Change model orientation
Add support structures
3) Select the best means of printing the lion model successfully.
Add 45° slope to each overhang using CAD
Change model orientation
Add support structures
If you are ready to submit your answers, press the SUBMIT button. You will not be able to change your answers after submitting.
SUBMIT
44% Complete

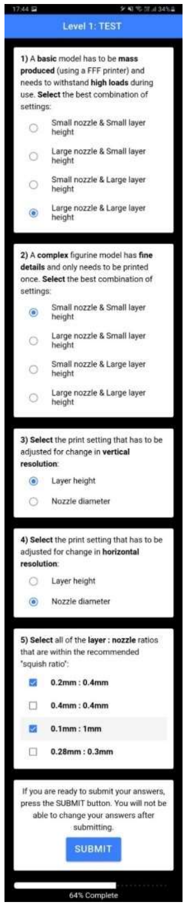

Model Orientation
Some models are difficult to print successfully/dimensionally accurate regardless of the orientation and even with support structures. Splitting and printing the model in multiple pieces and joining them afterwards is an option as seen in Level 5 of training:
LEVEL 5:
MODEL SPLITTING
Organic shapes: Rounded organic shaped models, with small contact points to the build plate and steep overhangs, can be difficult to orient, requires plenty of supports and are difficult to print successfully.
These models can be split into multiple parts and printed separately (example of split planes below). This can be achieved using CAD software or by limiting the printed model in the slicing software (placing segments of the part outside of the print volume or restricting the print height).
Note that each split plane creates a flat surface which is ideal to be placed flat on the build plate (increased stability = higher chance of successful print). The print now only requires a total of two support pillars.
Unreachable supports: Models that require internal supports (which cannot be accessed for removal after printing), can be split open and printed separately. This can completely remove the need for support structures if the split planes are carefully selected.
Do you remember the model above? This is a great opportunity to split the model at the top to form a box-and-lid assembly. The print no longer requires support structures.
Large models: Sometimes the model is too large for the print area of the FFF printer. The part can then be split up into smaller parts and assembled after printing. In some cases all of the smaller parts can even fit on the build plate during one print as in the example below:

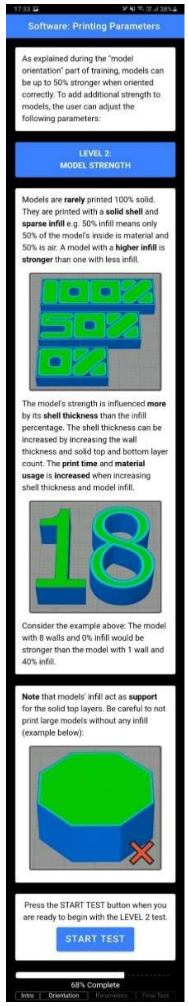

Rejoining parts after printing: After printing the separate parts, they can be joined together in various ways:
Mechanically:
The model is designed with clips to snap together after printing.
Heat:
The plastic parts can be carefully melted together using a flame/heat gun/soldering iron.
Chemically:
Some plastic materials react to chemicals e.g. ABS parts can be welded together using acetone.
Adhesive (glue):
The parts can be bonded together using adhesives e.g. glue gun, epoxy, super glue etc.
Drawbacks of splitting models: The model is typically weaker at the split plane if not bonded together properly and an aesthetically displeasing split line might be visible in the final model. The extra time, labor and cost of joining parts after printing can also be avoided when printed as one model. Always keep the number of split planes to a minimum.
The Level 5 and Level 6 tests are combined and will start after the Level 6 training.
NEXT
48% Complete
Intro

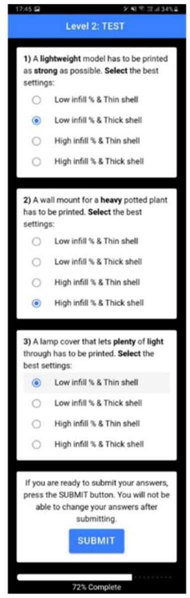

Model Orientation
The parts of an assembled model does not always have to be printed separately. The layer-by-layer FFF process makes print-in-place assemblies possible as seen in Level 6 of training:
LEVEL 6:
PRINT-IN-PLACE
Below is an example of a complex bearing model that is printed-in-place, removed from the printer and is immediately ready for use.
Note that it is actually impossible to print the parts separately and then assemble the model since they are interlocked. Likewise, some "impossible" models can be created using the FFF technology.
Note that models printed using the FFF technology is not dimensionally very accurate. As the plastic is extruded through the nozzle of the printer, it is squeezed onto the previous layer which makes it slightly wider. If the gaps in between parts are too small, they will fuse together as one. Typical FFF printers require a gap greater than 0.2mm between parts in an assembly.
>0.2mm gap
Press the START TEST button when you are ready to begin with the LEVEL 5 and 6 test.
START TEST
52% Complete
Intro

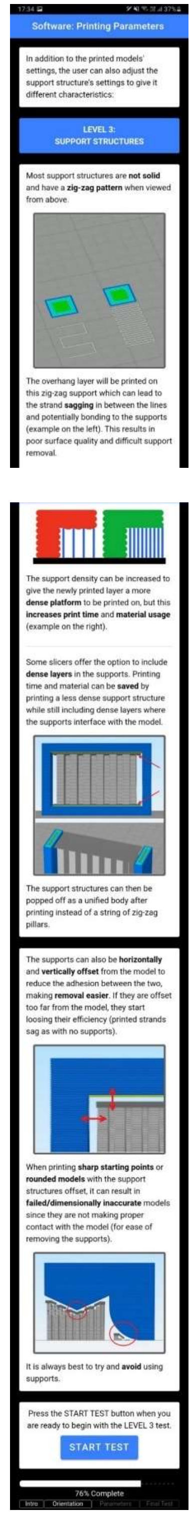

Level 5 & 6: TEST
1) Select the split plane(s) that should be used to make the model printable.
2 Planes
3 Planes
1 Plane
2) Type the typical minimum gap (in mm) between print-in-place parts which won't cause the hinge to fuse together (when using FFF).
0.2
Click or tap anywhere on the screen to update the page.
If you are ready to submit your answers, press the SUBMIT button. You will not be able to change your answers after submitting.
SUBMIT
56% Complete

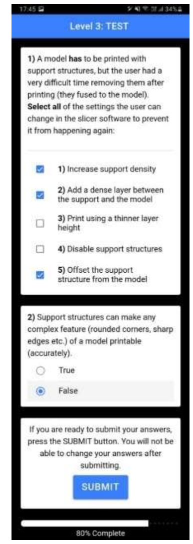

17:32
Software: Printing Parameters
Welcome to the second half of the training course, namely **Printing Parameters**.
After orienting the model in the most optimal way, the user has to specify the settings that the model will be printed with.
LEVEL 1:
PRINT QUALITY
Layer height influences the **vertical** step resolution of the model. If the layer height setting is **reduced**, the software will slice the model into **more** layers which increases the step resolution as seen below.
3D Model
0.3mm
Layer Hight
0.05mm
Layer Hight
When the layer height is **reduced**, models are printed **more true** to the 3D model e.g. slopes are flatter and rounded corners are more round. The **print time** is **increased** since more layers has to be printed.
The opposite is true when the layer height is **increased**.
Nozzle diameter influences the **horizontal** resolution of a model. **Smaller features** of a model can be printed if a **smaller diameter nozzle** is installed on the printer. A smaller nozzle deposits less material per second which **increases print time**.
The opposite is true for **larger diameter nozzles**. Models printed with a larger nozzle are also **stronger** since it has fewer gaps between individual stands.
The printer has to slightly **squish** the newly printed layer onto the previous for good layer adhesion. A good rule of thumb is to set the **layer height to 75% or less of the nozzle diameter** e.g. a maximum layer height of 0.3mm or less when using a 0.4mm nozzle.
Nozzle: 0.4mm
Layer: 0.3mm
Nozzle: 0.4mm
Layer: 0.4mm
Text on a model should ideally be **embossed** (sunken into the model) instead of **debossed** (text stands out) since any thin debossed strands can easily break off.
Press the START TEST button when you are ready to begin with the LEVEL 1 test.
START TEST
60% Complete
Intro
Orientation
Parameters
Final Test

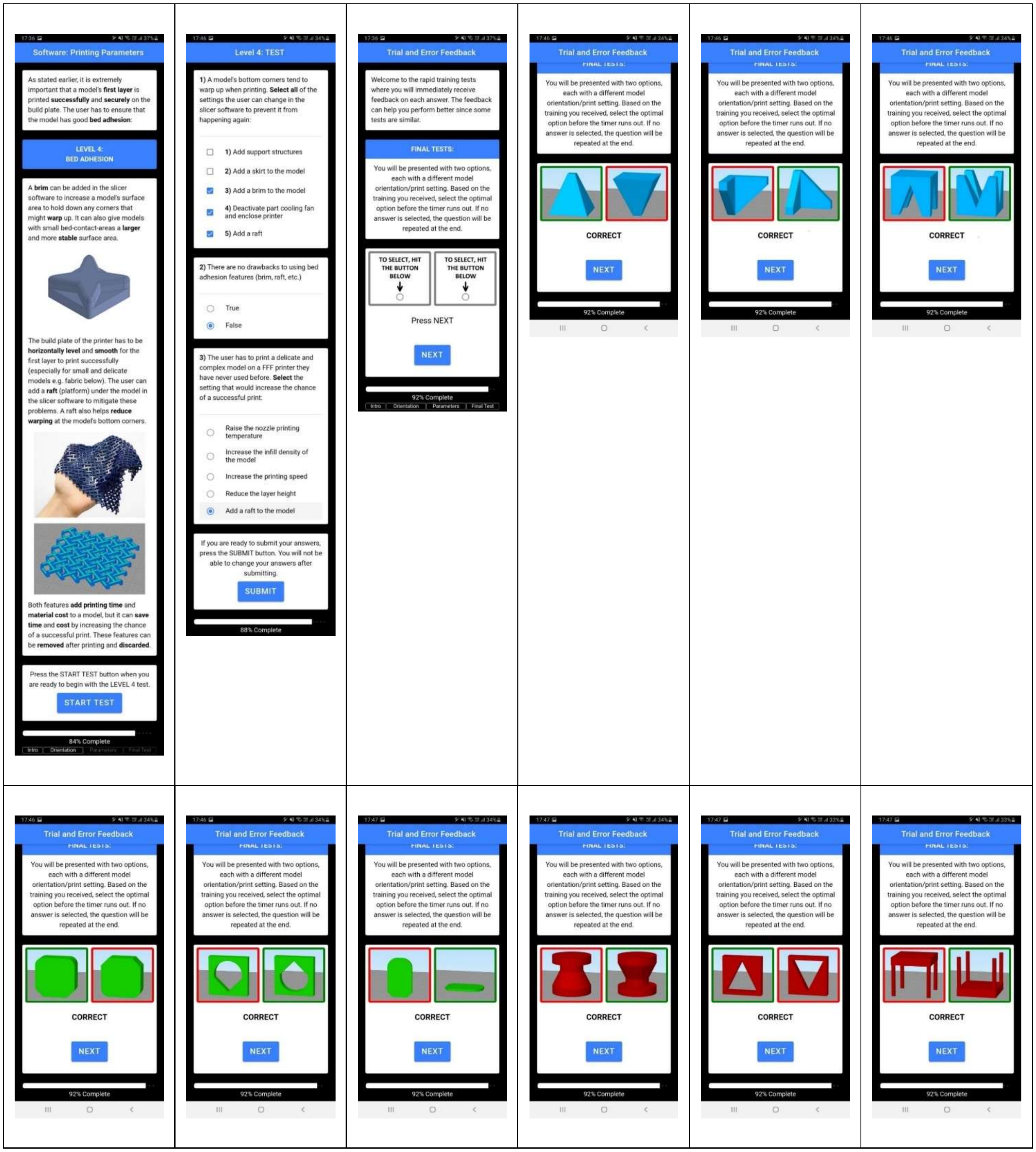

17:44
Level 1: TEST
1) A **basic** model has to be **mass produced** (using a FFF printer) and needs to withstand **high loads** during use. **Select** the best combination of settings:
Small nozzle & Small layer height
Large nozzle & Small layer height
Small nozzle & Large layer height
Large nozzle & Large layer height
2) A **complex** figurine model has **fine details** and only needs to be printed once. **Select** the best combination of settings:
Small nozzle & Small layer height
Large nozzle & Small layer height
Small nozzle & Large layer height
Large nozzle & Large layer height
3) **Select** the print setting that has to be adjusted for change in **vertical resolution**:
Layer height
Nozzle diameter
4) **Select** the print setting that has to be adjusted for change in **horizontal resolution**:
Layer height
Nozzle diameter
5) **Select** all of the **layer : nozzle** ratios that are within the recommended "squish ratio":
0.2mm : 0.4mm
0.4mm : 0.4mm
0.1mm : 1mm
0.28mm : 0.3mm
If you are ready to submit your answers, press the SUBMIT button. You will not be able to change your answers after submitting.
SUBMIT
64% Complete


17:33
Software: Printing Parameters
As explained during the "model orientation" part of training, models can be up to 50% stronger when oriented correctly. To add additional strength to models, the user can adjust the following parameters:
LEVEL 2:
MODEL STRENGTH
Models are **rarely** printed 100% solid. They are printed with a **solid shell** and **sparse infill** e.g. 50% infill means only 50% of the model's inside is material and 50% is air. A model with a **higher infill** is **stronger** than one with less infill.
100%
50%
0%
The model's strength is influenced **more** by its **shell thickness** than the infill percentage. The shell thickness can be increased by increasing the wall thickness and solid top and bottom layer count. The **print time** and **material usage** is **increased** when increasing shell thickness and model infill.
18
Consider the example above: The model with 8 walls and 0% infill would be stronger than the model with 1 wall and 40% infill.
Note that models' infill act as **support** for the solid top layers. Be careful to not print large models without any infill (example below):
Press the START TEST button when you are ready to begin with the LEVEL 2 test.
START TEST
68% Complete
Intro
Orientation
Parameters
Final Test


17:45
Level 2: TEST
1) A **lightweight** model has to be printed as **strong** as possible. **Select** the best settings:
Low infill % & Thin shell
Low infill % & Thick shell
High infill % & Thin shell
High infill % & Thick shell
2) A wall mount for a **heavy** potted plant has to be printed. **Select** the best settings:
Low infill % & Thin shell
Low infill % & Thick shell
High infill % & Thin shell
High infill % & Thick shell
3) A lamp cover that lets **plenty** of **light** through has to be printed. **Select** the best settings:
Low infill % & Thin shell
Low infill % & Thick shell
High infill % & Thin shell
High infill % & Thick shell
If you are ready to submit your answers, press the SUBMIT button. You will not be able to change your answers after submitting.
SUBMIT
72% Complete


17:34
Software: Printing Parameters
In addition to the printed models' settings, the user can also adjust the support structure's settings to give it different characteristics:
LEVEL 3:
SUPPORT STRUCTURES
Most support structures are **not solid** and have a **zig-zag pattern** when viewed from above.
The overhang layer will be printed on this zig-zag support which can lead to the strand **sagging** in between the lines and potentially bonding to the supports (example on the left). This results in poor surface quality and difficult support removal.
The support density can be increased to give the newly printed layer a more **dense platform** to be printed on, but this **increases print time** and **material usage** (example on the right).
Some slicers offer the option to include **dense layers** in the supports. Printing time and material can be **saved** by printing a less dense support structure while still including dense layers where the supports interface with the model.
The support structures can then be popped off as a unified body after printing instead of a string of zig-zag pillars.
The supports can also be **horizontally** and **vertically offset** from the model to reduce the adhesion between the two, making **removal easier**. If they are offset too far from the model, they start loosing their efficiency (printed strands sag as with no supports).
When printing **sharp starting points** or **rounded models** with the support structures offset, it can result in **failed/dimensionally inaccurate** models since they are not making proper contact with the model (for ease of removing the supports).
It is always best to try and **avoid** using supports.
Press the START TEST button when you are ready to begin with the LEVEL 3 test.
START TEST
76% Complete
Intro
Orientation
Parameters
Final Test


17:45
Level 3: TEST
1) A model **has** to be printed with support structures, but the user had a very difficult time removing them after printing (they fused to the model). **Select all** of the settings the user can change in the slicer software to prevent it from happening again:
1) Increase support density
2) Add a dense layer between the support and the model
3) Print using a thinner layer height
4) Disable support structures
5) Offset the support structure from the model
2) Support structures can make any complex feature (rounded corners, sharp edges etc.) of a model printable (accurately).
True
False
If you are ready to submit your answers, press the SUBMIT button. You will not be able to change your answers after submitting.
SUBMIT
80% Complete


Software: Printing Parameters
As stated earlier, it is extremely important that a model's first layer is printed successfully and securely on the build plate. The user has to ensure that the model has good bed adhesion:
LEVEL 4: BED ADHESION
A brim can be added in the slicer software to increase a model's surface area to hold down any corners that might warp up. It can also give models with small bed-contact-areas a larger and more stable surface area.
The build plate of the printer has to be horizontally level and smooth for the first layer to print successfully (especially for small and delicate models e.g. fabric below). The user can add a raft (platform) under the model in the slicer software to mitigate these problems. A raft also helps reduce warping at the model's bottom corners.
Both features add printing time and material cost to a model, but it can save time and cost by increasing the chance of a successful print. These features can be removed after printing and discarded.
Press the START TEST button when you are ready to begin with the LEVEL 4 test.
START TEST
84% Complete
Intro
Orientation
Level 4: TEST
1) A model's bottom corners tend to warp up when printing. Select all of the settings the user can change in the slicer software to prevent it from happening again:
1) Add support structures
2) Add a skirt to the model
3) Add a brim to the model
4) Deactivate part cooling fan and enclose printer
5) Add a raft
2) There are no drawbacks to using bed adhesion features (brim, raft, etc.)
True
False
3) The user has to print a delicate and complex model on a FFF printer they have never used before. Select the setting that would increase the chance of a successful print:
Raise the nozzle printing temperature
Increase the infill density of the model
Increase the printing speed
Reduce the layer height
Add a raft to the model
If you are ready to submit your answers, press the SUBMIT button. You will not be able to change your answers after submitting.
SUBMIT
88% Complete
Trial and Error Feedback
Welcome to the rapid training tests where you will immediately receive feedback on each answer. The feedback can help you perform better since some tests are similar.
FINAL TESTS:
You will be presented with two options, each with a different model orientation/print setting. Based on the training you received, select the optimal option before the timer runs out. If no answer is selected, the question will be repeated at the end.
TO SELECT, HIT THE BUTTON BELOW
TO SELECT, HIT THE BUTTON BELOW
Press NEXT
NEXT
92% Complete
Intro
Orientation
Parameters
Final Test
Trial and Error Feedback
You will be presented with two options, each with a different model orientation/print setting. Based on the training you received, select the optimal option before the timer runs out. If no answer is selected, the question will be repeated at the end.
CORRECT
NEXT
92% Complete
Trial and Error Feedback
You will be presented with two options, each with a different model orientation/print setting. Based on the training you received, select the optimal option before the timer runs out. If no answer is selected, the question will be repeated at the end.
CORRECT
NEXT
92% Complete
Trial and Error Feedback
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CORRECT
NEXT
92% Complete
Trial and Error Feedback
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CORRECT
NEXT
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Trial and Error Feedback
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CORRECT
NEXT
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Trial and Error Feedback
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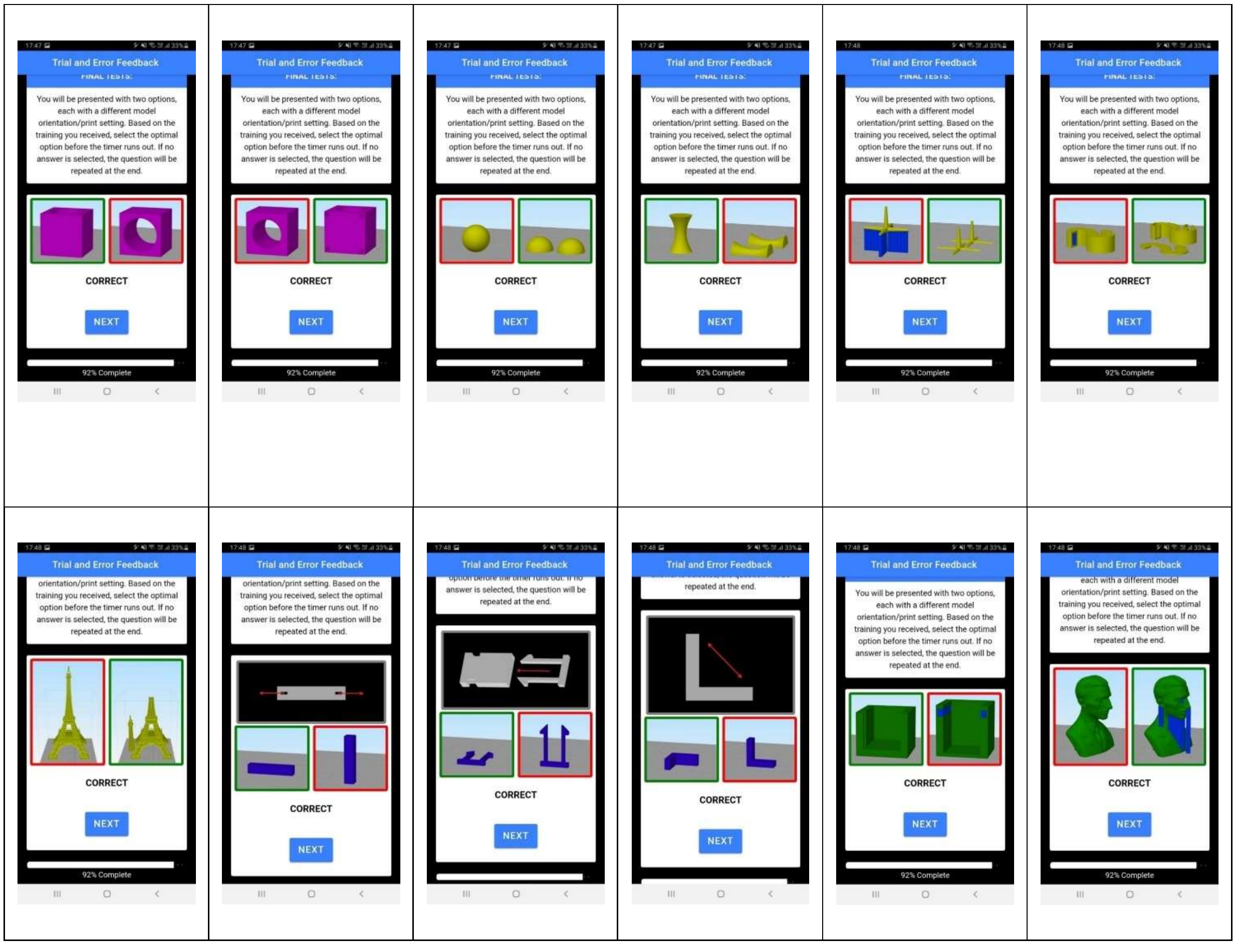
CORRECT
NEXT
92% Complete
Trial and Error Feedback
You will be presented with two options, each with a different model orientation/print setting. Based on the training you received, select the optimal option before the timer runs out. If no answer is selected, the question will be repeated at the end.
CORRECT
NEXT
92% Complete
Trial and Error Feedback
You will be presented with two options, each with a different model orientation/print setting. Based on the training you received, select the optimal option before the timer runs out. If no answer is selected, the question will be repeated at the end.
CORRECT
NEXT
92% Complete
Trial and Error Feedback
You will be presented with two options, each with a different model orientation/print setting. Based on the training you received, select the optimal option before the timer runs out. If no answer is selected, the question will be repeated at the end.
CORRECT
NEXT
92% Complete


Trial and Error Feedback
FINAL TESTS:
You will be presented with two options, each with a different model orientation/print setting. Based on the training you received, select the optimal option before the timer runs out. If no answer is selected, the question will be repeated at the end.
CORRECT
NEXT
92% Complete

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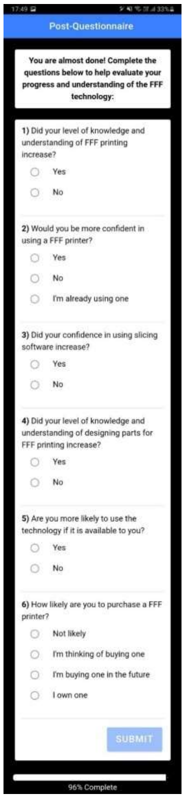
<td>
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Appendix B Assent and Consent Forms

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ELECTRONIC CONSENT TO PARTICIPATE IN RESEARCH

TITLE OF RESEARCH PROJECT:	Development of a digital course for rapid training: Additive manufacturing - Fused filament fabrication
REFERENCE NUMBER:	ING-2019-11380
PRINCIPAL INVESTIGATOR:	Roelof Pienaar van Wageningen
ADDRESS:	Industrial Engineering Building, Banhoek Road, Stellenbosch
CONTACT NUMBER:	0767213588
E-MAIL:	19075782@sun.ac.za

Dear prospective participant

Kindly note that I am a MEng student at the Department of Industrial Engineering at Stellenbosch University, and I would like to invite you to participate in a research project entitled *Development of a digital course for rapid training: Additive manufacturing - Fused filament fabrication.*

Please take some time to read the information presented here, which will explain the details of this project and contact me if you require further explanation or clarification of any aspect of the study. This study has been approved by the Research Ethics Committee (REC) at Stellenbosch University and will be conducted according to accepted and applicable national and international ethical guidelines and principles.

Please include the following details and make use of these sub-headings for ease of use:

1. **INTRODUCTION:** The Fused Filament Fabrication (FFF) 3D printing technology has been around since 1989, but there is still a "futuristic" connotation with the technology which is possibly induced by the media. This causes a false idea of FFF 3D printing to be inaccessibility, unaffordable and too complex to adopt or interact with.

2. **PURPOSE** The purpose of this study is to determine whether participants can be quickly and successfully trained in understanding and engaging with a 3D printing technology (Fused Filament Fabrication).

3. **PROCEDURES:** The participant will be asked to download the training app on their smartphone or visit the web app using a computer. They will complete a questionnaire before and after the training course on the app, as well as short tests during training.

4. **TIME:** The total time to complete the questionnaires and training is estimated to be 1 hour.
5. **RISKS:** The training course poses no risks to the participant and the course will not trigger any discomfort. If the participant is uncomfortable to use a digital device for the duration of the course, they are welcome to take a break or completely withdraw from the course.
6. **BENEFITS:** The participant will gain knowledge of FFF 3D printing and will be equipped to engage with and design for the manufacturing technology.
7. **PARTICIPATION & WITHDRAWAL:** If the participant decides to withdraw from the course, their progress data will be discarded and not used in the study. They will not be pressured to complete the course and they will not be penalized for not completing it either.
8. **CONFIDENTIALITY:** The participant will not supply any personal data during the course so they cannot be identified by their response. An anonymous user code will be generated for each participant.
9. **RECORDINGS:** No voice or video recordings are made during the course.
10. **DATA STORAGE:** The data collected during the course is completely anonymous and will be stored on a secure server and backed up on an external hard drive. The primary researcher will be the only individual with access to the data.

If you have any questions or concerns about the research, please feel free to contact the researcher Roelof Pienaar van Wageningen (19075782@sun.ac.za) and/or the Supervisor, Devon Hagedorn-Hansen (devonh@sun.ac.za). To request a copy of this text, please contact the researcher at 19075782@sun.ac.za.

RIGHTS OF RESEARCH PARTICIPANTS:

You can exit the survey at any time without giving a reason, but you have to answer all of the questions if you choose to participate. If you withdraw mid-way in the course, your response will not be used in the study and

will be erased. Please, do not feel pressured to complete the course. You are not waiving any legal claims, rights or remedies because of your participation in this research study. If you have questions regarding your rights as a research participant, contact Mrs. Maléne Fouché [mfouche@sun.ac.za; 021 808 4622] at the Division for Research Development.

I confirm that I have read and understood the information provided for the current study.	YES ☐	NO ☐
I agree to take part in this training course and survey.	YES ☐	NO ☐

DECLARATION BY THE PARTICIPANT

As the participant I hereby declare that:

- I have read the above information and it is written in a language with which I am fluent and comfortable.
- I have had a chance to ask questions and all my questions have been adequately answered.
- I understand that taking part in this study is voluntary and I have not been pressurized to take part.
- I may choose to leave the study at any time and will not be penalized or prejudiced in any way.
- If the principal investigator feels that it is in my best interest, or if I do not follow the study plan as agreed to, then I may be asked to leave the study before it has finished.
- All issues related to privacy, and the confidentiality and use of the information I provide, have been explained to my satisfaction.

As the **participant** I hereby select the following option:

	I accept the invitation to participate in your research project, and if I decide to be interviewed it would automatically mean that I have given consent for my responses to be used confidentially and anonymously.
	I accept the invitation to participate in your research project, and if I decide to complete the questionnaire it would automatically mean that I have given consent for my responses to be used confidentially and anonymously.
	I decline the invitation to participate in your research project.

DECLARATION BY THE PRINCIPAL INVESTIGATOR

As the **principal investigator,** I hereby declare that the information contained in this document has been thoroughly explained to the participant. I also declare that the participant has been encouraged (and has been given ample time) to ask any questions. In addition, I would like to select the following option:

	The conversation with the participant was conducted in a language in which the participant is fluent.
	The conversation with the participant was conducted with the assistance of a translator, and this "Consent Form" is available to the participant in a language in which the participant is fluent.

______________________________________ ___________________________

Signed at *(place)* **Date**

____

Signature of Principal Investigator

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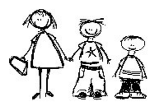
ASSENT FORM FOR MINORS



TITLE OF THE RESEARCH PROJECT: Creating a 3D printing training course

RESEARCHERS' NAME(S): Pine van Wageningen

RESEARCHER'S CONTACT DETAILS: 19075782@sun.ac.za

What is RESEARCH?

Research is something we do find **NEW KNOWLEDGE** about the way things (and people) work. We use research projects or studies to help us find out more about children and teenagers and the things that affect their lives, their schools, their families and their health. We do this to try and make the world a better place!

What is this research project all about?

The goal of this research project and the training course is to show people just how easy it is to use 3D printing to create toys, replacement parts and exciting new products.

Why have I been invited to take part in this research project?

You will learn how a 3D printer works and how to interact with it. This will enable you to use one or even design parts to be printed if you have access to it in the future. When 2D paper printers were invented, people had to learn how to use them. After learning how to use a 2D paper printer, people can to create beautiful and useful things and some use it daily. The same can happen for 3D printing and you get to learn more about it ahead of time.

Who is doing the research?

My name is Pine van Wageningen and I'm doing research on 3D printing. I want to share what I have learned about this exciting technology.

What will happen to me in this study?

You will be asked a few questions before and after the training course. During training, you will also complete a few tests that will help you to learn quicker.

Can anything bad happen to me?

Nothing bad can happen to you. You can stop participating in the training at any time if you feel uncomfortable.

Can anything good happen to me?

Yes, you will learn more about 3D printing and how to interact with it.

Will anyone know I am in the study?

You will not be asked to give any personal information about yourself so no-one would be able to identify that you partook in the study.

Who can I talk to about the study?

If you have any questions about the study, you can contact me (Pine van Wageningen) by sending me an email: 19075782@sun.ac.za.

What if I do not want to do this?

Even if your guardian (parents or teacher) allowed you to partake in the study, you do not have to. You can stop participating in the study at any time and you are free to not participate at all.

Do you understand this research study and are you willing to take part in it?

YES	NO

Has the researcher answered all your questions?

YES	NO

Do you understand that you can STOP being in the study at any time?

YES	NO

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PARENT/LEGAL GUARDIAN CONSENT FOR CHILD TO PARTICIPATE IN RESEARCH

I would like to invite your child to take part in a study conducted by myself Pine van Wageningen, from the Department of Industrial Engineering at Stellenbosch University. Your child will be invited as a possible participant in a training course in 3D printing.

1. PURPOSE OF THE STUDY

I developed a 3D printing training course that introduces participants to or further educate them on an affordable manufacturing technology that can be deployed in the home/classroom/office environment. 3D printing might come across more intimidating, inaccessible and unaffordable than it truly is, possibly due to the "futuristic" view media provides to the public of it. The purpose of the study and training course is to equip participants with the necessary knowledge to use and engage with the technology in the future as they have possibly adopted the computer/smartphone technology.

2. WHAT WILL BE ASKED OF MY CHILD?

If you consent to your child taking part in this study, the researcher will then approach the child for their assent to take part in the study. If the child agrees to take part in the study, he/she will be asked to either visit the web link or download the mobile app that contains the training course. They will start by filling out a questionnaire with basic questions about 3D printing to test their knowledge before receiving training. The training is comprised of informational slides on the 3D printing technology with small tests in between. They will fill out a feedback questionnaire after completing the training course. Both questionnaires and the training course are integrated into the mobile/web app.

3. POSSIBLE RISKS AND DISCOMFORTS

The questions and tests will not trigger any form of discomfort and will be no different from daily activities. If the child experiences any discomfort in using a digital device, they can withdraw at any time during the course and will not be penalized in any way. Their participation in the training is course completely voluntary. Furthermore, there are no foreseeable risks or discomforts linked to participating in the course.

4. POSSIBLE BENEFITS TO THE CHILD OR SOCIETY

The child will directly benefit from participating in the training course since they are receiving training and education on a technology they might use or personally adopt in the future. They will receive a new skill through the course, enabling them to state on their future CV that they have some exposure and experience with a 3D printing technology.

5. PAYMENT FOR PARTICIPATION

Participation in the course is completely free of charge and voluntary. The participants are offered free training and knowledge, but they will not be offered money in exchange for their participation.

6. PROTECTION OF YOUR AND YOUR CHILD'S INFORMATION, CONFIDENTIALITY AND IDENTITY

A user code will be generated for each new participant, meaning they won't have to disclose any personal information and they won't be identifiable through their responses either.

7. PARTICIPATION AND WITHDRAWAL

You and your child can choose whether to be part of this study or not. If you consent to your child taking part in the study, please note that your child may choose to withdraw or decline participation at any time without any consequence. The course requires participants to answer all of the questions. They can withdraw if they don't want to answer a question. The researcher may withdraw your child from this study if they attempt to deliberately sabotage the test results.

8. RESEARCHERS' CONTACT INFORMATION

If you have any questions or concerns about this study, please feel free to contact Pine van Wageningen at 19075782@sun.ac.za and/or the supervisor Devon Hagedorn-Hansen at devonh@sun.ac.za.

9. RIGHTS OF RESEARCH PARTICIPANTS

Your child may withdraw their consent at any time and discontinue participation without penalty. Neither you nor your child is waiving any legal claims, rights or remedies because of your participation in this research study. If you have questions regarding your or your child's rights as a research participant, contact Ms. Maléne Fouché [mfouche@sun.ac.za; 021 808 4622] at the Division for Research Development.

DECLARATION OF CONSENT BY THE PARENT/ LEGAL GUARDIAN OF THE CHILD- PARTICIPANT

As the parent/legal guardian of the child I confirm that:

- I have read the above information and it is written in a language that I am comfortable with.
- I have had a chance to ask questions and all my questions have been answered.
- All issues related to privacy and the confidentiality and use of the information have been explained.

I confirm that I have read and understood the information provided for the current study.	YES	NO
	☐	☐
I agree that the researcher may approach my child to take part in this research study.	YES	NO
	☐	☐

Appendix C Slicer Software Popularity

Table 27: Slicer Software Popularity Calculation

https://3dinsider.com/3d-printer-slicer-software/		https://all3dp.com/1/best-3d-slicer-software-3d-printer/		https://www.3dnatives.com/en/top-10-slicer-software-		https://3dsourced.com/3d-software/best-3d-slicer-printer-software/		https://www.inov3d.net/3d-printing-slicer-software-		https://pick3dprinter.com/3d-slicer-software/		https://www.cmac.com.au/blog/top-10-slicer-software-for-3d-printers					
Simplify3D	10	Netfabb Standard	10	Cura	10	Cura	10	Simplify3D	10	Simplify3D	10	Cura	10	Repetier	10	Slic3r	10
Cura	8	Cura	9	3DPrinterOS	9	Simplify3D	8.9	Cura	9	Slic3r	8.3	AstroPrint	8	KISSlicer	5	OctoPrint	6.7
KISSlicer	6	PrusaSlicer	8	ideaMaker	8	Slic3r	7.8	Slic3r	8	OctoPrint	6.7	CraftWare	6			IceSL	3.3
Slic3r	4	OctoPrint	7	KISSlicer	7	KISSlicer	6.7	KISSlicer	7	AstroPrint	5	MatterControl	4				
OctoPrint	2	MatterControl	6	Repetier	6	Tinkerine Suite	5.6	OctoPrint	6	3DPrinterOS	3.3	SelfCAD	2				
		Simplify3D	5	OctoPrint	5	PrusaSlicer	4.4	3DPrinterOS	5	Repetier	1.7						
		MakerBot Print	4	Slic3r	4	Reptier	3.3	AstroPrint	4								
		Repetier	3	AstroPrint	3	OctoPrint	2.2	Repetier	3								
		ideaMaker	2	Simplify3D	2	SelfCAD	1.1	Craftware 3D	2								
		Z-Suite	1	IceSL	1			IceSL	1								
Simplify3D		45.89				Cura		56.00	100								
Cura		56.00				Simplify3D		45.89	82								
KISSlicer		31.67				Slic3r		42.11	75								
Slic3r		42.11				OctoPrint		35.56	63								
OctoPrint		35.56				KISSlicer		31.67	57								
Netfabb Standard		10.00				Repetier		27.00	48								
PrusaSlicer		12.44				AstroPrint		20.00	36								
MatterControl		10.00				PrusaSlicer		12.44	22								
MakerBot Print		4.00				Netfabb Standard		10.00	18								
Repetier		27.00				MatterControl		10.00	18								
ideaMaker		10.00				ideaMaker		10.00	18								
Z-Suite		1.00				3DPrinterOS		8.33									
IceSL		5.33				CraftWare		8.00									
AstroPrint		20.00				Tinkerine Suite		5.56									
SelfCAD		3.11				IceSL		5.33									
3DPrinterOS		8.33				MakerBot Print		4.00									
CraftWare		8.00				SelfCAD		3.11									
Tinkerine Suite		5.56				Z-Suite		1.00									

Appendix D Project Expenses

Table 28: Project Expenses

Description	Price
Ionic Udemy Course	R300
Apple App Developer – 1 year	R1,778.21
Google Play App Store – Lifetime	R439.82
Total:	**2 518.03**

Appendix E Training Course Invite Flyer

Figure E.1: Training Course Invite Flyer