THE ETHICAL ISSUES OF ADDITIVE MANUFACTURING

By

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Abstract

Additive manufacturing (3D printing) has brought industrial manufacturing capabilities to the desktop, allowing the seamless transition from consumer-to-manufacturer-to-retailer and enabling anyone to use the technology outside of traditionally regulated spaces. This creates new challenges for information technology governance. The potential societal risks of additive manufacturing (AM) are not well known and there is a policy vacuum on how the technology should be used responsibly. As 3D printers become mainstream and are increasingly being used in homes, garages, SME's, educational institutions, large enterprises etc, this study explores the ethical issues promoted by the technology.

Considering that 3D printing has mainly been advanced by activities of DIY hacker groups and the sharing economy, this thesis is framed in the context of users from DIY hacker collectives like hackspaces, makerspaces, and FabLabs. The research investigates the ethical concerns of experts who are closely associated with such collectives to understand the types of issues they are concerned about. The study was also an attempt to understand the implications of expert participation in knowledge-making in terms of ethics.

An interpretive hermeneutic approach was followed in the collection and analysis of data from the experts that participated in this research. This approach helped the researcher to recognise how personal prejudices can be the basis of developing an understanding and to reflect critically on the cultural and historical background of 3D printing, the participants, and the researchers own historicity in a bid to derive meaning from the study.

The study has found that participants were able to identify several ethical issues which have been broken down into 26 subthemes. The main themes, however, are environment, health and safety, intellectual property rights, jobs, 3D printed guns, business ethics, offensive items, data security, and liability. Nevertheless, a closer inspection of these findings also indicates that individually, the participants have limited knowledge of the societal concerns of 3D printing. For example, when participants are split into academics and SME's to reflect their professional background, academics identified an average of 1.7 of the 26 subthemes, as opposed to an average of 3.7 issues by those from SMEs. This raises important questions about the reliability and validity of expert participation in knowledge-making for ethics-related studies. The findings also show that the hacking culture has had a double-edged effect on 3D printing. It has actively promoted the democratisation of the 3D printing by enabling anyone and everyone to participate and benefit equally. However, it has also passively promoted societal concerns by enabling the use of 3D printers in spaces outside of institutional control where ethical approval isn't required.

Dedication

This work is dedicated to the loving memory of my father Mr Godwin Ajogi Ogoh

Acknowledgement

This work has only been possible because of the invaluable contributions of a vast network of colleagues, family, and friends all of whom I am extremely grateful for. To these wonderful group of people, I cannot say thank you enough. They include my supervisors Dr Sara Wilford, Dr Catherine Flick, Dr Ofer Engel, and Dr N. Ben Fairweather with whom I started this journey. I sincerely appreciate all the feedback and detailed explanations that you kindly provided. Many thanks also to Prof. Bernd Stahl, and my colleagues at the Centre for Computing and Social Responsibility, De Montfort University.

To my family, I say thanks for your patience, your support, and encouragement. I couldn't have done it without you. Mummy, Joy, Bright, Young, Naomi, Goody, Nicho, and Stone, you guys have been my rock. Fendo nawa, you, Zazzau, and Zaltana have been a blessing and I appreciate you guys greatly. Thanks also to my wonderful nephews and nieces as well as my caring in-laws. Mimam, *you too much*. Maman TY *na gode*.

Ultimately, thanks to Jehovah for life, good health, and the ability to complete this programme.

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…The best laid schemes o' Mice and Men,
Gang aft agley,
An' lea'e us nought but grief an' pain,
For promis'd joy!
- To a Mouse (Robert Burns, 1976)

Chapter 1 : An Overview

1.1 Introduction

This research seeks to understand the ethical issues of additive manufacturing from a viewpoint of the users of the technology. Additive manufacturing (also referred to as 3D printing) is an emerging technology that challenges the traditional roles of the manufacturer, wholesaler, retailer and consumer as it allows the seamless transition from consumer-to-manufacturer-to-retailer. It has been promoted by the activities of DIY hacker collectives which has led to a democratisation of this manufacturing technology and has enabled anyone and everyone to get involved in making. Although it has had many benefits, putting such powerful technology in the hands of everyone has problematic implications for society. What are these implications? And, do the users understand the societal concerns?

To resolve such questions, this research is situated in the context of users from the DIY hacker collectives around the UK and parts of Europe. Experts were selected from hackspaces, makerspaces, fablabs and interviewed in an attempt to understand how they perceive the ethical issues promoted by the technology and how to resolve them. The study also attempts to examine the effect of the culture promoted by such communities on the ethical issues of 3D printing while also determining the implication of expert participation in knowledge-making.

To highlight the importance of this study, this chapter provides an overview of the additive manufacturing industry and describes how this research is positioned. It also presents the research questions along with the aim and objectives of the research and provides details about the structure of this thesis.

1.2 The Growing AM Industry

Additive manufacturing is transforming design and manufacturing (Ford, 2014, p.6; Gibson, Rosen and Stucker, 2014, p.483; Despeisse and Ford, 2015, p.130,131; Savastano et al., 2019, p.892) and has continued to grow in importance. For example, it has been estimated that in 2019, over 600,000 3D printers were sold with the sector seeing a cumulative growth rate of 25 per cent year-on-year in the past 3 years (Linares et al., 2020, p.1). From clothing (Brick, 2015; Valtas and Sun, 2016, p.4) to guns (Johnson, 2013, p.338; Ruben, 2017, p.129) and functional human organs (Murphy and Atala, 2014, p.773; Kang et al., 2016, p.312; Yi, Lee and Cho, 2017, p.1,2; Martinez-Marquez et al., 2018, p.2). AM has found wide applications in many fields including – but not limited to – the automotive, aerospace, and medical sectors (Royal Academy of Engineering, 2013b, p.6; Mao et al., 2017, pp.122–

140; Jiménez et al., 2019, pp.23 & 24) showing how quickly this technology is being adopted.

An indication of the growing importance of additive manufacturing is the increasing number of articles written by specialists in the field each year. The Royal Academy of Engineering has shown that over 16,000 articles on AM or 3D printing were published in 2012 compared with about 1,600 in the previous year. The 2016 Wohlers Report on the state of the Additive Manufacturing industry notes that the market for products and services grew by 25.9% to over $5 billion in 2015 (Wohlers Associates, 2016) and is expected to rise to about $26.2 billion by 2022 (Koenig, 2017). Also, Basiliere (2016) Research Vice president at Gartner which is arguably one of the world's leading information technology research and advisory companies has revealed that about 500,000 units of 3D printers were shipped in 2016, predicting that the total number of units shipped will total more than 6.7 million by 2020. This shows that the industry which has existed for about 30 years (Huang and Zhang, 2014, p.5380), is no longer in its infancy.

Interestingly, a look at the technology S-Curve framework (Foster, 1988, pp.31–35; Intepe and Koc, 2012, p.2491; Huang et al., 2017, p.12) suggest that while AM is not in its infancy, it cannot be said to be mature just yet (see Figure 1-1). According to Christensen (2000, pp.39–41), the S-Curve theory describes stages of a product's performance improvements over a given period. In the early stages, the rate of progress of a technology's performance (especially disruptive technology) is relatively slow; a stage of rapid improvement then follows when it accelerates as it becomes better understood and controlled resulting in an asymptotic growth; this is then followed by a period of declining improvement when the technology attains maturity as it reaches its natural or physical limitations such that further improvements become very difficult to achieve. Additive manufacturing can be said to be floating between the emergence and rapid development stages as it has not quite reached maturity yet.

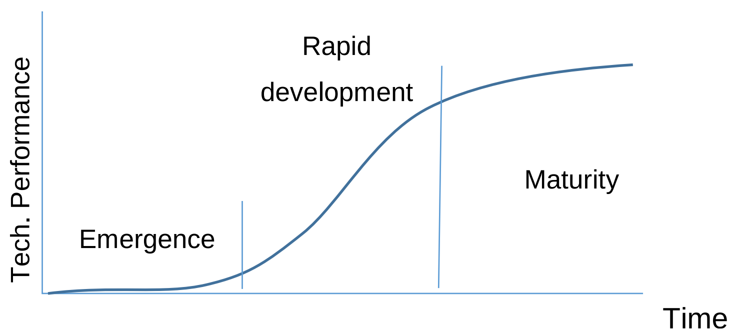

Figure 1-1 S-Curve framework

In a bid to demonstrate how AM might revolutionise certain industries, the Computer Sciences Corporation (CSC) produced a guide to show how AM might be adopted in seven important industries including defence, healthcare, and general manufacturing (Leading Edge Forum, 2012). This prediction is comparable with the timeline created by the Royal Academy of Engineering to illustrate the changing nature of the application of AM over time (see Figure 1-2). It suggests a surge in development of objects for Nano-manufacturing, architecture, biomedical implants, in-situ biomanufacturing, and even full-body organs (Royal Academy of Engineering 2013). In terms of the economic impact, BCG Global (2020) projects that if 1.5% of the total addressable manufacturing markets adopt AM by the year 2035, the market share of the technology could exceed $350 Billion (see Figure 1-3). All of these indicates that as additive manufacturing becomes more prevalent, its effect on everyday life, economy, and society will increase dramatically.

Despite their ability to transform society for good, and making tasks quicker and easier, such technologies are often depicted negatively as a result of the societal problems that these technologies have either introduced or are perceived to promote due to their nature (Mason, 1995, p.55; Kernaghan, 2014, p.295). The debates around the use of stem cells and embryo's in research and healthcare (Lo and Parham, 2009; Begum and Khan, 2017; Allum et al., 2017; Ede and Obeagu, 2018); debates about genetically modified organisms (GMOs) (Zhang, Wohlhueter and Zhang, 2016; Tsatsakis et al., 2017; Ricroch, Guillaume-Hofnung and Kuntz, 2018); and the debates around artificial intelligence and robotics (Lin, Abney and Bekey, 2011; Stahl and Coeckelbergh, 2016; Keskinbora, 2019) are all examples that illustrate how emerging technologies are often perceived.

Questions of production, access, and control are often at the heart of social challenges surrounding the use of information technologies (Sullins, 2016, p.2). Moor (2005, pp.110, 118) therefore argues for the need to pay close attention to ethical issues that they generate to "unpack the potential consequences of new technology" early. Although some of the ethical issues of such technologies are already in the public domain (McNulty, Arnas and Campbell, 2012) and may be easy to spot, others are not so obvious as is often the case with emerging technologies like additive manufacturing. Developing appropriate policy and regulation specifically targeting the use of AM technologies is therefore challenging. Yet, there is a likelihood that ethical issues in this field could have far-reaching consequences if not properly addressed. Thus, this research is a study of the ethical issues that arise due to additive manufacturing technology in a bid to make the issues explicit and to suggest suitable means of minimising the negative ethical consequences of AM

This timeline lays out past, present, and potential future AM developments and applications.
(courtesy of Graham Tromans)

1988–1994	rapid Prototyping
1994	rapid casting
1995	rapid tooling
2001	AM for automotive
2004	aerospace (polymers)
2005	medical polymer jigs and guides
2009	medical implants (metals)
2011	aerospace (metals)
2013 - 2016	nano-manufacturing
2013–2017	architecture
2013 - 2018	biomedical implants
2013 - 2022	in-situ bio-manufacturing
2013 - 2032	Full body organs

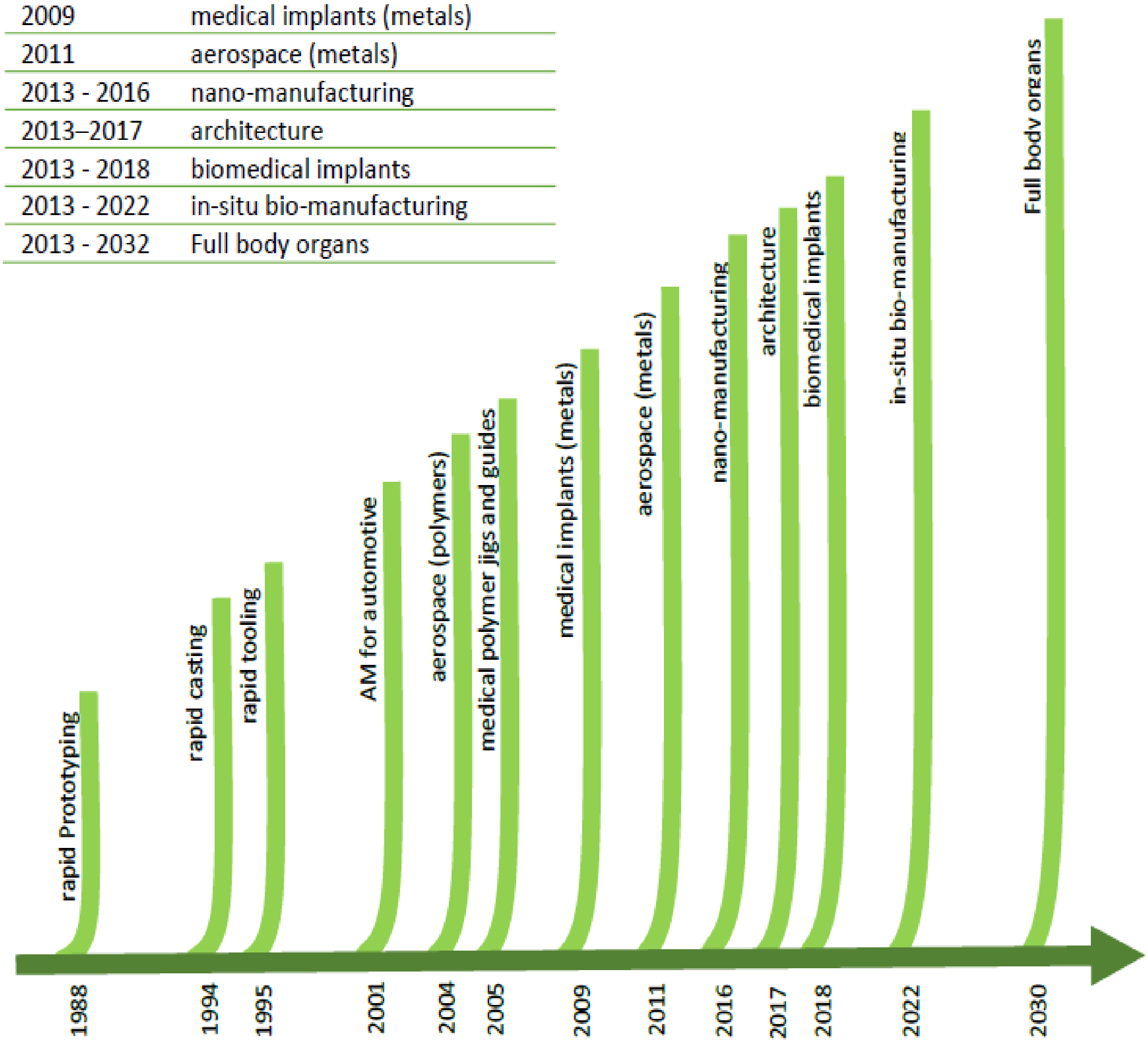

Figure 1-2 Projected timeline for adoption of AM (Royal Academy of Engineering 2013)

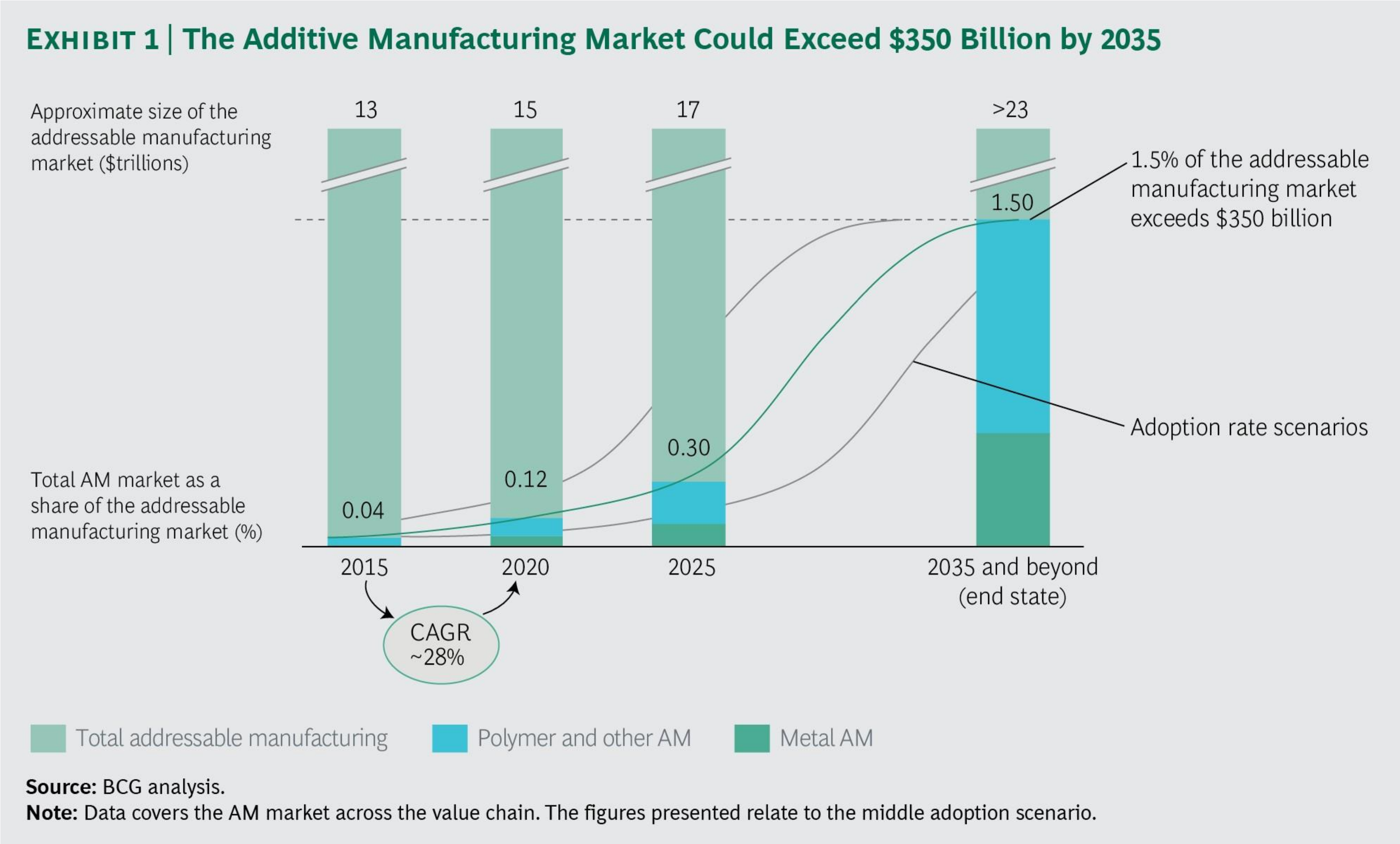

Figure 1-3 Projection of the economic effect of AM to 2035 (BCG Global 2035)

1.3 Positioning of the Research

The expected proliferation of additive manufacturing, as well as the nature of the technology, raises serious concerns, some of which this study will attempt to address. As the cost of acquiring 3D printers decrease and the technology improves, it is expected that users will be able to print out almost any object of their choice. Equipment like 3D scanners can be used to capture the geometry of objects along with physical characteristics, or designs may simply be downloaded off the internet (Ebrahim, 2016, p.41). The 3D model can then be printed out as physical objects on 3D printers. Objects may be formed from such materials as polymers, ceramics, and metals through processes like sintering, fusing, melting, or curing (Ford, 2014, pp.2, 4, 18; Gibson, Rosen and Stucker, 2015, pp.107–136). There are no barriers to access and its use outside of traditional scientific, medical, commercial institutional (Boucher, 2018a, p.7) raises genuine concerns among stakeholders including governments, the manufacturing industry, and businesses all over the world, as the technology is currently unregulated (Government Accountability Office 2015).

In a report commissioned by the Intellectual Property Office, it has been shown that much of the concern on additive manufacturing is centred on the inadequacy of current regulatory structures to deal with ethical dilemmas that arise from the use of this technology (Mendis and Secchi, 2015, p.41). One of the most avidly debated ethical issues surrounding AM technology has been on the property rights of artefacts that are produced (Rivera and van der Meulen, 2014; Mendis and Secchi, 2015, p.2). Another important issue for Additive Manufacturing was recently raised in the US by the National Institute of Standards and Technology (NIST) on the cybersecurity needs of the technology and the implications for information technology. In the report, it is noted that the vast majority of stakeholders are not aware that Additive Manufacturing technology is also susceptible to cybersecurity risks (Zimmerman and Glavach, 2015, p.52). It is suspected that issues like these are only a small portion of the social problems of AM and it remains to be seen to what extent these issues exist and what other social issues exist.

This study is an attempt to conduct an extensive investigation of the ethical issues that may arise from the use of Additive Manufacturing technology. The research seeks to identify and analyse ethical and other societal problems that are associated with the technology, as currently, these are yet to be fully understood. Already, some studies have been done in this regard by other researchers. For example, in the United States where issues of intellectual property are more hotly debated and have been the source of several high-profile legal disputes in the ICT industry, Grace (2014, p.265) of the Harvard Law School researched how consumer 3D printing will diminish the function of trademarks in America. The study concluded that ‘consumer 3D printing has the potential to change the role of trademarks in our society’ (Grace, 2014, p.287) and suggested that the courts and US congress must consider what changes are required to provide an appropriate balance of rights based on the trademark law.

Also, Harris (2015) has produced a research report on ‘The Effects of in-home 3D Printing on Product Liability Law’ highlighting the incongruence between 3D printing and the administration of product liability law in the US. Others like Desai & Magliocca (2013) considered issues surrounding the digitisation of 3D objects like patents, copyright, and trademark problems in the US. Thus, Desai & Magliocca (2013) recommends among other things, the extension of the Digital Millennium Copyright Act (DMCA) to websites that host 3D-Printing enabling materials to strike a balance between rights holders and intermediaries. This is because the DMCA was signed into law in 1998 and copyright laws only addressed 5 related issues including – online copyright infringement, copying of computer programmes for maintenance and repair, the function of copyright office exemptions in Copyright Act for libraries, implementation of World Intellectual Property Organisation (WIPO) copyright treaty, and protection for original designs of vessel hulls (Copyright Office, 1998, p.1). The DMCA does not directly address any of the issues associated with additive manufacturing.

It becomes obvious why such issues need to assume greater importance in policy discourse when one considers the democratisation of manufacturing which 3D printing enables. For example, Battersby and Grimes (2019, pp.97–98) point out the democratisation of manufacturing by AM means that almost anyone can manufacture almost anything away from regulatory control meaning intellectual property issues will be on the rise. This is because the risks of infringement increase significantly, and it becomes difficult to identify cases of infringement away from control. All of these make it impractical or almost impossible to enforce IP rights.

The ethical issues of additive manufacturing become quite significant when one considers how easy it is to access 3D printing materials, machines, and digital software (see section 2.4.3). Also, the impact of the 3D printing hacker communities and the hacking culture prevalent with additive manufacturing plays an important role in exacerbating the problematic nature of the technology (see section 2.4.5). Thus, this research does not set out to duplicate the work already done but to understand the ethical concerns of 3D printing from the perspective of those associated with 3D printing DIY hacker collectives, to investigate the impact of the hacking culture on the ethics of 3D printing and to develop an empirical understanding of the implications of expert participation in knowledge-making.

1.4 Research Questions

The questions that this research sets out to answer are as follows:

I. What are the ethical issues of additive manufacturing?
II. What effect does the hacking culture have on the ethics of additive manufacturing?
III. What are the implications of expert participation in knowledge-making?

1.5 Aim and Objectives of the Research

The research aims to examine the problematic societal impacts of additive manufacturing from the perspective of experts who use the technology and are associated with DIY hacker collectives.

The objectives are:

a. To explain the ethical issues of additive manufacturing.
b. To evaluate the effect of the hacking culture on ethics in additive manufacturing.
c. To understand how expert participants in research affects knowledge-making.

1.6 Structure of the Thesis

This research is conducted in 5 stages as shown in the table below:

Table 1-1 Structure of the thesis

Stage		Description	Chapter(s)
1	Literature review	This stage of relevant literature is consulted to help put this research into perspective. The review is presented in 2 chapters 2 and 3. While chapter focuses on additive manufacturing, chapter 3 addresses the philosophical and methodological underpinnings of the research.	2 & 3
2	Methodology considerations	The stage where concrete decisions about the research methodology are taken and decisions on the research design are implemented	4
3	Pilot Study	This is the testing phase of the research design. During this phase, 5 volunteers from the AM industry are interviewed about ethical issues of 3D printing to enable the assessment of the research design.	5

4	Empirical study	This stage is where participants (chosen from the AM community) are invited to contribute to the study through interviews. Several semi-structured interview questions are used to engage the participants in a discussion to identify their concerns of AM. Data presented in this research were collected from 16 participants	7
5	Taxonomy Development	Here a taxonomy of 3D printing users is developed along with a framework for the analysis of ethical issues	6
6	Discussion	Discussion of findings, a summary of the research is also provided	8 & 9

1.7 Conclusion

In this chapter, a case has been made for the need to investigate the ethical issues of additive manufacturing. It has highlighted the growing use of 3D printers and that this trend will likely continue until the technology reaches a state of maturity. The technology which was originally designed for use in regulated institutions such as corporations and universities has made its way into unregulated environments like homes and garages where it is being applied to all types of uses. Yet the ethical issues promoted by the technology are not well known. This study, therefore, aims to conduct an extensive investigation into these issues and to bring them to light while suggesting a suitable solution.

Chapter 2 : Literature Review

2.1 Introduction

This chapter is an attempt to put this study into perspective by reviewing extant literature on relevant subjects. It features a discussion of additive manufacturing and its relationship to the information systems field, explores the ethical issues of the technology as discussed in the literature, and provides an overview of the issues arising from the use of experts in IS research.

2.2 Additive Manufacturing Technologies

In recent years, additive manufacturing has received considerable interest among researchers, authors, policymakers, and industry analysts. Trend reports for the periods of January 2004 – May 2019 generated from Google Trends (2019) shown in Figure 2-1 show how interests for 3D printing and additive manufacturing has grown over the years. Note that the terms 3D printing and additive manufacturing are used interchangeably in this research to refer to "the process of joining materials to make objects from 3D model data, layer upon layer" (Li, Kucukkoc and Zhang, 2017, p.157). Although improvements to the data collection systems may have resulted in a slight drop in the uptrend from 2016 onward, it can be seen that interest in the technology has continued to grow. Some of the topics of interest have been on the history and technological process of additive manufacturing, as well as the growing array of materials and processes used in 3D printing. This section will provide a summary of some of these important themes.

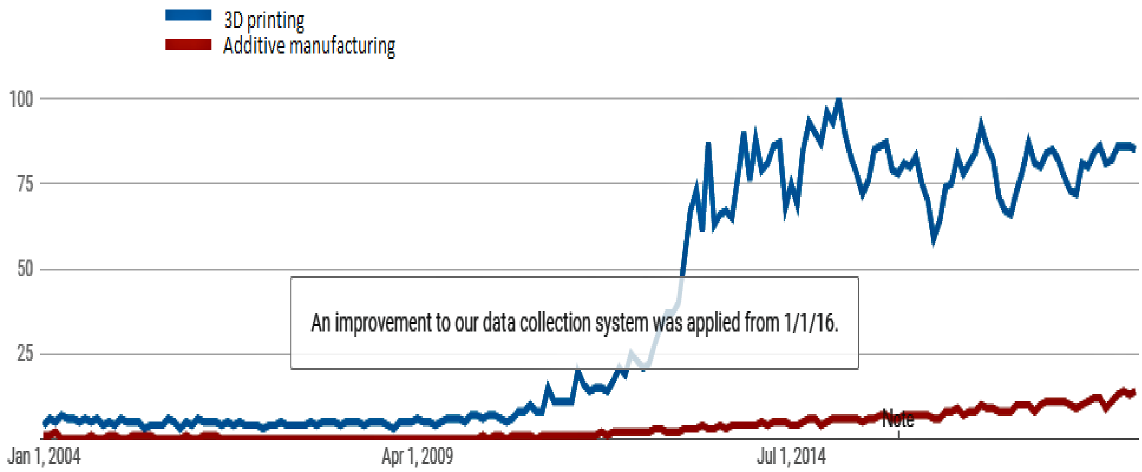

Figure 2-1 Trend reports for 3D printing and additive manufacturing (Google Trends 2019)

2.2.1 A Brief History of Additive Manufacturing

On August 9, 1977, Wyn Kelly Swainson of Berkely, California, was granted a patent for a technology he described as 'Method, Medium, and Apparatus for Producing a Three-Dimensional Figure Product' after making a filling on July 23, 1971, in the U.S (Swainson, 1977, p.1). This was a continuation of an abandoned patent filled by Swainson on July 11, 1968, titled 'Method of Producing a Three-Dimensional Figure' in Denmark. He suggests that the technology is to be used to create 3D objects with the aid of laser beams focused on materials in a vat that respond to the presence of radiation which traces surface elements of a figure transmitted by computer (Figure 2-2) and he maintains that architecture and sculpture are fields where this would be useful. It has been suggested that this patent was the precursor of the technology now referred to as 3D printing (Bradshaw, Bowyer and Haufe, 2010, p.5; Bowyer, 2014, p.4; Ma, 2017, p.2). Despite this innovative idea and the bold strides taken to propose such a technique, the technology did not take off until the 1980s.

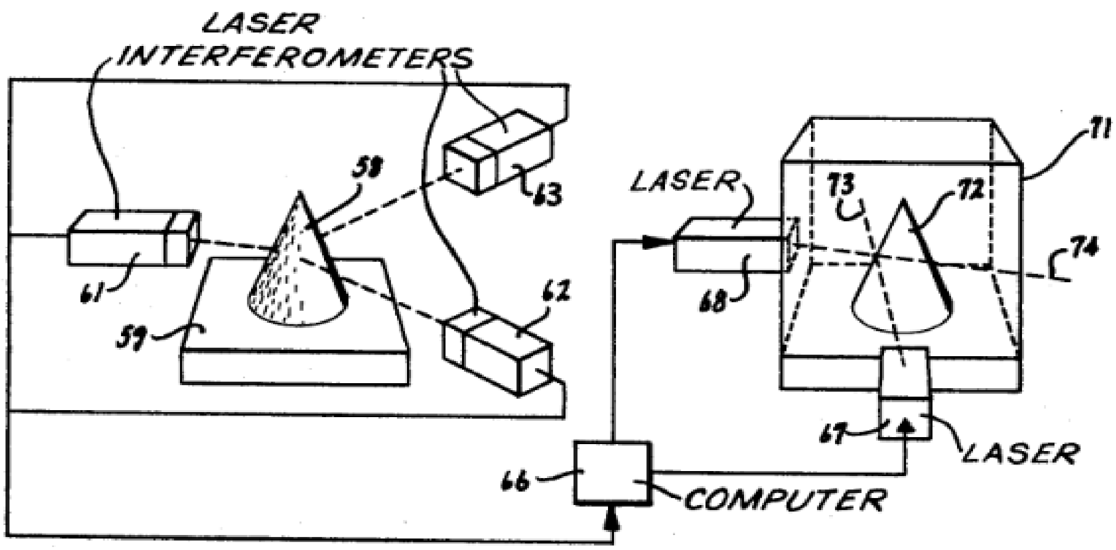

Figure 2-2 Development of 3D Print Technology (Swainson, 1977)

The first functional 3D printers were developed by Charles W. Hull who received a patent for the process he named Stereolithography or SLA on March 11, 1986, after making a filling on August 8, 1984 (Hull, 1986). He describes Stereolithography as a process and an apparatus for creating solid objects by successively printing thin layers of UV curable material. The stepwise laminar build-up of a 3D object results from the use of radiation, particle bombardment, and chemical reactions in a fluid medium (See Figure 2-4). In his patent application, Hull acknowledged the work done by Swainson and others but criticised their poor resolution and lack of reliability while maintaining that his method was a new and improved system that can be used to make all types of objects rapidly, reliably, economically, and accurately. Hull would go on to create the company called 3D Systems in 1987 to provide 3D printing services, printers, and peripherals including the universally used '.STL' file format, and technologies like SLS, MJP, CJP, DMS and PJP (see Figure 2-3) for a description of technologies) (3D Systems Corporation, 2014, p.4).

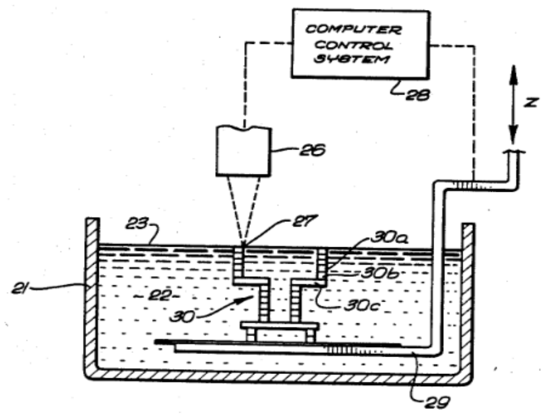

Figure 2-4 Stereolithography (Hull, 1986)

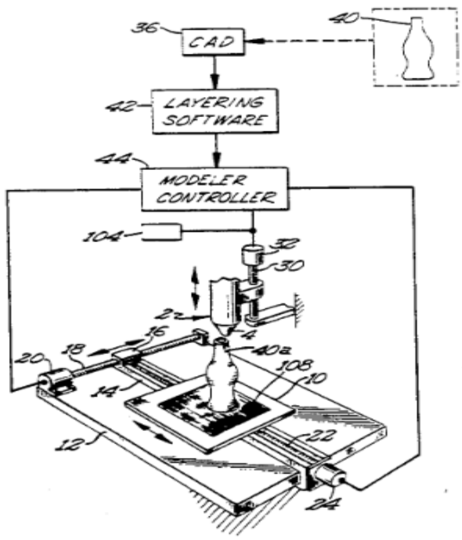

Figure 2-3 FDM technology (Crump, 1992)

Another important moment in the history of additive manufacturing occurred when Scott Crump invented Fused Deposition Modelling and was granted a patent on June 9, 1992, after filing on October 30, 1989 (Crump, 1992). He describes technology with a movable head driven by computer-aided software in a predetermined pattern to build a 3D object by repeatedly dispensing thin layers of material which solidifies almost instantaneously. Crump would go on to create a company called Stratasys with his wife Lisa (Stratasys Ltd, 2017). Matias (2015, p.551) maintains that this company along with 3D System are the most prominent companies in the additive manufacturing industry.

Until their patents expired, both Hull and Crump along with their respective company's 3D Systems and Stratasys effectively monopolised the AM industry and new entrants with different technologies were unable to compete. According to Kowen and Wohlers (2018, p.60) the average selling price of their 3D printers which are primarily designed for large industries, is $104,222, with pricey Fused Deposition Modelling (FDM) types going for over $400,000 while large stereolithography (SLA) 3D printers sell for over $990,000. They protected their patents jealously and used the court system to fend off new entrants who had attempted to develop 3D printing technology with anything remotely resembling their patents. For example, in November 2012 3D Systems filed a suit alleging that a company called Formlabs infringed on 2 claims of its patent and although they reached an out of court settlement and withdrew this case on 8 November 2013, the next day 3D Systems took Formlabs to court again, this time alleging infringement on 8 claims on its patents (Hornick and Roland, 2013). This sort of case has led many to argue that intellectual property (IP) stifles innovation, keeps prices of technology high, and is a barrier for new industry entrants.

Radical changes only began to happen in the AM industry after Adrian Bowyer initiated an open-source project he called the RepRap Project to make ‘self-replicating’ desktop 3D printers (Bechtold, 2015, p.6). RepRap which is short for ‘Replicating Rapid-Prototyper’ (See Figure 2-5) has been described as a robot that uses a process called Fused Filament Fabrication or ‘FFF’ to create 3D objects from thermoplastic polymers (Jones et al., 2011, p.178). Like Fused Deposition Modelling on which it was styled, the process of Fused Filament Fabrication uses computer modelling software to control the movement of a nozzle that extrudes thin layers of thermoplastic material, depositing it on a bed layer by layer until an object is formed (Nötzel, Eickhoff and Hanemann, 2018).

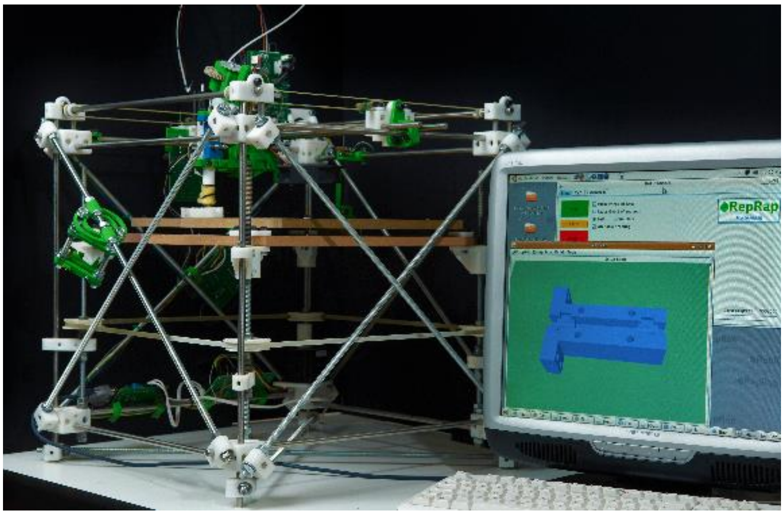

Figure 2-5 RepRap Version 1 Darwin (Jones et al. 2011)

The RepRap project has, since inception, continued to push boundaries, raise standards, and quite importantly, lower prices of 3D printers (Everard, 2019). Today, 3D Printers can be bought for as low as $100 (All3DP, 2019) all thanks to the RepRap Project which in 2017 was described as the most significant object that could be 3D printed (Peels, 2017b). Interestingly, all of these has only been possible because of the open-source nature of the RepRap project and the global ‘Maker Community’ it started.

It must be noted that although FDM and FFM are similar technologies in that they typically consist of an extrusion nozzle, a build platform, and printable filament which is melted at high temperatures and deposited in thin layers to ‘fuse’ together, there are differences in the way the printers work. According to Khanolkar (2018), the transition from the filament to the designed 3D object may be described as hot-hot-hot as the entire print process of FDM is isolated from the ambient environment with a print chamber maintained at 90ºC. This results in filament flowing from the hot extruder through a hot environment and onto a hot build platform. However, in FFF there is no heated print chamber and the filament traverses from a hot extruder through a cold ambient environment onto a build platform which may be hot or cold. Thus, by discarding the hot print chamber and naming their technology Fused Filament Fabrication, the RepRap system avoided infringing on the intellectual property of Stratasys who also trademarked Fused Deposition Modelling.

2.2.2 Standard AM Terminologies

The American Society for Testing and Materials (ASTM) has teamed up with the International Standards Organisation (ISO) to create standard terminology for additive manufacturing where they organised AM process into 7 categories (ISO / ASTM52900-15, 2015). Based on the 2015 standards (ISO, 2015), Table 2-1 provides a summary of the 7 process categories including a description of each process.

Table 2-1 3D printing process categories adapted from ISO /ASTM 52900: 2015

PROCESS CATEGORY	DESCRIPTION	TECHNOLOGIES	MATERIALS
Binder Jetting	Liquid bonding agent selectively deposited to bind powdered materials	PBIH, PP, CJP	Metals (Stainless steel, tungsten, titanium); Alloys (Inconel Alloy, carbide); Sand (Full-colour sandstone, silica sand); Polymers; Glass; Ceramic (Al202, Barium Titanate, Plaster of Paris)
Directed Energy Deposition	Focused thermal energy (laser, electron beam, or plasma) melts material	LMD, LENS, EBAM, DMD	Metals (Titanium); Alloys (Cobalt Chrome);
Material Extrusion	Nozzles are used to selectively dispensed material	FDM/ FFF	Polymers (Nylon, ABS, PLA, Polycarbonate PC, High Impact Polystyrene HIPS, Thermoplastic Poly-Urethane TPU etc)
Material Jetting	Selective deposition of droplets of build material	DoD, PJ, MultiJet, MJM; NPJ	Photopolymers, wax, metals
Powder Bed Fusion	Powder beds are selectively fused using thermal energy	SLM/DMLS, MJF, SLS, SHS, EBM	Metals (titanium, aluminium, steel, stainless steel); Polymers (cobalt chrome, nylon)
Sheet Lamination	Objects are created by bonding sheet materials	UC, CBAM, SLCOM	Metals, Paper
Vat Photo-polymerization	Light is used to selectively cure liquid photopolymer in a vat	CLIP, SLA	Plastic, Photo-polymers (UV curable photopolymer resin), Resin

Depending on the type of 3D print technology in question, there are several different types of feedstock used in the printer to create physical objects. FDM (Fused deposition Modelling) for example, ABS (Acrylonitrile Butadiene Styrene) and PLA (Polylactic Acid) are the common materials used for printing (Wu et al., 2015, p.5834; Cantrell et al., 2017, p.90); SLS (Selective Laser Sintering) uses polymers like nylon in their powdered form (Pomell, et al., 2015, pp.185 & 187), and SLA (Stereolithography) uses a liquid photo-curable resin (Taormina et al., 2018, p.214). The abbreviations used in Table 2-1 for the different technologies are explained inTable 2-2.

Table 2-2 Description of some 3D printing technologies

ABBRE-VIATION	TECHNOLOGY NAME	DESCRIPTION OF TECHNOLOGY
FDM / FFM	Fused Deposition Modelling / Fused Filament Fabrication	Heats up thermoplastic material (e.g. ABS or PLA) to melting point to create a physical object
SLS	Selective Laser Sintering	Creates 3-dimensional objects by melting powdered plastic polymer like nylon and then depositing it layer upon layer
SLA	Stereolithography	Uses laser beam to harden liquid photoreactive polymer resin layer by layer until a 3D object is created
PBIH	Powder Bed and Ink Head	Liquid binding material is selectively deposited on a bed of powder to create an object
PP	Plaster-Based 3D printing	Binding material is deposited on a print bed holding plaster powder layer by layer until an object is formed
CJP	Colour Jet Printing	A coloured binder is selectively jetted from print heads onto material that is spread over a build platform in a thin layer
LMD / DMD	Laser Metal Deposition/ Direct Metal Deposition	Metal powder via a nozzle is added to the weld pool which has been created with a laser to form object
LMD / DMD	Laser Metal Deposition/ Direct Metal Deposition	Metal powder via a nozzle is added to the weld pool which has been created with a laser to form object
LENS	Laser-Engineering Net Shaping	Lasers are used to build objects in layers from metal powders which are injected into a molten pool
EBAM/ EBM	Electron Beam Additive Manufacturing / Electron Beam Manufacturing	High powered electron beams are used to cure metal feedstock deposited in layers.
MJF	Multi Jet Fusion	Thermal energy is used to fuse droplets of powdered material
SLM / DMLS	Selective Laser Melting / Direct Metal Laser Sintering	Lasers are used to melt and fuse material. SLS uses powdered aluminium, and DMLS uses powdered alloys
DoD	Drop on Demand	The technique relies on two print heads – one for depositing build material, and the other for dissolving support material
NPJ	Non-Particle Jetting	Thin layer of liquid containing nanoparticles is jetted in thin layers of droplets. High temperatures inside the build envelope evaporate the liquid leaving a solid object
PJ	PolyJet	Ultra-thin layers of photopolymers are jetted onto the build bed and UV light is used for curing
SHS	Selective heat sintering	Thermal print head used to sinter thermoplastic powder

2.3 Additive Manufacturing and the Digital Technology Domain

This section is will focus on discussing the relationship between additive manufacturing and information technology, the place of 3-D Printing in the industrial revolution, and materialisation of social and ethical issues in additive manufacturing as an emerging technology.

2.3.1 The Role of Information Technology in the Development of Additive Manufacturing

Traditional manufacturing and production methods are in the throes of digital transformation (Deloitte, 2014, p.3; Polemitis, 2019; Vasudevan, 2019, p.2). Today, innovation in the manufacturing industry is being driven by information and communication technology (ICT) and other drivers like sustainability and customer demands. Traditional manufacturing processes indeed have in the past used automation and fragmented communication protocols for cutting, drilling, or moulding raw materials into final products (Pîrjan and Petroşanu, 2013, p.361; Djurdjanovic et al., 2018, pp.061010–2). However, the extensive adoption of information and communication technologies by manufacturing industries have seen them adopt "disruptive approaches to development, production, and the entire logistics chain (Deloitte, 2014, p.1). As a result of the adoption of digital technology, manufacturing processes now experience greater innovation, mass customisation, and greater energy efficiency.

The application of information technology (IT) to manufacturing is not a new concept (Centre for Social Justice Think Tank, 2019, p.16). Chryssolouris et al. (2009, p.451) suggest that the need for reduced development time and better customisation led to the introduction of the next generation of IT systems in manufacturing. Kurbel (2013, p.20) contends that the first IT systems for manufacturing were used in 'material requirements planning' (MRP) in the 1960s. MRP systems were designed to support the planning and scheduling of material requirements at all manufacturing levels including inventory management and procurement (Moustakis, 2000, p.2). However, limitations of the MRP systems including issues with data integrity and their inability to account for capacity constraints meant that their use was short-lived.

In the 1980s, the concept of computer-integrated-manufacturing (CIM) was introduced to coordinate the entire range of product development and manufacturing activities with the help of software packages to reduce the human element (Gunasekaran, 1997, p.265). Computer-Aided Design (CAD) systems are considered among the information technologies that have dramatically boosted productivity in the manufacturing industry (Chryssolouris et al., 2009, p.452). Following the introduction of AUTOCAD in the mid-1980s, the functionalities of such systems have improved so much that they became capable of three dimensions (3D) modelling, finite element analysis, as well as kinematic and dynamic analysis (Bilalis, 2000, p.2; Chryssolouris et al., 2009, p.452). Another important milestone in the use of information technology in manufacturing was the introduction of Computer Numerical Control (CNC) which enabled the direct link of 3D CAD models and their production (Majerik and Jambor, 2015, p.451). According to Chryssolouris et al. (2009, p.453), this was important because it gave birth to the concept of Computer-Aided Manufacturing (CAM) allowing for part design and product simulation.

Techniques used in additive manufacturing involves the use of computer models to create 3-Dimensional artefacts by depositing certain materials in very thin layers until the object is built. Explaining that 3D printers are very similar to traditional laser or inkjet printers, Berman (2012, p.155) and Siddique et al. (2019, p.3)suggests the main differences between the two printer types are in the printing ink and software. Rather than the multi-coloured inks of the traditional printer, 3D printers use either powder, filament, or resin to slowly build an image on a layer-by-layer basis and all 3D printers use 3-D Computer-Aided Design (CAD) software. It is because of this similarity to desktop printing that additive manufacturing is also called 3-D printing (DOE, 2012). Likewise, due to its reliance on computer-generated files, additive manufacturing is also referred to as ‘digital fabrication’ (Atkearney, 2015, p.1; Rayna and Striukova, 2016, p.1), ‘desktop digital fabrication’ (Ratto and Ree, 2012, p.1; Corum and Garofalo, 2015, p.55), or ‘digital manufacturing’ (Chryssolouris et al., 2009, p.451; DOE, 2012). The commonality between these terms or concepts shows a recognition of the influence of information communication technology on traditional manufacturing or production methods.

Is additive manufacturing an ‘information communication technology’ or is it just another manufacturing technology? According to Stahl et al. (2016, p.5), the increasing integration of computing artefacts into other technologies and the environment renders the idea of computers as easily identifiable objects obsolete. 3D printing allows manufacturers to deliver solutions that are at the crossroads of manufacturing and the digital technology of the internet (Barnatt, 2014, p.24) – without problematic manufacturing process like casting which often generates waste [about 5.5 billion tons of waste in the U.S alone each year (Sutherland and Gunter, 2001, p.2)]. The waste generated by product casting includes spent foundry sand (spent sand from moulding and used core sand), investment casting shells which are used only once and disposed-off in landfills, slag waste etc. (Risk Reduction Engineering Lab and Centre for Environment Research and Information, 1992). Additive manufacturing enables the ability to create and modify files with the aid of computing software and immediately produce an item without wasteful drilling or casting making it very attractive with sector-wide ramifications (DOE, 2012). In the words of the

Social Science Research Network (Dubuisson, 2014, p.6), 'the beauty of this technology is that it's both a manufacturing and digital technology'.

2.3.2 The Place of Additive Manufacturing in the Industrial Revolution

Recognising the potential of additive manufacturing to significantly impact production and distribution of goods and services, skills, as well as income distribution, the OECD Council has classified additive manufacturing in the category called 'Next Production Revolution' or NPR (OECD, 2016, p.3). The NPR refers to a confluence of technologies that are enabling digital transformation. They include nano-based materials, new processes like data-driven production, artificial intelligence (AI), synthetic biology, and other digital technologies like the Internet of Things (IoT), advanced robotics, and of course 3D printing. One of the important reasons behind the transformational impact of digital technologies for production has been attributed to the combination of different ICT's and their convergence with other

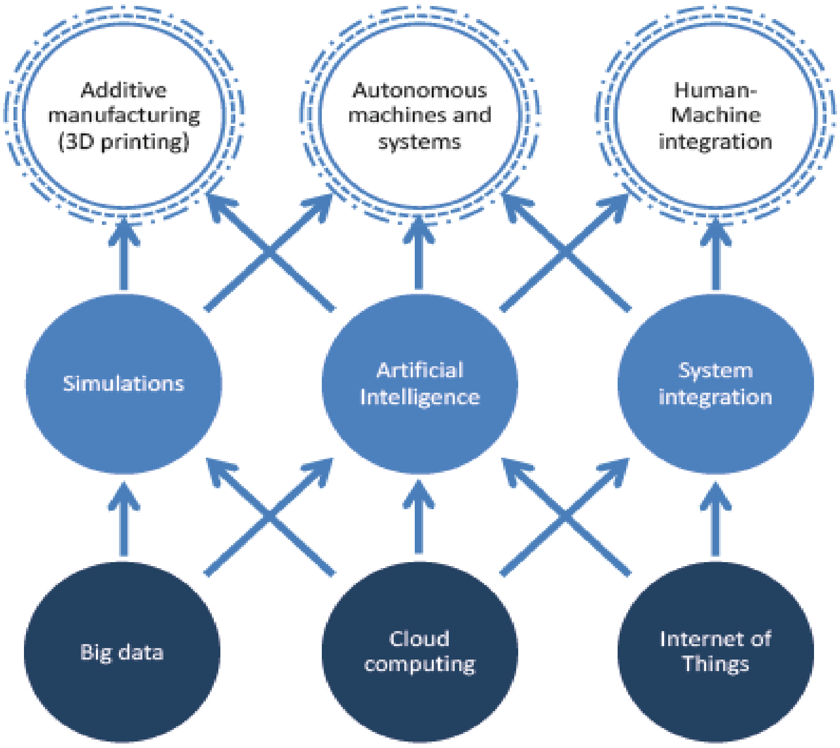

Figure 2-6 Confluence of technologies enabling industrial digital transformation (OECD 2016)

technologies (OECD, 2016, p.14). This convergence of ICTs and other technologies is illustrated in Figure 2-6.

Another term used to describe the integration of the above technology in the industry is the Fourth Industrial Revolution (or industry 4.0) (McKinsey Digital, 2015, p.7; OECD, 2016, p.15). The term was first used by the German federal government in 2011 to describe its high-tech strategy for the future (KPMG, 2016, p.2). According to Deloitte (2014, p.1), the fourth industrial revolution should not be confused with the greater level of production occasioned by developments in electronics and information technology of the 1970s and onwards. Rather, industry 4.0 is driven by the widespread adoption of information and communication technology by manufacturing industries which has resulted in disruptive approaches to production, development, and entire logistics chain.

Similarly, the 'International Electrotechnical Commission' describes the fourth industrial revolution as the convergence of the mechanical age of the third industrial revolution and the digital age (IEC 2015, p.3). It is a new phase of manufacturing which is driven by complete automation and increased use of digital technology. Brambley (2015) describes each of the industrial revolutions tracing the first to over 200 years ago (as illustrated in Figure 2-7) to a time when water and steam were used to mechanise manufacturing.

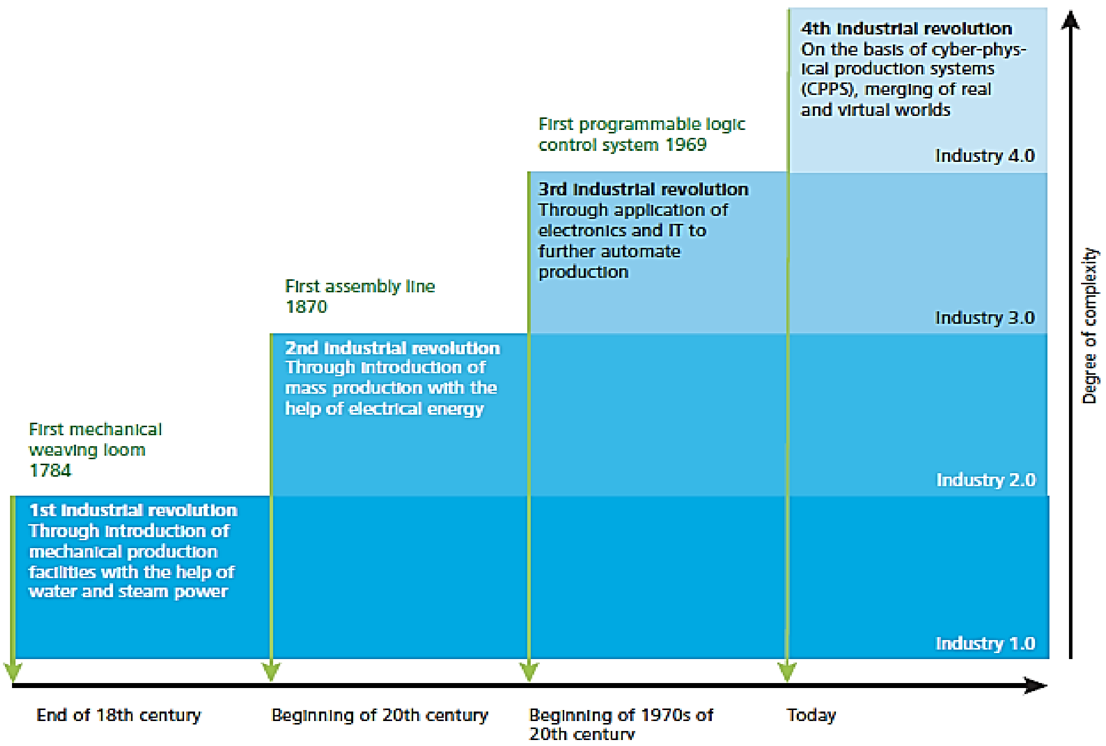

Figure 2-7 Industrial revolutions past and present (Deloite 2014)

The discovery of electricity spurred the second industrial revolution and led to mass production of goods in the early part of the 20th century. Electronics and computing led to a new phase of production of goods and services beginning in 1969 in the third industrial revolution. Brambley (2015) further suggests that industry 4.0 or the fourth industrial revolution refers to a connected network of people and technology in such a way that manufacturing is done better, faster, and cheaper, along with the creation of new innovations. While discussing the significance of 3D printing in the new industrial revolution, Gershenfeld (2012, p.43) notes that at the moment, other computer-controlled tools may be able to produce objects fasters, or with finer features, which may be larger, lighter, or stronger; however, the revolution is not additive versus subtractive manufacturing, "it is the ability to turn data into things and things into data".

In light of the above, it is interesting to note that not all industry analysts subscribe to a fourth industrial revolution in which additive manufacturing holds centre stage. Although they seem to all concede there's a revolution in the manufacturing industry, many suggest it is a part of the third industrial revolution. For example, Markillie (2012) agrees with the concept of a 'factory of the future' and suggests that digitisation in manufacturing will have a disruptive effect similar to those of other industries like photography and music that have gone digital; however, he argues that the consequences of these changes amount to a portion of the third industrial revolution – the first was driven by the mechanisation of the textile industry in Britain, and the second industrial revolution began in the U.S assembly lines in the early 20th century.

Similarly, Rifkin (2012, pp.4055–56) maintains that the third industrial revolution enables the production of personalised virtual information, durable goods, and energy and describes a 'new digital manufacturing revolution' in which everyone will potentially be their own manufacturer through 3D printing; he lauds additive manufacturing as a game-changer suggesting that it will have a similar effect as the internet which radically reduced cost of generating and disseminating information. The lower entry and production cost occasioned by the 3D print industry will challenge and potentially outcompete the big industries that were the centre of the first and second industrial revolutions.

Yet, other industry critics recognise the potential of additive manufacturing and its revolutionary tendencies but can't seem to decide if it's a third or fourth industrial revolution. Therefore, they use ambiguous expressions like 'the next industrial revolution' or 'the new industrial revolution' to describe the disruptive power of additive manufacturing. Guessasma (2015, p.1) argues that additive manufacturing is the most promising technology for design, a vector for creativity, and is the 'new industrial revolution'. 3D printing represents a 'new industrial revolution' notes Pierrakakis et al. (2014, pp.1 & 2) amidst claims that the technology will have profound implications in geopolitics, economics, and social, demographic, and security spheres. And Kennedy and Giampietro-Meyer (2015, p.958) suggest that over the next two decades, 3D Printing will overtake current technologies in some industries like construction as part of the 'next industrial revolution'.

Whether additive manufacturing forms part of a fourth industrial revolution or a third industrial revolution or is simply a new industrial revolution is arguable. What is not debatable, however, is the fact that due to developments in the digitisation of production, additive manufacturing possesses a transformative power in many industries. It has been successfully applied in industries like defence, aerospace, automotive, medical care, architecture etc. (Computer Sciences Corporation, 2012, p.26). Indeed, it's only recently that additive manufacturing technologies have been able to produce components of the same strength and quality as traditionally manufactured components (Kianian et al., 2016, p.7). Nonetheless, the potential for the additive manufacturing technology to replace many conventional manufacturing processes, enable greater engineering functionality (Huang et al., 2016, p.1559), support new products development, and allow new business models, as well as new supply chains (Royal Academy of Engineering, 2013a, p.1) to flourish, is undeniable.

2.3.3 Emerging Technologies, 3D-Printing, and Emergence of Social Issues

Computing technologies are being increasingly integrated into most features of human life be it private, social, or professional (Stahl, Timmermans and Mittelstadt, 2016, p.1). Depending on how well integrated these technologies are, they are either described as well-established or emerging technologies (Halaweh, 2013, p.108). Although well-established technologies are easily identifiable Rotolo, Hicks and Martin (2015, p.1827) argue that there is a lack of consensus on what classifies a technology as 'emergent'. According to Stahl et al. (2010, p.36), the term emergence can simply be understood as a "counterpoint to linear predictable developments" suggesting that emergent phenomena are not easily predictable. Based on established foresight methodology, Ikonen et al. (2009) define emerging ICT's, a phrase used interchangeably with emerging technologies in the ETICA (Ethical Issues of Emerging ICT Applications) project as "those technologies that are currently being developed and that hold the realistic potential to become a reality within the next 10 to 15 years."

Along with a lack of consensus in defining emerging technologies, there are also issues with the identification of what technologies are classified under this banner. Researchers in this field like Ikonen et al. (2009), Stahl et al. (2010), Halaweh (2013), and Rotolo, Hicks and Martin (Rotolo, Hicks and Martin, 2015), have all come up with concepts and methods to identify emerging technologies. For example, Rotolo, Hicks and Martin (2015, p.1831) suggest that the following five key attributes can be used to identify emerging technologies, namely: radical novelty, relatively fast growth, coherence, prominent impact, as well as uncertainty and ambiguity and define emerging technologies thus:

> *radically novel and relatively fast-growing technology characterised by a certain degree of coherence persisting over time and with the potential to exert a considerable impact on the socio-economic domain(s) which is observed in terms of composition of actors, institutions and patterns of interactions among those, along with the associated knowledge production processes.*

On the other hand, Halaweh (2013, p.112) suggests six characteristics that can be used to identify emerging technologies as follows: high uncertainty in terms of cost, social implications, and business models; network effect as its value increase with an increased number of users; relatively high costs due to firms trying to recover their investment in research and development; unseen social and ethical implications which only become evident after a period of use; they are usually limited to few countries and only become widespread after many years; also, due to their relative newness they are not yet fully researched at that stage. It can be seen that these 6 characteristics agree with the 5 proposed by Rotolo, Hicks and Martin (2015, p.1827) only in terms of uncertainty.

Unlike those mentioned earlier, Ikonen et al. (2010, pp.6 & 7) went beyond defining and describing characteristics and methods of identifying emerging technologies to suggesting 107 technologies including 3-D Printing, and 70 applications in this category. This list was further broken down to include a list of main high-level technologies which will potentially have serious effects on the way humans interact with the world. At that time, only 11 technologies were included in the list of main technologies including affective computing; ambient intelligence; artificial intelligence; bioelectronics; cloud computing; future internet; human/machine symbiosis; neuro-electronics; quantum computing; robotics; virtual/ augmented reality (Ikonen et al., 2010, p.44). Although 3-D Printing wasn't listed in this emerging technology report, events since then necessitate that additive manufacturing is considered an important emerging technology.

For example, section 2.3.2 noted that 3D Printing is regarded in many circles as one of the great enablers of the fourth industrial revolution (Almada-Lobo, 2016, p.16). It has found application in many fields, including medicine for example, where Huang et al. (2016, p.5380) suggests that recent technological advances have resulted in increased use of the technology to facilitate education, surgical planning, and organ transplant research among many other applications. Also, Stratasys (2015, pp.3 & 5) argue that 3D Printing has proven its relevance judging by its performance on the manufacturing floor where 67% of a 100 industrial manufacturers surveyed including the likes of Ford, GE, and NASA are using the technology. Surely, an industry which according to the Wohlers Associates (2014) that generated over $3billion from its products and services in one year (2014) and which about 40% of global trade is expected to be immersed by 2030 (see Figure 2-8) should not be taken lightly.

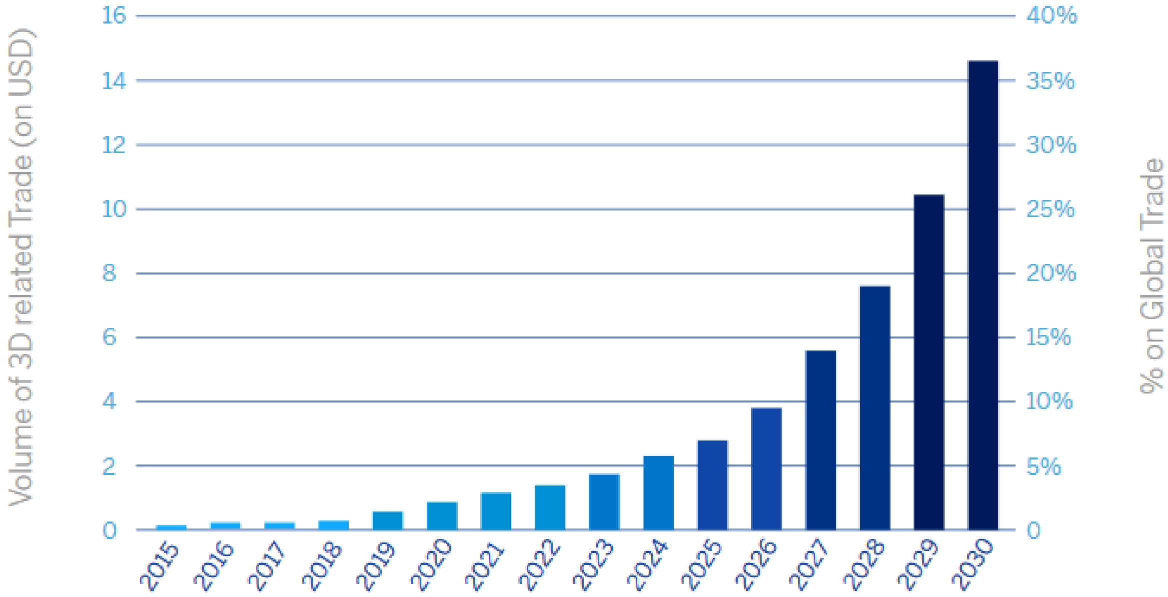

Figure 2-8 Impact of additive manufacturing on global trade (Kylau, Goerlich and Mitchell, 2015)

Although there is no agreement in the definition and identification of emerging technologies, the potential for them to raise ethical and social issues has long been recognised (Stahl, Timmermans and Mittelstadt, 2016, p.3). For example, despite their different approaches to emerging technologies Rotolo, Hicks and Martin (2015, p.1831) discuss the potential for emerging technologies to exert a considerable impact on the socio-economic domain(s) as a key attribute, and Halaweh (2013, p.111) also includes unseen social and ethical implications as an important characteristic of emerging technologies. Wakunuma and Stahl (2014, p.383) argue that the interaction between technology and human actors raises ethical concerns which need to be recognized and addressed. Stahl et al. (2016, p.3) however, suggests that identifying the social and ethical issues of emerging technologies is a complex endeavour and developing an appropriate balance between contradictory interests and values is similarly difficult.

Additive manufacturing is an emerging technology with the potential to transform the entire manufacturing industry, the supply chain that depends on it, and business models. Like other emerging technologies, the interaction between humans and 3-D Printing technology is bound to raise social and ethical concerns. As an emerging technology, identifying and analysing these issues is a complex endeavour and as Stahl et al. (2016, p.3) suggest, it is important that the issues are addressed even though it may require recourse to ethical theories and concepts to fully appreciate the depth of such problems.

2.4 Unique Characteristics of Additive Manufacturing

This section highlights several factors which highlights the unique, game-changing characteristics of 3D printing and which has enabled the transformation of manufacturing in such a way as to lead to far-reaching societal consequences.

2.4.1 Agile Manufacturing

Since the early 1990s, world-leading manufacturers have recognised the need to transition from mass production to an 'agile' form of production (Nagel, 1992, p.1). While mass manufacturing enabled relatively less expensive production of goods, the long delivery times and its inability to respond quickly to changing customer needs were seen as problematic (Radder and Louw, 1999, p.37). The concept of an agile manufacturing system was therefore borne from the need to develop a rapid and cost-effective means of developing products, production facilities, and software.

Agile manufacturing, therefore, demands a manufacturing system that enables effective production of a large variety of products (Gunasekaran and Yusuf, 2002, p.1359) at a low cost, and is responsive to changing product design requirements. Achieving all of these in manufacturing processes has been challenging because of the difficulty in balancing constantly changing requirements with the need for low production costs.

However, 3D printing makes it possible to meet the demands of agile production due to the digital nature of the technology that allows for constant design improvements, on-demand printing and enables the rapid reaction to ever-changing customer requirements. This is particularly useful for the manufacture of replacement parts which, as Reeves and Mendis (2015, p.6) point out, represents huge costs for many companies in terms of tied-up capital, associated storage costs, and the risk of obsolescence. Additive manufacturing is not just practical but also economical for replacement parts to be made-to-order when, and as required.

2.4.2 Customisation of Items

The influence of individualism on consumer trends has long been recognised (McCracken, 1990, p.20; Slater, 1999, p.31) and manufacturers have often struggled to balance between the benefits of mass production and of meeting the diversified demands of consumers (Huppes, 1987, pp.82–85). However, the ability to move rapidly from design to production using additive manufacturing technology has enabled a new reality of customizable one-off parts production as well as mass-customisation. The Aerospace Technology Institute (2018, p.6) maintains that additive manufacturing 'makes it viable to produce one-off items or small batch sizes' which is a vital aspect of manufacturing where mass production fails.

Thus, there is a growing trend to move from mass production towards one-off customisation using 3D printers (Mawere, 2014, p.2148; Johnson, 2016; All3DP, 2020). This may be due to the huge costs involved in prototyping via traditional production channels (Johnson, 2016, pp.2 & 9), or difficulty in finding parts for legacy products (Aerospace Technology Institute, 2018, p.6) and equipment that are manufactured in distant lands.

3D printing also enhances the ability for manufacturers to 'mass customise' items as they seek to satisfy ever-changing customer demands. Tseng and Jiao (1996, p.153) suggest that mass customisation seeks to balance the need for mass production with the need to provide customer satisfaction with increasing variety and customisation. Achieving efficient mass customisation has been quite challenging and critics have pointed out the difficulty of balancing manufacturing cost with customisation as well as the need to be responsive to needs of customers (Chen, Wang and Tseng, 2009, p.153). However, Tofail et al. (2018, p.23) suggest that the 'versatile, flexible, and highly customisable' nature of additive manufacturing enables manufacturers to overcome such challenges. Similarly, Jiménez et al. (2019, p.19) as well as Shahrubudin, Lee, and Ramlan (2019, p.1287) maintain that mass customisation with the aid of additive manufacturing has become a trend in the industrial sector. Current application of additive manufacturing for mass customisation includes the medical industry where it is used to produce hearing aids and dental products (Jordan, 2019, p.4) and in architecture (Sousa et al., 2018) where it is used for mass production of customised joints.

2.4.3 Low Entry Cost

In section 2.1, it was shown how the cost of 3D printers has significantly dropped from around $100,000 for FDM-type 3D printers to as low as $100 for FFF-type 3D printers which are similar technologies. This low capital cost makes it relatively easy for persons interested in manufacturing to get involved in the industry using 3D printers. Other cost-related factors of 3D printing which effectively lowers the barrier for involvement in manufacturing include the marginal production costs associated with the use of the technology. For example, Weller, Kleer and Piller (2015, pp.43 & 44) point out that the direct manufacturing processes of additive manufacturing mean there is no need for tooling and moulds as well as little or no need for assembly activities. Unlike many other manufacturing processes where the level of complexity determines product costs, with 3D printing, complexity has little or no impact on the final cost of products.

Besides the low entry costs for additive manufacturing, Halassi, Semeijn and Kiratli (2019, p.200) suggest that other factors like increasing usability and an exponentially growing database of 3D printable models have paved way for manufacturing to transition from an all industry activity to one where consumers actively participate. Thus, 3D printing has had a significant impact on manufacturing culture as it has enabled many who until recently could on be considered consumers to also become manufacturers in their own right.

This has engendered an interesting societal transformation as many have now gone beyond being mere consumers to also being producers. This transitioning is what some now refer to as the 'prosumer' culture (Pérez-Pérez, Gómez and Sebastián, 2018, p.2). In the context of 3D printing, Vesanto (2012) describes the prosumer as 'someone who has evolved from being a mere consumer to a point where they design and make products for themselves. With this ever-growing cultural change, it can be said that additive manufacturing has encouraged an exponential increase in prosumerism. However, it must be noted that the term prosumer was first used in the 1980s by Alvin Toffler to refer to 'people who produce some of the goods and services entering their own consumption' (Toffler, 1980, p.39) and that such concepts have existed for years (e.g. Do-It-Yourself and Grow-It-Yourself cultures).

Nevertheless, with 3D printing, the traditional roles of the consumer, designer, and producer are merging in ways that are unparalleled and unprecedented. Ordinary people are now able to use 3D printers at home and local community centres and tools and services that were once considered privileged for the highly educated or for the industry are now readily available. Thus, the concept of consumer manufacturing raises interesting challenges for regulators as the changing landscape of manufacturing from centralised-industrial manufacturing where it is easy to monitor and enforce standards to one where people can manufacture in their homes for both private and commercial use.

2.4.4 Distinct marriage of digital design with printing and individual needs

Although computers have been used in industrial manufacturing since the 1960s (Gisario et al., 2019, p.125), the introduction of additive manufacturing has remarkably transformed the relationship between manufacturing and computing technology. 3D printing creates a distinct marriage between digital design, printing, and individual needs like no other technology because it allows for the direct materialisation of digital information and the ability to meet the individual needs of the consumer. As noted in section 2.3.1 additive manufacturing enables digital models created or modified with computing software to be immediately produced as physical items without the need for drilling, moulding, or casting opening up the possibility for a very streamlined and agile process in manufacturing. And as shown in section 2.4.2 enables unprecedented levels of individualisation in the production process allowing for the needs of consumers to be taken into consideration.

Among other things, this has important ramifications for the confidentiality of data about individual parts as it requires ever greater collaboration between the consumer and manufacturer in co-creation processes. Künne (2017, p.71) notes that one of the key concerns of many firms involved in co-creation activities relates to the confidentiality of their propriety information. This is because of the difficulty of maintaining secrecy or minimising knowledge leakage to competitors through the consumers involved in the co-creation processes. Similarly, Alhonen et al. (2018, pp.15–17) point out that although user innovation and open innovation are becoming popular, there are situations where both buyers and sellers would like to prevent content from falling into the hands of competitors. An issue like this presents an interesting challenge for additive manufacturing where open-spaces like makerspaces and hackspaces are rife and provide extensive opportunities for co-creation between consumers and designers.

2.4.5 Appeal to Hacking Culture

In section 2.2.1 it was pointed out that the development of additive manufacturing owes an important part of its history to an open-source group known as the RepRap project. This group and many like them, are made up of hobbyists and activists and are generally looked upon as hackers (Seo-Zindy and Heeks, 2017, p.2). Richardson (2016, pp.653–4) notes that although groups like this refer to themselves as hackers, the title 'hacker' is commonly associated with unauthorised software breaking of computing technology. Nevertheless, Levy (1984, p.8) points out that the term 'hack' was first used in the 1950s at Massachusetts Institute of Technology (MIT) to refer to projects undertaken with wild pleasure and imbued with innovation, style, and technical curiosity even though not based on a desire to accomplish some constructive goal.

From this modest beginning, an interesting hacking culture has emerged over the decades. The revolved around 6 themes which Levy (1984, pp.23–31) enumerates as:

1. Access to computers – and anything that might teach you something about the way the world works – should be unlimited and total. Always yield to the Hands-On Imperative.: This is a reference to the general belief among hackers that by taking things apart and learning how they work, the knowledge gained can be used to develop new and more interesting things. They also advocated for total and unlimited access to computers and peripherals and despised rules designed to restrict access. Although they are mostly honest, their general attitude is one of 'wilful blindness' when it came to breaking the law to achieve their aims.

2. All information should be free: they have a basic belief that information exchange should be free and they promote free sharing of information especially when it is in the form of computer programs.
3. Mistrust authority – promote decentralisation: to enable the free sharing of information, they also promote open sharing which seeks to remove the barriers and bureaucracies created by institutions like government, universities, and corporate organisations.
4. Hackers should be judged by their hacking, not bogus criteria such as degrees, age, race, or position: they cared less about what they call superficial characteristics. What they cared most about was the ability of the individual to advance the general state of the hacker.
5. You can create art and beauty on a computer: A certain aesthetic can be created by the way computer code is written. It is the general belief among hackers that there is beauty in innovative code and optimised software.
6. Computers can change your life for the better: refers to the feeling of fulfilment and accomplishment from doing something new – the feeling that the hackers got as they irrevocably extended what computers could do.

Building on Levy (1984, p.8) Turkle (1984, p.208) description of important hacking periods, Taylor (Taylor, 2016, pp.628–9), Raymond (2000, pp.2–7) key periods in the emergence of this culture is highlighted in Table 2-3. It shows the periods between the 1950s from the first wave of hackers emerged to the 1990s when the opensource source movement and the so-called hacktivism began to make significant inroads into society.

One point that is not so obvious in Table 2-3 is how hackers have begun to move from the virtual to the real world. Drawing on insights that led to the digitisation of communication and computation, many hackers have begun to hack the physical world rather than the virtual one (Gershenfeld, 2012, p.43). This became more apparent in the early 1990s with the simultaneous development of open-source software and increased interest in computer hacker associations (Wilczynski and Adrezin, 2016, p.2). Note, however, that the open-source software is an offshoot of Free-Software movement started by Richard Stallman in the late 1980s (Vainio and Vadén, 2007, p.1). Rather than remain hidden in the virtual world, such associations promote the use of physical places where individuals immersed in the hacker culture could meet and socialise while pursuing like-minded activities. Kostakis, Niaros, and Giotitsas (2015, p.556) describes them as open organisations where people could share knowledge, ideas, tools, and equipment in community-driven physical spaces

Table 2-3 Key periods in the emergence of this culture

Hacking Culture	Description	Period
True Hackers	They emerged in the early days of computing and experimented with large mainframe computers. They are considered the pioneers of the hacking culture	1950s
Phone-phreakers	They used their deep understanding of the telephone network to make illicit telephone calls without incurring a charge	1960s
Hardware Hackers	They played a key role in the development of the personal computer and helped to dramatically decentralise computing hardware	1970s
Software Hackers	These were focused on creating or modifying software programs to enable them to run on new hardware being created	1970s
Game Hackers	They created popular gaming software for the hardware the previous generation had created	1980s
Hacker/Cracker	These terms describe persons who use illicit means to break into computing systems though not always for malicious purposes.	Mid-1980s
Microserfs	People with hacking skills who get co-opted into the structure of large technology organisations e.g. Microsoft	Late-1980s
Opensource movement/ Peer-production	Influential groups within the hacking movement who promote freer access to information and programs.	1990s
Hacktivists	The merging of hacking activity with an overtly political stance. Politics provided the reason for the existence of a new breed of hackers. It is a branch of the 1980s free-software movement	Mid-1990s

Early examples of such associations include L0pht which created a clubhouse initially based in a loft above a carpentry shop in Boston (Timberg, 2015) and the ‘New Hack City’ which was a major hacking group based in Boston (Menn, 2019). The anarchic nature of some members of these organisations can be seen in the case of ‘u4ea’ a hacker associated New Hack City who was implicated in the hacking of several Boston ISPs and the Boston Herald newspaper and arrested (Fisch and White, 1999, p.321; Desai, 2010, p.276). Similarly, the case of Kevin Mitnick once described as Americas most wanted computer outlaw (Littman, 1996; Shimomura and Markoff, 1996; Mitnick, Vamosi and Hypponen, 2017) who was incarcerated for long periods after gaining unauthorised access to the computers of corporations like Digital Equipment Corporation and Pacific Bell.

More recent groups include hackerspaces, makerspaces, and fab labs (fabrication laboratories) have changed the focus of such groups such that what is being hacked is the physical world rather than the virtual in what might be described as digital fabrication. Through the influence of the Chaos Computer Club (CCC) a hacker collective formed in 1981 and based in Berlin, the first hackerspace called c-base was created in the German capital in the mid-1990s (Mattos, Silva and Kos, 2015, p.2). They started an open space for social gathering and project development which inspired the creation of the Metalab Hackerspace in Vienna in 2006 and other similar groups subsequently sprung up all over Europe.

FabLabs were the brainchild of Neil Gershenfeld a Professor at MIT's Centre for Bits and Atoms who in 2003 set up the first lab to introduce urban communities around Boston to new technologies (Gershenfeld, 2012, p.47). Although they taught everything from video production to internet access, digital fabrication using additive manufacturing technology formed a very important part of the training they provided. The labs were equipped with such equipment as 3D printers, computer-controlled lasers and milling machines, and tools for moulding and casting parts as well as for producing electronics.

Makerspaces which are also described as creative spaces where people gather to tinker, create, invent and learn (Hughes, 2017, p.1) were started after Dale Dougherty (founder of the trendy '*Make'* Magazine) set up the Maker Faire in the San Francisco Bay Area in 2006. What began as a simple formula for getting people who make things to talk together in a community space and enable diverse ideas to be nurtured (Dougherty, 2012) have grown into a maker movement that has made important inroads within both academic and non-academic settings (Fourie and Meyer, 2015, p.519; Wilczynski and Adrezin, 2016, pp.1, 2 & 9). The maker movement has promoted the popularity of maker spaces and today they can be found in schools, college and university libraries, and many public and private facilities all over the world.

Despite their similarities, however, there are nuances which slightly set fablabs, hackerspaces, and makerspaces apart. For example, fablabs tend to emphasize the tools and equipment made available to the public to enable novices alongside professionals make just about anything; hackerspaces tend to focus more on 'hacking' or getting things (e.g. electronic components, computer programs and hardware etc) to do something unexpected; makerspaces on the other hand, are driven by the idea of enabling craft and therefore create the space for multiple types of crafts to enable hobbyists and professionals to share ideas. Nevertheless, they are all designed to support innovation and creativity while promoting the do-it-yourself culture and as such many of their activities are centred around the 3D printer.

It can be seen why there is a strong affinity in the hacking community for 3D printing as additive manufacturing enables the democratisation of production. The limited financial and technical barriers, as well as the adoption of the technology by hacker collectives, mean that the technology is within easy reach of many enthusiastic amateurs and 'hackers'. This raises questions about standards and regulation of manufacturing as production becomes more and more decentralised. Just about anyone armed with a 3D printer and 3D models openly available on the internet can become a manufacture overnight in an environment where current industrial standards may not be applicable.

A similar trend is emerging for 3D bioprinting were so-called 3D-biohackers, often referred to as DIY biologist are using 3D printers for scientific experiments outside of the usual scientific, medical and commercial institutions. In an in-depth analysis of 3D bio-printing presented to the European Parliament, Boucher (2018b, p.3) describes 3D bio-printing as 'the use of 3D printing technology for applications related to the body, whether the products themselves include biological material or not, and whether the product is medical or not'. In many cases, the applications have therapeutic and medical uses but are increasingly being used for leisure and artistic purposes as well as for human enhancement.

Biohackers are often categorised into two broad groups – DIY Bio and grinders (Ikemoto, 2017, pp.543–4). DIY Bio or Do-It-Yourself Biology refers to the operation of bioscience with a do-it-yourself spirit outside of the arena of bench science. It refers to the activities of life science enthusiasts situated in labs outside of the professional spaces (e.g. academic, corporate, or government spaces) and carried out often using unconventional and unregulated procedures. An example of DIY Bioactivities can be seen in the 'bioluminescence project' started in 2011 in California by a biohacker collective called 'BioCurious' which developed bioluminescent plants that glow in the dark (Keulartz and van den Belt, 2016, pp.4 & 5).

Grinders, on the other hand, are body hackers or those who modify their bodies in hope achieving some form of human enhancement. Many transhumanists would identify with this group (Popper, 2012; Ikemoto, 2017, p.542). They are people who actively seek to add a new 'sense' by putting electronic devices into their bodies – merging man and the machine so to say. According to O'Connell (2017, p.135) who visited 'Grindhouse Wetware' based in Pittsburgh and is one of the most prominent grinder groups, their goal is to augment humanity with the aid of opensource technology with devices developed for subdermal implantation. These devices are designed to enhance sensory and information capabilities of humans.

Biohackers have embraced additive manufacturing and are using 3D printers to carry out experiments in improvised labs at home and community spaces and operate outside of the regulated structures and environments of institutional science and business. Daily and Largetteau (2016) contend that 3D printers have provided a bridge between the world of makers and biohackers and Coward (2015) describes the domain of grinders as the space where body modification and hacking meet. These descriptions are based on the increasing number of people who have mixed a willingness to modify their bodies and other living organisms with an interest in hacking technology akin to what is seen in hackspaces around the world.

Interestingly, biohacking communities often called bio-hackerspaces are also springing up all over the world in a similar way as hackerspaces. According to de Lorenzo and Schmidt (2017, p.518), the idea for such communities after Tom Knight a biologist and computer engineer at MIT cofounded the synthetic biology 'International Genetically Engineering Machines' (iGEM) competition in 2004 to encourage students to construct novel engineered lifeforms. Examples include BioCurious (mentioned in previous paragraphs), Open Wetlab and BioHack Academy which are both situated within Netherlands *waag* technology and society (Keulartz and van den Belt, 2016, pp.3 & 4) and BioThena based in Slovenia (DITOs consortium, 2017). Illustrating how popular biohacking is becoming, Cuthbertson (2018) suggests that in Sweden, over 4000 people have had some type of electronic device implanted in their bodies.

Despite this growing trend, the biohacking space is minimally regulated. As they work from home, garages, and other similar spaces, many of their procedures do not get screened by ethics review boards (Walker, 2017). Bárd (2020, p.107) points out that biohacking is often associated with a disregard for societal conventions and a desire to sidestep prevailing frames of reference and normative conceptions about the body its function. Similarly, Fuisz (2017, p.658) points out that many biohackers even go as far as circumventing loose institutional barriers by taking advantage of existing loopholes in the system aimed at restricting the sale of certain scientific supplies (e.g. plasmids) to individuals and biohackers. Thus, their activities may sit on the fringes of legality as they seek to circumvent the law.

For example, biohackers without a medical license who need to carry out operations to implant devices into the body use surgical tools to carry out operations without administering anaesthesia (Benedictus, 2012). That is because the use of anaesthetic would put this activity in the medical practice category for which they require a license. Famous grinders who have attempted this include Kevin Warwick a professor of Cybernetics at the University of Reading (Warwick, 2016); Zoltan Istvan politician and former Presidential Candidate in America (Solon, 2016); and Tim Cannon the Chief Information Officer of Grindhouse Wetware who had a device the size of a pack of cards inserted into his forearm by a so-called body-modification ‘flesh Engineer’ (O’Connell, 2017, p.137).

All of these indicate how the hacking culture has led to greater democratisation of these technologies as their cost is increasingly being lowered and just about anyone with an interest can have access to them. It also indicates that the use of these powerful technologies outside of the traditionally regulated environments for which they were originally designed has led to some anarchic use and blurring of the relationship between science, society, and ethics.

2.5 Taxonomy of 3D Printer Users

The materialisation of data and information which 3D printing enables has found interesting applications among a broad spectrum of users and use cases. This can be attributed to the unique game-changing characteristics which the technology possesses as identified in the discourse in section 2.4. To understand the different categories of users and the relationship between them, it is important to create a taxonomy which classifies these users in a meaningful way. Rogerson (2018, p.8) describes taxonomy as a scheme of classification of things or concepts and suggest that although modern taxonomy may be said to have begun by Carolus Linnaeus in the 18th century, the origins of taxonomy can be traced to a period around 3000BC in China.

Taxonomies have become very important tools for understanding complex domains through the classification of objects (Oberländer, Lösser, and Rau 2019). Nickerson, Muntermann, and Varshney (2010, p.3599) point out that one of the disciplines where taxonomies have been used extensively is in Biology where several classification schemes have been used to order the living world. Taxonomies have also been a useful tool in the information systems domain where they have been used to, among other things, classify mobile applications (Nickerson et al., 2007, p.2081); provide a chronological taxonomy of tourism (Rogerson, 2018, p.10); and taxonomy of digital systems (Berger, Denner and Roeglinger, 2018). Such taxonomies have helped to provide greater clarity and understanding of information systems.

A literature search shows that several taxonomies have already been developed for additive manufacturing. For example, Kapetaniou et al. (2018, pp.29 & 30) developed a taxonomy of sectoral patterns of 3D printing to classify the different industrial sectors where the technology is being used. This taxonomy which builds upon elements of previous sectoral classifications has a ‘new category’ (see Table 2-4) which is said to categorise the competitive dynamics between firms. It also includes a category of technological content for determining possible applications of 3D printing and a category that shows the nature of consumer involvement in the production process. Although this taxonomy offers a detailed classification of industrial sectors where 3D printing is used, it, however, is limited as it doesn't take non-industrial use into account.

Table 2-4 Kapetaniou et al. (2018) taxonomy of industrial sectors of 3D printing

New category	Industry sector	Consumer involvement	Technological content[a]
Personalisation-dominated	Wearing apparel	High	Low
	Jewellery, bijouterie and related articles	High	Low
	Footwear	High	Low
Singular science-dominated	Motor vehicles	Low	High
	Air and spacecraft and related machinery	Low	High
Customization-dominated	Medical and dental instruments and supplies	Medium	High
	Consumer electronics	Medium	High
	Pharmaceutical	Medium	High
Collaborative science dominated	3D printing materials and equipment	None	High
	Software	None	High
Intermediary dominated	Design	High	High
	Online platforms	High	High

Another 3D printing taxonomy was developed by Rayna, Striukova, and Darlington (2015, pp.98 & 99) to categorise online 3D printing platforms. It is a service-based taxonomy which was created to understand the level of user involvement in 3D printing production processes as well as the nature of co-creation processes. This taxonomy goes a step further than Kapetaniou et al. (2018) taxonomy as it highlights four interesting categories, namely:

- Design marketplaces (where the main activity is the hosting of third-party 3D printing models);
- Printing services (platforms that 3D print on demand based on designs supplied by consumers or co-designed with them);
- Printing marketplaces' (i.e. platforms that act as intermediaries between individuals requiring 3D prints of their digital design and owners of 3D printers offering printing services); and
- Crowdsourcing platforms (where users can crowdsource both design and production of objects).

To explain how users are involved in such activities, they also developed a diagram (see Figure 2-9) that provides some indication of the relationship between these services and the user. Also, considering the interconnection between many of these activities, the diagram attempts to separate the manufacturing services from the design services and yet show their connection to the uses. However, their definition of the user is quite limited as they suggest a user is someone using a 3D printing platform to acquire a digital or physical object. This is because users can also include those who design and print at other private establishments without requiring platforms and to have a holistic view of societal implications, would extend to those who utilise such outputs. Thus, it can be said that this rather detailed taxonomy of online use of 3D printing does not take offline use and users into consideration.

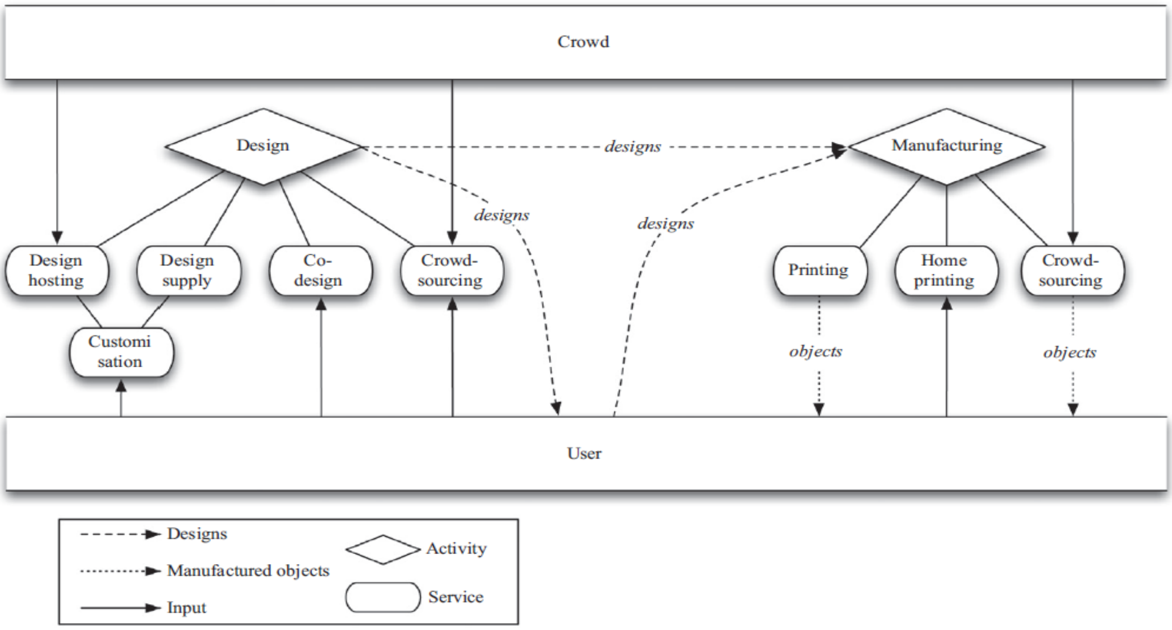

Figure 2-9 Classification of design and manufacturing activities of online 3D printing platforms (Rayna, Striukova, and Darlington 2015, pp.97)

Although they haven't used the word 'taxonomy' in their classification of 3D printing services, Rogers, Baricz, and Pawar (2016, pp.895–899) addresses some of the shortcomings of the taxonomy produced by Rayna, Striukova, and Darlington (2015, pp.98 & 99). They produced a classification of distinct service routes for both private and business consumers that addresses varying degrees of interest in and familiarity with additive manufacturing. This classification identifies three categories of services in the supply chain of a 3D printing service provider (see Figure 2-10). These are generative services (i.e. on-demand 3D printing services for generating 3D model e.g. scanning and or model design/construction with subsequent 3D prints); facilitative services (i.e. services focused on 3D printing and so target customers who already have 3D models for printing); and selective services (e.g. they enable customers who do not possess a model an opportunity to select suitable 3D printing models from their database).

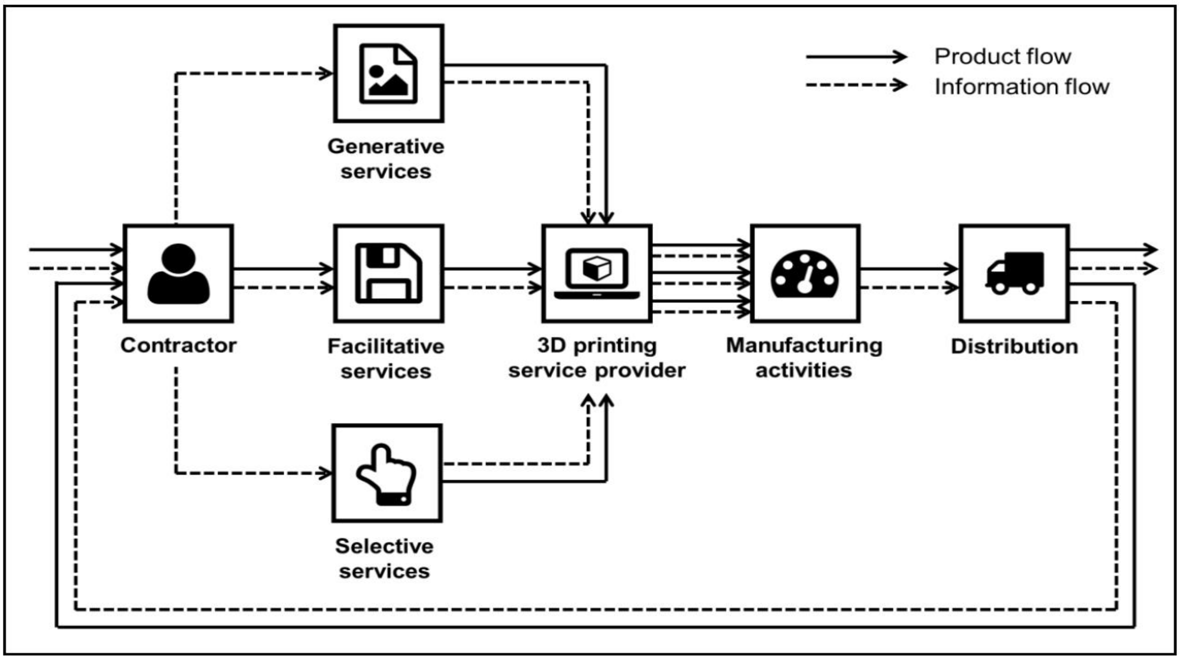

Figure 2-10 Classification of 3D printing services in a supply chain (Rogers, Baricz, and Pawar 2016)

From the various classifications schemes for 3D printing described thus far, it can be seen that certain classes of users of the technology have not been represented in the taxonomies. For example, prosumers or those who have evolved from being mere consumers to creating objects in the privacy of their homes or other such places have not been represented in any of these taxonomies. Similarly, they haven't presented a way of categorising hacking in additive manufacturing which has had an important impact on the trajectory of the technology. Therefore, a more holistic taxonomy which considers these shortcomings is required for classifying users of 3D printers.

2.6 Exploring the Ethical Issues of Additive Manufacturing

A literature review on the ethical issues of additive manufacturing was conducted during this study and the findings are highlighted in this section. Based on extant literature, the review was conducted to identify emerging issues that 3D printing promotes. This will help to identify gaps in understanding, as well as to make explicit some of the difficult policy choices in the 3D printing arena.

The review was done by manual web-based searches were performed using such search terms as "ethical issues" AND "3D printing" OR "additive manufacturing"; "3D printing" OR "additive manufacturing" AND "ethics"; "societal problems" OR "social issues" AND "3D printing" OR "additive manufacturing". The searches were done on relevant databases in

Scopus, PubMed, and Google scholar including a general search on Google. The decision to use these search engines took their relevance, popularity, and the size of these databases as well as the ability to access free full-text search results. Data considered in this research was obtained from the following types of literature:

I. Research publications and foresight studies and activities

II. Industry/trade journals

III. Policy-oriented publications (e.g. parliamentary or government publications)

IV. Research policy and programme descriptions (including research calls from the EU, US, Australia, Japan, others).

V. General press and media including blogs

NVivo was then used to analyse these documents to enable them to be sorted by relevant themes and sub-themes. Nvivo was selected for use in this research because of its versatility as it works well with wide-ranging qualitative research design and analysis methods like grounded theory, phenomenology, and mixed methods (Zamawe, 2015, p.13). Also, because it enables quicker and more efficient data retrieval than other Computer Assisted Qualitative Data Analysis (CAQDAS) like ATLAS.ti and MAXqda (Rodik and Primorac, 2015). Another factor influencing the choice of NVivo is its support for rich-text, character-based coding, and multimedia functionalities.

Relevant literature found during the searches were downloaded and saved to NVivo and then re-read to gain familiarity with the entire data corpus. Initial codes were generated by coding segments of data that were considered relevant to the research question. These initial codes were then organised into themes by collecting codes together in categories based on their relevance. For example, during initial coding one of the interesting segments of data that discussed 3D printed toys and their safety around children was initially coded as ‘safety of toys’. This, along with another piece of data that highlighted safety issues of 3D printed foods and coded as ‘safety of printed foods’ were then grouped under the theme ‘Safety’ (see Figure 2-11).

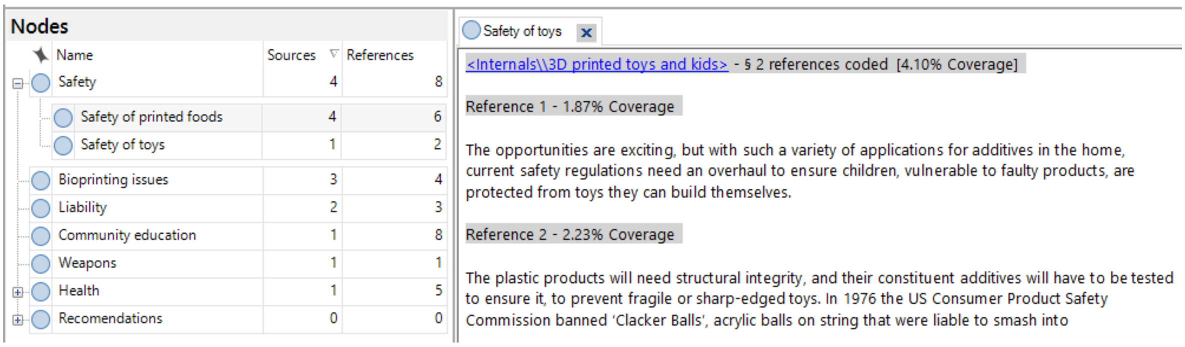

Figure 2-11 Developing themes and sub-themes through coding and analysis

However, on a further re-examination of the codes, it became apparent that some of the themes weren't descriptive enough and it was necessary to modify them to better describe the data. For example, the 'safety' theme was later modified to 'safety issues' while the subthemes 'safety of toys' and 'safety of printed foods' were changed to 'safety of children's toys' and 'safety of 3D printed foods' respectively (see Figure 2-12).

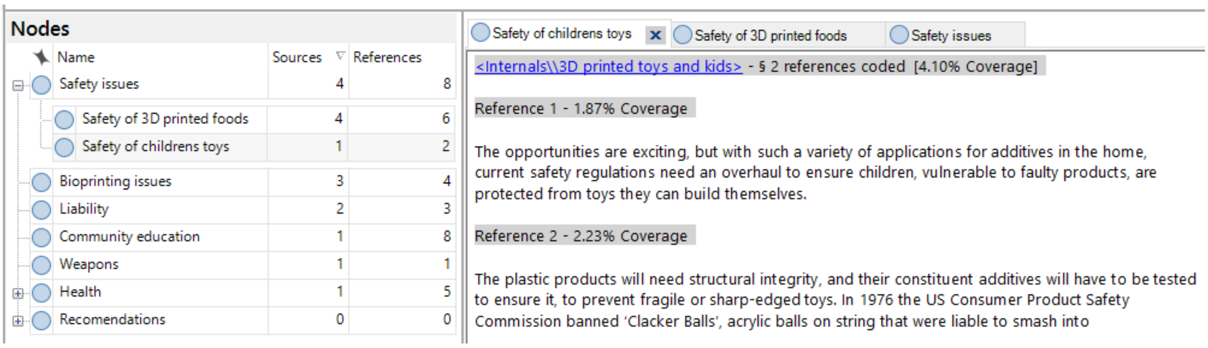

Figure 2-12 Modifying themes and sub-themes to describe data clearer

After extensively re-reading and reflecting on the contents of the data, the codes generated, and their organisation into themes, the issues identified were grouped into 10 themes (see Table 2-6 for a short description of these themes). The themes are environmental issues, health-related issues, safety issues, intellectual property rights, 3D printed weapons, employment issues, bioethical issues, information security, liability and biohacking. The next section describes these issues.

2.6.1 Environmental Issues

The environmental impact of 3D printing has been a topical issue. However, much of the literature, especially those from the industry have suggested that the environmental impact of AM is mostly positive. For example, Campbell et al. (2011, pp.2 & 6) suggest that AM could substantially reduce the carbon footprint of manufacturing, transport, and energy as it eliminates the need to move products around the world, reduces waste, and limits energy used in manufacturing; Krassenstein (2014) maintains that 3D printing will ensure a safer environment around the world as waste plastic can be recycled and turned into filaments for 3D printers, localised printing results in less transportation and reduction in fossil fuel use, and because it adds material layer upon layer, it results in far less waste; Griffiths (2014) also contends that 3D printing is sustainable by nature because it cuts down on material waste and product transportation; Phansey (2014) who agrees with these view maintains that both ABS and PLA are environmentally friendly thermoplastics that can be re-melted and reshaped into new objects. These views hold that 3D printing is less wasteful as it is unlike traditional manufacturing that creates objects by either removing material from a block until the desired shape is reached or injecting material into a mould; that it cuts on transportation and use of fossil fuels because it encourages localised production; and that the plastic filaments used in 3D printing are recyclable.

It has often been pointed out that PLA is starch-based and obtained from renewable sources like rice-wheat, and tapioca (Gadhave et al., 2018, p.24), as well as corn, potatoes, sugarcane, and whey (Reddy, Reddy and Gupta, 2013) and, is therefore 100% biodegradable (Tokiwa et al., 2009, p.3730; Gadhave et al., 2018, pp.23 & 24; Bender, 2018). Also, ABS an oil-based thermoplastic is generally considered in the industry as fully recyclable, or 100 per cent recyclable (MEEE, 2018; PRO-FORM, 2019) suggesting it can be reused over, and over again. Some have therefore begun seeing additive manufacturing as the infrastructure for a circular economy as it ‘promotes environmentally sustainable product lifecycle’ (Unruh, 2018). A circular economy has been described as one that is sustainable and eliminates as much waste as possible and uses renewable resources. It thus has been suggested as an alternative to the ‘take, make, dispose of’ approach of today as it ensures that materials are kept in a high-value state for as long as possible (Zero Waste Scotland, 2016). And Prendeville et al. (2016, p.586) suggest that the social nature of makerspaces, their use of AM technology, and willingness to repair and reuse means that they could enrich the circular economy.

Consequently, some attention has also been given to investigating such claims linking AM to environmental sustainability with interesting results. For example, on the issues of waste, it has been suggested that the argument of waste-free AM might not be completely correct. Keppner et al. (2018, p.24) as AM generates waste from misprints as several trials are often required; waste from support structures for processes using binder jetting, extrusion, and powders; and waste due to thermal degradation of filament during printing. Studies have also shown that although ABS is indeed recyclable, the processes cannot go on and on due to material degradation. For example, Mohammed et al. (2017, p.541) found degradation in mechanical properties that resulted in 13 – 49% decreased strength of printed material when they reformed 100% waste ABS plastic. And Pivnenko et al. (2015, p.1) explain that factors such as polymer cross-contamination, non-polymer impurities, and the presence of additives all contribute to making recycling a difficult process.

Attempts have also been made to compare the energy consumption of different AM technologies with other manufacturing techniques (e.g. injection moulding) and yet the results are not clear due to a complex combination of factors that must be considered in such life cycle assessments – including the type of equipment, processing of input material, and machine utilisation (Ford and Despeisse, 2016, p.1575). However, one such study conducted by Duflou et al. (2012, pp.64–66) comparing the specific energy demands of AM technology (SLS) with conventional manufacturing processes like milling, injection moulding (IM), and laser cutting shows that energy used by the SLS process is higher than all other conventional manufacturing processes apart from laser cutting (See Figure 2-13). Thus, Frăţilă and Rotaru (2017) maintain that AM's credential as ecologically friendly is questionable due to high energy used up by processes requiring melting, curing of resins, or lasers.

MJ	Theoretical	In-depth approach	
		Min.	Max.
Turning	0.26	0.44	30.26
Milling	0.26	0.47	39.84
Laser cutting	1.3	74.32	157
Bending	0.0014	0.056	0.216
SLS	0.4	52.2	237.67
Injection moulding	0.30	0.72	3.39

Figure 2-13 Consumed electrical energy of SLS VS conventional manufacturing processes (Duflou et al., 2012, p.66)

Similarly, another study carried out by Telenko and Seepersad (2012, pp.14 & 31) comparing the energy use of SLS with that of IM for different production volumes of paintball handles, found that SLS uses significantly more energy than IM for production volumes exceeding 300 (see Figure 2-14).

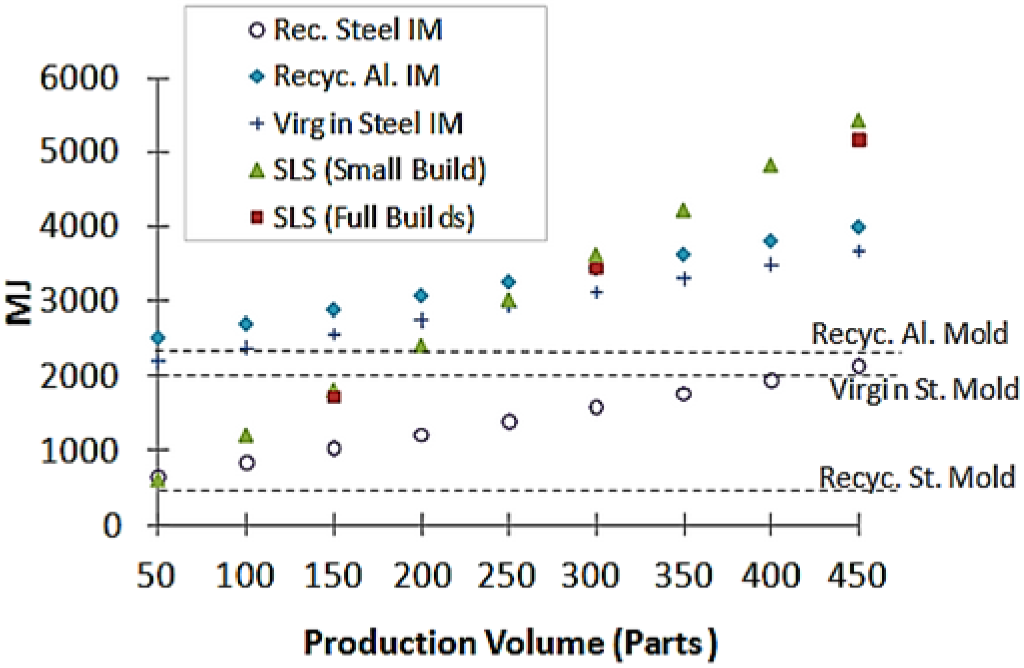

Figure 2-14 Comparison of energy use per production volumes for SLS and IM paintball handles (Telenko and Seepersad, 2012, pp. 31)

In summary, although AM has often been hailed as more environmentally friendly and sustainable than traditional manufacturing processes, there is a need for caution in making such claims as there are too many variables involved and a lot of underlying issues that make it difficult to arrive at a definite conclusion. The findings above on waste, recyclability and energy consumption indicate that AM may not be as sustainable as many in the industry have claimed.

2.6.2 Health and Safety Issues

Studies have shown that only very little is known about the impact of additive manufacturing on health (Oskui et al., 2016, p.1; Ryan and Hubbard, 2016, p.2) even though 3D printing has been around for over 3 decades and has become quite popular in recent years. Many have long held the view that the commonly used 3D printing materials like PLA are inert and sterile because they are derivatives of starch (Freeman, 2012). An opinion likely fuelled by studies like those of Conn et al. (1995, p.282) and Rankin et al. (2014, p.197) who maintain that the inert nature of PLA means that it has an excellent safety profile and Moyle et al. (2004, p.86) who explains that PLA is immunologically inert and so does not trigger inflammatory reactions.

A material is said to be inert when it is chemically inactive and does not react chemically with other materials. Cuiffo et al. (2017, p.580) suggest that this property of PLA is due to it being a starchy substance derived from corn and sugarcane but that under 3D printing conditions, it undergoes chemical and structural changes due to the presence of inorganic additives. Furthermore, the structural changes increase the potential for reactivity with the atmospheric contaminant, as well as cells and organisms. Nevertheless, interest in this topic has been growing and several noteworthy pieces of research have been conducted to determine how safe some of these materials are when used or 3D printing by studying the nature of emissions given off during the printing process.

Ultrafine particles and Volatile Organic Compounds

The first known study which was conducted by Stephens et al. (2013, p.338) using desktop 3D printers determined that ultrafine particles UFP's of up to 200 billion particles per minute (□1.9×10^{11} min^{-1}) were emitted when operating ABS feedstock for 20 minutes to print small plastic figures. It also found that PLA feedstock emitted approximately 20 billion particles per minute (□2.0×10^{10} min^{-1}) when printing small plastic objects for 20 min. However, another study by Kim et al. (2015, p.12050) found lower concentrations of UFPs to the tune of 1.61×10^{10} ea/min for ABS, and about 4.89×10^{10} ea/min for PLA which are 1 and 2 magnitudes lower, respectively, than the previous study although they suggest the differences may likely be due to factors including differences in the printer and print cartridges. They, however, maintain that the concentrations of particles detected for ABS during the experiment were 345 times higher than before the experiment, and up to 26 times higher for PLA during the experiment. The experiment also detected gaseous material which they identified as volatile organic compounds (VOCs) and some BTEX (Benzene, Toluene, Ethylbenzene, and Xylene). The Geometric Mean concentrations of VOCs emitted for ABS were found to be 159.9 ppb and increased concentrations of toluene, ethylbenzene (16.4 times), and xylene (2.9 times) were recorded for PLA.

The two studies mentioned above show that UFPS were higher for ABS print materials than when using PLA and a similar result was obtained in a follow-up of Stephen's 2013 study which was done with slightly different study design (Azimi et al., 2016, p.1265). The study found that emission rates of UFPS for ABS ranged from □2.0 x 10^{10} min^{-1} to □9 x 10^{10} min^{-1} while emission rates for PLA filaments were approximately 2 magnitudes lower (□ 10^{8} min^{-1}). A crucial point in these experiments is an indication that the use of 3D printer enclosures did not alter the results significantly. The results of VOC emissions measured in the experiment (see Figure 2-15) show that emissions ranged from about 3 µg/min for polycarbonate filament to □200 µg/min for nylon filament. Up to 113 µg/min of Styrene was emitted which was found to be the dominant VOC emitted by ABS filaments and interestingly, printer enclosures didn't help very much. Nylon filaments emitted up to 180 µg/min of caprolactam and results of other VOCs emitted can be seen in Figure 2-15.

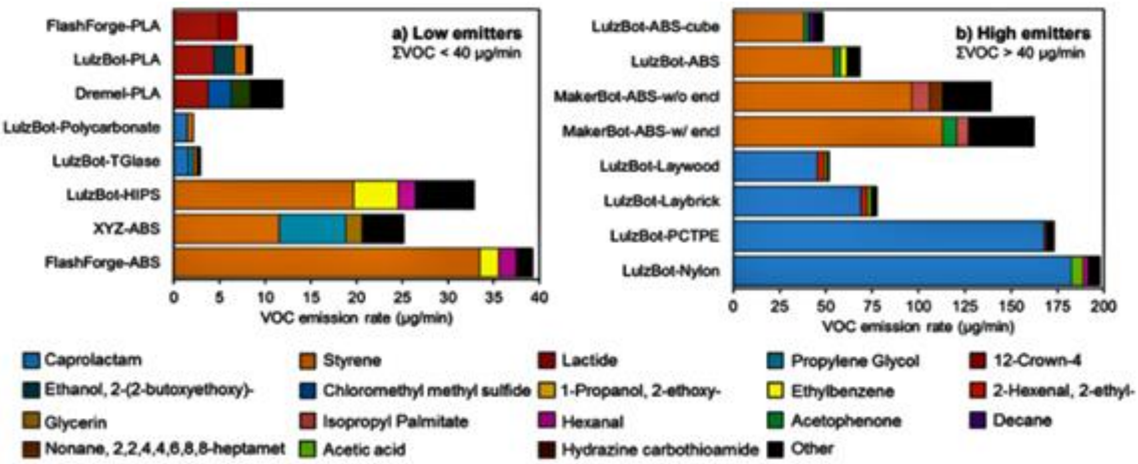

Figure 2-15 VOC emission rates for some filament and printer combinations (Azimi et al. 2016)

More recent studies conducted by Stabile (2017, p.398) and Zhang et al. (2017, p.1284) show that particle emission rates for FDM 3D printers using ABS were in the orders of 10^{12} min^{-1} and 10^{10} min^{-1} respectively. Most of the particles emitted in all these studies are UFPs whose sizes are smaller than 100nm which is important because UFPs whose diameter measure below 100nm is defined as nanoparticles (Pennsylvania State University, 2016, p.3; Defra/Air Quality Expert Group, 2018, p.44; Dobson, King and Jarvie, 2019). In these concentrations, the extremely tiny sizes of these particles mean that a good portion of them will penetrate the human body and interact with the organs.

Of particular concern are the presence of ethylbenzene, acetaldehyde, formaldehyde, and 4-vinyl cyclohexane in the ABS emissions because they are recognized as carcinogens and styrene, another probable carcinogen (Weber et al., 2016, p.122). Recall that Azimi et al. (2016, p.1266) found large amounts of styrene which is classified by the International Agency for Research on Cancer (IARC) as carcinogenic was emitted by ABS filaments. Also, Davis et al. (2016) and Davis (2017, pp.15 & 16) maintain that other key emissions include caprolactam which causes respiratory and ocular toxicity; and methyl methacrylate classified as an irritant is given off by PLA (Dormer, Gomes and Meek, 1998, p.4; Zhang et al., 2018, p.1099). Interestingly, the World Health Organisation suggests that methyl methacrylate impairs locomotive activity and has learning and behavioural effects on rodents exposed to it.

Also, isocyanic acid and cyanate ion (NCO^-) is part of the UFP's emitted by ABS. According to Zontek et al. (2017, p.23), these are associated with such ailments as atherosclerosis, cataracts, rheumatoid arthritis, as well as mild eye irritation due to the presence of n-decane. ABS is one of the most commonly used thermoplastic materials possibly due to its tensile and flexural strength which is described as 40 – 70% greater than other FDM materials (Fischer, 2011, p.2). So naturally, it would be of serious concern that any fumes that might be emitted during the printing process may cause adverse health effects.

Although there is yet no definitive proof of negative health impacts due to the use of 3D printers, yet studies like those of Chalupa et al. (2004, p.882) have shown how people with respiratory diseases like asthma are increasingly susceptible to the health effects of pollution when exposed to UFPs. Also, Stölzel et al. (2007, p.464) found statistically significant associations between concentrations of UFPs and cardio-respiratory mortality rates. Toxic pollution was also recently linked to the death of nine-year-old Ella Kissi-Debrah in London after suffering series of seizures at a time when local air pollution levels were higher than legal limits fixed by the EU (BBC, 2019a). All these examples show how exposure to toxic particles and fumes can have a serious impact on health.

Another recent study provides further indication of the sort of impact UFPs have on marine life. An experiment involving SLA 3D Printers was conducted in a laboratory test involving zebrafish embryos at the University of California. The test performed by Oskui et al. (2016, p.1) assessed the toxicity of different polymers used for fabricating 3-dimensional objects for medical purposes. The results of the experiment showed that most of the embryos exposed to printed parts from stereolithography died within 7 days and that only very few managed to hatch by day 4 with severe deformities. Although human tolerance for the sort of toxicity described in this report might be much better, the results nevertheless are cause for concern.

Besides FDM and SLA 3D printers, SLS 3D printers have also been studied and 2 important studies have shown the possibilities of health hazards from the use of these printers. Although one of the studies simply states that Selective ‘Laser Sintering produces harmful fumes’ (Kinstlinger et al., 2016), the other, a risk assessment report on 3D printers and products sponsored by Danish ‘Ministry of Environment and Food’ indicates the presence of Laurolactame also called Azacyclotridecan-2-one (or dodecalactam) in concentrations of 230mg/kg (Ministry of Environment and Food of Denmark, 2017, pp.54 & 55). Interestingly, the Safe Drinking Water and Toxic Enforcement Act (1986) of California colloquially referred to as Proposition 65 list Azacyclotridecan-2-one as a carcinogen warning that it ‘contains chemicals known to the state of California to cause cancer, birth defects, or other reproductive defects’ (Ecomass, 2016, p.9). It thus appears that long term exposure to the fumes and particles emitted by most of the additive manufacturing technologies and materials present significant health risks that cannot be ignored.

Safety standards in other areas of 3D printing have also been questioned. While current industrial manufacturing relies on centralised processes and testing to ensure that products meet safety standards before being certified for use, 3D printing allows for local ‘decentralised’ production (Peels, 2017a). This means that objects can be produced locally wherever and whenever necessary. According to Neely (2016, p.1288) ‘one important issue of 3D printing involves how to ensure the safety of 3D printed products’ suggesting that the absence of safety standards for 3D printed products, the lack of certification systems that indicate what products are safe for use and under what circumstances, as well as the ability to print objects locally at homes, are among elements that makes safety an issue with 3D printing.

Similarly, Greatorex (2015, pp.15 & 16) contends that insufficient checks and the layered nature of AM may lead to products with limited strength, low heat or moisture resistance, fatigue, and less durability. A King (2015) suggests that there is little real data regarding most aspects of safety of 3D printers and that most desktop printers contain few or no safety features and that even their manuals have little or no information about safety. As 3D printers become more popular and begin to replace regular manufacturing process, Neely (2016, p.1291) argues that although it is impossible to prevent all risks, society cannot ignore the ramifications of moving to a system that hasn't done enough to protect the consumer. Safety issues in 2 areas where 3D printers are often used – children's toys and food items are highlighted next.

Flammability of powdered material

One interesting safety problem found was about the flammability of powdered material used in SLS 3D printers. This was interesting because almost no record was found in academic journals. An extensive search was done with several different combinations of search terms like 'flammability of SLS and 3D printing' and 'combustion of SLS in additive manufacturing' finding little or no results in academic literature linking 3D printing, SLS powders, and flammability or combustion. One of the important finds in this area was Beaman et al. (2013, p.261) who mentioned how SLS processed Alumina with ammonium dihydrogen phosphate binder is combustible. Some other articles discuss cases of combustible dust fires and explosions due to powders used in the plastic industry (Schmid, Amado and Wegener, 2015). Interestingly, discussion websites like Reddit had results showing that some in the additive manufacturing industry do have serious qualms about using SLS due to the propensity of their flammability.

Blogs were found more likely to mention this issue even though it only receives a brief mention. For example, the Director of 3D printing business in an interview with O'Connor (2017) mentioned how used powders are considered hazardous in terms of inhalation and high combustibility; Dejay (2015) a member of the RepRap organisation stated how metal powders are more dangerous in terms of their combustibility and toxicity, And Trujillo and Steve (2018) who maintain that powdered metals like titanium and aluminium used in additive manufacturing burn very fast and produce extremely high temperatures and pressures and therefore require extra caution when using them.

A report by the U.S Department of Labour shows why caution is extremely important when dealing with powdered metal (OSHA, 2014). It states that a company called Powderpart Inc. was cited a penalty of $14, 000 for 1 wilful and $50, 400 for 9 serious violations of safety standards after an explosion at the company caused 3rd degree burns to an employee. The report notes that fire and explosion hazards when dealing with materials in powdered form are well established and that the company violated safety standards in the way the powders were used and stored.

Safety around children

The variety of applications for additive manufacturing in the home keeps increasing and now includes printing of toys for kids which Wright (2017) suggests is often much cheaper than buying those industrially produced. Current industry regulation mandates that toys are made from suitable materials which meet chemical standards and are designed to mitigate against such dangers as choking, laceration and puncture, pinching or crushing fingers, and injury etc. But when toys are printed at home, there is no guarantee that the toy design, material, and environment are safe (Hendrixson, 2017). To this end, Carlon (2017) raises the question of children's safety with regards to 3D printed toys in terms of structural integrity, constituent additives, fragility, and sharp edges and suggests that current safety laws will need an overhaul to ensure that children are protected from toys that they can build themselves.

Safety of 3D printed foods

Another emergent use of additive manufacturing is the fabrication of food products as the technology allows food makers to customise and commoditise food in very interesting ways. It has been suggested that this can even help in solving problems of food insecurity in regions of the world where access to fresh and affordable ingredient is scare (Wiggers, 2017). Lupton (2017, p.44) maintains that the technology which uses cartridges filled with a pliable, edible matter like food pastes, purees, powders, dough, liquids and gels has received mostly positive representation in the media so far with only little reference to any risks or harms.

As with other AM techniques, the 3D printed material is heated to create a malleable substance that can pass through the printer's extrusion nozzle and then solidifies as it cools. According to Porter et al. (2015), this heating and cooling process may make foods susceptible to microbial growth, fungus, or bacteria. And Tran (2016, pp.870–875) contends that such foods could result in food poisoning, food allergies, and may result in long term changes to the human body in ways little or nothing is currently known. Also, according to Flynt (2018), the layer by layer nature of 3D printed objects results in the creation of striations and grooves along layer boundaries of the final product which makes it problematic for use as food containers as leftover food stuck in them cannot be easily removed by traditional cleaning methods making them prone to bacterial growth.

2.6.3 Intellectual Property Rights

The World Intellectual Property Organisation (WIPO) defines intellectual property as 'creations of the mind: inventions; literary and artistic works; and symbols, names, and images used in commerce' (WIPO, 2018, p.2). The same organisation goes on to describe two types of IP - industrial property (patents, trademarks etc), and copyright (literary works like novels, films, music, artistic works like drawings and paintings, architectural designs, etc) (WIPO, 2018, p.2). Explaining the difference between copyright and patents, Santoso and Wicker (2016, p.145) maintains that patents must be formally applied for and offer 20 years or 14 years protection for utility patents and design patents respectively; on the other hand, copyright which is obtained automatically after work has been created, offer much lengthier protection calculated as the life of an author plus an additional 70 years.

The ability for 3D printing users to copy almost every object with or without the authorisation of those who hold rights in such objects has been a source of concern for some (Malaty, 2017). And the UK Intellectual Property Office has suggested that 3D printing affects all aspects of intellectual property including copyrights, patents and trademarks (Webber, 2015). According to Olla (2015, p.78), 3D printing is creating serious challenges to policymakers and regulatory officials because of uncertainties about the application of current IP laws to 3D printing.

2.6.4 3D Printed Guns

The idea that functional guns could be made with AM technology has generated a lot of controversy since 2013 when Cody Wilson developed the 'Liberator' – the first 3D printed gun – using blueprints of an actual gun and released the design files online freely (Walther, 2015, p.1435). Bryans (2015, p.907) describes the Liberator as a single-shot weapon named after FP-45 Liberator (see Figure 2-17 and Figure 2-16) which, ironically was also a single-shot weapon airdropped by the Allied Forces to resistance fighters in France and China during World War 2. Over a million of the FP-45 were said to have been dropped behind enemy lines and although it is not clear if they were ever used in combat, their presence was enough to diminish the morale of the Axis troops (Andrews, 2015). It has been suggested that this is the type of effect that Wilson, by making downloadable designs freely available online, hopes to replicate on the U.S Government where the right to bear arms is promoted by the Second Amendment (Anthony, 2013). However, the Liberator is made almost entirely from ABS plastic apart from a piece of metal that was incorporated in the design to meet U.S regulation.

Figure 2-17 FP-45 Liberator

Figure 2-16 The Liberator

Unlike many other countries where strict gun laws prevent ownership and sale of guns, this sort of weapon is considered legal in the U.S and just about anyone can own one. According to the U.S Bureau of Alcohol, Tobacco, Firearms, and Explosives (ATF), a licence is not required to make a firearm solely for personal use. However, a licence is required to manufacture firearms for sale or distribution. The law prohibits a person from assembling a non-sporting semi-automatic rifle or shotgun from 10 or more imported parts as well as firearms that cannot be detected by metal detectors or x-ray machines' (ATF, 2017). Thus, Wilson appears to have incorporated a piece of metal in his design so as not to fall foul of the Law, and as he made the schematics freely available online, he appeared to still be within the ATF's rules. Nevertheless, within a short period, there was a huge uproar in many media outlets as the thought of a plastic gun that can be freely printed and remain untraceable through conventional processes in the event of a crime, left many shaken.

Within a few days of uploading the Liberator schematics online, it was downloaded over 70,000 times all over the world (Popkin, 2013). As word spread quickly, the US State Department ordered the immediate removal of all data related to the gun from public access, citing the 'International Traffic in Arms Regulations (ITAR)' (Greenberg, 2013). It appears the State Department felt publishing the design files freely online amounted to the export of arms secrets (Thierer and Marcus, 2016, p.834). This led to years of long legal battles between Cody Wilson's organisation, Defense Distributed, and the US State Department, although the damage had already been done as so many downloads had already been done worldwide.

One of those who had downloaded the files was Yoshitomo Imura in far-away Japan who in 2014 successfully redesigned the 3D printed gun (Lata, 2014) to create what he called the Zig-Zag Revolver – a .38 calibre type revolver capable of holding 6 bullets. He successfully test-fired this gun and posted the video and digital files online and was quickly arrested and jailed for 3 years (Ensor, 2014). This is because of the strict nature of Japan's anti-weapons laws under the Firearms and Sword Possession Control Laws (Allemant, 2000, p.165) enacted to prevent access to weapons by organised crime and the general public.

Since then, 3D printing has continued to improve quite rapidly, and more interesting versions are being created. For example, an improved version of the Zig-Zag Revolver was made by another organisation called Free Open Source Software and Computer-Aided Design (FOSSCAD). They named their gun which is capable of holding 8 of the .38 type rounds the 'Imura Revolver' in honour of Yoshitomo Imura (Milkert, 2014). Another interesting design is the PM 522 Washbear (See Figure 2-19), a fully 3D printed revolver apart from the firing pin which is a roofing nail, the elastic bands which act as springs, some detectable metal to comply with regulations, housed in the grip (Grunewald, 2015). There are 2 versions of the Washbear – one version made with nylon holds 6 shots, and the other made from ABS holds 8 shots with steel chamber liners included.

Besides revolvers, important gun components that have been 3D printed include functional lower receivers for AR-15, extended AR-15 and AK-47 magazines which are said to be as capable as the usual firearm components (Bryans, 2015, p.908). Other types of guns that have also been created with 3D printers include the EMG-01A a full-auto coil gun made by Jason Murray and David Wirth of Arcflash Labs (See Figure 2-18). It is an electromagnetic gun made almost entirely 3D printed and features a 9 round coil spring magazine (Arcflash Labs, 2018). Tests show bullets from the gun penetrating 20-gauge steel (Murray, 2018) and Nardi (2018) maintains that this is not a toy and would need to be handled responsibly.

Figure 2-19 PM 522 Washbear revolver (idarts 2015)

Figure 2-18EMG-01A Coil gun (Nardi 2018)

All these developments have come about mainly because Cody Wilson had released the 3D models online for free, prompting many to download the files and improve upon his work. Interestingly, the legal battles between Wilson and the State Depart were temporarily settled in 2018 when the Trump administration gave permission for such files to be accessed, used, reproduced, discussed, and benefited from, effectively allowing them to be shared freely on the internet from August 1, 2018 (Branham, 2018; Lartey, 2018). Nevertheless, a temporary restraining order was later imposed by a Federal District Judge barring the implementation of the settlement.

There has been a mixed reaction to this news as many are concerned that the proliferation of such files and firearms could result in much danger to society. For example, the Newtown Action Alliance (2018, p.2) maintains that two mass shooters – John Zawahri and Kevin Janson Neal who murdered 5 people each in 2013 and 2017 respectively – wouldn't have been able to commit their crimes without access to homemade weapons.

The case of Eric McGinnis who referred to himself as 'Eric the Ruler' and wanted to get a gun despite being barred from possessing a firearm, was recently reported on ABC News (Date, 2019). He had gone to a gun dealer in Texas where the required criminal background check revealed that he was prohibited from owning firearms due to a protective order against him. He then went on to buy a 3D printer, downloaded design files online, and printed parts he was legally unable to purchase and then went on to build an AR-15 style rifle with a short barrel (see Figure 2-20) even though it is illegal to have an unregistered rifle with a barrel under 16 inches. He was arrested after police officers heard gunshots in the woods and went to investigate and along with the rifle, was found with a document titled 'List of American Terrorist' which included names and addresses of members of Congress.

Figure 2-20 Eric the Ruler AR-15

Despite situations like this, there are those like Campbell (2018) and Allhands (2018) who are on the other side of the fence when it comes to regulation of 3D printed weapons. They maintain that 3D printed guns are not a threat because they are not effective, that it's cheaper to simply buy a gun, and that criminals have access to better weapons anyway.

2.6.5 Employment Issues

Over the years, as new innovative technologies emerge and become commonplace, concern has often been expressed over the nature of the relationship between new technologies and employment (Handel, 2003, p.3; Roosevelt Institute, 2015, p.1; Nübler, 2016, p.1). Very often, the debate about this relationship revolves around such themes as increased unemployment, suppressed wages, and greater inequality (Bruckner et al., 2017, p.1). AM has also been featured in these debates and there is a worry in some quarters that this technology might hurt employment.

One such argument asserts that as AM is a digitally controlled technique, it reduces the need for manual labour in the manufacturing process and could therefore lead to significant reductions in the workforce (de Laubier et al., 2018, pp.13 & 14). In a recent conference paper, the Economist Intelligence Unit (2018, p.20) said they foresee a significant impact on labour markets due to the replacement of manual processes like welding and machining and contends that the impact is already being felt in the area of prototyping, where AM has displaced the small-scale models and iterations that used to be done manually.

However, some have challenged the notion that automation brought about by 3D printing negatively impacts employment. It has been suggested that the move to greater customisation rather than mass production in the factory of the future; the ability of AM to drive down production cost especially in low volume complex products; as well as quicker delivery times to customers due to localisation of 3D printers are factors that can lead to an increase in jobs (Kianian, Tavassoli and Larsson, 2015, p.94). It has also been suggested that new business models will be created around 3D printing resulting in the creation of new professions and employment profiles that did not previously exist (Barcelona Activa, 2015, p.18). Thus, for these, the impact of 3D printing on employment is only positive, resulting in the creation of more employment opportunities and new professions.

Nevertheless, others maintain that the labour patterns due to AM are two-fold depending on the geographic location in question. For instance, it has been suggested that low-cost 3D printers will enable more local production at, or near the point of use, thereby removing the advantage of producing in low wage countries (Weller, Kleer and Piller, 2015, p.45). By this analysis, it appears that while in developing countries some jobs will be lost, there will be employment gains in more developed countries. In line with this, Gebler, Uiterkamp and Visser (2014, p.161) maintain that the economies of developed countries will benefit from the automation that AM offers, but destabilise developing countries as production re-shifts to consumer countries. And Mahon (2016) explains that in low wage countries like Cambodia, 3D printing can be said to be a silent killer of jobs as it poses a dire threat to workers.

In summarising these developments, Pîrjan and Petroşanu (2013, p.365) contend that the development and spread of 3D printing will result in the creation of new professions, jobs, and industries in such areas as production and supplies of 3D printing hardware, software, as well as products engineering and design; as a result of its automation, however, it will reduce the need for human labour in other areas leading to significant workforce reduction in the export industries.

2.6.6 Bioethical Issues

Another interesting application of 3D printing where the ethical implications are still not well known is bioprinting. Jessop and Whitaker (2018, p.5) describe bioprinting in simple terms as a process in which a 3D printer uses a syringe containing biomaterials and cells to create a 3D macrostructure of tissues or organs. The technology uses the regenerative self-healing processes of the human body to create repair tissues and organs using cells from an individual patient to create tissues or organs outside the body which can then be implanted later (Li and Faulkner, 2017, p.443). It has been suggested that bioprinting provides a viable means of compensating for shortages of donor organs for transplant due to such advantages as cost-effectiveness, precision, and minimal risks of rejection after transplantation (Jang, 2017, p.71; Derakhshanfar et al., 2018, p.144). However, Li and Faulkner (2017, p.441) argue that the idea of printing organs on-demand challenges the traditional regulatory framework as only small fractions of current regulations are relevant and there is no 'sui generis' (or specific) regulatory regime governing the whole bioprinting process.

Bioprinting raises several ethical issues and Li et al. (2015, p.154) suggest that safety guidelines of bioprinting haven't been well established and questions around the side effects, continuous tissue synthesis, biomaterials degradation haven't been well addressed. Also, Vermeulen et al. (2017, p.621) and Tanuj (2019) argues that safety risks abound as the paradigm hasn't been tested enough and therefore risks exposing people to such illnesses as teratoma and cancer and raise issues of social stratification resulting from a tiered system of organ replacement due to cost where only those who can pay for such organs live longer. And Dodds (2015) contends that as the technology improves, there exists the potential for 3D bioprinting to extend human capabilities beyond what is normal making some humans less susceptible to injury, fatigue, or other types of illness and thus raising ethical issues akin to those in sports where performance-enhancing medical technology is heavily regulated.

Another important issue raised by Gilbert et al. (2018, p.77) was about the dual-use possibilities of 3D-bioprinting which could either be used for beneficial purposes or harmful purposes. And Boucher (2018b, p.12) who agrees with this view asserts that the ready availability of 3D bioprinting equipment could open up the possibility of using it for the creation of bioweapons and biohazards.

Issues around justice in access to bio-printed organs and tissues have also been raised by Sigaux et al. (2019, p.4) asserts that this is a costly procedure and as such would mean that only those who can afford such treatment would have access to it. By applying the 'maximum rule' theory of distributive justice which suggests that technology can only be considered to advance justice if it benefits those worse off economically, Vijayavenkataraman (2016, p.13) illustrates how 3D bioprinting raises ethical questions around justice.

2.6.7 Data Security

The use of AM in safety-critical products required in industries like aerospace, transportation, and healthcare will become more important in the coming years (Linares et al., 2020, p.1). For example, Lockheed Martin the largest defence contractor in the world was recently awarded a $5.8 million contract by the U.S Office of Naval Research to develop 3D printing for the aerospace industry (Saunders, 2018). But 3D printers are computerised technologies that can also be targeted with malicious software by individuals or state actors. And according to Yampolskiy (2016, p.58), the compromise of 3D printers can include manipulation of mechanical properties of safety-critical systems to weaponize them to endanger life, disrupt critical infrastructure, or create significant economic or social damage.

These sorts of attacks could be launched by manipulating either the computer CAD model, the .STL files, the toolpath file, and the physical 3D printing machine itself (Sturm et al., 2017, p.156). Turner (2015, p.43) suggests that some of these attacks might be launched in the following ways:

- Using non-secure file transfer mechanisms like emails and USB drives to launch attacks especially as the many designers have not yet incorporated the habit of encrypting design files.
- By port mapping to discover nonsecure ports that are opened by AM equipment by default for remote printing, debugging, and remote control, a hacker could then inject commands to alter files or launch a Denial of Service (DoS) attack.
- Traditional network attacks like the man in the middle attacks could allow the attacker to modify parts and bypass safety systems.
- The lack of quality control processes in the AM industry also makes them susceptible to attacks as there is no easy way to detect deviations from design specifications.
- Social media could also be used to launch attacks especially as the 3D printing community often share files online through social media.

A recent security risk assessment study which was conducted by Linares et al. (2020) indicates that 3D printing faces several high-impact risks including IP of design and specification files, malicious modification of dimensions or shape of a 3D model, introduction of defect or the malicious reduction in the structural integrity of 3D printing artefacts, and trojan firmware installation on 3D printers. This information is summarised in Table 2-5.

Table 2-5 Assessment of AM security risks

Threat Scenario	Vulnerability Description	Impact	Likelihood	Estimated Risk
IP theft from design and specification files	Weak access controls and improper authentication and authorization			
Reverse engineering/reconstruction	Lack of digital rights management			
Ransomware attack	No backups, weak controls to critical content			
Corruption of design files or material databases	No backups, weak controls to critical content			
Malicious modification of dimensions or shape of object	Inadequate tests, weak integrity controls, lack of proper validation			
Malicious reduction in the structural integrity of the 3D artifact, introduction of defects	Insufficient structural integrity tests, file integrity controls, and post-production testing			
Irreversible damage to hardware and mechanical elements of the 3D printer	Lack of hardware fail-safes, inadequate input validation			
Installation of firmware Trojan on 3D printer	Weak authentication, authorization and privilege management, insecure update process			
Corruption of calibration of the 3D printer	Insufficient file integrity controls, weak file access validation			
Memory safety violation on 3D printer firmware using malicious/out of spec file inputs	Inadequate input sanitizing, weak control flow integrity checks			
Evading post-production structural integrity tests	Limited granularity in test methods, limited resolution of tests, inadequate sample size			

Using a 3D printed drone propeller, a recent study demonstrated how a cyber-physical attack on computers can be used to cause serious damage to critical infrastructure by maliciously modifying files of 3D models. In the study, Belikovetsky et al. (2016, pp.10–14) demonstrated the entire chain of attack that eventually resulted in physical damage to a drone's propellers. The attack was launched from a remote computer to modify some parameters of the 3D model of the propeller, after which it was 3D printed and then attached to a drone. When the drone was flown after a few trials, the sabotaged propeller broke mid-flight. Although the attack was demonstrated on a drone, it shows what can happen if a high powered and more sophisticated attack is launched on safety-critical equipment used in the aerospace industry.

2.6.8 Liability

To the untrained eye, 3D printing may appear to be a simple process of downloading schematics or 3D models of objects on the internet and then clicking a button to print out the physical form. In reality, however, it involves a complex mix of people and processes including various types of hardware and software products and producers, as well as product designers in a way that is quite different from those involved in traditional manufacturing. AM technology has revolutionised how products are made, who is the maker, and stirred up the industry, as well as the law (Beck and Jacobson, 2017, p.147). Thus, Joëlle Bergeron of the European Parliament maintains that while 3D printing is creating opportunities for companies, it also raises challenges regarding civil liabilities because the complex nature of processes and the many people involved make it difficult for those affected to identify the person responsible (European Parliament, 2018). Also, the lack of legal precedence in the kinds of issues that may arise further complicates matters of civil liability.

With 3D printing, it has been suggested that the complex nature means that liability may among other things, arise due to defective designs of a printed item, malfunction of 3D printer, or error due to inadequate maintenance of 3D printers (Morjaria, 2018); it may lie in any of several places including the owner of the 3D printer, 3D printer manufacturer or supplier, the creator of the product (Coraggio, 2015); or as Bergeron (2018, p.6) puts it, liability may lie with the creator of the 3D file, the producer of the 3D printer or the software used in the 3D printer, the supplier of materials used, or the creator of the 3D printed object.

Liability laws in place today were designed for an era where mass manufacturing was the norm, the retailer separated the producers from the consumers, and consumers were not required to understand the complexities inherent in consumable (Nielsen and Griggs, 2016, p.737). For example, the EU Product Liability Directive (85/374/EED) which is one of the most important Laws with regards to product liability is based on the 1965 Restatement (second) of Torts (Davies and Snyder, 2014, pp.210–212). And although Bergeron (2017, p.5) maintains that the 1985 Directive along with Articles 10 and 14 of the Commission proposal 'on certain aspects of contracts for the supply of digital content' is useful for resolving the question of liability, a later report she produced for the European Parliament (Bergeron, 2018, p.11) calls for the creation of a specific liability regime for objects created using 3D printing technology. This goes to show that there are deep-rooted uncertainties with the way liability is apportioned with the use of additive manufacturing technology and the growing use of the technology will likely raise more issues in this area.

2.6.9 Biohacking

The section on 'appeal to the hacking culture' in section 2.4.5 explains that bio-hacking is an attempt to bring science to individuals to enable them to experience biology first-hand and further deconstruct knowledge by making it available for all. It also showed that such initiatives allow individuals and communities to run labs in their homes, garages, and similar spaces without the support and supervision of regulatory structures such as Ethics Review Boards (ERBs).

Thus, one of the concerns of biohacking relates to the risks involved in its use as there could be serious issues as resulting from embedded technologies into the human body. For example, it has been pointed out that implanting electronic chips into the body is risky because they might interact with the human body in unexpected ways or create future complications (Gangadharbatla, 2020, p.4). Similarly, magnetic implants may corrode and the implant site may get infected (Bárd, 2020, p.100) thus causing serious health issues. An example is the situation of Tim Cannon mentioned earlier in section 2.4.5 who inserted a device into his forearm (O'Connell, 2017, p.137) and complained about lots of fluid build-up which had to be regularly drained and complained of being in a constant state of paranoia fearing the battery would leak into his bloodstream and poison him.

Many of the procedures undertaken by biohackers lie on the fringes of the law making it difficult to apportion blame when there is a problem as a result of a risky procedure. The voluntary nature of participation and the fact that biohackers are not bound by ethical standards like those of the Nuremberg code (1947) which advocates for the avoidance of all unnecessary physical and mental suffering and injury, means that issues around liability will be difficult to resolve.

In some situations, however, it is possible to show that the law has been broken and appropriate action can be taken. One example of this can be seen in the way CRISPR, a gene-editing tool that consists of Cas9 enzyme used to cut DNA and RNA sequence being used. This technology which would normally be restricted to traditional laboratory context is being increasingly used by biohackers as the cost is now so low and continues to drop (Fuisz, 2017, p.658). Some of its use poses ethical and legal challenges as some biohackers have attempted to use it for personal enhancement e.g. Josiah Zayner who have attempted to use this to knock out his myostatin gene which inhibits the growth of muscle cells to enable him to increase his muscle mass (Zayner, 2018); and He Jiankui a Chinese scientist who genetically modified copies of a gene (CCR5) of human embryos to make them resistant to HIV and then implanted them in women (Cyranoski, 2018, p.14). West and Gronvall (2020, p.83) point out that this violated a longstanding norm prohibiting genetic modification of human germline, and as result, he was found guilty of medical malpractice in a Chinese court and jailed.

Nevertheless, in the hands of biohackers, gene therapies using technologies like CRISPR that essentially try to rewrite the natural biological instruction in the body may negatively interfere with the body to induce tumours (Anand, 2018). They could also inadvertently foster misuse and or/intentional development of products that threaten public safety (DiEuliis and Giordano, 2018) for example researchers can now easily recreate certain pathogens (West and Gronvall, 2020, p.83) as a scientist has published the genomes of many.

2.6.10 Summary of Ethical Issues

A summary of the ethical issues identified from the review of relevant literature as discussed in the preceding sections has been summarised in Table 2-6.

Table 2-6 Summary of ethical issues of AM

Ethical Issues	Description
Environmental	There are issues are around waste, recyclability and energy consumption which indicate that AM may not be as sustainable as many in the industry have claimed.
Health-related	Ultrafine particles (UFP), harmful fumes, volatile organic compounds etc which are potentially dangerous to health are emitted by 3D printers
Safety	There are safety issues that need to be addressed with AM. This is particularly urgent with the production of children's toys and food items with 3D printers
Intellectual property rights	With AM, the risks of IP infringement increase significantly. It is also difficult to identify cases of infringement away from control and in many cases, it is impractical or almost impossible to enforce IP rights
3D printed weapons	AM makes it relatively easier than most technologies to create weapons away from regulatory control. As the technology is quickly improving, there is a worry that this might become the technology of choice for criminals wishing to create undetectable weapons
Employment	The impact of AM on employment is hotly debated. There is a feeling among many that increased use would lead to job loses, while others feel that it will have a positive effect on employment
Bioethics	Bioprinting raises several ethical issues. For example, risks are high as there is little or no safety guidelines; also, issues around justice in access to bio-printed organs and tissues need to be addressed
Information security	As AM becomes more widely used in safety-critical products in industries like aerospace, transportation, and healthcare, issues around information security will become more important in the coming years
Liability	Liability laws in place today were designed for an era where mass manufacturing was the norm. As 3D printing has further democratised manufacturing and just about everyone can manufacture artefacts in their homes, it becomes difficult to legally apportion liability when something goes wrong
Biohacking	The prevalent hacking culture associated with AM means that 3D printing is increasingly being used outside the usual institutional control. For example, for biohacking. Such anarchic use raises among other things, safety fears.

2.7 The Use of Expert Interviews in Research

A good portion of this study is based on the interview of experts and this section examines some of the pertinent literature on the use of expert interviews in research. The section has been developed to highlight how expert interviews inform research and the limitation of approaches that mainly rely on technical expertise.

It has long been recognised that expert interviews play an important role in qualitative research. They are useful not only as a means for shortening time-consuming data collection processes but are also seen as a crystallisation point for practical inside knowledge as experts are assumed to possess comprehensive knowledge about the subject under investigation. Although expert interviews have significantly informed qualitative researches for many years, it was only in 1991 that a systematic debate on the value of expert interviews began to take place (Bogner, Littig and Menz, 2009, p.1). Among the issues raised in this debate include the question of what constitutes an expert and their role in the research design. Such debates were initially galvanised by an article published by Meuser and Nagel (191) which although focused more on the methodological issues of expert interviews, raised interesting questions about the quality of expert interviews.

Re-echoing similar sentiments almost two decades later, Mueser and Nagel (2009, p.1) point out that the expert interview is an ambitious method which cannot be considered to be on a sound footing in every situation. This is likely due to the subjective nature of the criteria for qualifying research participants as experts considering that the ‘expert’ is a relational status (Meuser and Nagel, 1991, p.443) and every expert is to some degree a construct of the researcher's interest (Korkea-aho and Leino-Sandberg, 2019, pp.32 & 35). As expertise is interactional and situational, the researcher, therefore, must reflect critically on the choices of experts selected for participation in research and the decisions made.

Some of the criteria used by researchers when identifying and selecting participants as expert include:

- Privileged access to information about groups of people or decision-making processes (Meuser and Nagel, 1991, p.443)
- Possession of specific kind of specialised knowledge that is not available to the researcher (Bogner and Menz, 2009, p.47)
- Active participation (regardless of social status) in the affairs of particular groups (Gorden, 1975, p.199)
- Possession of special knowledge about a social phenomenon (Gläser and Laudel, 2009, p.117)

The above indicates that the prevailing view among researchers who interview experts as part of their research is that experts possess substantial information about the phenomenon under investigation and will make important contributions to the research. Although it is recognised that experts possess a wealth of knowledge and are particularly important when dealing with abstract systems or phenomenon which the researcher might not understand (Bogner, Littig and Menz, 2009, p.4), the question of the value of the expertise provided is still relevant. For example, Collins and Evans (2008, p.2) maintain that experts do not make the correct judgements in every situation, rather, a good part of the time, their judgments are likely to be wrong. This is likely because, in some situations, experts face cognitive uncertainty or non-knowledge (Bogner, 2005, pp.27–28) which though is amenable to more research, might mean that inadequate or irrelevant information is provided.

An alternative approach to expert interviews is citizen-based participatory approaches. One example of such an approach is the Community Based Participatory Research or CBPR. According to Jull, Giles, and Graham (2017, p.152), CBPR is a 'collaborative approach to research that equitably involves all partners in the research process and recognises the unique strengths that each brings'. Several variants of CBPR include Participatory Research, Participatory Action Research, Community-Based Research, Action Science, Action Inquiry, and Cooperative Inquiry (Holkup et al., 2004, p.1634).

Interestingly, CBPR and all its variants are derivatives of the methodology called 'Action Research' which was developed by Kurt Lewin in the 1940s (Lewin, 1946). Such methodologies are considered more egalitarian and democratic than most of the traditional research methodologies that employ expert interviews. They are often touted as a more ethically aware methodology as they actively seek to equitably involve all stakeholders and minimises issues of power (Gilroy et al., 2011, p.6). They enable communities to participate in technical decisions making which often results in more effective solutions than interventions that privilege expert-led technical fixes.

For example, a relatively recent study by Gudowsky and Rosa (2019) found interesting discrepancies when comparing the content of expert and citizens based fore-sight studies for informing policy decisions on societal challenges. Note that societal challenges reflect major concerns shared by European Citizens including health, food security, clean energy, green transport, and secure societies (European Commission, 2013). The study illustrates how experts focus on science and technological fixes sometimes miss out other socio-cultural details that members of the society consider important. Some of the more pertinent issues noted in the study are summarised below along with the relevant societal challenge:

- The Health, demographic change and wellbeing: although the expert reports analysed highlighted very specific fields of technological research in the area of health and wellbeing, the authors point out that such specificities cannot be considered socially robust knowledge because they failed to address other issues like the overarching goal that technology-focused policy should address.
- Food security, sustainable agriculture and forestry, marine and maritime and inland water research and the bio-economy: the study indicates that experts-based foresight reviews acknowledge the essential nature of food and rightly point out how the growing middle class increases pressure on resources like water and foods like meat and dairy. However, they roundly forget the critical role that food plays in shaping individual and cultural behaviour and they failed to show an appreciation for the un-nuanced roles that food plays in shaping daily life, behaviour and delineating cultural practices.
- Smart, green, and integrated transport: the study found that citizens-based focus groups placed primacy on recommendations related to organisational, institutional, and structural design that accompany socio-technical development, and emphasised the building of participatory and inclusive governance infrastructure. In contrast, the expert focused groups prioritised the development of technological and scientific fields to address such issues.
- Climate action, environment, resource efficiency and raw materials: the authors maintain that analysis of the expert focus groups indicates that they mostly ignored alternative waste management frameworks like up-cycling and the sharing economy which other focus groups stress. Rather, the experts who rightly often pointed to resource scarcity as a driver of change were keener on providing a wide range of research and innovation recommendations to help minimise such problems.

Thus one of the conclusions that were reached in this study was that the outcomes of community-based research differ quite considerably from expert-based studies in terms of direction and focus. According to Rosa, Gudowsky and Warnke (2018, p.12) citizens based studies were found to be better able to focus on issues that expert-based studies seldom emphasise like the impact of technological developments on personal well-being, relationships, work ethics, and community life.

Like these authors, Lambrinidou (2018, p.2) argues that interventions that privilege expert-led technical fixes over community-based technical and structural fixes often reduce complex societal problems into narrow technological ones. This is as Giddens (1991, p.31) points out, expertise is becoming increasingly narrowly focussed and is liable to produce unforeseen or unintended consequences. Such analysis provides some indication of how abstracted expert knowledge can be from lived experiences and yet many of such expert advice feature prominently in policies. It is no wonder then, that in some industries the question of who gets to determine policy is being hotly contested.

Of particular relevance to this discourse is the situation in the tech sector where the identification, tracking, and mitigation of ethical consequences of technology are beginning to feature prominently such that considerable resources are being invested in this pursuit. In a recent article, Moss and Metcalf (2019) highlight how this has resulted in hotly contested debates on the questions of 'who gets to decide the meaning and practices of ethics in the tech industry. This has become more pertinent as it is becoming obvious that there are wide gaps between the practices of 'doing ethics' and what people think of as ethical. Also as ethics has become a site of power in the industry due to the added investment in this area it has resulted in greater internal and external pressures to respond to the ethics crisis.

An important issue raised by Moss and Metcalf (2019) is how all of these have exacerbated the problem of meritocracy in dealing with the question of who gets to decide the meaning and practices of ethics in the tech sector. Following the tradition in Silicon Valley where meritocracy infuses everything from hiring practices to policy positions, ethics is now framed towards faster and smarter approaches as if these virtues automatically resolve ethical problems. As such tech experts like Engineers now see themselves as best suited for addressing ethics-related issues rather than those who are less technically inclined. However, the authors point out that as ethics is a specialised domain that requires deep contextual understanding, tech experts may not be the most suitable to scan for the consequences of their products.

All of these go to show that although experts are very knowledgeable in their areas of expertise, and can provide invaluable contributions in research, policy agenda-setting, and the technology solutions, it is not in every situation that the expertise received is of the best quality.

2.8 Conclusion

In this chapter, the results of the literature review on ethical issues of additive manufacturing have been presented. Those identified include health-related illnesses that UFPS and VOCs given-off by 3D printers may lead to, environmental problems due to difficulties in managing 3D printing waste, intellectual property disputes which 3D printing may give rise to as the technology becomes more popular, and problems with 3D printed weapons. Other issues were highlighted around the safety of 3D printed items, bioethics of 3D printed organs, possible reduction in employment, information security, and the problematic nature of liability as it becomes more difficult to hold anyone legally responsible for damage or injury caused by additive manufacturing.

Unique characteristics of 3D printing have also been highlighted here. They include issues like the appeal to the hacking culture outside of institutional control and the low entry cost which makes it easy for anyone to get involved in 3D printing. Such issues make it imperative that some form of regulation is needed for the industry. Also, issues around current taxonomies of 3D printing have been addressed in this chapter and the need for a clearer taxonomy of users have been argued here.

Chapter 3 : **Philosophical and Methodological Underpinnings of the Research**

3.1 Introduction

Typically, research is guided by the author's view of reality and is often underpinned by certain philosophical positions that inherently influence the researcher's way of contributing new knowledge (Kamil, 2011, p.67; Oppong, 2014, p.224). The views and philosophical approaches taken by researchers make up the overall theoretical research framework, or paradigm, which (Slevitch, 2011, p.73) describes as a "cognitive perspective or a set of shared beliefs to which a particular discipline adheres."

Information Systems researchers apply several competing paradigms or approaches (Gonzalez and Dahanayake, 2007, p.845). This influences the nature of research conducted, the process, and results obtained based on some ontological and epistemological positions which are reflected in the methodology and methods adopted (Niehaves and Stahl, 2006, p.2; Scotland, 2012, p.9,10). To that end, this chapter will discuss many of the philosophical assumptions that guide research generally, and then relate this to information systems research, while explaining the research design adopted for this study.

3.2 Ontology

Ontology, according to Slevitch (2011, p.74) is derived from two Greek words, *onto* which means 'being' and *logia* which denotes to 'science, study, or theory'. To this end, Mack (2010, p.5) defines ontology as the study of entities that exist. Agreeing with this definition, Scotland (2012, p.9) argues that ontological positions are "concerned with what constitutes reality" and therefore there is a need for researchers to take a position that indicates their understanding of how things are and how things work.

Consequently, the ontological questions that researchers endeavour to answer are usually concerning the form of reality, and what is to be known about it. In this regard, researchers usually adopt one of two mainstream ontological positions, that is realism on the one hand, or idealism on the other (Oppong, 2014, p.242). The ontological position of the realist is one of objectivity where reality is said to exist independently of one's perception. Thus, a realist researcher views the existence of the object (that which is perceived) impartially (Wahyuni, 2012, p.69). Conversely, the idealist holds a subjective ontological position which suggests the researcher's perception of the world may influence the object of perception and does not support a 'world of physical entities or matter' (Schuh and Barab, 2007, p.72). Accordingly, Wahyuni (2012, p.69) maintains that subjectivists hold the view that reality depends on social actors and individuals can influence social phenomena.

Nevertheless, constructivism is another approach that takes a similar ontological view of reality to the interpretivists as they both believe that to understand this world, one must interpret it (Guba and Lincoln, 1994, p.222). However, the position of the constructivists, called relativist, holds that reality is created socially and experientially upon multiple mental constructions dependent on the persons who hold them (Guba, 1990, p.27; Gray, 2009, p.20). It suggests that multiple interpretations can be arrived at from any investigation due to the multiple realities that exist in the minds of people. Thus the constructivists argue that social entities can be considered social constructions built on the perception of multiple actors (Dieronitou, 2014, p.4). Interestingly, constructivists do not answer the question about the nature of the world. There seem to be a mix up between the question of the natural world (ontology) with knowledge of the natural world (an epistemic question). Constructivism is thus criticised as ‘epistemic fallacy’ (Bhaskar, 2008, p.26) because statements about being cannot be analysed in terms of statements about knowledge of being. Suchting (1998, p.74) provides a more thorough criticism on this topic in his article on ‘Constructivism Deconstructed’.

Yet another ontological stance is critical realism. It was developed in the 1970s by Indo-British philosopher Roy Bhasker with the help of some of his colleagues including Margaret Archer and Andre Sawyer (Gorski, 2013, p.658). Critical realism applies a transcendental form of argument which follows the Kantian procedure that asks such questions as what must the world be like for this to occur or to be intelligible? (Mingers, 2006b, p.22). According to Archer and Bashker (1998, p.22), the transcendental realist or the critical realist believes that the world is real, though structured. This position is similar to that of the ontological realist (Dean, Joseph and Norrie, 2005, p.7) however, critical realist argues that although there is one real world, it is stratified and not all of its structures are observable (Zachariadis, Scott and Barrett, 2010).

Thus, critical realism is distinguishable from empirical realism which treats the world as though consisting of only atomistic objects that can be easily observed and measured. Critical realists argue that there are intransitive “real things and structures, mechanisms and processes, events and possibilities of the world” that endure and operate independently of human perception, knowledge or experience and the conditions that allow access to them (Bhaskar, 2008, pp.12, 15). This is also quite unlike idealism which views the world and objects, as well as mechanisms that generate phenomena as human-constructs. Interestingly, transcendental realism and idealism both agree that social activity is important to produce knowledge.

For the purpose of this research, the ontological position adopted is that of the critical realist. This position is important because, like Bashker (2008, p.15) the researcher believes that there is a real-world out there with real objects, structures, and events which are not dependent on human knowledge, perception, or experience. Like other critical realists, the researcher agrees with the argument that scientific processes apply to both the natural and social domains as per the limits and characteristics of particular social environments. It is thus acknowledged here (as suggested by Mingers (2006b, p.25) that social structures are different from material structures and therefore limits the success of scientific methods in the social environment

3.3 Epistemology

Epistemology focuses on "ways of knowing and learning about the world" (Ormston et al., 2013, p.6). The philosophical dimension of epistemology places emphasis on what constitutes valid knowledge (i.e. its form) and the nature of this knowledge (Scotland, 2012, p.9; Ihuah and Eaton, 2013, p.934). This is because the word epistemology comes from the Greek word 'epistêmê' which denotes 'knowledge' (Krauss, 2005, p.758). *Epistemology is* concerned with 'how we know what we know' and 'deals with the nature of knowledge, its possibility, scope, and general basis (Crotty, 1998, p.8). Thus, epistemologists are interested in how knowledge is generated, understood, and how it is used. As such, the epistemological question is centred on the relationship between the researcher and the researched, and what can be known*.*

Although this might appear straightforward, the great paradigm debates stirred by Auguste Comte [1798 – 1857] (Comte, 1858, p.28; Bourdeau, 2018) have continued to dominate social research. Today, a plethora of alternative epistemic approaches now exist as researchers are unable to agree that a single approach is ideal.

One of the key epistemological issues concerns the nature of the relationship between the researchers and their subjects and the interconnection between their personal beliefs and the world they observe. In this regard, the foremost epistemological positions are the positivist and the post-positivist epistemology of interpretivism (Oppong, 2014, p.245). Others include constructivism, criticality or critical realism (Archer and Bhaskar, 1998, p.734) and pragmatism (Niehaves and Stahl, 2006, p.6; Goldkuhl, 2012, p.135) and the following discourse provides a brief description of these:

Positivist Approach

Positivism is an approach that has as its foundation the belief in a reality that is independent of the observer (Comte, 1853, p.92; Stahl, 2007, p.118). It, therefore, relies on scientific methods of natural science like theory testing and hypothesis (Buddharaksa, 2010, p.1). The positivist holds the view that the world exists independent of our knowledge of it (Marsh and Stoker, 2010, p.193). This suggests an objectivist viewpoint and thus positivism is often associated with the realist ontology.

As the positivist's researcher seeks an objective reality, it is necessary to maintain some distance to the subject to prevent the introduction of bias to the study. This type of research is considered value-free because of the alleged neutrality of the researcher who disconnects personal values from the research. Positivism holds that only through objectivity, control, and numerical measurement can objective knowledge be realized. However, this paradigm has been criticised by the likes of Immanuel Kant for placing primacy on experience to the detriment of understanding and thus cannot provide coherent knowledge (Hirschheim, 1985, p.21). Another criticism of positivism stems from the notion among positivists that observations must be made objectively, and yet observations are "value-laden, theory-laden, and interpreted" (Hudson and Ozanne, 1988, p.515) making it impossible to be objective (Mack, 2010, p.7).

Interpretivist Stance

The interpretive model or interpretivism is an approach that attempts to understand phenomena through conscious interaction with the world (Scotland, 2012, p.11). Researchers applying interpretivism strive to understand, explain, and demystify through interaction with the world (Cohen, Manion and Morrison, 2000, p.131). The relationship between the researcher and subject is interactive and interconnected (Slevitch, 2011, p.77) and the values are said to be mediated through the research or between the researcher and subjects (Ormston et al., 2013, p.8). Although It is acknowledged that research is not value-free, the researchers attempt to minimise the influence of their values, assumptions, and biases on the outcome of the research.

Rather than apply the rigorous scientific procedures for verification, the interpretive model embraces a flexible and more personal structure for research by looking for meaning in their social research. Interpretivists utilise a variety of research approaches including case-studies where events or processes are studied in depth (Scotland, 2012, p.12); phenomenology in which direct experience of people is studied to understand their perception and interpretation (Smith, 2004, p.39); hermeneutics which seeks to find meaning in literary texts (Mingers and Willcocks, 2004, p.103); and ethnography where cultural groups are studied over some time (Denzin, 1997, p.127,128; Smart, 1998, p.111). A limitation of interpretivism arises because it has abandoned verifiable scientific procedures and thus it is difficult to generalise results (Mack, 2010, p.8). Another criticism of interpretivism suggested by Hudson and Ozanne (1988, p.516) is on the question of how the researchers bias influences the outcome of the work. This stems from the subjective nature of the interpretivist ontological position and illustrates the difficulty in eliminating bias acquired from the researcher's social/cultural backgrounds from the study.

Constructivist Ideology

The constructivists believe that both the inquirer and the inquired are fused into a single entity (Guba, 1990, pp.26, 27). Meaning (of the world) is derived primarily from the relationship between experiential and physical events (Benton, 2001, p.142). A subjective interaction, therefore, is the only way to unlock the individual's *Erlebnis* or 'lived experience' (Ponterotto, 2005, p.131). This subjective position thus requires a close prolonged interpersonal relationship with the participant to get a full grasp of their socially constructed world. Therefore, like the interpretivist, the constructivists are also criticised for what Schwandt (1994, p.224) describes as the paradox of developing an objective interpretive stance of subjective human experience. Also, the constructivists confuse ontology and epistemology resulting in 'epistemic fallacy.'

Note that constructivism is also sometimes referred to as Interpretivism as it places great emphasis on the construction of meaning from social and political phenomena (Mack, 2010, p.9). Although both constructivism and interpretivism hold a similar ontological viewpoint in terms of the subjectivity of reality, they differ in their views on what reality is, and how meaning is made of the world. According to Schuh and Barab (2007, pp.71 & 72), the idealist holds the view that the world is not separate from the mind hence reality is mental. On the other hand, the relativists are 'ontologically sceptical about nature' (Benton, 2001, p.142) and believe that there is no absolute truth.

Critical Realism

Following from the criticisms of positivism, interpretivism, and constructivism, Bhaskar (1986, p.13) developed critical realism as an alternative approach (Carlsson, 2012, p.294). Critical realism distinguishes between the three overlapping domains of the real, the actual, and the empirical (Bhaskar, 2008, p.47). This is important because it distinguishes the critical realist from the empirical realist as it separates structures and mechanisms from the events that are generated. The domain of the empirical consists of what is experienced making it possible to distinguish between the physical, the socio-cultural, biological, chemical and psychological (Dean, Joseph and Norrie, 2005, p.8). The domain of the actual refers to events and behaviours (Carlsson, 2012, p.295); and the domain of the real is identified as causal mechanisms, relations, structures (Elder-Vass, 2007, p.10). Therefore, the critical realist attempts to attain true knowledge by filling the gap between the real and the experiential in the different layers of nature.

Unlike the constructivists who reject the notion of ‘truth’ (Schwandt, 1994, p.238,239), the critical realist accepts that true knowledge of real objects in nature is possible (Sayer, 2000, p.2). The fallibility of knowledge is also readily accepted suggesting that knowledge lacks guarantee due to the reality of constraints on human knowledge (Dean, Joseph and Norrie, 2005, p.8). It is no secret that such factors as time and space act to constrain what is known, how much is known, and when it is known. The concept of truth presented by the critical realist (referred to as alethic truth), however, has been criticised by Groff, (2004, pp.70–72) as being unsound and untenable because it appears to be an absolutist theory of knowledge.

The nature of this research on ethical and social issues of additive manufacturing features more or less in the social domain and it requires close interaction with the subject whether directly or indirectly. The researcher believes that social reality is co-constructed and that although the world, as well as its structures, are real, active interaction of individuals with the world helps shape their meaning of reality (Horner, 2016, p.22). This view is expressed most coherently by the critical realist who also agrees that the world is real with real structures, events, and mechanisms and recognises the need to apply different methods to find knowledge (Mingers, 2006a, p.14). The critical realist understands that natural laws cannot be applied to the study of society because of inherent structural differences. It also recognises the need to go beyond the observable to investigate mechanisms behind and beyond events to derive a true understanding of social situations (Buchholz, 2016, p.1). Therefore, a critical realist epistemology is well suited to this research as its application would enable the researcher to demystify and understand any ethical issues that might be associated with the use of the technology and explain how the technology could be better utilised to minimise the negative social effects.

3.4 Hermeneutics

The term Hermeneutics was derived from an ancient Greek word *hermeneuein* which can be rendered ‘to translate’ or ‘to explain’ (Introna, 2011, p.232; Zimmermann, 2015, p.10; Palmer, 2016, p.13) and refers to the art of understanding and making oneself understood. The history of Hermeneutics dates back to Aristotle (Caputo, 2018, p.6) who wrote the book ‘*Peri hermeneias*’ a treatise on interpretation and highlighted how words, whether spoken or written, can be considered as expressions of the inner thoughts. According to Ermarth (1981, p.175), there are two distinct forms of hermeneutics i.e. traditional or methodological hermeneutics and the radical or ontological hermeneutics. While the traditional version is more concerned with the justification of interpretive understanding as a 'science', radical hermeneutics goes deeper than that and is at the very nature of understanding itself.

Traditional hermeneutics can be traced back to the 17th century when hermeneutics became increasingly important for interpreting the biblical text (Harrison, 2006, p.116). The goal of such theologians was how to reach the right interpretation of scripture. During the enlightenment period, hermeneutics was expanded to an all-encompassing general theory of textual interpretation following in the example of Aristotle and having close links to logical positivism (Magee, 2011, pp.35–36). It was in this period that hermeneutic rules were developed as the basis for good interpretive practice that could be applied to all type of subject matter.

One of those who made major contributions to hermeneutics around this time was Friedrich Schleiermacher (1768-1834). He extended the understanding of what is now known as the 'hermeneutic circle' – the idea that understanding the meaning of text involved repeated movement between the whole and the parts – to every aspect of human understanding (Zimmermann, 2015, p.29). He felt that while the written text remains constant, the context in which it was written was relevant and so the purpose of hermeneutics was to enable understanding by reconstructing the original context to understand the author's intentions.

In the 19th century, hermeneutics reached a different turn. Wilhelm Dilthey (1833-1911) was prominent in this period and he saw hermeneutics as the foundation of the humanities and social sciences (Introna, 2011, p.5). He, however, advocated for a more objective approach to hermeneutics while focusing on '*verstehen'* or understanding and less on the problem of explaining nature. Dilthey (1989) confronted the problem of the hermeneutic circle and emphasised the role of 'human experience' in this. He suggested that to understand a text, one must have a prior idea of its whole meaning, yet can know the meaning of the whole through knowing the meaning of its parts (Newton, 1988, p.103) thus emphasising constant interplay and feedback between the whole and parts. It, therefore, became evident that the historical position of the interpreter could influence interpretation (Strenger, 2001, p.12458) and the model of one meaning behind the text was seen as problematic.

Ontological hermeneutics, the form that took off in the 20th century, claims to be radical in the sense of being truly philosophical, fundamental and critical (Ermarth, 1981, p.176). Proponents of radical hermeneutics have advanced many of the ideas of the more traditional hermeneutics. For example, while hermeneutics was extended from special canonical text to more general forms of text by the traditionalist, radical hermeneutics moved hermeneutics further to include the subject of being (ontology). One of the most influential ideas of hermeneutics includes those of Heidegger (1927). Heidegger promoted hermeneutic phenomenology and the use of hermeneutics in art and poetry (Hainic, 2012, pp.233, 244). According to Zimmerman (2015, p.5), Heidegger viewed hermeneutics as the kind of interpretation that listened for an important message or announcement of crucial importance. He felt that understanding isn't confined to interpretation of a text, but is encapsulated in what he called '*Dasein*' or existence, suggesting that human existence is embedded in understanding.

Building on Heidegger's ideas, Gadamer (1960) one of his students, developed a distinctive dialogical approach to hermeneutics which conceived of hermeneutics as a dialogue and dialectic set in the text. This conception of hermeneutics was a break from the methodological context for which the subject was previously approached. According to Kögler (2014, p.48) dialogue is a real agent of interpretation because it would always lead to a new shared view of the subject matter even when agreeable outcomes are not achieved. Analysis following the dialogic approach requires some preunderstanding of the subject matter and the relationship between the interpreter and the text in question can then be modelled on a real conversation between two individuals having a real conversation. The cultural and historic background of the interpreter thus plays an important role in the realisation of the meaning of the text as it enhances the process of understanding.

In the wake of its rich history and its practicality, hermeneutic ideas have been applied in many other fields including law, business, accounting, auditing etc (Olson and Carlisle, 2001, pp.2030 & 2031). In was however in the 1980s and early 1990's that Information Systems researchers began to actively apply hermeneutic approaches to their research (Introna, 2011, p.1). One of the earliest to apply hermeneutics in the IS field is Boland (1985, pp.184–185) who argued that text is central to information systems as an output, in the use of IS, and in organisations, where the interpretation problem could be solved hermeneutically. Similarly, Introna (1993, p.3) argued for the application of the hermeneutic paradigm in IS research explaining that to understand information, one must start with the most fundamental theory of meaning i.e. hermeneutics. Examples of how hermeneutics have played an important role in some 'IS' research can be seen in Olson and Carlisle (2001, pp.2030–2033) and Introna (2011) who have highlighted some interesting uses of hermeneutics in this field.

One way hermeneutics can be used in IS research is by the application of the dialectic approach based on the works of Gadamer (1975). Myers (1995) argued for a contemporary dialectical hermeneutic approach in IS research in an article titled 'Dialectical Hermeneutics: a theoretical framework for the implementation of information systems. In the article, it is pointed out that dialectical hermeneutics places emphasis on the idea that social reality is historically constituted. When doing such research, data from interviews, case study notes, or documents that record the views of research participants and events need to be ordered, interpreted, and explained according to the researcher's theoretical position. To fully understand this data, the researcher needs to compare one set of text with the other, for example, comparing a participant's statement with that of a document. A dynamic interplay does ensue between a hermeneutic analysis and theoretical critique that is grounded in social reality. Also, the whole is continually revised as a result of a reinterpretation of the parts as the researcher gains more understanding. The researcher must therefore be aware of their history as it influences the research as well as the dialectic between the text and the interpreter. The dialectic hermeneutic is interpretive, critical, not purely subjective, and historical.

Another prominent suggestion for the application of hermeneutics in IS research has been made by Klein and Myers (1999, p.72). They propose a set of 7 principles for interpretive Information Systems research following the hermeneutic approach. These principles include:

i. The fundamental principle of the hermeneutic circle which suggests that understanding may be achieved by iterating between the interdependent meaning of the parts and the whole;
ii. The principle of contextualisation which requires critical reflection on the historical background of the study and its context to show how the current situation of the study emerged;
iii. The principle of interaction between researchers and subject which requires critical reflection to show how socially constructed data was collected through the interaction between researcher and participant.
iv. The principle of abstraction and generalisation which applies principles, general concepts, or one or two theories to describe the ideographic details obtained from the data.
v. The principle of dialogical reasoning where sensitivity to possible contradictions in the theoretical preconception that influence the research and the findings obtained cycles of revision.
vi. The principle of multiple interpretations where researchers show sensitivity to a possible difference in the way participants interpret the subject as they provide different narratives.
vii. The principle of suspicion where sensitivity is required in addressing biases and systemic distortion in participants narratives.

While it has been suggested that these principles are interrelated, they are not bureaucratic rules of conduct and their use is not mandatory (Klein and Myers, 1999, p.71). Yet, there is no suggestion that some principles may be selected arbitrarily while ignoring others. The choice of principles used will depend on what the research is and judgment and discretion should be used in deciding what principles are used how they are applied. In a similar vein, Zimmerman (2015, p.2) agrees that hermeneutic cannot be reduced to a set of interpretive because hermeneutics is an art rather than rule-governed science that is inherent in day to day activities when one tries to grasps the meaning of something. In this research, hermeneutics provides the theoretical framework guiding the data collection and analysis.

3.5 Conclusion

This chapter has shown the importance of the philosophical approaches of ontology and epistemology to research. Although they are sometimes not explicitly stated in studies, this is a very important issue and all researchers must take a stand on what section of the divide they stand. It has been shown here that the researcher believes the world is real and that the dynamic nature of humans means that society is constantly changing. Therefore, the ontological and epistemological position of the critical realists best fits the researchers' beliefs and is thus applied in this work. It is also compatible with the inductive learning logic as they all encourage inference from a specific premise even if they are based on probability rather than certainty. It has also provided a description of hermeneutics which has informed the methodological considerations for this research.

Chapter 4 **Research Methodology**

4.1 Introduction

An attempt has been made in this research to structure this inquiry as closely as possible to the principles of interpretive hermeneutic research as proposed by Klein and Myers (1999, p.72) and highlighted in section 3.4. Although the principles are said to be interrelated, there are no hard and fast rules for their application and their fastidious use is not mandatory. The selection of appropriate principles for any research project requires discretion and the exercise of judgment in deciding whether, how, and what principles to be applied and appropriated.

4.2 Collecting and Analysing Research Data

4.2.1 Data collection

Data for this research was collected primarily from DIY 3D printing hacker groups like hackspaces, maker spaces, and fablabs based mostly in the UK in cities like London, Leicester, Bolton, and Glasgow, and at least one based in Germany. Before selecting participants, it was important to consider the principle of contextualisation which Klein and Myers (1999, p.72) maintains requires the application of critical reflection on the historical background of the study and its context.

The researcher reviewed the historical origins of 3D printing (see section 2.2.1) and understood the important role played by DIY hacker communities in the development of the technology. They helped in bringing the technology to the desktop and made it accessible and quite affordable for the general public. Also, the researcher felt that openness was an important theme in the culture of such groups, they were likely to be more open to discoursing issues around the ethics of AM. Therefore, a decision was made to situate the research in the context of such communities to provide an opportunity for relevant stakeholders to share their perspectives and knowledge on the issues being investigated in this research.

However, it is important to point out that in selecting participants, no reserve was taken to specific industries where additive manufacturing is used e.g. biotechnology, medicine, fashion etc. The researcher's interest lies mainly on cross-cutting issues which the technology promotes and specific industries wouldn't capture all the issues associated with the technology. This decision sits well within Klein and Myers (1999, p.73) view that "various context can be explored… the choice largely depending upon the audience and the story the author wants to explore". The researcher feels that the lived experiences of users in the selected category (i.e. DIY hacker groups) will enrich the discourse based on the rich history and culture of such groups.

The issue of access and approachability was also considered by the researcher. Initially, the researcher felt that the DIY groups were ideal because of their ethos to openness and their willingness to not only talk about topics related to 3D printing. An effort was therefore made to recruit participants from hackerspaces, fab labs, and maker spaces due to the approachability and community atmosphere around such groups. However, on visiting some of the groups e.g. the Leicester hackspace which was at the time situated in the premises of DMU, the researcher found that some were wary of talking about ethical issues. In the Leicester hackspace, apart from the problem of low attendance to the hackspace, the few who were available were 'too busy' and advised the researcher to try the London hackspace which was bigger and had more active members.

On visiting the London hackspace, the researcher soon found that it was a members-only area and other than on open-days, visitors weren't welcomed. To get access to members and to become better acquitted with the technology, the researcher then decided to become a registered member of the London Hackspace for a year. Due to time and distance, however, the researcher was only able to attend events once each month and data collection spanned a period of 13 months starting from February 2018 to March 2019. Nevertheless, these meetings presented opportunities for the researcher to observe and socially connect with the 3D printing community. It also presented an interesting learning experience for the researcher, creating more understanding of the 3D printers are used and extending the researchers horizons.

The researchers understanding was boosted by not only watching but also participating in 3D printing activities including being part of the entire process to print keyholders like the one shown in Figure 4-1. Such activities enabled the researcher to see first-hand how 3D printing promotes some issues e.g. plastic waste as several prints had to be discarded midway during the process due to errors.

Figure 4-1 3D printed keyholder which the researcher participated in creating

A total of 17 participants were involved in this study, however, the quality of one of the recordings was too poor and it couldn't be used for the research. Before concluding the data gathering section therefore, the researcher had to determine if the interviews conducted were sufficient for this research. The question of the number of participants had to be addressed as some research especially those with a quantitative approach usually had more participants. Dworkin (2012, p.1319) however notes that samples in qualitative studies are normally much smaller than those in quantitative studies. This is usually because frequencies and confidence intervals are rarely important in qualitative studies. For some research, a single case or an occurrence of the phenomenon could form the basis of such studies (Mason, 2010, p.1). Also, meaning-making is more important in qualitative studies than a generalised hypothesis which usually requires large data sets.

The approach to sampling or participant selection for this research closely follows the purposive sampling technique where respondents are selected based on their fit to the research theme. The choice of this technique takes into consideration the nature of the technology under investigation. As an emerging technology, additive manufacturing is not yet well understood by a large proportion of the society, and so it is only appropriate to consider only those with some level of expertise in its workings. Also, such factors as time, effort, and finance which are quite limited for the research were taken into consideration. Therefore, participants were selected with a bias to expertise or knowledge in the field of additive manufacturing. Only those who work closely in innovation or research with the technology were considered for participation. Particularly, the research looked to interview members of 3D print communities 'HackSpaces', makerspaces, and FabLabs around Europe.

The 16 interviews that were eventually used have generally been classified into 2 groups – those from academia and those from SMEs. Four of the participants were from academia and engaged in teaching at UK universities. While one of them was also a post-doc researcher of 3D printed smart materials otherwise referred to as 4D printing, a second was also involved in PhD research of 3D printed textile fabrics. Interestingly, the third participant (P9) who teaches 3D printing at a university, also has a second job in a 3D printing start-up. Note that in section 5.5 of the pilot study report, participant P5 who is an ex-lecturer and a major innovator in the 3D printing arena and has made huge contributions to the development of the desktop 3D printer.

Nevertheless, the involvement of P5 in additive manufacturing is described in section 5.5 with regards to SMEs. This is because of the dual role this participant plays as an academic and involvement in a 3D printing start-up. This should not be considered a contradiction as P5 is one of the few participants (along with P9) that can sit conformably in either group.

Also, classifying it in this way allows for an interesting dissection of P5's involvement in additive manufacturing. For participant P5, it was academic research in the field of Mechanical Engineering that first led P5 to the innovative contributions made in desktop 3D printing. However, after retirement from academia, much of P5's involvement in AM has continued via SMEs like RepRap maker communities. A summary of the participants from academia is shown in Table 4-1

Table 4-1 Participants from Academia

PARTICIPANT	INVOLVEMENT IN AM INDUSTRY
P5	Ex-Lecturer and innovator of 3D printer
P8	Lecturer and Post-Doc Researcher (4D printing)
P9	Lecturer and 3D printing technician at start-up
P12	Lecturer and PhD candidate (3D printed textile fabric)

With regards to participants in the SME category, three of the participants – P10, P11, and P15 are all company directors and owners of 3D printing businesses. Interestingly, one of these directors also works as a volunteer in a global volunteer organisation providing plastic prosthetics mainly for children who are growing. Another of the participants (P2) is a 3D print store manager with a background in mechanical engineering who also serves as a consultant in the business. While participant P6 is the editor of a prominent 3D printing magazine, participant P7 is a graphics and media designer for a 3D print bureau. P14 indicates he is a design engineer applying his skills in a 3D print business. Participants P3 and P4 are both product designers although P4 describes himself as an engineering product designer. Also, participant P13 who is actively involved with hackspaces and has contributed greatly to the development of open-source software for 3D printers is a robotics engineer and electronics design consultant.

A summary of the roles of participants in the SME category is shown in Table 4-2. It shows that the participants include 3 company directors and the manager of a 3D printing business; 2 product engineers, a design engineer, an electronics consultant who also doubles as a robotic engineer, as well as the editor of a 3D printing magazine it also shows that one of the participants was a 3D scanning and printing intern and another a graphics and media designer.

Table 4-2 Participants from SMEs

PARTICIPANT	INVOLVEMENT IN AM INDUSTRY
P1	3D scanning and 3D printing intern
P2	Manager & Consultant (Mechanical Engineer)
P3	Product Designer
P4	Engineering Product Designer
P6	Editor, 3D Print Magazine
P7	Graphics and Media Designer
P10	Company Director and Volunteer 3D prosthesis maker
P11	Company Director (Mechanical Engineer and a Product Designer)
P13	Electronics Design consultant and Robotics Engineer
P14	Design Engineer / ISO subcommittee member
P15	Company Director (Engineering Product Design)
P16	Hobbyist and Fablab enthusiast

During data collection, the researcher endeavoured to remember that the interaction between the researcher and subject is the heart of the research process and that there is a tendency to interpret the research phenomenon through the lens of the developing relationship. Thus calling to mind the principle of interaction between researcher and subject which Klein and Myers (1999, p.81) suggest requires critical reflection to show how the socially constructed data was collected through the interaction between researcher and participant. Before data collection and throughout the process of data collection, the researcher spent time reflecting on how best to interact with each participant to get the best out of the process. The researcher recognised that in some cases the profile of the participant meant that the balance of power might be skewed towards the participant. For example, one of the participants had been awarded the honour of Member of the Order of the British Empire (MBE) for achievements in the AM industry, and therefore the researcher had to reflect on how best to cultivate the relationship with the participant.

Data were collected by administering a set of semi-structured open-ended interview questions (see section 5.6 for details of interview questions). Participants were encouraged to contribute as much detailed information as they felt appropriate. The questions were designed to address the three research questions of this study. According to van Manen (2016, p.98), “the art of the research in the hermeneutic interview is to keep the question (of the meaning of the phenomenon) open, to keep himself or herself and the interviewee oriented to the substance of the thing being questioned." Therefore, open-ended questioning was used to encouraged the participants to reflect on their experiences and provide a rich description of their ideas.

Also, Zimmerman (2015, p.55) points out that our understanding of the world emerges through conversation with others. To keep the questions as open as possible, a conversational interview format was utilised as it enabled the dialogue between the researcher and participant to flow flexibly while exploring the research subject. And as Gadamer (1975, p.330) stated that "the art of questioning is that of being able to go on asking questions" the interviews were designed to allow enable follow up questions to be asked where there was a need for further clarification or explanation. Note that more details of this are provided as part of the pilot study discourse in section 5.6 and 5.7. However, some it should be noted here that some of the techniques used to enable the conversation to go on include encouraging the participants to tell their story and to provide further details where necessary.

4.2.2 Transcription of interviews

During the interviews, digital recorders were used to capture the conversation between the researcher and the interview participant(s). Also, on getting relevant permissions from participants, Internet Relay Chat (IRC) was used to communicate with some of the volunteers in this research. Other methods for capturing data were also considered including note-taking and analogue tape recording. However, note-taking wasn't deemed suitable for this study as a primary method of data collection because of the distractions it will bring into conversations with participants. Nevertheless, it must be pointed out the periodically, notes were taken to supplement the primary data collected. A tape recording was also discounted because of the poor quality of such recordings due to background noise and tape hiss introduced while recording. Digital recordings allow for a more accurate account of the communication to be obtained. Where necessary, digital editing software tools like 'Audacity' was used to improve audio quality.

Following the interviews, verbatim transcription was done so that a full written version of the interview was taken. This was done with the aid of transcription software 'oTranscribe', a free web application developed to minimise problems associated with transcription (Bentley, 2013). Unlike other paid-for tools like 'Rev', 'oTranscribe' has the advantage of being a free web-based tool. Another benefit of 'oTranscribe' has over other such tools including 'Cogi' is that it auto-saves data being typed in, minimising data loss in the case of the computer suddenly going off. Another advantage is that the audio player and text editor are located on the same page thus reducing the need to toggle between two programmes. Also, it auto-rewinds a few seconds during stop-and-play to assist the researcher to easily follow the progress with the transcription.

4.2.3 Data Analysis

Analysis began after each interview was transcribed. However, it should be pointed out here that there were several phases of analysis in this research but only three of the main ones will be highlighted here. One phase of the analysis required reading and re-reading each interview transcript in an attempt to ‘hear’ the meaning of the participant's message without altering the meaning. After this was done for the first five interviews that made up the pilot study, the second phase involved reading all five transcripts as if it was one document and trying to enter into a dialectic with the text. This was done by asking questions of the text, and seeking clarification when the answers weren’t quite clear as if engaging in a conversation with the interviewer all over again, then letting all five transcripts ‘talk to each other’ to get a fuller picture of the text. Kögler (2014, p.48) notes that the interpretation of a text or the actual speech is a dialogical process since it is two perspectives about a shared issue that are conjoined. Thus, this was one way that the fundamental principle of the hermeneutic circle (Klein and Myers, 1999, p.80) was applied in this research. Its application enabled terms to be clarified and helped to increase the researchers understanding of the data.

The third phase of analysis involved using the knowledge gained from the pilot study to shape the remaining data collection and analysis phases. Some of the interesting themes and issues raised during the pilot study were fed into the interviews as it helped to expand the researcher's understanding. This agrees with Klein and Myers (1999, p.79) view that as the ‘understanding of the parts become clearer’ it helps to ‘co-determine the meaning of the whole’. While the main questions didn’t change substantially, sub-questions were asked to allow the participant to reflect on their experiences. Supplementary questions like ‘what do you think about the particles emitted during 3D printing?’ or ‘does the smell of fumes bother you?’ were asked during the interviews. Such questions were not part of the original study design were fed into the interviews conducted after the pilot study phase to enable better understanding or to get clarification of some of the issues raised by participants in the pilot study phase. By moving back and forth between the different narratives and engaging in a dialectic with the who document, the understanding of the parts became clearer and helped to codetermine the understanding of the whole.

The hermeneutic circle can thus be said to have occurred during the repeated movement between each participants response and those of the group to find patterns by comparing metaphors and narratives, or explanations. Whenever further clarification was sought, the researcher continued to circle back between the responses of the relevant participant and those of the other participants to get the full meaning of the relevant text. This means that there was a continuous movement of understating during data analysis as the study involved which eventually resulted in a fusion of understanding. For example, when discussing their view on intellectual property issues, some of the participants put their responses in the context of the historical development of 3D printing but none painted a full picture of the situation. By circling between the individual responses and those of the group, a clearer picture was gained by the researcher which indicated that many in the industry didn’t feel that they were encroaching on the intellectual property rights by copying or scanning the works of others and 3D printing them for profit.

Thematic analysis was also done through several layers of coding to reduce the amount of raw data to what is relevant to the research question. In order words, to break the data into manageable sections for the development of themes (Vaismoradi et al., 2016, p.104). The analysis began with open-coding after first going through the transcripts to become immersed in the data. Initial coding was done manually in Microsoft Word by highlighting every segment of text that seemed relevant or that addressed the research questions (see Appendix III). This allowed relevant themes (words or short phrases) that sum up what was said in the transcripts to be easily identified. During initial-coding all meaningful, recurrent ideas, and key issues in the data were highlighted and coded.

After the initial coding stage, the coded text was reviewed, refined, or synthesised and all relevant data were gathered into potential themes. In cases where the codes were found to fit together, similar codes were clustered together in relation to the research questions and then labelled and in other cases, some of the initial codes were dropped as clarity developed. Each of the labelled themes only contains codes with similar meaning and the labels were carefully chosen to give a sense of the main ideas of the category (see Appendix III). It should also be pointed out that colour coding of the pilot study was done manually on printed paper, before repeating the process using Microsoft word by colour coding relevant text. It was done this way because it was the first attempt at coding for the researcher who wanted to get familiar with the concept of coding before using automated tools.

As the data grew and became difficult to manage manually, they were then transferred to NVivo which improved manageability and eased analysis. NVivo is a great tool for managing large volumes of data. It made it easy to track the coding of key concepts as they emerge. It also made it easy to locate the important themes that came out of the analysis. By constantly reviewing and comparing previous findings of themes and data, new categories or new concepts evolved and helped expand understanding of the data. Throughout the analysis, the reflective notes that were made during the interviews helped the researcher to make meaning, to remember, and to question the data where necessary. The ideas and themes were also compared with literature to help in the building up the researchers understanding. This meant that some of the researcher's initial understanding changed and some preconceptions were clarified, resulting in a new and improved understanding or fusion of horizons.

4.3 Detachment and the Problem of Prejudice

The idea of a dispassionate inquiry, which is what the positivists advocate is an impossible dream (Jaggar, 1989, p.163). Unlike the objective stance adopted in the positivist paradigm, research following the interpretive approach is often characterised by the need to understand the world from a subjective viewpoint within the frame of reference of the study participants (Ratner, 2002, p.1; Ponelis, 2015, p.538). This means that interpretivist researchers are not neutral disembodied observers and that their research is often influenced by their preconceptions, beliefs, and values (Walliman, 2011, p.22). Despite the subjective nature of interpretive studies, it has been argued that the interpretive researcher endeavours to remain detached enough to collect and analyse relevant data for the research (Norris, 1997, p.173; Baker, 2006, p.172; Takyi, 2015, p.865). Interestingly, however, Gadamer (1975, pp.273 & 273) points out that such a negative connotation of prejudice is problematic because prejudice can have a legitimate positive value for research, and in reality, all understanding inevitably involves some prejudice.

This is because to understand notions, concepts, or beliefs expressed by others, a connection with things already known has to be made, and then compared, adjudicated, revised, and transformed and understanding increases as the matter becomes clearer (Kögler, 2014, p.48). It can therefore be said that cultural and historical understanding and prejudice that a researcher has for a subject is an essential tool that enhances understating rather than reduce it. Thus, the principle of dialogical reasoning which requires the researcher to confront the preconceptions that guided the original research with data emerging through the process (Klein and Myers, 1999, p.76) played an important role in this research as it helped the researcher to see how prejudices could help enhance understanding of the research.

The principle of dialogical reasoning was instrumental in helping the researcher to confront personal biases and prejudices in the course of this research. One of such biases was instrumental in motivating this investigation into the societal issues of 3D printing which was inspired by the involvement of the researcher years ago in 2D design and printing. On learning about 3D printers, the researcher's fascination was mixed with curiosity on recalling that back in 2007 there was public debate about the health effects of indoor office printers as a result of an article written by Masters (2007) in Times magazine. The article exposed the problem of hazardous ultrafine particles being emitted by about 30% of printers used in offices. The ensuing controversy led to new regulations and corrective actions being taken by the print industry. Very little was known about any societal issues related to 3D printers in 2011/2012 and naturally, the researcher was worried that there could be similar health implications with 3D printers.

Another issue that may have led the researcher to some prejudice about 3D printers was informed by stories in the media about 3D printed weapons. As 3D printed weapons began to feature prominently in the media, the researcher was concerned about the proliferation of such weapons and the problematic impact this could have on society. The researcher felt that as 3D printers became more accessible in the home, they could easily be used to create weapons in the home and later be used for crimes that would be very difficult to prosecute. Such issues were the starting point for this research and informed the study design that required the consultation of experts who use the technology for their opinions on the problematic societal issues the technology may promote.

As the researcher interacted with participants, it was interesting to see how many in the industry weren't worried about such issues and weren't concerned about ethical issues of 3D printing. Interestingly, the first interview was with a participant who had a 3D printed weapon prominently displayed in their business premises and the interview aroused a kaleidoscope of emotions in the researcher as the participant discounted the media stories about 3D printers and made it quite clear that 3D printed weapons weren't a threat to society. Through dialogic reasoning, the researcher endeavoured to probe further to understand why the participant held such an opinion and to tactfully help the participant to reflect on their opinion by using questions like "*but do you think the ready availability of 3D printers could make the issues of 3D printed weapons a bigger issue?*" Yet, the response of the participant still did not change and the majority of participants also held similar views.

Such responses from participants made the researcher begin to feel the initial motivations for this research were unfounded prejudices and biases. However, taking into consideration that the principle of suspicion also requires sensitivity to the biases of the subject and their distortions of narratives (Klein and Myers, 1999, p.77), the researcher went on to conduct a thorough investigation into 3D printed weapons and found that their proliferation should remain a societal concern (see section 2.6.4). Thus, it appeared that socially created distortions were having an impact on the 3D printing community. The investigation revealed that the historical origins of 3D printing and the culture within the DIY Hacker community may have influenced some of the distorted narratives of some of the participants in this research.

4.4 The Research in a Nutshell

The diagram below (Figure 4-2) is an attempt to provide a summary showing how the hermeneutic approach influenced this study. Starting with the innermost circle, the diagram illustrates how the initial idea for this study began with the researchers prejudiced pre-understanding of ethical issues of AM. Recognising that prejudices are the basis of developing understanding, these guided the research design in the choice of questions and participant selection for the empirical study. The interviews were composed of open-ended questions during which the researcher endeavoured to proceed conversationally while also ensuring to get clarification on misconceptions. This enabled the dialogue to lead to an exchange of knowledge between the participant and the researcher.

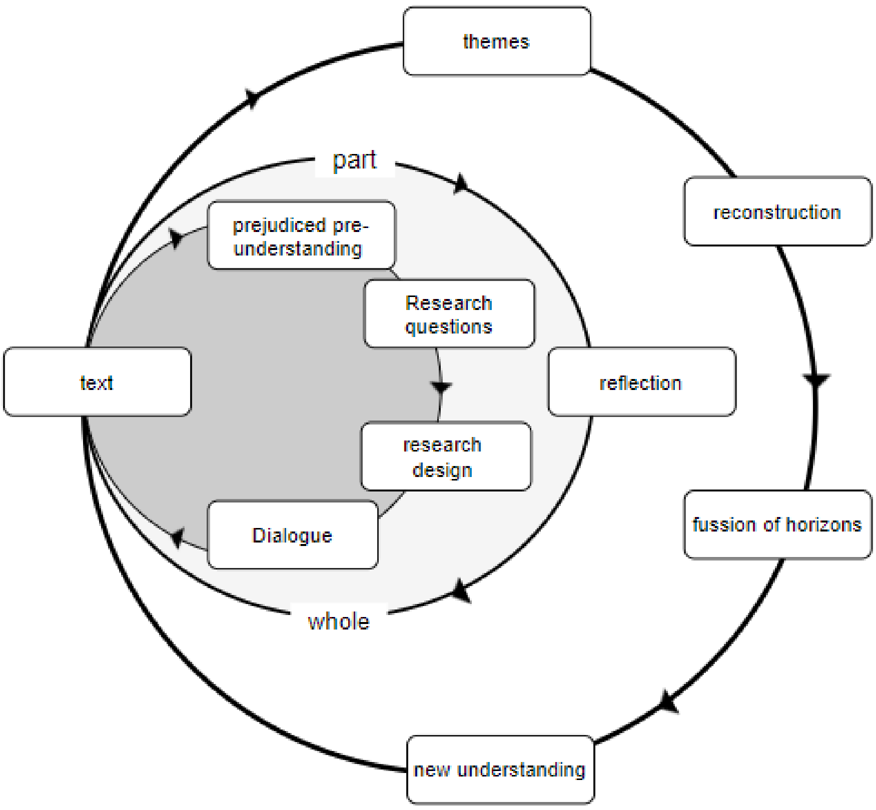

Figure 4-2 Illustration of the hermeneutic approach of this study

The audio-recorded interviews were then transcribed into text format. Interpretation proceeded through a systematic approach involving a dialectic with the text where the researcher asked specific questions of the text and then attempted to develop a full understanding by going back and forth between relevant parts of the text and the whole transcript. Critical reflection also played an important role in helping the researcher to get a fuller understanding of the data. This is because the research had to constantly reflect critically on the cultural and historical background of 3D printing, the participants, and the researchers own historicity in a bid to understand the information emerging from the study. Reading and re-reading the text alongside critical reflection was instrumental in enabling a clearer understanding of the researcher.

Data resulting from the analysis were then collected under relevant themes which were often reviewed to ensure correctness. The process of searching for themes was also an iterative process the researcher regularly went back and forth between different portions of text and the whole document to get meaning. The resulting information helped the researcher to reconstruct initial misconceptions and discard false prejudices. All of these enabled a fusion of horizons where new understandings were developed by the researcher based on initial prejudices which were broken down and the different world views of the participants.

4.5 Conclusion

In this chapter, an account of the methodology used in this research has been provided along with the reasoning behind the choices made. The account explained that hermeneutics is the approach upon which this research is based. The chapter also describes how this has guided the interpretation of the data collected and above all, the conduct of the researcher during this project.

Chapter 5 : Pilot Study

5.1 Introduction

A pilot study was conducted based on a smaller scale version of the research design to get insight on the feasibility of the research instruments and methods. The study was done to, among other things, test the clarity of the research questions, and to examine the appropriateness of the proposed research participants for the study. This chapter will describe the process of piloting, and then discuss the outcomes and the significance for this research.

5.2 Importance and Goal of Piloting

Piloting plays an important role in research studies. It has even been suggested that pilot studies are so important that they can be considered as the cornerstone of good research (Hazzi and Maldaon, 2015, p.53). An explanation for this can be seen in the definition of piloting supplied by Doody and Doody (2015, p.1074) thus "*A pilot study is a small scale version of a planned study conducted with a small group of participants similar to those to be recruited later in the larger-scale study*". As it is a small-scale version of the original study, a pilot study serves as a test-run for identifying issues with the research design. For example, Thabane et al. (2010, p.1) argue that 'a pilot study is synonymous with a feasibility study' and its main goal is to assess the feasibility to avoid potentially disastrous consequences.

However, contrasting arguments attempt to downplay the significance of piloting by suggesting that a feasibility study can be differentiated from a pilot study based on the goal of the exercise. Arain et al. (2010, p.4) for instance, takes this position which is also the agreed-upon position of the National Institute of Health Research (2018a). They argue that feasibility studies only answer the question 'can this study be done?' and is used to estimate important parameters (e.g. sample size and ease of participant recruitment) needed for the design of the main study. This is, in contrast, to pilot studies which are miniature versions of the main study and are focused on ensuring processes of the main study like randomisation and recruitment run smoothly (Arain et al., 2010, p.5; National Institute of Health Research, 2018b). Likewise, Whitehead, Sully and Campbell, 2014 (2014, p.130) warns against confusing feasibility with a pilot and maintains that while feasibility is an overreaching term, a pilot is a specific type of study that closely resembles the intended study.

Nevertheless, what remains undisputed is the value that piloting (which for this research is taken as a mini or small-scale version of the original study) is the value it adds to the research. As the pilot study closely resembles the original study, it allows the researcher to test out the research design and effectiveness of the data collection and analysis techniques. In the words of Feeley et al. (2009, p.85) it helps in ‘assessing the feasibility and acceptability of the design and procedures’.

Thus, the pilot study was an important stage in this research as it provided an opportunity for the researcher to test the study design, identify the types of issues that might prove problematic during this research, and to develop strategies to minimise issues with data collection and analysis.

5.3 Research Ethics Application

Prior to the start of the pilot study, an application for ethical approval for the research was first sought and approval was given by the Faculty of Technology Human Research Ethics Committee. This was done to ensure that the research survey instrument, consent forms for participants, information sheets, and the research project outline complies with the university’s ethical standards.

The ethical approval process required the researcher to identify ethical issues that may result from the research along with plans to address them and to put these to the Board. As the study will involve human subjects by way of interviews, the researcher identified several ethical issues that could result from this including issues of informed consent, beneficence, as well as privacy and confidentiality. Other issues identified are those relating to integrity like correctness of data, fabrication, negligence, authorship, intellectual property, and plagiarism.

To address the ethical issues identified, the researcher agreed to abide by relevant codes of ethical conduct and guidelines to protect the dignity, rights, safety and well-being of participants. The Social Research Association (SRA) ethics guidelines were used in this research0. The overriding principle in this regard is that the research causes no harm either during the investigations or by dissemination of the results. Participants were recruited voluntarily. Although translators were not used in the study, prior arrangements were made to ensure that any participants whose first language isn't English and required translation, would receive such a service to enable them fully understand the research objectives and to give informed consent. All volunteers in this research were also informed of their freedom to withdraw from the study at any time along with a signed acknowledgement.

Also, sources of data and other information collected through books, journals, articles, etc. have been acknowledged by way of references. Where necessary, permission was sought before the work of other publishers were included in this research. The researcher also agreed to use data collected only for research purposes and this data was neither manipulated, misrepresented, nor falsified to ensure integrity.

5.4 Sampled Population

Participants for this research were recruited from the additive manufacturing DIY hacker collectives within the UK and Europe. Based on their professional occupation, some participants may be said to be from academia, but of particular interest were persons from Small to Medium Enterprise (SMEs) involved in additive manufacturing. The Organisation for Economic Cooperation and Development (OECD) policy on SMEs notes that although SMEs are defined as non-subsidiary independent firms that employ fewer than ‘a given number of staff’, there is no universal agreement as to what that number is, even though in Europe, 250 is the most frequently used upper limit (OECD, 2000, p.2). For this research, therefore, the European definition of SMEs was adopted as the research specifically focuses on 3D printing users in this region. SMEs, therefore, is taken to mean non-subsidiary independent organisations that have less than 250 employees.

In recruiting participants, care was taken to ensure that they are all associated with the DIY 3D printing hacker communities like ‘hackspaces’, makerspaces, or FabLabs. Hackspaces are described as ‘community-operated physical spaces where people share their interest in tinkering with technology, meet and work on their projects, and learn from each other’ (Hackerspaces, 2015). On the other hand, Troxler (2016, p.109) describes FabLabs or fabrication laboratories as publicly accessible workshops or spaces offering digital manufacturing technology and electronic tools to anyone. And makerspaces are spaces that enable participants to create a range of artefacts specialist tools and resources like 3D printers and laser cutters (Marsh et al., 2017, p.7). However, in this research, the terms will be used interchangeably as Van Holm (2015, pp.2 & 15) maintains that they are synonymous with community spaces where members share tools for professional gain or hobbyist pursuits.

All the participants who volunteered for this research are associated with hackspaces, although many of them have other research and/ or innovation-related jobs where 3D printing is used extensively (e.g. those from academia). Some of the participants were from the official London and Leicester Hackspaces which are registered with the Hackspaces Foundation, some of the other participants are from Hackspaces not registered with the Foundation but are hackspaces nonetheless. Examples are the Hackspaces located in the Institute of Making at University College London (UCL), and the Innovation Centre located in DMU.

Five (5) persons volunteered to participate in the pilot project. The overriding principle applied in selecting participants was their involvement in 3D printing. Due to the nature of the research, specialist knowledge of the technology and the way this relates to social issues from the user's viewpoint were considered important factors for the recruitment of participants. The researcher was privileged to find volunteers that occupy a variety of positions within the AM industry and their varied opinions add dept to the research.

To put the sampled population into perspective, the number of participants is usually compared to the total population from which the sample was selected. It is, however, difficult to determine the exact number of DIY 3D printing hackerspaces available currently as the industry is still emerging and not well regulated at the moment. Nevertheless, to put this into perspective, Nesta (2020) an independent organisation that keeps tracks of the activities of such groups in the UK pegs the current number to 97.

Also, the UK Additive Manufacturing Steering Group (2016, p.20) suggests there were 250 organisations involved in AM in the UK in 2016. A similar estimate was suggested by Hague, Reeves and Jones (2016, p.22) as well as Li, Myant and Wu et al. (2016, p.26) who explain that 245 named AM organisation participated in additive manufacturing research projects in the UK between 2014 and 2016. Thus, a sample of 5 can be considered as an adequate representation for this research project. It should be stressed here that although all the participants are associated with 3D printing DIY hacker collectives, all the participants in the pilot study can be said to be from SMEs.

However, it is worth noting that although 5 is adequate for this study, another reason why the researcher had to work with only these during the pilot study was due to issues of access related to hacker groups. At the start of this study, the researcher had high hopes of recruiting many participants from hackspaces for this project as DIY groups like hackspaces have a culture of openness which the study could benefit from. However, while attempting to recruit participants, many said they were too busy and could not spare time for an interview. It appeared to the researcher as if they were happy to talk about 3D printing but weren't too keen on talking about ethics-related issues.

In a bid to boost the participant numbers, the researcher joined the Internet Relay Chat of the London Hackspace where regular free-flowing live conversations related to 3D printing usually takes place. The researcher felt that the virtual chat environment was a suitable alternative because it provided conditions for conversations that were similar to face-to-face conversations. After telling members of this group about the study, it was interesting to see that many were happy to get involved and immediately began to provide interesting insights into the ethical issues of AM. However, one of the participants raised an issue about the dissemination of the group's chat and pointed out that publishing these chats was against their policies. The researcher, therefore, decided to discontinue the conversation and destroyed the data collected from this group. As discussed in section 4.2.1 this was another reason that informed the decision to begin attending physical events of the London Hackspace in an attempt to recruit participants for the main study.

5.5 Pilot Participants Characteristics

As noted in the preceding section, the overriding principle guiding the selection of participants for this research was their involvement with additive manufacturing. The participant's involvement in 3D printing was in such areas as on-demand 3D Printing, 3D Scanning and modelling, manufacturing, as well as sales and service of 3D Printers and accessories. For anonymity, rather than use the real names of the participants in this report, they have been referred to with the alphanumeric codes P1 to P5 throughout.

Participant P5 who is the Director of a 3D print company has a background in Mathematics and Engineering, and while working as an academic at a university in England was actively involved in the invention of the first self-replicating desktop 3D printer called RepRap. P2 has a background in Mechanical Engineering and is the Manager of a 3D printing establishment, works as a consultant, is involved in the assembly of 3D printers, 3D scanning, and on-demand 3D printing. Participant P3 who has a degree in Product Design works in 3D design and production of 3D printed objects for a company and is a specialist jewellery designer. On the other hand, both participants P1 and P4, are they are involved in 3D scanning, 3D Printing, and sales of 3D printers and accessories.

These participants can also be characterised using the taxonomy of 3D printing developed in this work (see section 6.5). The classification identifies 3 main groups of 3D printing users namely, the direct users, the indirect users, and the intermediary users. Depending on the level of specificity sought, these three groups can be broken down further into subgroups which provides more details of the users in 3D printing. The participants can all be classified as direct users because of their direct involvement in the manual operation of 3D printers. On the AM user cube (see section 6.26.2 and 6.3), they are represented on the y-axis node i.e. (0,1,0).

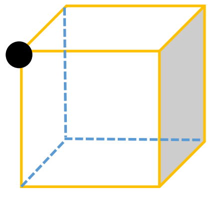

Figure 5-1 Representation of pilot participants on the AM user cube

The pilot participants are all in the generative service category because they are all involved in the generation of models and their subsequent manufacture using 3D printers. Furthermore, using the taxonomy of 3D printing users shown in section 6.5 these participants may all be placed in the hacker category due to their active membership and participation in hacker groups that uphold the opensource culture and many of the hacker ethos. This is as shown in Figure 5-2 which is a simplified way of showing that all the pilot participants are direct users who provide generative services and are all associated with the hacking culture.

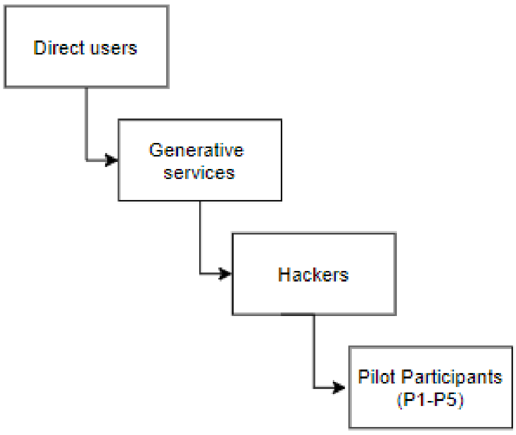

Figure 5-2 Simplified classification of the pilot participants

Nevertheless, it must be pointed out that Figure 5-2 oversimplifies the classification of the pilot participant because it doesn't take into consideration the actual use of the technology. This is because even within the hacker groups, members have different abilities and use 3D printers. A more accurate representation of the pilot participant is therefore shown in Figure 5-3 which splits the participants into 2 main groups i.e. facilitative services with a linked subgroup of printing service; and generative services with the linked subgroup of hackers and co-designers.

One of the pilot participants (P1) has been classed in the printing service group because the role he plays at his workplace mostly requires him to 3D print already designed models for customers. Participant P5 has been classed in the hacker group because he is a true tinkerer in every sense and was one of the founding fathers of 3D printing hackspaces in the UK. On the other hand, participant P2, P3, and P4 are grouped in the co-design class as they are involved in consultancy for 3D models, model design, and printing of objects.

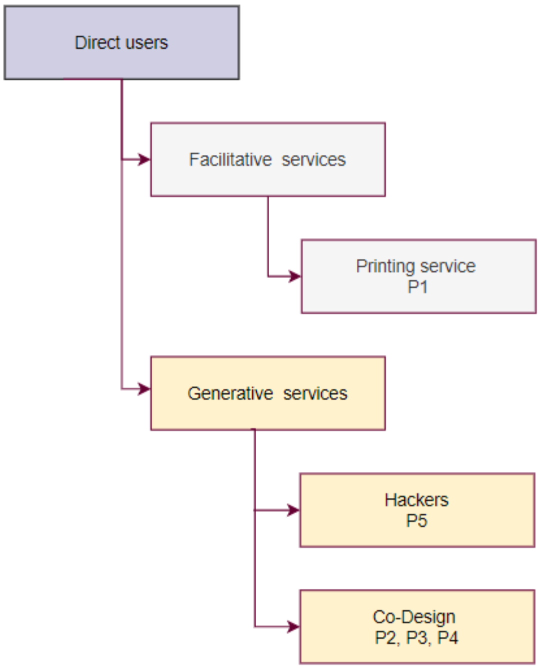

Figure 5-3 Rational classification of pilot participants

5.6 Pilot Data Collection Procedure

To ensure that participants were well informed about the study and that their consent to participate was properly documented, all participants were provided with an information pack. The information pack contained the following documents:

- Information sheet – this was a letter inviting recipients to participate in the research, stating the voluntary nature of participation, and the aim and objectives of the project, and that the interview data will be anonymised to help ensure privacy and confidentiality.
- Research project outline – provided a brief overview of the research and highlights the importance of studying ethical issues of emerging technologies like additive manufacturing. It also outlines points that will be considered during the interview.
- Consent forms – among other things, this form sought permission to record the interviews and to use anonymised quotes from the interviews in this research and other publications that may come from research, and that participants can withdraw at any time without any penalties.

Participants were encouraged to ask any questions that they might have regarding the research and to indicate that they had read and understood the information provided and consented to participate by signing the form provided. An audio recorder was then used to record the interviews. As the interviews were semi-structured, an interview schedule containing 10 points was used to guide the interview questions. The interview schedule was structured in such a way as to reflect the objectives of the research with the following points:

i. Involvement in the industry
ii. Who are the stakeholders
iii. How stakeholders are involved
iv. Unintended consequences of AM work
v. Awareness of ethical concerns
vi. How ethical issues are accounted
vii. Use of ethics code of conduct for guidance
viii. Understanding of responsibility
ix. Barriers to responsibility in the AM industry
x. How to ensure responsible innovation

As the interviews were semi-structured, the points in the interview schedule were designed to serve only as a guide to the researcher during the interview process to focus the line of questioning on relevant subjects. The points were presented as open-ended questions devised in such a way as to encourage participants to talk expansively about experiences, perceptions, events, and actions.

It is important to note that the pilot interviews were not fundamentally different from the main study interviews. The same interview schedule was used in both the pilot and the main studies, however, lessons learned from the pilot study especially those related to the interview process made it easier for the researcher to navigate the process during the main study interviews. For example, the researcher found that 4 of the 5 participants of the pilot study were completely unaware of developments concerning responsible innovation and had never heard of this concept before. The researcher felt this was a snag as the participant will be required to respond to questions about responsibility. To overcome this hurdle, a simple project outline was prepared to provide more details about the research and the relevance of responsible innovation.

5.7 Pilot Data Analysis

Analysis of the data collected from interview participants was done using thematic analysis. Braun and Clarke (2006, p.82) describe thematic analysis as a method for identifying, analysing, and analysis of themes within data. And Boyatzis (1998, p.4) describes a theme as a pattern in the information which describes important observations or interprets useful aspects of the phenomenon. Thus, activities usually performed during a thematic analysis includes labelling phenomena, and discovering and naming the categories, and developing categories into themes in terms of their properties and dimensions.

As the researcher sought to determine the participant's perceptions on the nature of ethical or social issues that AM may promote to bring the opaque issues into view or to quote Brey (2000, p.12) make these issues 'explicit', relevant themes were explored from transcripts of the semi-structured interviews. During this process, emergent codes where codes were inductively drawn from participants' responses. The decision to use these two coding techniques was made based on the philosophical assumptions guiding this research in terms of epistemology i.e. inductive approach (see Chapter 3) and the practical realities of the research shaped by the research objectives.

Data analysis was also influenced by the hermeneutic approach applied throughout this research. This meant that interpretation was stimulated by taking into consideration not just a single "part" of a statement but letting the analysis be influenced by a constant movement between the "whole" and the different "parts" of participants' statements. Thus the separate fragments of the responses received to the interview question, influenced the understanding of the whole interview, and vice versa. This is just as Klein and Myers (1999, p.71) explain that "to understand the individual parts of a sentence, we must attempt to understand the meaning of the whole of the sentence." By constantly circling between the parts and whole, an improved understanding of each part of participants' responses was obtained.

This pattern of interpretation involving circling from parts to the whole, also referred to as the principle of the hermeneutic circle, was applied throughout this research even when moving between participants' responses. It helped the researcher to develop a complex "whole" of shared meanings in terms of the ethical issues of AM. The interpretation was enhanced by the preconceptions the researcher had in terms of the prejudices that influenced this research (see section 4.3). It helped the researcher to identify personal misunderstandings of AM technologies and to adopt a critical attitude throughout the research such that false misunderstandings were suspended and true ones were better understood.

It should also be pointed out that to ensure that the anonymity of participants is maintained, the names of individual participants and their organisation was not used during the data analysis process and in the presentation of data. All the participants were represented with the alphanumeric codes P1, P2, …. - P(x). Also, to avoid using the real names of the companies that these participants worked, they are represented using the codes C1, C2 …- C(x). A summary of the outcome of the analysis is presented in the following section.

5.8 Pilot Study Outcome

The findings from the pilot study are to be discussed in combination with the main study findings to avoid unnecessary repetitions as the data are quite similar in terms of sampling frames and methodologies and because the characteristics of the pilot study sample isn't distinct from those of the main study sample. As noted in section 5.4 above, the most important consideration during recruitment was the participant's familiarity with AM technology and active involvement either in research or innovation. All the participants recruited for this study are experienced users of AM technology even though their experiences are at varying capacities and to varying extents.

Piloting helped identify the need to limit the study to the DIY 3D printing hacker community due to difficulty in recruiting individuals from large corporations as well as hobbyists who use the technology only at home. At the start of the study, it was assumed that the capacity at which the 3D printers were utilised didn't matter very much, however, early on in the course of piloting, the researcher found out otherwise. For example, one of the participants contended that:

> *… 3D-Printing is such a vast term and we need to remember that, so, 3D-Printing on this level compared to 3D-Printing on the medical level or in an industrial level… they are completely different beasts … (P3).*

It is now clear that simply describing the research as studying 'ethical Issues of additive manufacturing' may lead to confusion about the context of the research and how far it goes. This is because the context of the discussion here does not cover all types of stakeholders that use additive manufacturing technology. This research has found that different categories of users of 3D printing technology exist as can be seen in the taxonomy of 3D printing developed in section 6.5.

The context described here isn't so far-reaching and does not cover all these sub-groups due to difficulties in accessing some of these groups. For example, it was quite difficult to recruit participants from large additive manufacturing companies who engage in industrial-scale 3D printing and so the decision was reached to preclude such companies from the research. However, it is recognised here that there may be inherent differences in the way different users perceive the technology based on the historic or professional use of the technology. For instance, the issue of 3D printed guns as described by participants in this research might be addressed differently when looked at through the lens of industrial 3D print companies that are capable of 3D printing with metal alloys. While industrial 3D printers like those using Laser Sintering technology prints in metal easily, those commonly found in homes and small offices usually print in plastic filaments and resins.

Also, it later became apparent that issues faced by individual home users of 3D printers may not be addressed adequately in the course of this research due to differences in frequency of use of the 3D printers and the environmental differences between the home and office. It was, also decided that these groups are precluded from the research as the researcher would have problems with access to those individuals who use 3D printers at home only. As these types of users will usually only 3D print occasionally, some of the issues at stake might be different for them. For example, environmental issues due to waste plastic materials, and health-related issues due to fumes and ultra-fine particles (UFPs) emission might be negligible as the printers are not regularly used. Consequently, it seemed logical to contextualise the research as looking at ethical issues of 3D printing from the perspective of the DIY hacker communities as incorporate many different types of users.

The outcome of the emergent coding scheme which was applied during the analysis was the identification and selection of a broad category of themes for further analysis tagged 'ethical issues of AM' with sub-themes as indicated in Table 5-1.

Table 5-1 Main theme and Categories from Pilot Study

THEME	Ethical issues of AM
SUBTHEMES	Health-related Issues
	Environment
	Jobs
	Liability
	3D Printed Guns
	Business Ethics
	Offensive items
	Intellectual property rights

The emergent coding process was done inductively by using participants' experiences and opinions to build broad themes i.e. working from the bottom up, so to say. Through a hermeneutic process of reflection and interpretation which was guided by such questions as, 'what does this information represents?', what is being conveyed?' or 'what is at issue here?', initial codes were first developed, from which categories were named subthemes defined.

These subthemes were then revised and regrouped into the theme ‘ethical issues of AM. For example, the statement by participant P2 ‘*my biggest ethical issue is that am printing so much plastic*’ was considered important and was initially coded and then categorised as ‘plastic issue’. However, on further reflection, this statement was recorded under the subtheme with the label ‘environmental issues’. Eventually, the various social and ethical issues that emerged from, or were identified in the data were then collected under the theme ‘ethical issues of AM’.

5.9 Shortcomings of Pilot Participant Sample

It must be pointed out here that the pilot population though adequate for this study is not a sample of the public. It is only a sample of UK 3D printing hacker communities which is in reality only a small community compared to the population of the UK. Therefore, this may be seen as a limitation of this study because it is not large to be representative of the public. This means that in basing the discussion of this thesis on the results of a small population, a critical discussion which covers a wider societal perspective is being overlooked.

Also, this study may be criticised for being about meritocracy as it is situated within a population of experts. As shown in section 2.7 there is currently an ongoing debate on meritocracy in the tech sector where experts like engineers are considered the right people to make ethical decisions as opposed to ethicist and other stakeholders who can provide deep contextual understanding. Like Bogner, Littig, and Menz 2009 (2009, p.3) the researcher also feels that ‘limiting the selection of experts to the consideration of technical expertise alone places cognitive constraints on the analysis’.

Thus, to overcome this shortcoming, the researcher made effort to recruit participants who although are experts in 3D printing, have diverse backgrounds in terms of education and work such that their diversity could infuse an interesting mix of historicity and cultural perspectives into the study. It should be pointed out that the aim of this study is not about how scientific the experts can be but to understand ethics from the world view of the experts. The researcher believes that to effectively shape better ethical use of 3D printers, it is important to understand the attitudes, beliefs, and desires of the users of the technology, hence the use of experts in this study.

5.10 Conclusion

This pilot study was done to test the adequacy of the research instruments as well as assess the feasibility of a full-scale study. The test was successfully conducted with 5 participants while being guided by an interview schedule of 10 important points for consideration. The process was completed successfully, and sufficient qualitative data was gathered. Analysis of the data highlighted important themes related to the ethical issues of AM and responsibility in the AM industry which would be considered in the main study. This indicates that the research methods utilized, and the research design is suitable for the main research. However, the pilot study has flagged up important issues related to those related to health and the environment, which require further investigation. Consequently, additional investigation will be performed to ascertain the veracity of the claims made concerning the health and environmental impact of 3D printing. Nevertheless, the pilot study showed that the main study is feasible and that there is little or no need for changes to the study design. As the data from the pilot study was considered valuable for the main study, they have also been used alongside data collected for the main study.

Chapter 6 : Developing a Taxonomy of 3D printing Users

6.1 Introduction

In this chapter, the discourse on the taxonomy of 3D printing users which was started in section 2.5 is extended towards the development of a more complete taxonomy of 3D printing users. The section goes on to show how the taxonomy can be used to map existing taxonomies and illustrates how the taxonomy can be used to classify and assess societal issues of 3D printing.

6.2 The User Cube for Classifying 3D Printing Users

To classify users of 3D printers, this work draws inspiration from the 'User Cube' developed by Cotterman and Kumar (1989, p.1316) for classifying end-users of computer-based information systems (CBIS). They define an end-user as "any organisational unit or person who has interaction with a computer-based information system as a consumer or producer/consumer of information". This definition will be adopted for this work. However, the terms 'end-user' and 'user' are used here interchangeably to refer to anyone who interacts with a 3D printer either directly or indirectly as a consumer or producer-consumer[1] of information.

Note that the above definition only considers 2 categories of users i.e. the 'consumer' and the 'producer/consumer' while leaving out the 'pure' producer or 'producer-only' category. This is because the 'pure' producer or 'producer-only' category refers strictly to those individuals or organisations whose role is limited to the production of CBIS or in the case of this research, production of 3D printers. Thus, to classify end-users this group are not taken into account as they are not considered end-user in line with the definition of the term.

This agrees with Moilanen and Vadén, 2013 (2013, p.2) who define 3D printing end-users as those who use 3D printing services or 3D printers to create objects but are not involved in the development of 3D printing software or hardware. For this discussion, organisations and individuals who produce AM technology strictly for sale are not considered end-users. It is then, also important to understand whom the 'consumer' and 'producer-consumer' refer to. Cotterman and Kumar (1989, p.1314) describe the consumer as those who use or

[1] Note that producer-consumer is used here rather than producer/consumer to indicate a single idea. This is because '/' often connotes 'OR which is contrary in this context

consume the products of the computer-based information system. In this case, the consumer refers to users of additive manufacturing technology.

The producer-consumer, as opposed to ‘pure’ consumers, refers to those individuals or organisational units who both produce and consume the outputs of the CBIS. However, Cotterman and Kumar (1989, p.1315) identified three dimensions of ‘producer-consumer’ namely, Operation (i.e. initiation, termination, monitoring, or operation of a CBIS); Development (i.e. performance of tasks related to systems development including, programming, specification of system requirements and/or system design), and Control (i.e. decision-making authority to acquire, deploy, and use 3D printers).

These three dimensions of operation, development and control as defined by Cotterman and Kumar (1989, p.1315) were likely very useful for classifying CBIS at an age where computer-based information systems were either too expensive or the expertise required for operating them were scarce. These days, there is a very thin line between operation, development, and control with many CBIS. The 3D printer is a good example of such. It is a versatile tool that is easily available to many and allows for a wide spectrum of uses and users where such dichotomy is not so clear cut.

However, it must be said that there are certain situations where such distinction may still be valid today. For example, formal manufacturing where there is a strict separation of roles and responsibilities and the technology in use is too expensive to make it to the mainstream. Also, surgery is another area where the Cotterman and Kumar (1989) dimensions can be easily applied due to the nature of the job which requires a high level of expertise not readily available to the general public. In these situations, there is a clear distinction between those who are involved in the operation and termination of CBIS systems or manual operation of relevant tools; those who are involved in systems development and design; and those who control or have the authority to acquire and deploy such CBIS based resources or tools.

Nevertheless, such distinctions are not very useful for developing a taxonomy of 3D printing users because there is usually no clear separation of user based solely on such activities. For example, the owner and staff of SMEs where AM technology is used would likely be all jointly involved in the operation, control, and development of the technology. This is usually the situation where the technology is acquired for use in places like Hackspaces, Makerspaces, and FabLabs, or even where the technology is acquired for personal use.

One might argue that in bigger organisations like academic institutions with AM workshops, there is a clear-cut separation of powers and the dimension of control – the authority to acquire and deploy technology like 3D printers – is quite evident. Nevertheless, even in such institutions, it is usually not so easy to separate the other dimensions of operation and development as most people with the technical know-how to operate 3D printers also can develop to varying degrees software and hardware for 3D printers. Thus, it can be said that the separation of these dimensions is much blurrier for additive manufacturing.

6.3 The AM User Cube for Classification of Users of 3D Printer

For this work, therefore, the classification of end-users would be based on the seminal works of the Conference of Data Systems Languages CODASYL 1968, which categorises the consumer into 3 groups, namely indirect end users, intermediate end users, and direct end-users.

In this case, the indirect end-user is said to those whose only interaction with the technology is through artefacts and products they consume (for example children who utilise 3D printed toys for which they have not been involved in designing or manufacture). Direct end users actively use the AM technology by participating in the manual operation of terminals. This may be either through the development of software or hardware or through the design and manufacture of artefacts. They may also participate in the execution of manual tasks necessary for the operation of the technology. In the SME example earlier mentioned, the staff and owner of the 3D printing business would all be direct end-users. Intermediate end users, on the other hand, are midway between direct and indirect end users. They are actively involved in the specification of requirements for the development of artefacts for which they have a vested interest in. They are, however, not involved in the operation of terminals or the design and development of software. An example of an intermediate end-user would a customer at an SME who provides the specification for the design and manufacture of an artefact.

Interestingly, using this categorisation scheme in institutions like the university mentioned earlier, it is possible to classify users of AM technology into each of the three categories of indirect, direct, and intermediate users. The university administration or decision-making authority for acquiring, deploying, and assigning development priorities may be classed as an intermediate user as their role is one of ‘specifying requirements’. Within the institution, those individuals or personnel responsible for the design and development of artefacts and are involved in the manual task associated with AM technology are direct users. On the other hand, indirect end users refer to consumers of the outputs of the technology as their only interaction with it is either through the use of the products or through other societal impacts.

The benefits of using this classification scheme can also be seen in addressing societal issues due to additive manufacturing as it is now possible to classify those who do not have direct interaction with the technology but who are nevertheless impacted by its use and/or outputs. Such individuals or personnel can be classed as indirect end-users based on the CODASYL system. This addresses another problem of the end-user classification scheme proposed by Cotterman and Kumar (1989, p.1315). Grouping end-users into the categories they proposed – development, control, and operations to assess the risks associated with CBIS, alienates indirect end users who are also impacted by such technology.

The user cube developed by Cotterman and Kumar (1989, p.1315) is an interesting way to visualise the different dimensions of the end-user and it will be used here to visualise the end-users of AM. However, rather than represent the 3 dimensions of operation, development and control, suggested by the authors, in this case, the various possibilities presented are those of the direct, intermediate and indirect users. This is illustrated in Figure 6-1 where the x, y and z axes of the cube represent the indirect, direct, and intermediate users respectively. The 0 -1 limits at each of the cube's corner represents the extremes of each of the dimensions or the limits of a continuum.

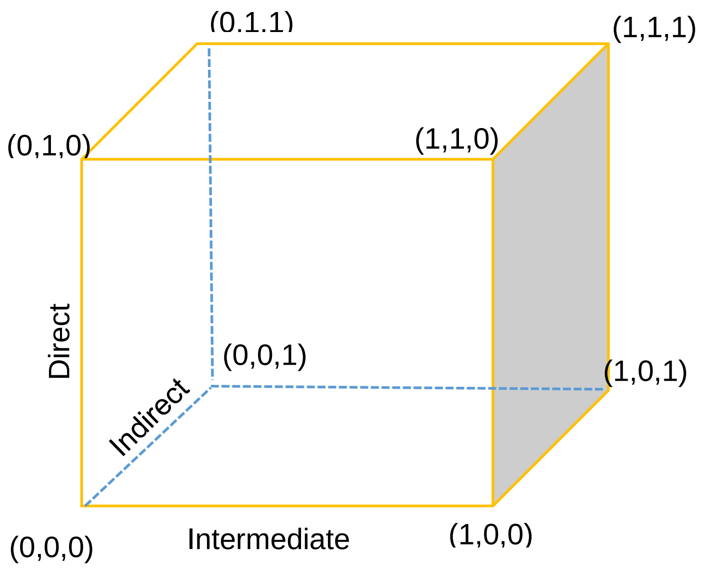

Figure 6-1 Additive Manufacturing User Cube

The different possibilities of user classification are described in Table 6-1. It shows that node (1,0,0) represents intermediate end users of AM technology who either specify requirements or have the authority to acquire and deploy AM technology in an organisation. Such ones have no direct use of the technology, but consume the output whether knowingly or unknowingly. For example, customers who simply by 3D printed artefacts such as fashion accessories; or in an organisational setting (e.g. for academic institutions) where some management staff have the authority to specify requirements for the use of 3D printers but do not get involved in the daily operation of the machines, and yet are impacted by some of the outputs of the machines e.g. noxious fumes and ultrafine particles. Indirect end-users correspond to node (0,0,1). They neither carry out any operational activity on 3D printers nor specify the requirements for their use. And node (0,1,0) represents the direct end-users who interact with terminals and participate in the manual operation of 3D printers.

As pointed out in previous discourses, the ease of using AM technology and the ready availability of cheap desktop 3D printers mean that there much greater fluidity in how end-users interact with it than with CBIS of the ’70s and ’80s. It is, therefore, not uncommon to see individuals who not only use outputs of the technology but also specify requirements and actively participate in carrying out manual operations on 3D printers. Such ones are also represented in the AM user cube in nodes (1,1,1), (1,0,1), (0,1,1) and (1,1,0) depending on the combination of user dimensions (see Table 6-1). For example, a prosumer or hobbyist who not only specifies the requirements of artefacts they ultimate use but also manually operates a 3D printer to create an artefact that they use would be represented on the nodes (1,1,1) – i.e. direct-to-intermediate-and-indirect user – indicating that they operate 3D printers (direct users), specify requirements (intermediate users) and use the objects printed (indirect users).

Table 6-1 User classification and description

Node (x,y,z)	User classification	Description
(0,0,0)	None	At the origin, all nodes are zero, implying there is no user
(1,0,0)	Intermediate	The x-axis references the intermediate users. They are involved in the specification of requirements for artefacts or systems for which they have a vested interest in. It also refers to the decision-making authority to acquire or deploy AM technology.
(0,1,0)	Direct	The y-axis represents direct users of the technology. They actively participate in the operation of terminals. This may be either through the development of software or hardware or through the design and manufacture of artefacts
(0,0,1)	Indirect	Those represented by the z-axis are the indirect users whose only interaction with the technology is through artefacts and products they are consumers
(1,1,0)	Intermediate-direct (i.e. intermedia and direct user)	These group of users are involved in both requirement specification (either in terms of software, hardware, or artefacts) and the operation of 3D printers
(0,1,1)	Direct-indirect (i.e. direct-and-indirect user)	They operate 3D printers and are also consumers of the outputs
(1,0,1)	Intermediate-indirect (i.e. intermediate and indirect user)	These do not operate 3D printers but may be involved in requirements specification and consumption of outputs
(1,1,1)	direct-intermediate-indirect (i.e. direct-to-intermediate-and-indirect user)	These are all-rounders who not only specify requirements but also operate 3D printers and are consumers of the outputs thereof

Another important advantage of the AM user cube over Cotterman and Kumar (1989) user cube can be seen at the origin of the cube correspond to the node (0,0,0). They contend that the indirect end-users or the 'pure' consumer corresponds to the origin of the cube, thus suggesting they do not exist. However, here they are properly represented in the z-axis of the cube making it possible to also consider their needs during the assessment of risks.

6.4 Mapping the Classifications in AM Literature to the User Cube

An attempt will now be made to map the taxonomies identified in the AM literature to the user cube developed for AM end users. Starting with the classification of 3D printing services in a supply chain developed by Rogers, Baricz, and Pawar (2016), it can be seen that they have identified 3 service categories i.e. generative, facilitative, and selective services which can be mapped to the user cube. For the generative services which they describe as services for generating 3D models and 3D printing, this corresponds to the node (1,1,0) on the cube because for this service, they use the 3D printer to create objects which after working with customers to understand and specify requirements. The facilitative service corresponds to the node (0,1,0) as their main business is to actively use 3D printers to manufacture physical objects. On the other hand, the selective services are represented in the node (1,0,0) because they are mainly a service for hosting 3D models and is a service that doesn't require manual contact with 3D printers or actual use of manufactured objects. This information is summarised in Table 6-2 below.

Table 6-2 Modelling the classification of 3D Printing Services described in Rogers, Baricz, and Pawar (2016)

AM Service	User			Corresponding Node
	Direct	Indirect	Intermediate	
Generative	x		x	(1,1,0)
Facilitative	x			(0,1,0)
Selective			x	(1,0,0)

The taxonomy developed by Rayna, Striukova, and Darlington (2015) can also be mapped to the AM user cube. Based on their description, those involved in design hosting (also called design marketplace) need not interact with the 3D printer and do not necessarily utilise the objects designed, they are therefore classed here as intermediate users (see Table 6-3). Similarly, design crowdsourcing and printing crowdsourcing can be categorised as intermediate and direct users respectively as there is no interaction with 3D printers for crowdsourced design while crowdsourced printing requires manual operation of the machines. Likewise, those who are involved in printing services only are classed here as direct users as this requires manual operation of 3D printers.

Table 6-3 Modelling the classification of 3D Printing Services described in Rayna, Striukova, and Darlington (2015)

AM Service		User			Corresponding Node
		Direct	Indirect	Intermediate	
Design	Design hosting / marketplace			x	(1,0,0)
	Design supply			x	(1,0,0)
	Co-design			x	(1,0,0)
	Crowdsourcing			x	(1,0,0)
Manufacturing		x			(0,1,0)
	Home printing	x			(0,1,0)
	Printing service	x			(0,1,0)

Interestingly, it can be seen from Table 6-2 and Table 6-3 that neither of these taxonomies considers the indirect users – whose only interaction with the technology is through artefacts and products they consume. This then means that, in discussions about the societal impacts of technology, a big segment of society will be left out and their needs and concerns would not be accounted for in such deliberations. Consequently, the benefit of the end-user taxonomy is evident in that it makes it possible to consider the impact of AM technology not only on those who carry out manual operations on 3D printers but also on those who consume the outputs of the technology.

6.5 A Taxonomy of 3D Printer Users

Having developed a classification system for users of 3D printers which has three dimensions of users i.e. direct, indirect, and intermediate users, the next step has been to adapt this information for the development of a full taxonomy of users of the technology. This was done by merging the existing classifications in literature with those of the AM user cube (Figure 6-1) to create the unique taxonomy of 3D printer users shown in Figure 6-2.

The taxonomy in Figure 6-2 is in 5 levels of hierarchy and shows that subsequent nodes are a subset of the higher-level nodes. It begins with the dimensions of the AM user cube which represents the higher-level segment of the taxonomy i.e. level 1. Then the facilitative, generative and selective activities described by Rogers, Baricz, and Pawar (2016) are the subsequent level i.e. level 2. Likewise, the classifications of online 3D printing platforms described by Rayna, Striukova, and Darlington (2015) and the Kapetaniou et al. (2018) taxonomy of industrial sectors of 3D printing form the basis of the level 3 category of the taxonomy. Level 4 is a subset of one of the dimensions of level 3 and is an entirely new category in the taxonomy of 3D printing as it has not been recognised in previous taxonomies. Similarly, level 5 which is a subset of 4 is an interesting category that should not be left out of any taxonomy of 3D printing users as has been the case so far.

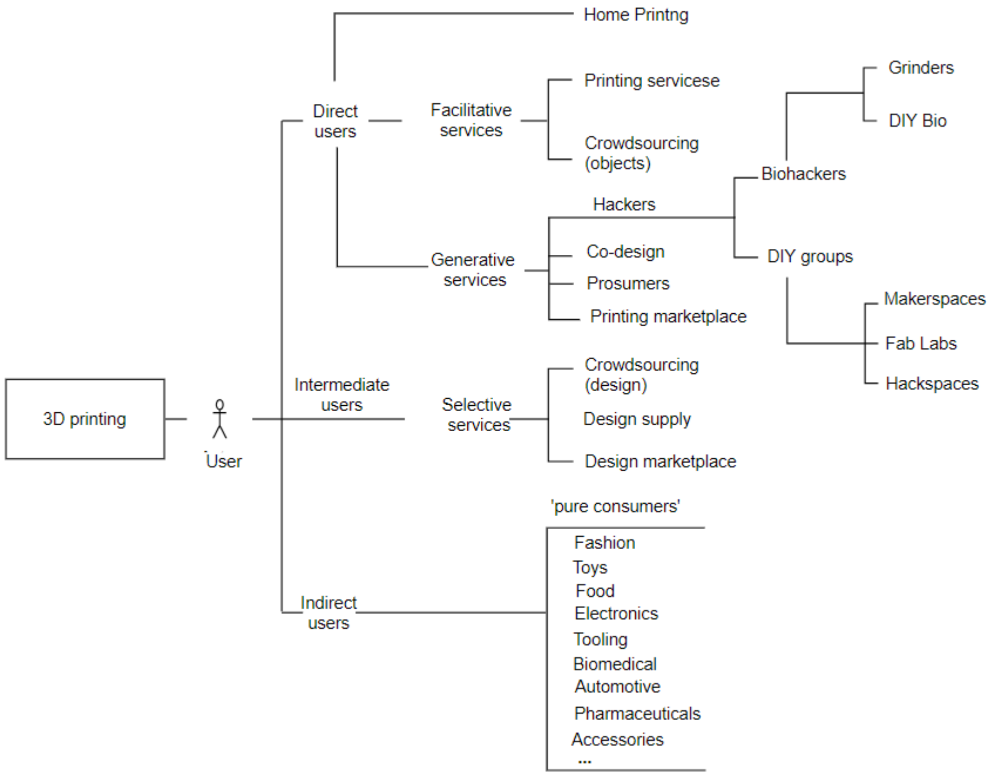

Figure 6-2 Taxonomy of 3D Printing Users

Besides indicating the connection between the existing 3D printing taxonomies, and adding new categories to the taxonomy of 3D printing users, it also makes it possible to include the ‘pure’ consumer – those whose contact with the technology is limited to the outputs they consume – in the taxonomy. Importantly, this new taxonomy of 3D printing also considers other types of users of the technology whose activities lie on the periphery of the regulated environment i.e. hackers and the subcategories associated with them i.e. biohackers with their DIY bio and Grinder categories; and DIY groups with the makerspaces, hackspaces, and fablabs. All of these make it possible for the impact of technology on the users to be assessed systematically. Table 6-4 describes the users in different categories.

Table 6-4 Description of main categories of the 3D printing taxonomy

Category	Description
Direct users	these actively use the AM technology by participating in the manual operation of terminals.
Indirect users	those whose only interaction with the technology is through artefacts and products they consume i.e. they are '**pure consumers**'
Intermediate users	they are midway between direct and indirect end users. They are actively involved in the specification of requirements for the development of artefacts for which they have a vested interest in
Generative services	they provide on-demand 3D printing services for generating 3D model and subsequently, 3D print them
Facilitative services	their services are focused on 3D printing and target customers who already have 3D models for printing
Selective services	Platforms that enable customers to select suitable 3D printing models from their database
Crowdsourcing design	refers to the co-creation of a 3D model by several people
Crowdsourced objects	an extension of the methods of crowdsourced design to objects such that several people with 3D printers pool these resources together to create objects
Home printing	those who manually operate 3D printers at home to create physical objects with models purchased elsewhere
Printing services	their primary business is the manufacture of custom objects for which consumers supply a design
Prosumers	having evolved from being mere consumers, these can now design and make products for themselves
Co-design	involves significant input from users who supply 2D images for transformation to 3D models and objects
3D printing hackers	refers to those who have adopted the hacking culture and ethos by their strong connection to opensource DIY space, tools, and resources
Biohackers	also referred to as DIY-Bio, they are DIY biologist who uses 3D printers for scientific experiments related to the body outside of the usual scientific, medical and commercial institutions.
Grinders	body hackers or those who modify their bodies in hope of achieving some form of human enhancement. Many have adopted some of the transhumanists philosophies
Design supply	These are platforms that offer 3D models of designs created inhouse either freely or for a fee
Design marketplace	platforms for hosting third-party designs that can be downloaded either freely or for a fee
DIY Groups	These are grassroots groups that have adopted the hacker ethos of sharing information, promote the DIY culture and create a space for community and cooperation
Makerspaces	They are driven by the idea of enabling craft and therefore create the space for multiple types of crafts to enable communities of hobbyists and professionals to share ideas
Hacspaces	Immersed in the hacker ethos, these community-led spaces tend to focus more on 'hacking' or getting things done and the tools required
Fablabs	They tend to emphasize the tools and equipment made available to the public to enable novices alongside professionals to make just about anything;
Printing marketplace	Hubs that provide on-demand 3D printing services for creating custom digital 3D models and 3D prints

In this new taxonomy of 3D printing users, ‘design marketplace’ and ‘design supply’ have been classed here as selective services because these are mainly a platform for hosting and downloading 3D models. Although crowdsourcing of design can be differentiated from design marketplaces and design supply as they enable co-creation of design, they have also been grouped as selective service because they also mainly offer a platform for hosting designs which have been co-created.

Crowdsourcing of objects and printing (as a service) have been grouped here as facilitative services because of their focus on 3D printing of already designed models. On the other hand, home printing for this discourse is not considered as service in the commercial sense and so represents direct users who with a touch of a button, can 3D print objects at home with models obtained elsewhere. What this means is that it now possible to distinguish between home printing and the activities of prosumers – those who not content with being mere consumers, have evolved to a point where they design and print artefacts for themselves.

It also means that for the first time, prosumers and hackers can occupy a place in the taxonomy of 3D printing users as these important categories of users have been ignored by previous 3D printing taxonomies. Prosumers and hackers (including the two subgroups of biohackers and grinders) are classed here with the generative activities because they involve the generation of 3D print models and their subsequent production as physical objects.

Another important class of users that this new taxonomy of 3D printing users takes account of are the so-called ‘pure’ consumers. Recall that this group includes those who consume outputs of 3D printing without necessarily having to operate 3D Printers or design of artefacts, or to specify the requirements for their use. Thus, they are classified here as indirect users with the various dimensions based broadly on the taxonomy of industrial sectors of 3D printing developed by Kapetaniou et al. (2018) (see Table 2-4). The industry sectors indicate some of the many of the ways the outputs of 3D printers are consumed.

6.6 A Framework for Classifying and Assessing Ethical Issues of 3D Printing

Beyond classifying different types of users of 3D printing, the AM user cube can also be used to organise and assess the problematic societal implications of the technology. This can either be done using a top-down approach, or bottom-up approach as shown in the next subsection

6.6.1 Bottom-Up Approach for Assessing the Risks of 3D Printing

The Bottom-up approach is used to assess the risks posed by 3D printing to users in the three main classes described by the AM user cube. It is useful for assessing the likelihood of 3D printing users to be affected by issues already identified. To use this approach, a user persona or profile is created based on either potential or factual use of 3D printing and then compared against several known issues depending on the level of detail needed. In doing this, the taxonomy of 3D printing Figure 6-2 is consulted and then working upwards from the lower levels to those higher up (i.e. bottom-up), the user is identified either as a direct user, indirect user, or intermediate user. This profile or persona is then matched against the different issues already identified. The matrix shown in Table 6-5 illustrates how the three categories of users (i.e. those on level 1 of the taxonomy derived from the AM user cube) can be compared against the various societal risks of AM identified in section 2.6. It also shows that there are different levels of risks (i.e. either high risk, medium risk or low risk) associated with the ethical issues in each user category.

Table 6-5 Matrix for assessing risks of 3D printing using the bottom-up approach

Users	Environment	Health & Safety	Intellectual Property	3D Printed guns	Jobs	Bioethics	Data security	Liability	Biohacking
Direct	High risk	High risk	High risk	High risk	High risk	High risk	High risk	High risk	High risk
Intermediate	Medium risk	Low risk	High risk	High risk	Low risk	Low risk	High risk	High risk	Low risk
Indirect	High risk	High risk	Medium risk	High risk	Low risk	High risk	High risk	Low risk	High risk

Note: ● High risk ● Medium risk ● Low risk

For example, to understand the types of issues that might affect those involved in design marketplace, the first step will be to create a user profile that will help to determine the user category that they belong to on the AM taxonomy. In this case, it can be seen that design marketplace is in the intermediate user category (see Figure 6-3) because design marketplace is a subclass of selective services, and selective services are also a subclass of the intermediate user category.

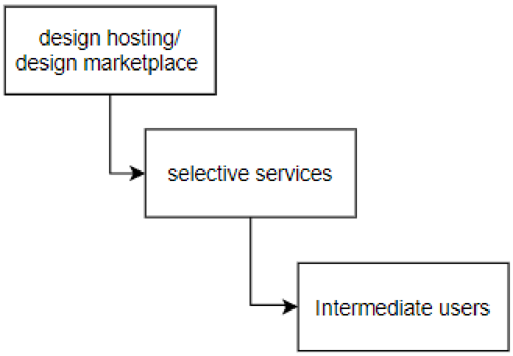

Figure 6-3 User profile for design marketplace

Having determined that design marketplace is in the intermediate user category, the next step is to examine the row related to intermediate users in the matrix for assessing risks of AM in the top-down approach (i.e. Table 6-5). This matrix indicates that indirect users are at high-risk concerning such issues related to intellectual property rights, 3D printed guns, data security and liability. In this case, 3D printed weapons have been flagged up as high risk because in most countries including the U.S (Zaveri, 2019) it is illegal to host or make blueprints of 3D printed guns available online and also because they could poss a real danger to just about anyone in the society.

Also, data security is a high-risk issue for design marketplace because of the digital nature of 3D printed models making design marketplace susceptible to malicious attacks. Design as 3D printing makes it easy to copy or scan designs, design hosts are at high risk of infringing on the property rights of rights holders and therefore for design marketplace IP related issues are high-risk issues. Likewise, the design hosts are at high risk of liability issues because the complex nature of the 3D printing value chain makes it possible that files of 3D models hosted could contain errors that could lead to harm when objects are 3D printed.

For design marketplace, issues related to the environment are considered medium risk here because such would likely require a higher-than-average energy consumption and therefore contribute appreciably to environmental issues. On the other hand, health and safety, jobs, bioethics, and biohacking issues are low risks issues for intermediate users and hence for design marketplace because these issues are not very relevant for design marketplace.

6.6.2 Top-Down Approach for Assessing the Risks of 3D Printing

The top-down approach may be used to determine the category of users that are at risk of already identified problematic issues of 3D printing. Using this approach, specific issues or groups of issues which have already been identified can be compared against the three main categories of users at level 1 of the taxonomy derived from the AM user cube. In this case, a matrix is developed as shown in Table 6-6 where the risks identified can be compared against the users in the main categories of the AM taxonomy i.e. direct, indirect, and intermediate users.

To use the top-down approach to understand the users most at risk of any of the ethical issues identified in section 2.6, the specific issue is identified and described, and then compared against the risk levels in the matrix shown in Table 6-6.

Table 6-6 Matrix for assessing risks of AM to in the top-down approach

Risks	Users		
	Direct	Indirect	Intermediate
Environmental	🔴	🔴	🟠
Health & Safety	🔴	🔴	🟡
Intellectual Property	🔴	🟠	🔴
3D printed guns	🔴	🔴	🔴
Jobs	🔴	🟡	🟡
Bioethics	🔴	🔴	🟡
Data security	🔴	🔴	🔴
Liability	🔴	🟡	🔴
Biohacking	🔴	🔴	🟡

Note: 🔴 High risk 🟠 Medium risk 🟡 Low risk

As an example, to understand the types of users that are at high risk with 3D printed guns, a look at the table shows users in the 3 main categories are at high risk and would likely be impacted negatively by 3D printed weapons. As pointed out in section 2.6.4, most countries have created laws to criminalise the production of 3D printed weapons. Thus, the direct users of the technology who actively participate in the development of such weapons would likely find themselves entangled in the web of the long arm of the law. This will likely also be the case for intermediate users who either participated in requirement specification or failed to provide appropriate supervision in their organisations to prevent such use. Indirect users i.e. the consumers would also face similar risks if found to have such a weapon or if a crime is committed with it, as well as issues around insecurity which the immediate community might face. The table thus makes it easy to see how some risks have far-reaching consequences on not just the direct user, but also the immediate and indirect users as well-meaning the whole society can be impacted by certain uses of 3D printing.

Chapter 7 **Ethical Issues of AM (Empirical Research)**

7.1 Introduction

At the onset of this study, it was suggested that very little is known about the problematic ethical impacts of additive manufacturing (AM) which are especially worrying as the technology is increasingly being utilised by industries, hobbyists, and outside of traditional institutions like homes and garages. To understand the perception of users of this technology, an empirical study was conducted with participants from the additive manufacturing community around Europe.

All the participants are associated with 3D printing DIY hacker collectives like hackerspaces. However, based on their professional occupation, some of the participants can be said to have been drawn from SMEs, and the others from academia. They all kindly responded to semi-structured interview questions as outlined in section 5.6. The responses obtained were then transcribed and analysed following a hermeneutic process (see 0) to enable a fuller understanding of the text. This chapter presents the findings.

7.2 On Ethical Issues of AM

An important part of the empirical study was to understand their opinion on ethical issues that are a concern to them and hopefully to the wider additive manufacturing community. The intention, in this case, was to ground the issues in the context of actual users of AM technology, and to see what role their culture and history might have on their understanding of these issues. It is hoped that the information gathered from this exercise can be used to shed light on gaps in knowledge between actual users of the technology and the literature on the subject.

7.2.1 No Ethical Issues

Several participants in this research suggested that there was nothing of ethical concern with regards to their use of 3D printing technology. Among these was participant P3 who said:

> *A lot of the stuff we do is, is kind of the beginning stages of the design... for jewellery, it's the final stages... but yeah there's nothing really ethically at least which is a concern… (P3)*

This participant's initial impression of 3D printing was that nothing of ethical or societal concern was present with the use of technology. Nevertheless, the participant provided an interesting discussion on some of the issues related to intellectual property, 3D printed foods and weapons which will be discussed in the relevant sections.

A similar opinion was expressed by another participant:

… within the industry, I haven't come across any bad ethical thing when it comes to 3D-Printing… I haven't really had any unethical issues regarding the 3D-Printing… (P4)

Concerning his job with 3D printing and knowledge of the 3D printing industry, this participant also suggested there were no unethical practices. But again, as with participant P3, after further reflection the participant would go on to discuss important issues around health impacts of 3D printing, 3D printed weapons, and impacts on intellectual property etc.

Similarly, participant P5 who as an inventor developed an important 3D printer suggested that the ethical impact of 3D printing was benign. He said:

I thought about the ethical aspects of it… I thought that... it should be benign… (P5)

This feeling was also probably reinforced by the level of positivity that was received after publicising his work and alert the public of his intention to develop a desktop 3D printer.

… I got in touch with the university's publicity department because I wanted to tell everybody that this is what I was going to do… and quite a number of fairly prominent journalists picked up on this and articles appeared in the New York Times, the Guardian, and on the BBC…, but the actual result was that nobody said, oh you shouldn't do that, or whatever.... but people did say, oh, can I get involved? And so that was how the whole thing got going…(P5)

Even when the idea to bring 3D printing to the desktop was made public, it appears that at that time, the general public was also not aware of any ethical issues that may arise from using the technology.

Another interesting response in this general direction was one suggesting that AM technology doesn’t promote any new ethical issues.

I don't believe 3D printing creates any new ethical questions… I don't think there are any ethical questions related to 3D printing that are not identical to the same questions with any other digital manufacturing method CNC machining, laser cutting, even large-format printing… (P13)

The use of the expression “new ethical issues” in the participant’s statement appears to suggest that even if 3D printing promoted ethical issues, the public shouldn’t be concerned as they were not “new” issues and as society has learned to live with similar issues promoted by other technologies, any issues promoted by 3D printing should be ignored.

Another participant with a similar opinion said:

As a device, I don't see that my printer has a vastly different environmental impact compared to, say, a printer (case, PCBs, motors, shafts, etc) ... (P14)

He also suggests that if 3D printing promoted any issues, there were not very different from those of other related technologies, as such the society should be worried about them.

It appears that many in the 3D printing industry hold similar views that there are little or no ethical issues of 3D printing that society should be worried about. However, some contrasting views are presented in the following sections,

7.2.2 Environmental Issues

Some issues around the environmental impact of 3D printing were raised during some of the interviews and a variety of mixed responses were provided. While several participants suggested that the impact of 3D printing on the environment was negligible, others describe some important issues. As one of the participants puts it, the environmental impact of AM depends on the type of technology and the printing process.

> *It would depend heavily on the other process, and the particular 3D printing technology too… (P14)*

This probably explains why participants based much of the discussion of the environmental impact of 3D printing on the type of technology in questions.

1. Sustainability

Some of the participants argued that 3D printing is advantageous because it is a sustainable means of production, while others disagreed. For example, one participant said:

> *… 3D printing is brilliant from a material sustainability perspective because it completely minimises waste compared to other manufacturing methods… (P8)*

This participant suggests that 3D printing is a sustainable manufacturing process because waste is minimal even when plastic support structures are created as part of the printing process and discarded when the object has been created.

Another participant with a similar opinion said:

> *It's… more material-efficient as well, compared to subtractive manufacturing methods there's very little waste material, and onsite manufacturing for prototypes means much-reduced transport and packaging emissions… (P13)*

Like participant P8, this participant feels that 3D printing uses up less material than subtractive manufacturing processes and that as it allows for localised manufacture (i.e. at home or nearby SMEs) it is a more sustainable technology.

And a comparable argument reads:

> *... It's less wasteful than a lot of other materials used in making stuff... we can reduce transport costs, delivery...so, I think the ethics… is a positive thing … (P9)*

This participant (P9) compared 3D printing with subtractive manufacturing processes that use milling technology and argues that 3D printing is more sustainable than this process as it utilises just what is needed while creating objects, unlike the subtractive processes where waste results from milling. Another reason this participant put forward for believing 3D printing is positive in terms of ethics includes the localised nature of 3D printing which reduces the need to transport goods around the world as they can be manufactured on a 3D printer either at home or a nearby location.

However, a counter-argument was presented by another participant, who said:

> *…There is a lot of waste… I'll say between 20 and 40 per cent wastage… It's all crap what people say about it being environmentally friendly... if you are using a CNC mill… you collect all the swab that gets milled off and then you send that off to recycling whereas with this, it gets wasted…(P15)*

P15 disagrees with much of the sustainability arguments which favour 3D printing and suggests that such arguments are an over-exaggeration of the real situation. The participant argues that people will generally look to buy the cheapest options available and will rather buy from across the world if it is cheaper that way rather than from the local 3D printing shop, thus debunking the localised manufacturing argument proposed by P9. Furthermore, also argues that waste from 3D printing gets discarded, unlike subtractive milling processes where they easily recycled and therefore have lower wastage.

2. Plastic waste pollution

On the issue of waste from 3D printing processes, one participant suggested that this was the most important issues to her concerning the ethical impact of 3D printing:

> *Well, my biggest issue is like environmental issues… the things that we are doing like while we are prototyping. … my biggest ethical issue is that am printing so* much *plastic and that also am throwing so much plastic which I don't... like… (P2)*

This participant suggests that 3D printing constitutes an environmental problem because it contributes to the plastic pollution issues that already blights society.

Another participant who described how some of the waste in the 3D printing processes occur said:

> *... you'd see that print after print failing, and you're... just throwing away loads, and loads of plastic, it doesn't feel great... (P6)*

Like participant P2, this participant appears to be unhappy with the situation in the industry where a lot of plastic material is thrown away due to print failures.

Another participant provides an even more vivid description of how wastage occurs in her 3D printing processes:

> *Sometimes when I have printed on the fabric, the filament is not good, because they can be very weak. When I do my experiment I do many times, for example, I did 10 times... sometimes it's very strong, sometimes, it's very weak, eh, until now ... I don't know why it's happening… (P12)*

This participant whose research focus is on 3D printed textiles suggests that she goes through several iterations to try to get the right quality of fabric for her fashion designs and is having difficulty resolving the printing errors. Describing why so much wastage occurs in the printing processes, another participant said:

> *I mean, erm… because it is so easy to 3D print things – people just throwing ideas, and then they just print things for the sake of printing things – Erm, and with 3D printing, there is a significant percentage of error, erm so you print to your printer, and then after 3 hrs you realise, it actually missed one of the layers and then you need to start from scratch. So, what's gonna happen to that waste material? You just chuck it away… (P11)*

This directly relates to the low entry cost to 3D printing and the ease of using the technology where with just a touch of a button, users can simply print out almost any object that they like.

Another participant who describes the scale of the problem of plastic wastage said:

> *… There is a lot of waste, we are… on our systems downstairs we have I'll say between 20 and 40 per cent wastage from material that goes in… (P15)*

This much waste may constitute a big problem in the environment as 3D printing gets increasingly popular and its use in homes, and SMEs and industries increases. It appears the problem of plastic pollution in the environment would likely increase significantly if no actions are taken to minimise errors and waste from the printing process.

3. Biodegradability

It has been suggested that problems around plastic waste could be resolved effectively through the use of biodegradable plastic that allows micro-organisms to break them down during a process of decomposition. Thus, along with the problem of plastic pollution, participants discussed issues around the biodegradability of the materials used in 3D printing. While some suggested certain 3D printed materials were biodegradable and therefore not a problem to the environment, others didn't agree. For example, one participant said:

> *PLA itself is pretty good material from the environment, it's derived from renewable sources, erm, that's better than some sort of petrochemical sources. Erm, and yeah, they could be broken down… (P8)*

This participant suggested that PLA which is one of the most common materials used in 3D printing is derived from renewable sources, it would decompose and therefore would not cause harm to the environment. This appears to be the reasoning behind the next participant's comment:

> *I've read and talked to people about every single argument in 3D printing. It all depends on the plastic you use. This is Polylactic Acid, it's compostable erm, we call it PLA, so you can bury it in the garden, 6 months it'll slightly get a bit soggy, within 12 months it'll start to break down… (P10)*

This participant (P10) who was 3D printing keyholders at the time of the interview and had experienced quite a several printing errors during the period the interviews lasted suggested that he wasn't concerned about the impact of such waste. He argued that the material he was using (PLA) is biodegradable and that it will start breaking down after just 12 months suggesting that it was environmentally friendly. Another participant who made a similar comment said:

> *… I think PLA, in general, is from corn starch, isn't it? So, it's natural... it's not such a big environmental impact in throwing that away and it's biodegradable as well … (P9)*

Like the previous participant, this P9 also maintained that PLA filament is biodegradable as they are sourced from natural materials like corn starch and feels therefore that the negative environmental impacts are minimal

However, another participant rejected the notion that the biodegradability of PLA takes a short period and that PLA doesn't constitute a problem. The participant said:

> *… And like they say, okay erm, PLA is biodegradable, okay, a plastic bag can be biodegradable, but it needs 100 years to melt... what does this mean? It doesn't make sense… (P2)*

This participant suggests that technically, PLA doesn't decompose because it takes much too long to breakdown and so the problem of plastic waste will persist. This was likely the reasoning of yet another participant who contends that as the materials being printed are plastic and are not biodegradable:

> *I can imagine that since it's plastic, it's not really you know... it's not biodegradable … (P1)*

Interestingly, another participant who experimented to determine the biodegradability of PLA provides a compelling argument on the ethical implications of 3D printed plastic on the environment:

> *… If you just take a PLA object, and you bolt it on to the side of your house, which in fact I did do about 4 years ago with a fan bench for ... an extractor fan, you look at it today, it's as good as new! And it's been in the sun, the snow, and the rain for 4 years. So, it's not that biodegradable.… (P5)*

This participant (P5) provided some interesting arguments about the biodegradability of 3D printed objects and discusses issues around two of the most popular 3D printing materials – PLA and ABS. In the first assertion, he goes on to suggest that PLA (made from organic materials) is biodegradable only in theory because it only breaks down under specialised conditions and an experiment he had conducted to investigate its biodegradability showed that after 4 years of exposure to the elements, it remained virtually the same. P5 then compares this with ABS (made from oils) and he suggests that this is not biodegradable because it is made from oils and that although in theory ABS can be recycled, he contends that impurities make it difficult to recycle this material. As it happens, the recyclability of 3D printed materials became another important talking point for participants.

4. Recyclability

Besides biodegradability, recycling has often been suggested as another important means of reducing plastic waste in the environment and many of the participants also brought this up with regards to 3D printed objects. Some participants suggested that the plastic pollution problem from 3D printing can be minimised by recycling 3D printed objects:

> *…but I also can see the other side where we can recycle more plastic and rework with it... re-melt it… (P1)*

This participant (P1) suggests that a way out of the plastic waste problem from 3D printing would be to recycle them, and P11 appears to agree with him:

> *I think work on things like recyclable materials so anything that went through an error erm, you can put that material into this recycling magic machine and then you would turn that into reusable eh, recycled filaments... (P11)*

However, like participant P5 quoted in the previous section who argued that impurities make 3D printing materials hard to recycle, other participants shared similar opinions suggesting that resolving the problem by recycling printed objects may not be as easy as it appears to be:

> *Inherently with the Fused Deposition Modelling, you have to use thermoplastics, inherently these can be recycled because they could be melted down and created into other objects, erm, in practice, the materials property degrade every time you do that, so in practice yes you can recycle 3D printed objects but you can't use it for very high-quality products or highly engineered things after you've done it once… (P8)*

Yet, another participant maintains that this hurdle may be resolvable:

> *Erm, there are some limitations, erm, the plastic is already been through the heating and cooling process, erm, so normally you'd, you'd grind the stuff up and you'll mix it with some virgin plastic just to try and give it a smoother overrun, but it can be done… (P10)*

However, for participant P15, it appears that this an oversimplification of the issues around recyclability of 3D printing material:

> *… a lot of the materials used in 3D printing... if they can be melted it generally means they can be recycled, eh, but the issue is most printed parts don't come out with a recycling emblem on them, so when they go into recycling plants, they end up getting chucked in the bin because they are unidentified as to what material they are… (P15)*

Unlike recyclable plastic which usually carries the Mobius loop symbol (a triangle composed of 3 arrows in a loop), most 3D printed objects do not display this symbol to indicate that they are recyclable and so end as waste material anyway. This participant went on to point out another important issue he has with recycling:

> *Erm, disposal of waste here, is quite tricky because there's no one who really specialises in disposing of 3D printers waste. Unfortunately, downstairs we get mixed media, so we get a mix of sand and nylon powder, so it's very difficult to separate... and it looks like a big bag of white powder but it's actually two different media in there. Obviously, they are not gonna be recycled together…(P15)*

And so, the problem is not only that 3D printed items and filaments don't display the recycle symbol, when printing is done with powdery materials, they waste gets mixed up with other materials making it much more difficult to recycle as there are no specialists for such materials.

Nevertheless, one of the participants doesn't feel that unrecycled waste causes any harm to the environment:

> *… the materials that we use as far as I'm concerned, they are... I mean, okay, they are not 100% recyclable or anything but erm, I don't think they are damaging the environment, but having said that, at the end of the day, it's plastic… (P11)*

While this participant doesn't feel that unrecycled plastic doesn't constitute a problem, some of the others had opposite opinions. For example, one said:

> *We know one very serious environmental problem which, is the problem of micro-particles of plastic in the environment in general – getting into fish, getting into the oceans and all those sorts of things. And of course, to the extent that powders are used… and some of them are spilt, wasted and generally, not recycled which is inevitably the case with any process, you're going to get some accidents in some ways… this is going to make things worse, so, yes we've got a problem there… (P5)*

Unlike P11 quoted earlier, P5 feels that unrecycled waste plastic could create serious problems not just for humans, but also for marine life. And participant P2 who isn't pleased with this situation said:

> *… One of my issues is that the filament... you couldn't recycle with filaments... (P2)*

All these arguments indicate that that more needs to be done on the issue of recycling 3D printing objects and that was the position of participant P7

> *…the responsibility then falls on the companies to either make these things recyclable or there's gonna be some ethical way of getting rid of this material, like, that's, that's the problem… (P7)*

This participant suggests that more needs to be done to find a means of ethically disposing of plastic waste material from 3D printing to minimise waste from the technology.

5. Energy consumption

As environmental awareness keeps growing, people have increasingly questioned the energy implication of technology in terms of cost and the environmental impact. This has also been the case with additive manufacturing with participants providing a mix of opinions, including the following:

> *It's definitely dramatically more energy-efficient than any other method for prototyping… (P13)*

This participant who was comparing 3D printing with other prototyping technologies was of the view that 3D printing had better energy efficiency than other similar technologies. So that would likely mean that if the energy consumption rates of 3D printers were compared with that of another technology that produces a similar object, the 3D printer would be found to be more energy efficient.

However, another participant had a different opinion and said:

> *Now, if you were talking about producing thousands of widgets with a 3D printer, then I don't know how the energy would stack up. My guess is that something like injection moulding would be much more efficient, but you do need a metal mould, and metal costs energy… (P14)*

Although P14 suggesting he wasn't sure of what energy consumption rates for 3D printing thousands of items were, unlike P13, he felt that other technologies like injection moulding would be more energy-efficient as they could mass-produce much more with less energy.

Another participant who makes a similar argument:

> *You are using a hell of a lot of energy to produce compared to mass production. If you are using injection or moulding technology, you are using very little energy per unit put in, eh, whereas with erm, 3D printing, you are using an extremely high amount of energy… (P15)*

Another participant who feels the same way about the energy use of 3D printers said:

> *There's the environmental impact, if I 3D print that coat hook which I mentioned, that uses more energy than making it in a factory in an injection moulding machine... considerably more energy. On the other hand, I've saved on the transport cost of the moving things around, so it's not quite as*

> *straight forward as that. But I suspect that if one were to go into detail in the calculations, we would find that it's not the most energy-efficient method of manufacturing things… (P5)*

This participant was referring to a coat hoot that he had made with a 3D printer and suggested that producing it with an injection moulding machine in the factory would have used up less energy than that used by his 3D printer due to energy savings that result from mass production. He also suggests that although 3D printing offers the advantage of localised production, the energy consumed during transport of fabric produced items likely still compared favourably with that used up by 3D printers. This participant would later go on to say that he wasn't too worried about this energy consumption issue because he uses solar panels which help negate any problematic impact on the environment.

The issue of using solar energy to reduce the environmental impact of 3D printers was indeed raised by another participant:

> *I wish these machines could run on solar, but they don't, they are energy-hungry pieces of kit, and eh... I know very little about this side of them, unless... just...there's, there's… (P7)*

Recognising that 3D printers use up quite a bit of energy, participant P7 who works in a busy 3D printing bureau suggests he would have preferred for the 3D printers in his workplace where solar-powered to minimise problematic energy use.

6. Circular Economy

Some participants brought up issues related to the circular economy in their assessment of the ethical issues of 3D printing. One of the participants said:

> *The material is not… so environmentally friendly… I think you have to look... on the circular economy… that means that all products can be fully recycled etcetera, and then you do not produce a lot of energy and resources... from this point of view, 3D printing is not very ecological… (P16).*

For this participant, it is important to look towards the circular economy as a solution for the environmental problems of 3D printing particularly as the technology is not ecological.

Another participant provides a similar argument:

> *One area where 3D printing could make an impact is increasing product lifecycles, manufacturing replacement parts for partially damaged products, especially in cases where the manufacturer no longer wants to support the product or has discontinued it, or has gone out of business… (P13)*

Although this participant felt positive that the principles of the circular economy were good for 3D printing, he however later admits that even though he and others in the 3D printing community do engage in such activity, and he wasn't sure that it was prevalent in the industry and couldn't much of an impact it would have on waste reduction.

7.2.3 Health and Safety Issues

As additive manufacturing is still emerging, the health-related risks are not well known. While some participants appeared concerned about any negative impact on health due to AM, some weren't so worried and appeared to brush the issue aside. For example, one participant said:

> *I suppose if, like I said, the trajectory of bringing 3D printers into the home, we already have quite a lot of toxic chemicals in our homes already, and we've been using cleaning products for a long time, so, I don't foresee 3D printing being anymore toxic or dangerous to health than any other chemical that we have in our homes already…(P8)*

This participant assumes the health risks of 3D printing are similar to those of other cleaning products used in the house and so isn't worried about negative health effects. An indication of why this might be the case can be seen in the next participant's comment:

> *…the health risks that we don't even know about yet is one of those things that's very hard to, to guess what's going to happen, and you know, it's one of those things that if we are really concerned and we don't know the risks, would we ever do anything?... (P3)*

Although P3 admits that the health impact of additive manufacturing isn't well known, he just feels that the best course of action is to ignore the situation and will carry on using the technology.

However, a few of the participant had a contrary opinion. For example, one said:

> *Erm, people have been worried about this… I don't think there's been enough studies… (P5)*

Even though this participant acknowledges that not much is known about the health effects of 3D printing, unlike the P3 and P8, he recognised that there was a need to be concerned about the situation.

Another participant who expressed concern about the dearth of information about such issues said:

> *I try to search that on the internet and they don't say something… (P2)*

This participant was worried enough to actively engage in some form of research to understand what the health effects of 3D printing are but didn't find much information in that regard. This shows that there is a need to understand the problems that might result from the use of 3D printers. Some participants did discourse what they considered to be health risks of additive manufacturing and the findings are presented in the following.

1. Exposure to ultrafine particles and volatile organic compounds

One of the points that repeatedly came up in discussions with participants on the health effects of 3D printing was that they gave off fumes and particles that they were concerned about.

> *Erm … with other technologies there are fumes given off... some of the desktop printers... consumer-grade ones do... so you are having fumes in your house which isn't great…(P15)*

Although the participant suggests some worry about fumes given off particularly with consumer-grade 3D printers (likely the types used in homes and SME), he isn’t clear about what his fears are. Another participant who expressed similar worry pointed out something interesting in that regard. He said:

> *Erm, the environmental impact of the technology in terms of the fumes and so on that it produces, of course, it entirely depends upon the polymer that people are working with, assuming they are working with polymers at all … (P5)*

According to P5 however, the fumes and particles given off during the printing process would depend on the 3D printing technology in question. This probably explains why much of the discourse centred on different types of health effects based on particular types of technology. Four 3D printing technologies were mentioned by participants in terms of particles and fumes given off as can be seen in the following discussion:

Acrylonitrile Butadiene Styrene (ABS)

Three of the participants expressed concern about 3D printers that utilised ABS thermoplastic filaments for the creation of objects:

> *ABS which is the same plastic LEGO is made of. Now, to print ABS, it has a high concentrate of particulate in the fumes when it melts and there have been recorded cases that the parts per million when you print ABS can be harmful…(P10)*

The printing process requires the melting of filaments and this participant points out that when ABS filaments are melted, they give off fumes and a large number of particles which can be harmful.

Another participant gives further details of this problem:

> *ABS which is one of the more popular materials is oil-based, there are fumes and odours from that which can be dangerous. Now, of course, you’d need to lean over the printer and be inhaling them for it to have any immediate effect but then again that’s one material is ABS… (P3)*

Although this participant only mentioned the immediate health effects of inhaling fumes and particles given off by the printers, another participant points out long-term effects that could be very serious:

health issues, yea... like you know... if you print with ABS the fumes are… some substances are 100% cancerous… (P2)

The participant suggests that the impact of such particles and fumes could so serious that they could even result in cancers which is quite a worrying prospect especially as there isn't very much information to alert users.

Polylactic Acid (PLA)

Some of the participants also suggested that they were worried about PLA which is described as another very popular material used in 3D printing although they also admitted that the health impacts are not so obvious:

Even PLA we don't know what these fumes can cause… (P2)

Another participant suggested that because PLA was mainly made from starch he considers the fumes to be fairly safe, but wasn't sure about the particles:

Of course, the particles and things we don't know anything about really, but it also depends on where this printer is…(P3)

The participant points out that there isn't much information about the impact of particles given off during the printing processes using PLA but also felt that any effect would depend on the proximity of the printer to the individuals in the printing area. A similar comment was made by P5:

... As I understand it, some of the particles are starch. Now, it ought to be the case, again, I'm not entirely sure, but it ought to be the case that starch is reasonably benign material from the point of view of the human body. Even ingesting it into the lungs, I would have... I'm... I'm guessing here, I don't know enough biology but I'm guessing the starch would probably not be too damaging…(P5)

This participant (P5) suggests that although PLA gives off particles during print processes, the particles are likely harmless because the predominant material used in making PLA filaments is starch. However, like P3, he also points out that he is not sure about the effects of such particles on health.

Selective Laser Sintering (SLS)

Selective Laser Sintering which uses powders to create objects was another 3D printing technology that participants were worried about. One participant said:

Sintering and powder binding printers emit dust…(P13)

The participant here is expressed concern about dust particles given off during the printing process although he didn't specify why he might be so worried about the dust particles, some more details can likely be found in the next participant's comment:

> *You are using powdered nylon which does get airborne so there is obviously a health risk of inhaling it or ingesting it … (P15)*

Participant (P15) comment suggests that the nature of the material used in the SLS process (i.e. powdery plastic) means that the particles are constantly airborne and that there is a high risk of inhaling these substances. It is therefore likely that it is the number of particles being ingested that P13 mentioned earlier was worried about.

Another participant who appears to agree with this said:

> *For SLS process the powder... this powder can go very deep inside your pores, it goes inside your lungs…(P2)*

This participant suggests that the particles given off are small enough to penetrate skin and body tissue from where they can then get to the lungs. Although it is not clear what the impact of inhaling the powdery particles into the lungs are, the participants appear to be worried that this could result in serious health problems.

Another participant feels that some of the particles could cause serious problems:

> *Erm, but of course there are some powders that would be rather damaging…(P5)*

Interestingly, participant P2 quoted earlier indicates that her fears of health damage that might result from these powders once led her to take drastic steps:

> *…I had like a job offer to move from FDM printing to SLS printing and I didn't do it because I have to sacrifice my lungs and there was a 2 years commitment contract… because you leave your phone there, and then after 3 minutes you are touching the phone and it has a layer of dust and this is everywhere... like everywhere. And I ask them like how many of these would I have inside my lungs after 2 years? And he said to me, if you pose it this way, I can't tell you something. But no men, this would fill every single particle of your lungs. It's so small, it's like 10 times smaller than your pores… (P2)*

This shows how serious the participant takes this problem. The participant rejected a lucrative contract in a 3D printing firm utilizing SLS for their work for fear that the tiny particles given off while printing might cause harm to her health. And it understandable why such a drastic step was taken by the participant as she maintains that within a few minutes of being in the vicinity of the 3D printer her phone was covered in a fine layer of dust and she wouldn’t know how much dust would have ingested while working there.

Stereolithography (SLA)

With regards to fumes and particles given off during 3D printing, one of the participants suggested that the stereolithographic process was also not left out and gave off toxic fumes as well:

> *For resin, if you inhale resins, resin is toxic. It's toxic for your lungs… (P2)*

Interestingly, it was only this participant that seemed to be aware of the likely health effects of SLA.

2. Noxious odours

Another issue that came up during the interviews besides problems with fumes and particles is that of noxious odours emitted by some 3D printers and described by some participants as quite unpleasant. One participant said:

> *When I use the machine... sometimes the smell… not very nice... I want to go out to have natural air and come back… (12)*

This participant (P12) suggests that she feels discomfort as a result of the odours given off while printing and often needs to go out for fresh air. Another participant describes these odours as irritants:

> *Fused filament printers emit small amounts of airborne irritants, depending on material… (P13)*

While P14 said:

> *As far as I know, it smells worse, and I have a very small space, so I don't really want to gas myself and I only use it for a few little gimmicks rather than on any kind of production scale stuff… **(P14)***

The participant who contends that he doesn't use the printer he has at home for large scale printing because the smell is quite bad and is worried about 'gassing himself' which likely translates to fear that the odours might cause serious damage. Similarly, participant P3 who describes ABS as one filament where there exist *'odours from that which can be dangerous'* maintains that:

> *I wouldn't recommend having a printer in your bedroom for example… because of the odour and things like … (P3)*

P3 suggests one of the reasons he wouldn't recommend having a 3D printer in the bedroom is because of the odours which hare potentially dangerous.

Regarding PLA however, another participant feels there is nothing to be worried about with regards to the odours and he said:

As best I can see looking at their research, erm, certainly for the plastic that's most commonly used which is Polylactic Acid which is a polymer sugar, the emissions from the technology seem to be roughly comparable with the sort of thing that happens in the average kitchen. Erm, you know, if you caramelise sugar, that also gives off various, things that possibly are bit doggy, but then the very act of cooking almost anything does, and we seem to be happy to... (P5)

3. Bioprinting risks

It has often been suggested that additive manufacturing presents useful techniques for creating human organs in medical labs that could be used to replace damaged ones through what is now referred to as bioprinting. This aspect of AM also came up during discussions with participants and one who felt upbeat about the prospects the technology has to offer said:

It's really safe when it comes to that… the implants for skin grafts and things like that… so again, I'm not a doctor, I don't know the safety side of that but it's still in the early stages… (P2)

However, another participant who appeared to be non-too pleased about the development said:

There are areas that have... high ethical concerns which is the 3D printing of human organs, biotechnological 3D printing... it's connected to the debate on this human organ production which they tried … to manipulate liver of a … pig or a sheep or whatever with some human cells, and then you grow up liver which is similar to the human liver... (P16)

Although the technology promises to solve the pressing problems around the replacement of damaged organs, this participant (P16) appeared to take a more cautious position as he contends that ethical questions need to be answered. The participant thus suggests that there are legal and ethical issues that need to be resolved around responsibility for organs that breakdown or those that don't work after implant.

4. 3D Printed medicines

It has been suggested (Service, 2018) that the broad reach that additive manufacturing already has, could be extended to 3D printing of medicines to allow drugs to be printed on demand. One of the participants maintained that he had worked with a group of researchers who are working on technology that working towards this in future, said:

I don't know if it's even possible. I know a group that is working on this using 3D printed reaction vessels to make small batch organic chemistry work, I worked with them on this… 3D printing won't be displacing the pharmaceutical industry ever, and I don't believe anything manufactured by this method would ever be certified safe for human use just because of contamination risk and the inability to verify the purity of the end product… (P13)

P13 contends that he is not aware of any 3D printed medicines and that the vast majority of medication cannot be made using 3D printers and even they are, they can only be done in a well-stocked lab. He also suggests that 3D printing medicines are likely not going to be safe for human use due to risks of contamination and purity of the product.

Another participant, however, said:

> *Well I mean, they're just tools. If they can make better "whatever's" then great! It's really no different than using a 5-axis mill to make it… (P14)*

This participant (P14) feels that so long as the technology works well, then its good thing and he suggests that the type of technology used doesn't matter, it's the end product that does.

5. Safety around children

3D printers are often used in an environment where kids are present like homes and classrooms. Some participants raised some interesting points on safety around children. One participant said:

> *... for [3D printing] to be at a level where it is consistent and safe for kids because the printers... they are not dangerous but still, there's a lot of maintenance for the 3D-Printer… (P3)*

Although the participant feels that 3D printers are generally safe, he feels that a lot of maintenance is required to keep them safe around children. And another participant who also brought up the issue of safety said:

> *Some …maybe want some toys or things like that… you always have to be hazard oriented, like you always have it... down in your head that okay, ... this is gonna make it very uncomfortable for a user... or what if this design is to go on a shelf, what if it drops and falls on a child? So... everything you design you always have to consider your audience, and... what they're using it for … (P4)*

Unlike the previous participant who was more concerned about the safety of 3D printer around kids, this participant (P4) was more concerned about the safety of 3D printed objects around kids and points out that designers should always have children's safety in mind when designing anything even toys.

Another participant who puts the safety issue with toys in more clearer terms said:

> *You 3D print a toy and then if it goes into the mouth of a baby, what's gonna happen? So, is that material really safe… for that baby? And that's the thing because you cannot control these things … So, you buy something from Sainsbury's, erm, a toy again, but those toys are manufactured with regulations, so that's the thing with 3D printing, we don't have regulations in place so you just assume it's just a prototype, and you kind of pass that responsibility to the consumer…(P11)*

The participant appears to agree with P4 that it is important to consider the safety of 3D printed toys for kids use especially as the industry is not as regulated as that used in industrial manufacturing of toys. He also contends that the lack of regulation in this regard means that the responsibility for the safety of children's toys is often passed to the consumer.

6. Food safety

As additive manufacturing has also been adapted for use in the food industry, it is hardly surprising that this was brought up by participants. Although many participants didn't think there was anything to be worried about, some raised questions about the safety of such use of the technology. One participant said:

> *So, the 3D-Printed food … of course there's loads of different versions but essentially the 3D-Printed food is... depending on the thing, you can have chocolate, you can have like Jell–O things... essentially, it's extruding like a syringe the food, like molten or jellified food, layer by layer, by layer. So, it's essentially just a robotic arm with a syringe so there's no real [danger]… (P3)*

And another participant who agrees with this opinion said:

> *I don't really see how it's much different to current food production. I mean, a soft-serve ice-cream cone is sort-of 3D printed… (P14)*

His view appears to be similar to that of the P3 as he also suggested it isn't very different from current food production techniques such as those used in making ice cream cones. One of the participants who used 3D printers to create food said of the technology:

> *We had a printer that can print chocolate...so, instead of plastic you used Nutella, like chocolate spread... it doesn't give security to people to see a 3D printer, printing in food... I mean, even personally myself, I wouldn't eat chocolate that comes out of a machine like that. But I mean, in theory, it is fine, I mean it health and safety-wise. All the nozzles you use, they're all you know, certified by health and safety organisation… So, at end of the day, it's Nutella, eh, it's just chocolate. But … I mean, first of all, 3D printing is very slow..., so if you go to a restaurant, is it going to be quicker to 3D print food? Or, is it quicker to do with the traditional way? And food is something that I think, again, that's my personal opinion, but, it's something that needs to be handcrafted, so, if you 3D print things like food, erm, I think the love will be missing ...(P11)*

Although the participant feels that 3D printed food is safe, he raises an important question about how the technology might make humans lose the personal touch that comes with eating hand-crafted foods.

Another participant who raised important questions about the safety of 3D printers said:

> *… a lot of the people have sort of created designs... really impressive stuff with food, but you look at it like, well, actually is it safe? Is the material you need to use to print up food safe? And, can it be cleaned properly?... (P6)*

On the issue of food hygiene raised by participant P6, another participant pointed out some relevant things:

> *Depends how clean the printer is kept. The entire material feed chain must be kept to food hygiene standards. This is possible, as shown by soft ice machines for example, that have the same handling problem. But it requires everything to be cleaned and kept clean. In fact, slushy machines and soft ice machines are the closest equivalents. They are an excellent breeding ground for bacteria if not kept clean just like any kitchen product. It doesn't matter if the piping nozzle is held by a human or robot, if it's clean or if it's dirty, it won't make a difference either, it's bad in both cases… (P13)*

Thus according to P13 agrees with P6 and suggest that the hygiene of the 3D printers and food should always be considered.

One participant who took a slightly different position said:

> *If you are talking about food, then… that's something very unethical to do in my personal opinion cos that's going into someone's body. They can sue you and also got substances inside… that's putting people's health at risk… that's extremely unethical… (P4)*

This participant (P4) appears to have taken an even more radical position than the other participants who raised issues around 3D printed food. The participant feels that 3D printing food is unethical as it could cause harm to people once ingested.

7. Flammability

Moving the safety issues to another important point about the flammability of some of the materials used in 3D printing, one participant said:

> *For SLS process, the powder... is very flammable in high, you know... in high concentration... (P2)*

Interestingly, it was only this participant who suggested that the powder used in Selective Laser Sintering is highly flammable.

8. Toxic photopolymers

A participant mentioned another important safety issue regarding the toxicity of resins used by SLA printers:

> *Some substances that we use for example, with the SLA printer, it uses a substance which is a liquid that's drawn out, and it gives off a certain resin... it's not the safest material to come into contact with when it first has come out, but that's the just the nature of the printer… (P4)*

As it is only one participant that has raised this issue, it appears that is another issue that isn't well known by many in the industry.

7.2.4 Intellectual Property (IP) Rights

Since additive manufacturing became so accessible with the development of desktop 3D printers, intellectual property issues have become an important talking point along policy lines in the manufacturing industry. Issues around intellectual property rights were also discussed by participants who presented many interesting arguments. One participant explains why this issue might be so important:

> *... I don't actually know the specific regulation or laws surrounding that, whether it even has been regulated... I suppose this is really the first time, that we've ever seen a proper manufacturing product coming to the home, coming to the desktop, so in a way, it was sort of inevitable that this kind of technology was gonna be used for bad as well as for good, but that's the same with a lot of science and technology…(P8)*

P8 suggests that additive manufacturing is the first technology that has brought 'proper manufacturing' to the home and that like most science and technology, there is the potential for it to be used either for good or bad and yet it appears that there is no specific regulation or laws to govern its use. An indication of why this might be a problem can be seen in the next comment:

> *I mean intellectual property still belongs to the designers, so, if somebody is creating something that has been manufactured, its either the company or the individual. Erm, I haven't personally come across a lot of problems with, eh, people copying designs save for people for example, who are printing a character or a mickey mouse or something. Nobody is doing it on a scale where its causing issues… (P7)*

The participant (P7) appears to suggest that the ease of copying and reproducing objects doesn't diminish the ownership privileges of the IP rights holder whether it is a company or an individual and so infringing on such rights could be an issue. He also, however, maintains that he hasn't come across many of such problems because it isn't being done on a large scale. One participant who also has a similar view said:

> *I don't really feel like stealing intellectual property on a mass level is going to happen. You have these pockets of people who are doing it as a hobby thing and again sharing files, you are sharing them to a community, you expect people to download them and things like existing designs, existing things, yes if you redesign it you redesign it and if you sell it then it's a problem, if you share it... that's a grey area… (P3)*

Participant P3 appears to support the view that there isn't much of an issue with intellectual property theft as he argues that it isn't happening on a mass scale even though he recognises that people are downloading designs and sharing them freely online. He, however, maintains that there could be IP rights problems where people resell these designs online. However, a participant with a slightly different view said:

> *… I don't think it's gonna be a huge issue for a little while purely because, I mean, 3D printing is still quite niche, and I don't think anyone is really that concerned about the rights as yet. But particularly with things like 3D scanning, where you can just take a commercially produced object, scan it, and recreate it. Erm as that becomes more of a thing, it's definitely gonna be clashes over it, and yea, issues there... (P6)*

This participant (P3) argues that although matters around intellectual property rights are not such a big issue at the moment, the ease with which additive manufacturing allows objects (including those of commercial value) to be reproduced will become more of a problem in future as the technology becomes more widely embraced. Another participant adds:

> *3D-Printing can be bad for intellectual properties and everything… I think it could be a real issue if someone is spending, I don't know maybe 110 hours stuck... just on a design, who is you know, trying to make things work… when it comes to the printing and, if someone just takes this one, do slight modification and something like this, like just basically.... take his work and… reproduce, it can… be an issue because he can sell the product… or the design and… yea, that's an issue… (P1)*

P1 argues that 3D printing can be bad for intellectual property and that it'll probably become a real issue when complex designs or objects that take hours to produce are taken by others and sold for their personal benefit. And participant P7 adds:

> *IP will become very important. They will need to hold and enforce their IP because someone's going to copy it. Eh, there's free CAD out there already, there's free services out there already to duplicate and to copy… you can do that already. I'm not saying that hasn't happened a million times over already, so I think this is just another manufacturing process that will have the same problem… (P7)*

The participant suggests that as IP issues become more important due to the use of AM technologies, owners of IP will need to enforce their rights more closely to prevent their designs from being copied. Another participant describes how this is already happening:

> *Now there are companies like erm... the games workshop, who do those kinds of table-top gaming figures, like eh you know… like dungeons and dragons and that sort of thing... now they've taken out a bunch of lawsuits against people 3D printing their models. Because their models are fairly expensive, you are paying £20 for a couple of these little plastic models. But to 3D print them you'll pay a couple of pennies. So, they are very scared of 3D printing as an industry, so they have taken out a lot of legal action against things like that… (P3)*

The participant suggests that fear of intellectual property rights infringement has led a company to take action to minimise such problems. He describes a situation where one of the companies involved in the manufacture of gaming figures has had to take out legal injunctions against supposed IP rights violations.

Nevertheless, other participants don't feel that 3D printing contributes to the problem of intellectual property rights violations. One such participant said:

> *I don't think 3D printing affects intellectual property rights at all. I don't see it as in any way equivalent to a technology that transforms a field like the printing press was to the written word, 3D printing is, like all other prototyping tools, a method for manufacturing one-off parts… But if you compare with say the printing press or injection moulding, those were technologies by which you could mass-manufacture exact copies of things. 3D printing is more like a lathe than it is like a printing press. I would definitely say it doesn't promote infringing intellectual property rights… (P13)*

This participant feels that 3D printing hasn't really transformed the manufacturing industry and isn't much different from other prototyping technologies already in existence. He suggests that as 3D printing hasn't enabled mass production, it doesn't have an impact on intellectual property rights. And another participant said:

> *Still, they need quite long to produce particular parts where for example… they are much faster … computer-aided production centres which are much faster produced... with much higher precision with them than 3D printers. Although the 3D printer is very flexible, and it can do it in more… very complex production of things, but when you need a high number of particular components they are still... companies are still not using the 3D printer... (P16)*

The participant suggests that even though 3D printers allow more complex designs to be made, he doesn't feel they present much of a problem to intellectual property because they lack the speed and precision of other computer-aided manufacturing processes.

1. Copyrights and Patent Issues

One of the issues that participants talked about with regards to intellectual property is related to the copying of items that are protected by copyrights and patents. One participant said:

> *I think there is... definitely an ethical issue with this sort of thing … sort of easily reproducing something that has a copyrighted design… I think there's a problem with that… (P6)*

It appears this participant is referring to the nature of 3D printing which makes it easy for just about anyone to reproduce almost any object. When asked about ethical issues of 3D printing, another with a similar opinion said:

> *I mean the one that comes to mind first is probably IP issues, copyright infringement, etc well, it makes it very easy to copy things in a way that is not controlled by the IP owner, things that previously would not be so easily copied… (P14)*

Like the previous participant, P14 also points to an inherent issue of 3D printing – that the technology makes it easy for people to generally copy things that previously could not be easily copied and by so doing infringe on the copyright of IP owners. Another participant who thinks this is an issue said:

> *Erm, obviously the biggest issue was copyright… (P11)*

This participant (P11) made this statement while suggesting that copyright infringement is one of the biggest issues plaguing the additive manufacturing industry. Fear of the impact of this sort of problems has led some companies to take action:

> *Some of the bigger Italian furniture brands you know like Ponti and all those, they've taken out a lot of erm copyright to protect their furniture from 3D-Printing which sounds a bit ridiculous now, but you never know in the future. If you can 3D scan a chair and reproduce a chair which at the moment is kind of crazy but in the future possibly. So, there are companies that are scared about this 3D-Printing but … (P3)*

P3 suggests that the ease with which 3D printing enables items created fear of copyright infringements among some companies with that an Italian furniture brand was one of such companies as they have taken out copyright protection for their designs to minimise the impact of copyright violations.

However, not all participants like the idea of using copyrights for protection. One such participant said:

> *... I don't believe in patents and copyrights and all that sort of thing… (P5)*

This participant maintained that he doesn't believe in copyrights and patents, while another with a similar view, said:

> *I don't care about the copyright of the design...(P2)*

One reason why some participants may feel that way about copyright and patents can be seen in the comments of another participant:

> *I don't really personally have huge issues with copyright to be honest IMO the terms are excessive, and it doesn't really provide the social service it's supposed to since so much "important" copyright ends up in corporate hands and it's often used excessively to clamp down on "unauthorised use" but I can see that it can be important for smaller players to be able to protect their IP… (P14)*

Like participants P2 and P5, this participant (P14) appears to be against copyright because he feels that they are being excessively used to stifle innovation.

Another participant with a similar opinion said:

> *I don't think 3D printing affects intellectual property rights at all … (P13)*

The participant made this comment after pointing out that abused their privileges to restrict the development of 3D printing to only a few between the 1980s and early 2000s. It was only after those patents expired that the development of the technology began to grow rapidly with inputs from the DIY hacker community.

2. Open Source and 3D printing

The additive manufacturing DIY hacker community which sprang up after the expiry of patents and helped to speed up the development of the technology and making them widely available on desktops both positive and negative effects on the industry. One participant described the situation thus:

> *I suppose… the one that people tend to think about first when we walk about ethical issues in 3D printing is the opensource nature of the files, and actually the hardware as well, and that is its strength and weakness. The brilliant strength of it is that it's very much a global community which benefits researchers like me, cos it means that there is a whole host of people all over the world that are interested in and would be able to give me assistance if I needed it. The negative side of it is because it's all opensource, anybody can get hold of a file and physically 3D print it themselves… (P8)*

The participant (P8) who is an academic researcher maintains that the opensource community has generally had a positive impact on the development of the technology and benefits people like her greatly in terms of access to information. She, however, suggests that a negative side to that has to do with free availability of data which means that anyone with access to a 3D printer can copy 3D designs freely.

Another participant who also had a similar opinion said:

> *… 3D printing is kind of in that* open source community, *where everyone sorts of helps each other out and you'd upload your work, and you can share and, and so, erm, that's really helped to grow up to the point it has, because people can download stuff and remix and re-edit, and modify things other people have made and then... so yea... for the time being, I think it's working okay, but there will come a point where it becomes kind of out of the hobbyist thing and early adopter thing into a more, mainstream thing that we would do, where they're gonna need to change that model because it can't sustain itself, erm, by not having any money coming and I guess … (P9)*

Like the previous participant, P9 suggests that even though the opensource model of 3D had a positive effect, by allowing anyone to copy and reproduce designs means that the industry will be unsustainable as the financial incentive would be depleted.

3. Devaluation of Intellectual Property

Another related issue that came up was about the potential damage openly sharing designs and models might have on IP. One participant said:

> *... there is an issue like under the surface of it. Erm, I mean, it's kind of goes to the wider issue of the internet as well though... I mean, the fact that you can share data now so easily... a lot of people are happy to kind of just for the recognition and not for financial reward, they'll design things erm... but that's kind of the same across sound, across graphics, across all sorts of*

different types of data. But … in 3D printing… I don't know if there's much of an issue with people stealing intellectual property, but I think that there is an issue with a lot of people giving intellectual property away for free, which is potentially devaluing the whole, kind of process of design… (P9)

This participant (P9) like the previous participant feels that 3D printing is creating a new problem which he described as the devaluation of intellectual property rights. As designs become more freely available online, P9 suggests that the market value for original concepts and designs will depreciate similarly as digitisation has led to a reduced market value of films, music, books etc.

Another participant who acknowledges that this sort of file share could be problematic said:

Now there are different classes of how much you want to share something. You can share something completely; you can share something for only people to print it themselves without selling it. And there's been a lot of problems with that kind of thing, where people have shared a file and people have been selling that file on ETSY – selling prints of peoples files on ETSY which is a problem… (P3)

All of these goes to show that even in the opensource/hacker community not everyone likes the idea of sharing everything freely. Etsy.com which he mentions is an internet platform where creatives can sell their products.

One other participant who isn't very pleased about the free availability of such data online due to the impact on IP said:

The main thing… everybody seems to be moaning about at the moment is IP. Lots to bear in mind about IP. There are lots of websites… where you can download stuff for free… I know that a lot of it, is marked with the creative commons licence, and there will be people who'd say… you know... download it as much as you like for personal use, but… I'd rather you didn't say that … P10

The participant (P10) appears to be of the view that the people who put work into the creation of the designs shouldn't make them freely available as the case is currently rather they should make them more commercially available rather than opensource.

7.2.5 3D Printed Guns

One of the more heavily debated issues of 3D printing relates to its use in the production of guns. It was no surprise, therefore, that it featured prominently in the discussion with participants. However, the participants had mixed reaction about this issue.

When asked about the ethical issues of 3D printing, one of the participants said:

One of the other things that you'll need to think about is guns, 3D printed guns and…I don't actually know the specific regulation or laws surrounding that, whether it even has been regulated… (P8)

Recognising how much of an issue 3D printed weapons have become even though this participant wasn't sure of the state of the regulation around them, he was able to point out that this was an important issue to be considered in this research.

Another participant pointed out two important things regarding the controversy over £D printed weapons:

> *The reason there's this hype around 3D printing weapons is because of the idea that anyone can download some files from the internet and print a gun and so gun control would become ineffective… (P13)*

Thus, the participant (P13) noted that the controversy over 3D printed weapons has been driven largely by the idea that schematics for gun design are freely available and that current regulation of such weapons is ineffective. Another participant with a similar opinion said:

One participant who sees the problem said:

> *This is quickly a real ethical area. I think when you have this opensource community stuff and you find the plans or the programs for printing a weapon in the net and you have such a 3D printer at home and you can print it… (P16)*

Drawing attention to the exploits of the AM opensource community who freely make such files readily available over the internet, P13 feels that this is problematic as it could to the proliferation of weapons.

Another participant who agrees that this is an issue said:

> *It's definitely an issue I mean… I mean I'm personally of the view that … we need to restrict access to guns and that sort of thing, and I would have an ethical issue with people hosting files that could, you know… easily be used to create weapons … and that also feels … ethically wrong... (P6)*

Interestingly, another participant who runs a 3D printing business maintains that people have brought such designs to his business:

> *We've had that gun that was put on… the Liberator that was put on the internet, we've had that twice … (P15)*

The Liberator is one of the more popular 3D printed guns whose files are readily available online despite a government crackdown on sharing such data on the internet. This illustrates how easily such files can be obtained and shows that there is real interest in using such files to create weapons.

However, one sceptical participant said:

> *The whole point in that 3D printed gun was to have this debate…It's a fantastic talking piece and it's scared a lot of people especially people who are in the, in kind of places of leadership and it brought about this*

conversation. But the actual gun itself and the idea of a 3D printed gun out of plastic is just not there yet and I don't think it's going to be there for a long time… (P3)

Interestingly, this participant (P3) who had a beautifully crafted 3D printed gun prominently on display at their business premises felt that the gun debate is overrated and 3D printed weapons do not pose any sort of danger to society.

Another participant with a similarly sceptical view to those of P3 said:

I don't know how much... this is feasible, like the 3D-Printed guns, because I can tell you this... this plastic, it melts at 240^{o}C and when you have something like a bullet inside... it exceeds this temperature so that means that it should melt… (P2)

This participant (P2) who is a mechanical engineer suggests that the melting point of the plastic material used in creating 3D printed guns like the Liberator is 240^{o}C but that a bullet gets to higher temperatures and so she doesn't feel that 3D printers can create really feasible weapons. Another mechanical engineer with a comparable view said:

The 3D printed gun thing, I find rather amusing…two reasons... the first reason is that 3D printers are actually an extremely bad way of making a gun. If a person makes a gun with a 3D printer, the person who is most in danger from that gun is the person who made it. It's just such a poor technology for that sort of mechanical device. The other aspect to that which I find amusing is that… strictly from an engineering perspective if you have to make a gun, a lathe is the machine to go with, not a 3D printer. Lathe's cost about same as a 3D printer and you can make a really serious gun in a lathe, and this is a technology that's been available to everybody for 200 years, and it hasn't been a serious problem. So, simply on that historical precedence, I think that the idea of 3D printed weapons, is probably not too serious a problem, because it's not a new capacity in that particular sphere of engineering… (P5)

Although this participant's view of 3D printed weapons appears to be based on his experience of the technology and the historical use of other technologies like the lathe milling machine which he draws comparisons on, it provides some indication of the views of many other 3D printing experts.

A similar opinion was shared by another participant:

I think the entire discussion around 3D printed guns is basically bullshit. You can't make a viable firearm with a 3D printer and current materials, not even a single shot. It is likely to fail catastrophically on first use, and as likely to hurt the user as the target... any machinist that has a lathe and mill and knows how to use them can make a real gun, because that's how they were made before mass production. It's still the wrong technology - you can't make a smooth inner bore with any 3D printing method and if you don't have that, the weapon won't shoot straight. But literally, any auto repair metalwork shop has all the tools needed to make a real gun … and you can buy a lathe for about as much as a 3D printer and make literally anything on that out of steel… (P13)

Like the previous participant (P5), P13 feels that technology for producing guns have been readily available for years and have never really been a problem for society and so doesn't understand why people are worried about 3D printed guns.

Other participants looked at developments in the metal 3D printing industry which some have said is the future of additive manufacturing. One such participant said:

> *Weapons… Eh, well, again it's like 3D printing is supposed to make it easier but the technology that is good enough to make an effective weapon is not available to everybody. There are many easier ways of making a weapon than 3D printing, so, there really isn't a concern... The functional parts of the gun have to be made out of metal so that's not really going to happen in 3D printing because it's very expensive and it's not accessible… (P7)*

And participant P3 quoted earlier said something similar:

> *Industrially, you can print directly into metals now and of course, if you have... access to one of those kinds of printers you can print weaponry very easily, but again that technology is very expensive and very dangerous for health and for everything. But again, that's completely way off from anyone's grasp apart from people in the industry and of course, the industry is already incredibly regulated by what you can do with 3D printers... (P3)*

Like P7, participant P3 also feels that there is no reason to be worried about 3D printed weapons because metal 3D printing isn't readily available to the general public due to its high cost. However, one participant who looked into the future application of metal 3D printing technology said:

> *… I know people are experimenting with metal and stuff like that at the moment... that sort of changes and potentially stuff could become much easier to make…(P6)*

This participant (P6) appears to be of the view that in the future, creating objects like guns could become much easier to make using metal technology as the technology continues to improve.

7.2.6 Jobs

Participants also discussed their views on the effect of 3D printing on employment. Similarly to the other well debated issues, they provided an interesting mix of opinions. While some felt 3D printing could be detrimental to jobs, others felt it boosted employment. It was interesting to see how some of their views are closely linked to the projected trajectory of 3D printing. For example, one participant said:

> *I sort of see the future in that we have a box in everyone's house or maybe one in your local high street, and anything you buy, you go there, and it just makes it there for you, so you don't have to get things made in China or whatever, and shipped over on boats, we can just have stuff… (P9)*

With a 3D printer in almost every home and home-based manufacturing widespread, this participant suggests that jobs (at least those in China) will be affected negatively.

Another participant with a similar opinion said:

> *I think the cost of them will come down, we've seen that already... that's the trajectory that they've taken, and I think that … these 3D printers can enter the home and then anyone can use them... so, not just materials engineers, or engineers, or architects, or sort of the enthusiasts use at the moment. So, in that sense, these desktop 3D printers are becoming more, and more user friendly and will be probably seen in the home, just like 2D printers are now…(P8)*

Drawing attention to the trajectory that the development of 3D printers has taken over the years from very expensive, difficult to manage machines to much cheaper machines that can be easily used out of the box, participant P8 also appears to agree with the previous participant.

However, some participants had a contrary opinion about the prevalence of 3D printers and suggested they may not be so widespread after all. One of those participants said:

> *If 3D-Printing is a household thing… I don't think its anywhere near there or if its ever going to be there. Most people have a 2D printer at home they don't use. I don't see people using a 3D-Printer all the time … (P3)*

Unlike participant P8 and P9 who suggested that availability of 3D printers will eventually become as commonplace as 2D printers, this participant (P3) argues that 3D printers may not be so widespread and even if they are, the situation will be similar to that of 2D where they aren't going to be used very much in the home.

Another participant with a similar view said:

> *So, the assumption of everyone going to have a 3D printer in their house is not happening, and I don't think it's gonna happen anytime soon… (P11)*

This participant feels quite pessimistic about the future developments of additive manufacturing and doesn't feel the printers will be in every home, as suggested by P8 and P9. Although not part of the comment above, he attributes this opinion to the limitations inherent in the technology like how difficult it is to improve curing times to allow another layer of material to be added during printing. Another argument of P11 is that other manufacturing technologies like injection moulding are much more efficient than 3D printing and so those will likely always be preferred to additive manufacturing.

One of the things that came out of participants discussion on the impact of 3D printing on employment was that there wasn't any clear agreement on whether it would lead to job losses or result in more employment. One participant who expressed this type of opinion said:

> *It could help develop technical skills somewhat for future generations. That might or might not have a visible impact on employment, I don't think it's possible to say… (P13)*

Other participants also felt the effect of AM on employment would be both positive and negative as shown in the comments of P9:

> *I'm kind of the view that the more jobs that we can automate, the better … but, only if it's done in the correct ways… I mean there will be new jobs, I mean like 20 years ago… my job as 3D printing technician at university wasn't a job, and now because of it, there is a job… I'm sure there will be job loses with it as well… (P9)*

This participant view illustrates many of the views on the double-edged effect that 3D printing will have on jobs.

With regards to the ability of AM to create new jobs, a similar comment was made by P15:

> *What it will do is bridge the gap between mass production and one-off items... and you are also creating a lot of jobs in terms of people making machines, people servicing machines, people supplying materials, transport and logistics and stuff like that for all those items… (P15)*

Like P9, the participant (P15) feels that additive manufacturing will create a lot of news job in such areas as manufacturing of 3D printers and accessories, servicing and repairs of the machines etc. Another participant who had a similar view said:

> *In terms of employment, technically it should open up a new area of manufacturing… we've even noticed like even on our stretch of arches here, there are two other businesses that have opened up in the last year. So, there is definitely more jobs out there because once the entry price gets lower as the technology gets more available you will get more and more people wanting to do it, because its a creative process there's a lot of people who are naturally born creative or whatever, they'll head towards there… (P7)*

Unlike the other participants whose opinions appeared to be midway between positive and negative effects on employment, P7 appears to lean more towards a positive effect as it has opened up new areas of manufacturing which will get more popular as 3D printers get cheaper.

Another participant who also felt positive about the impact of 3D printing on employment said:

> *I think that particularly the manufacturing industry ... employs so few people, you know... you can churn out vast amounts of plastic whatever, from a factory that employs few people that there's not a huge number of people that I think stand to lose their job, yet there is quite a large possibility for new jobs to be opening up as designs can be tweaked and customised on an on-going basis… (P6)*

To point to the beneficial nature of 3D printing for employment, this participant (P6) draws an interesting comparison with the and mass production in the manufacturing industry. He points out that not a lot of people are employed in such industries as opposed to 3D printing which allows for better customisation but fewer outputs per time.

One participant who feel that 3D printing would not lead to job losses said:

> *At the moment, 3D printing isn't very automated. Like, yes, the process itself involves sort of a robotic arm, that goes around and builds up the object, but it requires a human to make the computer files, it requires a human to press play on the machine, it requires a human to take the object out, cut off all the support structures – any post-processing that you wanna do on it, that requires human as well. So, although, on the face of it, it does it like a robotic manufacturing method, actually, you do still require a quite a lot of human input, so, I wouldn't say that 3D printing will take away from any jobs any time soon… (P8)*

However, one participant who had a contrary opinion to the previous narratives on employment gains due to additive manufacturing said:

> *Perhaps more importantly, things like erm, a simple reduction in employment. You know if I have a 3D printer, and I print all the coat hooks in my house, which as it happens I do, and I have, then somebody who makes coat hooks is out of a job…(P5)*

Although not part of the quote above, P5 made an interesting analogy on AI and other related technologies to show how they affect jobs. The participant appears to support the view that 3D printing will affect jobs and points out that there are important questions for society in this regard.

7.2.7 Business Ethics

It is not uncommon to find that moral problems also do arise in business environments and as the additive manufacturing industry is still emerging, it is not surprising that certain aspects of business conduct by some individuals or organisations did concern some participants. The issues discussed all revolved around marketing strategies as shown in the next comment:

> *I know there is a filament brand that … that are supposed to be anti-microbial, and they say we can use it with food... but to my mind, it's not really true because when you print, there are still some particles that you cannot entirely master what happens in the process. So, to mind, it is probably just marketing... I mean theoretically, we can use it for food but in practice, it's not really safe... (P1)*

The participant suggests that some businesses engage in false advertising by making misleading claims about their brand of filaments. Although this should not come as a surprise, curiously, very little has been said in the AM industry about such practices.

A second participant who narrated another marketing issue he felt was controversial said:

> *So, there's a company near Leeds, they say they do recycle filaments. I think it's a little bit of a marketing con from one of the filament manufacturers to be*

honest because their samples which are supposedly recycled filament is actually as good as the stuff you get from this particular place in the Netherlands, and I know because I've dealt with them for a while, that I know the sort of stuff you get... samples even look exactly the same as the samples, in the same packaging, with the same zip ties in the same place… (P10)

Similarly to P1, participant P10 discusses another false advertising issue where a filament brand makes false claims about their products.

A third participant who mentions a different type of false advertising practice in the industry said:

I see companies that they try to create something else... you know because they are looking for long term customers, they want you to be with them and spend on them like they want devotion. It's basically…like you have a machine that doesn't cost that much, but then if you want to print with materials, you have to pay and also you need to use... specifically, the round slicer and this is not true… I have so many closed sourced machines, but I can tell you, all of them are working with 3rd party filaments and this is a huge lie...(P2)

7.2.8 Offensive Items

As the popularity of 3D printers increase, there is a growing trend for people to use them in creating all sorts of items. Participants indicated that they are aware of some instances where 3D printers have been associated with the printing of offensive items. One participant said:

I know the story that Shapeways… once somebody wanted to print a Swastika, and then Shapeways refused to that...(P2)

The participant pointed out the refusal of the company to print Swastika's for a customer resulted in a long and expensive legal dispute.

However, another participant had a different view of such items said:

... the truth is in my history of 3D printing, I've printed some funky things, things I'd never considered doing myself, but they are artistic or personal to those people. It doesn't really bother me. On a small scale not really… Its offensive to me… but, you know... instead of 3D printing something, I could get 2 pieces of sticks and stick them together to make a sign and that's like, yea if somebody really wants to do that then, 3D printing isn't the only way of doing… (P7)

The participant appears to have taken purely business decision rather than a moral one in deciding to go ahead and print items that he feels are offensive as he's pointed out, there are other ways the customers could get the same thing so rather than lose money, he decides to accept their custom.

A third participant who viewed this as a dilemma said:

> *… it's easy to sort of say things like, oh no, I think this is hateful, therefore, I think this one shouldn't be allowed. But obviously… there was... various cases recently of cake makers refusing to make items for gay weddings and that's gone through the court and, in that case, they've felt that… you couldn't discriminate against them for that. Erm, so yeah… if you are a private 3D printing service, should you be forced to make anything that was legal? … that's genuinely a tough question. On balance I think…provided it's a legal request and not something that's… encouraging violence or, encouraging discrimination, or that sort of thing, then I think, probably you should be required to… (P6)*

The participant (P6) draws attention to the recent cases in the UK where a cake maker refused to make cakes for gay couples and was dragged to court. A long-drawn-out legal dispute ensued resulting in heavy fines and subsequent appeals. He, therefore, suggests that to avoid such issues, as long as the item being printed is legal, even if it is offensive, then the item should be printed.

7.2.9 Data Security

One interesting issue that was mentioned by a participant had to do with data security. He said:

> *We've had credit card skimming devices, which I've identified. That was really early on, that was in 2011 I think when that happened, and we actually worked with the police and they got the guy … (P15)*

This is a good example of the type of illegal activities that might be promoted by 3D printers.

7.2.10 Liability Issues

Issues of liability also came up in the discussions with participants as they attempted to explain who becomes legally liable when something goes wrong with 3D printed items. Participants had several interesting takes on this matter. For examples, one participant said:

> *It may not be your fault that whatever you design has caused an accident somewhere but you're responsible because you* designed *it and the way you designed it has caused an issue… within that relationship between the designer and the stakeholder em, everybody is responsible to a certain degree… (P4)*

While this comment also shows how responsibility can be split between stakeholders, it appears to oversimplify the problem because of the difficulty in determining where any problem may have emanated from.

Recognising the difficulty to apportion blame when a hobbyist 3D print items at home and it results in an accident occurs, another participant said:

> *When you do DIY printing and you repairing something … these particular industrial norms on industrial safety [do not apply] when you do it yourself... I think this is a problem… (P16)*

The participant (P16) suggests that the industrial rules may not apply to those who use 3D printers at home when problems occur with objects that have been created at home.

P13 who also looked at the liability issue mainly from the perspective of a defective item said:

> *I would say you are clearly liable because I don't see who else could be. You selected a thing to print, and printed it, and used it in a particular way. I still think at that stage it's your responsibility to verify that - in this instance, you are the manufacturer… (P13)*

In this case, this participant (P13) seems to put liability squarely on the shoulders of the consumer and absolves others down the supply chain of any responsibility.

Recognising that the 3D printing environment is muddled when it comes to matters of liability, one participant who felt the need to take proactive action to protect his business, said:

> *We have a disclaimer on our website and our terms and conditions that the data we get sent is the responsibility of the sender and not us. So, we'll print it out and we will send it out. So… we say, you know if you are breaking the law in any way, shape or form, it's on you we are printing, and they agree to that before they place the order. I don't know how well that covers us legally but again as I said, it's the customer's data and they are responsible for the repercussions of what they do… (P15)*

The participant maintains that to protect his business from legal disputes due to copyright infringement on items he prints for customers, he makes them agree to take full responsibility as they've sent these items to his business. He, however, admits that he isn't sure of how much protection this gives him.

7.3 On a More Responsible AM Industry

The purpose of this section is to highlight the participant's perception about barriers to a more responsible AM industry and their opinion on how to encourage greater responsible practices among users of the technology. The barriers pointed out include lack of knowledge of ethical issues, the impact of the absence of specific regulations for the industry, the cost of compliance, and technical issues related to additive manufacturing. The participants have therefore suggested that education about ethical issues, environmental friendliness, sensitivity to intellectual property rights, transparency in business, are some of the actors that can help enable a more responsible industry.

However, it should be pointed out here that at least one participant felt that there was no need to promote responsibility in the 3D printing industry. The participant said:

> *I think responsibility is orthogonal to manufacturing technology because there's nothing particularly new or different about 3D printing compared to*

> *other prototype manufacturing methods. It's not a new thing subject to research, it's just yet another tool that is now more accessible to researchers. … so I don't see how researcher responsibility should change in any way based on what tool they use … (P13)*

The participant (P13) argues that that *'responsibility is orthogonal to manufacturing*' and appears to be of the view that there was no need to encourage responsibility in AM because there is nothing special about 3D printing that requires ethical consideration.

However, another participant who appeared to have a contrary opinion to that of P13, went on to provide a general description of what responsibility in the industry should mean as follows:

> *... I guess general responsibility is not printing dodgy materials that make your room full of gases and nasty fumes, trying to minimise the amount of plastic that you're dumping in bins, and then, yea, not stealing other people's files… (P9)*

7.3.1 Barriers to Responsibility

Having given their opinion on what it takes to be responsible in the additive manufacturing industry, some participants discussed issues that could be a barrier to people acting responsibly.

1. Inadequate understanding of the societal implications

It was interesting to see that some participants felt that inadequate education was a possible barrier. One participant said:

> *I mean, some of it is just lack of knowledge or understanding of the issues whether it's safety, or whether that's intellectual property. So, certainly a sort of clear explanation of the issues… so basically it's either a lack of understanding or lack of care that can many people are irresponsible...(P6)*

The issue of lack of care also mentioned by the participant is important as illustrated in the next participant statement which came in form of a question:

> *Are manufacturers going to bother to do that [I.e. use filters] if they don't see the particles as being particularly dangerous? ... (P5)*

This question raised by participant P5 concerns filters being developed to minimise air pollution by 3D printers. The question suggests that additive manufacturers who don't understand the dangers caused 3D printers may not bother using filters.

2. Absence of Regulation

As the 3D print industry is currently not well regulated, participant P11 suggests that the absence of regulation has had some impact on the way he works. He said:

> *With laser cutting, you need an exhaust unit anyways, because the fume is toxic. So, laser cutting it's compulsory especially indoors. With 3D printing, they don't have any regulations around it… We don't use any exhaust unit because, I mean, first of all, it's a small machine and the amount of... not particles, but eh…fumes is negligible… (P11)*

The participant maintains that he uses exhaust units with the laser cutting equipment too because it is mandated by regulations. Interestingly, he, however, doesn't use similar equipment for 3D printers because there is no regulation requiring this, and also because he feels the machines are really small and so the effect of the fumes is negligible. This illustrates how the absence of regulation could hinder responsible practice. It also shows how a lack of knowledge or awareness could lead to serious risks being taken.

3. Cost of Compliance

Some participants indicated that the cost of complying with regulation could also hinder responsible practice in the AM industry. For example, participant P7 said:

> *It's like even basic things like disposing of waste... the right way of disposing of waste. If it comes at a cost, that people would much rather avoid, then that's an issue... (P7)*

The participant went to explain that there are some processes that his company would like to adopt but have been unable to do so currently because of the enormous cost involved.

Another participant provided another example of how the cost may hinder responsible practice:

> *So, the technical solution is from an engineering standpoint straight forward at least as far as that is concerned, but then …you know, the manufacturer that leaves the fan and filter out is going to sell a cheaper machine, all the things being equal… (P5)*

P5 suggests that in future 3D printers may have fans and filters attached by default by some manufacturers while others may leave such safety features out in a bid to sell cheaper 3D printers.

4. Technical Barriers

Three areas where technological issues have hindered responsible practice in the AM industry were highlighted by participant P15.

i. Lack of technology for detection of IP theft and offensive items

One of the problems that P15 mentioned is to do with IP theft infringement as he said:

> *As for theft of IP, it's almost impossible for us to know whether that's has happened or not…The parts come through with no identifying features on them other than their shape and we can't really track every shape to an existing item… (P15)*

Another problem P15 identified was the difficulty in identifying banned or offensive objects:

> *I mean if we can identify banned objects, we won't print it, but often we don't know. We don't have a library of everything in the world that's banned. Erm, yeah again…. it's impossible to identify… (P15)*

These issues appear to all be technical issues and have been classed here as such.

ii. Recyclability of 3D printed waste

Participant P15 also indicates that he experiences difficulties with recycling and disposal of waste from his 3D printers as he said:

> *Disposal of waste here is quite tricky because there's no one who really specialises in disposing of 3D printers waste, unfortunately, downstairs we get mixed media of sand and nylon powder, so it's very difficult to separate... obviously, they are not gonna be recycled together…(P15)*

This also appears to be a technical problem as it appears the technology to recycle mix-media 3D printed waste isn't available. It, therefore, means that such waste will be discarded and will likely result in some environmental problems as time goes on.

P15 also suggest that he'd like to see an easier way of appropriately disposing waste from 3D printers as he describes another problem he is faced in this area thus:

> *Erm, so, we are actually looking at putting a recycling logo on our parts as an optional extra obviously for a charge but which we can digitally just put on. Erm, but again it's very difficult for a lot of these items because they are not mass-produced, they don't come as a generic item and therefore it's difficult for a recycling company to identify… (P15)*

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7.3.2 Enabling Factors for a more Responsible AM Industry

The next phase of the research, having identified the ethical issues of additive manufacturing, was to seek the participant's opinion on how to encourage a more responsible AM industry. Some of the other participants felt that some changes were needed and offered suggestions in such areas as education, eco-friendliness, regulation, technical solutions, and business ethics. Also, some even went further to discuss barriers to responsibility or factors that may make it difficult for users of AM to act more responsibly. The following discourse provides a summary of some of these findings:

1. Education

The importance of education was highlighted by some participants as a means to help encourage responsibility among users of the technology. One participant said:

> *It's always good to direct people to a proper... to a nice... to a good direction, like to orientate them towards positive, not towards negative… I believe in motivating instead of suppress, so you will try to push them to cultivate and improve towards something positive without mentioning the negative... because if you mention and if you, if you stand on the negative, then this is gonna attract attention to some … (P2)*

The participant (P2) appears to be of the opinion that although technology could be used for good or bad, rather than suppressing its use with rules more should be done to motivate positive use of technology.

Another participant with a similar view said:

> *I always like to think if you explain to people why then you shouldn't need to enforce it with the punitive… I'd like to think you can just explain why it's a good idea to be safer… (P9)*

Like P2, participant P9 suggests that people should be taught why it is a good idea to be safe when using 3D printers.

Another participant with a suggestion along these lines said:

> *…so you as a prosumer know how to 3D print, you should always have in mind that there may be someone who knows less than you, so, you would have to... it's incumbent upon you to actually always be willing to teach and correct others whenever they are doing something... (P4)*

Like participant P2 and P9, this participant (P4) agrees that it is the responsibility of people who understand 3D printers to teach others or to correct those who do not know.

As many additive manufacturing machines are now being used in businesses, one participant suggests how users in that category can be educated on responsible use. The participant said:

> *I think there could almost be a whole educational process for businesses on, you know, in terms of trade-shows, just how you are dealing with materials, just more focus on the quality of materials, re-usability, helping companies like us to... even things like protection and health and safety. We're doing it ourselves because we feel this is the right thing to do rather than there being a kind of body or guide within the industry to say this is the way to do it, how to do it… (P7)*

According to the participant, his organisation recognises the importance of educating people and have taken concrete steps to do so through for example trade shows, rather than wait for regulation or regulatory body to do so.

Besides tradeshows, another participant suggests other areas where this type of education can be provided:

> *I guess when people learn to 3D print, whoever teaches them, or whatever guides they look at, that is an opportunity for educating people about responsibility and safety in 3D printing. So, there is probably is an onus on*

people that are doing the training... they have the 3D printers for example here in the makerspace, erm, there is a responsibility there for people to disseminate the knowledge of being responsible as well… (P8)

Showing how seriously the participant views the issues of education, P8 maintains that it is '*an onus*' on the trainers to also teach about responsibility and also suggests that such education should also be included in 3D printer guides.

Another participant who is already doing something like that describes how he goes about it:

So, everybody who wants to use the printers here, they have to go through a 40-minute induction *with us… we kind show them like, processes in terms of the software and the files you need and all that stuff. But, we also explain the safety, and a few other things about it… no one's allowed to put your hands inside when it's printing, you can't touch the nozzle, you have to wait for it to cool down before you remove the thing, and then in terms of sort of stuff like maintenance, changing the reels of filaments, all that sort of stuff, we always do that ourselves … (P9)*

The participant who runs a makerspace maintains that he puts all new members through a 40-minute induction to teach explain how they can use the printers safely and responsibly even though most of the safety rules mentioned are basic, they are still an important part of being responsible.

2. Enviro-friendliness

Participants discussed actions and practices which uses of AM technology may engage in to help ensure a safer environment, including recycling, waste management, using biodegradable products, ensuring clean air while using the printers, conservation of energy, and helping to ensure a more circular economy.

i. Waste Management

Having noticed how waste management is becoming a problem in the additive manufacturing industry, some of the participants who were conscious of this issue suggested that more responsible waste management practices were required in the industry. For example, one participant said:

Waste, I think is something that... we could do better out here… (P9)

Another participant highlighted how his business was already taking action in this area:

We try not to reprint stuff as much as possible… (P15)

Recognising however such action alone might be insufficient, the participant continues:

Getting a way of having an industry where its recognised materials can be disposed of will be a good way of doing it.., (P15)

One of the problems with waste management from 3D printers is due to waste management companies not recognising what the chemical properties of the materials used in 3D printing are. The participant, therefore, suggests having a way to help them identify 3D printing waste could help is the problem as the waste management companies can then provide appropriate treatments.

ii. Recycle

Given the plastic waste problem of 3D printers, some participants were of the view that recycling would help ease the problem. One of the participants said:

> *I think the most realistic is just to start at least from recycling... (P2)*

Another participant who agrees with this said:

> *The responsibility then falls on the companies to either make these things recyclable or there's gonna be some ethical way of getting rid of this material … (P7)*

And one participant who admits that there was room for improvement in this aspect in his business, said:

> *I guess one side of it is waste as well, which I think is … one of the things we could do better out here. So, one thing we tried to have before is about investing in a machine for recycling plastic filament. We haven't got around to doing that yet. But we would really like to get a machine so that we can reuse direct filament, cos whenever there is a print that goes wrong, at the moment it just gets thrown away… (P9)*

Thus the participant not only shows recognition of the problem but was also actively seeking solutions to it.

iii. Biodegradable Materials

Another suggestion proposed by a participant has to do with biodegradation. He said:

> *Responsibility towards the environment...I mean, our responsibility, we are manufacturers, so at the end of the day, the stuff that we manufacture it goes back to nature at some point… (P11)*

The participant (P11) suggests that a responsible additive manufacturing industry will endeavour to use materials that can breakdown naturally to help limit the problem of plastic waste in the environment.

iv. Clean Air

Recognising how 3D printing contributes to air pollution which can in turn cause health problems led two participants to propose limiting this problem. One participant said:

> *The environment... the air is not brilliant anyway, so we don't wanna make it any worse by having loads of 3D printer fumes...I guess general responsibility*

> *is not printing dodgy materials that make your room full of gases and nasty fumes...minimise any kind of hazardous results from the printing in general…(P9)*

Further to this, the participant describes what his business was doing to minimise the problem:

> *So, for instance, we don't allow ABS printing here, we just print in PLA because the fumes are less harmful; we try and keep the printers in closed cabinets as much as possible but we can't always do that; we try to take steps like that just to minimise the amount of exposure to the gases and stuff and yea if we do anything in any other materials we make sure it's in an enclosure with an extraction…(P9)*

The participant (P9) thus show that his business was taking steps to minimise fumes from the printers.

Similarly, another participant said:

> *Health is major... we are in a dusty environment, so you know, like in the last year we spent almost a hundred thousand pounds on extraction, just to remove dust and things like that… we've got air conditioning that is constantly treating the air… (P7)*

The is another good example of what can be done to minimise air pollution. By installing air extraction equipment, the participant shows a good understanding of the importance of minimising pollutants from 3D printers.

v. Energy conservation

As some 3D printers are known to consume a lot of energy, one participant feels that another way of being responsible to the environment involves using less energy. He said:

> *We don't run our machines when we don't have to so, that saves a bit of energy, I mean that's both beneficial to us and saving cost but also beneficial and saving energy for the environment…(P15)*

Interestingly, this was the only participant to point out what they were doing as a business to minimise energy use.

Vii. Enabling a circular economy

Another interesting proposition for responsible use of additive manufacturing came from P15 who said:

> *Convincing people they don't need to buy a set amount. Convince them that they can buy what they need erm, so that can benefit the environment in a certain way… (P15)*

This is one of the principles of the circular economy where waste is frowned upon and people are encouraged to purchase just what they need.

In a similar vein, another participant said:

> *One area where 3D printing could make an impact is increasing product lifecycles. Manufacturing replacement parts for partially damaged products. Especially in cases where the manufacturer no longer wants to support the product, or has discontinued it, or has gone out of business. I've seen this happening in the 3D printing community - people will make replacement parts or repairs for things that they would otherwise throw away… (P13)*

The participant concept of increasing product lifecycles is another important principle of the circular economy where reuse, recycle, and reduction of waste is promoted.

3. Sensitivity for IP Rights

Other ways of ensuring a more responsible AM industry were suggested by participants who were concerned about issues around intellectual property. One participant said:

> *I guess general responsibility is erm… not stealing other people's files… (P9)*

This suggestion was made in the context of IP theft and here the participant appears to suggest that users of the technology need to avoid IP theft.

Another participant goes further to suggest other measures as follows:

> *… and the other sort of legal responsibility I guess we've got is, on the copyright... whatever we're printing, is that infringing on somebody's copyright? And whether... the person who did actually design the things we're printing or whether they, you know, designed their own you know, that is ripping off [others]… (P6)*

The participant proposes valid questions that need to be considered by other users of the technology considering how easy it is to infringe on the IP rights of others.

Those providing online hosting services were also considered by another participant who said:

> *... I don't know, the word is controversial, or ethically problematic when you got issues like 'Thingiverse', where they sort of host the files and you can, you know with the plugins now, you can just hit print and it will send it to a 3D printer manufacturer and they'll send it back to you. And I think the then... there are issues with that sort of thing cos they're... they're hosting a file, they're advertising it as, you know something that's available erm, and, you know, questions could be raised, and you know, do eh... I don't know, the sort of libraries that 3D printer files do... I think they probably do have a responsibility to make sure that what they're hosting is legal... (P6)*

The participant appears to be of the view that websites that host designs of models for 3D printing should make it their responsibility to make sure that whatever they are hosting is legal as they are currently making it easy for people to infringe on copyrighted material.

4. Transparency in Business

Like every other business, how additive manufacturers conduct themselves has an impact on the way it is perceived, and some participants suggested that business in the industry out to be transparent when dealing with customers. One said:

> *I think it's definitely a certain amount of transparency. If you're providing something that you can't guarantee for health and safety or whatever like that, you have to... you have to clearly communicate about that...if a certain use of it is either irresponsible or illegal you need to clearly flag that... in particular in the industry it really comes down to transparency and making sure that users understand what their responsibilities are and what their limitations are… (P6)*

Another participant who supports being open or transparent said:

> *But the only thing I can really imagine is that having the community for 3D printing… where everything is more or less open, there's a lot of dialogue between people who are at the same level with 3D printing. Having that open source mentality means that there will be regulation. It means that if you are doing something particularly controversial people will bring it up and people will explain why it's controversial. There will be limits on things like erm, on the ethics of an object just because of the object's nature of it… (P3)*

This highlights how being open or transparent can have a positive impact on issues around ethics as it'll help the community to self-regulate.

7.3.3 Regulation

Participants were asked for their opinions on suitable regulatory approaches for additive manufacturing. The responses received were then classed to reflect their ideas which include those that felt that current regulations are adequate, on the need for codes of conduct, standards and certifications, and those that call for regulatory mechanisms for intellectual property.

1. Current regulations are Adequate

Many of the participants were against the creation of any new regulations for the AM industry as they felt that existing regulations are adequate to address any issues in the industry. One of the participants with such an opinion said:

> *It's already regulated by various regulations that apply to similar machinery. Electrical safety regulations, machine tool regulations, material regulations, applications to particular fields such as medicine and food and patent laws and design copyrights apply to designs. I don't see 3D printers as in any way different to any existing manufacturing tool. So, it's already being regulated under EU and national laws...I don't see any new legal questions arising from 3D printing that would justify more specific regulation… (P13)*

Extending the issue of new legal questions raised by P13, another participant who explained why he feels current laws are adequate said:

I think the copyright law probably already covers CAD, 3D models are fine... I guess at the moment there's also the threat [that] if we've been printing ABS here since I arrived, and no one has told me that was bad, and then I developed some sort of lung problem and you can sue my employer, so there is already that responsibility for health and safety to all the people in your space from an employer or from an organisation's point of view. So, erm, maybe that's already enough of an incentive for them to make these many steps they can to keep stuff cos they have to show... reasonable steps have been taken to make stuff safe… (P9)

This participant who strongly agrees with P13 that current regulations are adequate for 3D printing feels that the threat of legal liability on the issue of health and safety is enough incentive for users of the technology to take steps to ensure that stakeholders are well cared for.

Another participant with a similar view said:

I don't think any new laws can really do anything about it … (P3)

Like P9, this participant (P3) doesn't think any new laws would be necessary for regulating the use of 3D printers...

A similar position was taken by participant P14 as he said:

Because it's a "new thing", you can see governments might be prone to overreacting with special rules too. Copyright, patent or trademarks are all established protocols, regardless of the technology used I would be, generally speaking, against them (the laws) industry is regulated already in terms of IP, etc safety regulations and so on are also already extant… (P14)

Also arguing that current regulations were sufficient, P14 was of the view that as additive manufacturing was relatively new, there is a tendency for governments to 'overact' with special rules and he doesn't feel this is necessary.

This participant, however, provides an interesting reason some may be sceptical about new regulations in the industry:

So, you don't need special rules to govern 3D printing in particular, but you could see how larger players would lobby for additional restrictions… (14)

The participant suggests that the push for regulation may not be altruistic after all but is likely being pushed by selfish interests.

Apparently, in agreement with this view, another participant said:

With 3D printing, they don't have any regulations around it, but I think, the manufacturers of exhaust unit, they are pushing to implement regulations for 3D printing as well, but I think they are not at that stage, so there is as I say, there is no law or regulation around it… (P11)

P11 who was referring to the use of exhaust units to help minimise the dangers of particles and fumes from 3D printers contends that although there are no regulations around this currently, some manufacturers of such equipment are pushing for regulations requiring their use.

Similarly, P10 provides another reason for caution in terms of creating new regulations:

> *If your gonna start saying, now you know, this is all gonna be regulated and whatever, we're gonna check everything you do, erm, I think it'll kill all that, and I think it's a really bad thing… (P10)*

The participant thus suggests that new regulations could stifle the industry.

The only argument in favour of regulation was from a participant who said:

> *... it's not the technology as such, it's actually the use of the particular sort of technique or of machining like weapons, like human organs, maybe other areas as well, maybe in food industries, you have to look on hygiene standards and all sort of regulation… you can easily print out a steak or whatever out of cells… and so I think…and you have to regulate really what is in this meat, and how it is produced, what are the hygiene standards. This is a cutting-edge area which is quite interesting to regulate... (P16)*

It appears that the participant is suggesting that rather than regulate the entire industry, particular applications of the technology should be regulated. He contends that such areas as food hygiene, 3D printed weapons, the printing of bio-organs, etc. require regulations to help ensure quality and safety.

2. Code of Conduct

Having seen that many in the industry are opposed to new regulations or laws for additive manufacturing, participants were asked for their opinions on more voluntary rules like codes of conduct. It was interesting to see that many were of the view that this could benefit the industry. One participant who wasn't sure if there were any such codes in the industry said:

> *I don't even know if there is one to be honest…to my knowledge, there isn't one for 3D printing, erm, and it might possibly be cos as an industry, or as a thing, It's very immature… (P10)*

The participant suggests that the immaturity of the industry meant that codes of conduct were not yet required.

Another participant who referenced the maturity of the industry said:

> *It would be nice to have laws, but because, I mean, first of all, the technology is changing so rapidly, the laws will find it difficult to adapt to the uncertainty of the technology… it's still erm, you know like at the, at the baby steps at the moment, and I think that needs to be a bit more mature, a bit more stabilised… so in the meantime, people just act on their common sense, and I mean, as I mentioned, no guns, no violence, that sort of thing, and no dodgy materials; be a bit more careful about the materials used, that sort of thing, and recycle as much as possible… (P11)*

The participant who feels that laws might be beneficial for the AM industry around such areas as health and safety suggests that it would be premature to create any such laws at the moment because the industry is at the 'baby steps' stage. He, however, maintains that common sense rules around the societal issues of 3D printing are what is needed at the moment.

Another participant in support of such codes of conduct said:

> *If there was a sort of erm, I don't know what the term is really, but perhaps a code of conduct or, code of allowed stuff that would be easy for people to sign up to, so, if there was a sort of standard thing if it wasn't a sort of mandated thing you could say I support this ethical code… (P6)*

The participant maintains that he supports the idea of a code of conduct if they were voluntary.

Also, in the agreement of such voluntary codes for users of the AM technology, another participant said:

> *Of course, regulating the entire industry or even more than one industry of 3D printing… a lot of it is... yea, it's communications, dialogue... its understanding where the technology is, where it's going, what other people are doing with the technology. Again, yes people are developing guns but, why are they developing guns? If they are not printing ammunition?... (P3)*

Participant P3 maintains that regulating the AM industry would be an incredibly difficult thing to do but supports the idea of an ethical code for users of the technology. He suggests that what might be more helpful is communication or dialogue among users and appears to be of the view that it will foster reflexivity by seeking answer asking hard-hitting questions like '*why are they developing guns?*'

It was interesting to see that some in the industry are already thinking along those lines and are already producing documents similar to codes of conduct as seen in the following participant's comment:

> *We have got a 20-page health and safety document which we failed quite a lot of things on. So, we've got to make sure we get those up to scratch so that at least our employees are all safe and anyone visiting is safe. Erm, we feel it's pretty safe but there's still a few things here and there that are do need doing… (P15)*

The participant maintains that his organisation has created a 20-page health and safety document to ensure that staff and visitors to the business are kept safe although he admits that they have not yet met all the conditions of the document yet.

Nevertheless, it is important to note that not all the participants were in support of such a code as one who did not like the idea said:

> *3D printing is not "special", it's just another tool in the box. Maybe it makes some unethical behaviours easier, maybe it doesn't, but it doesn't really attract a whole new framework just because it's new(ish) and if it were to open a door to some kind of malfeasance that was not previously possible, it shouldn't be singled out unnecessarily…so basically, I mean this whole framework makes sense, but it's not specifically brought into necessity just because a print head moves around rather than a milling cutter… (P14)*

This participant (P14) maintains that although 3D printing makes certain 'unethical behaviours' easier, it doesn't require a whole new framework or code of conduct just because it is a relatively new technology. The participant maintains that although the idea of a framework makes sense, it is not specifically necessary because existing rules are adequate.

3. Standards and Certifications

Besides codes of conduct, participants were also of the view that new standards and certifications could help in ensuring a more responsible additive manufacturing industry. One such participant said:

> *It's likely there will space for things like (more) ISO standards for 3D print quality and so on, but that's more of a technical thing than a legal thing as a relatively new technology that's only recently made its way into the consumer area, I imagine the are areas that do not have complete standardisation… (P14)*

This participant (P14) who earlier had rejected the idea of new regulations specifically targeting the AM industry suggests that there might be a need for more standards like those offered by the International Standard Organisation (ISO) on such things as the quality of 3D printed objects.

Already some in the industry are working towards professional certifications as can be seen from the following comments:

> *So, we are going for ISO 9001 certification here... so we are in the process of achieving it. (P15)*

Another participant who is also working towards this said:

> *We are currently going for ISO rating which is between us, but that is a recognised symbol that what you are producing adheres to certain conditions… (P7)*

Other reasons why some users of the AM technology like P7 and P15 might view certifications like those offered by the ISO an attractive option can be seen in the next comment:

> *…well I'm actually on an ISO subcommittee. If I'm following ISO 9001, it doesn't matter if I use 3D printing, a lathe or chiselling it out with pieces of frozen yoghurt, the point is the end result - am I providing the services and*

> *products correctly? Well, I mean they affect how you design products… and if you're selling something and you want to put "complies with ISO 1234:2012", then you probably should have made sure it does. 3D printing is the same, if I'm selling some 3D printed whatever and I say, "this part has a 3D-wibbly-index of greater than 56 according to BS 4567 (3D printed coat racks - Testing protocols)", then it better have that index… (P14)*

Participant P14 who is a member of an ISO subcommittee suggests that following the ISO standards suggests that standards affect how products are designed and complying with such standards helps assure quality. This, therefore, means that getting such certifications would help AM business like those offered by P7 and P15 to provide some form of assurance to their clients of the quality of their products.

4. Regulatory mechanisms for IP

Interestingly, while most participants objected to the creation of new regulations for the additive manufacturing industry, some participants suggested that this was a special need for some regulatory mechanism in the areas of intellectual property. One said:

> *I think the best thing is to create an organisation that works similar to patents. I mean, the purpose of patents is to share ideas with people. So, to improve the development skills of everyone… well, also to protect the idea of the original design, and I think we need both. We need to see the designs of other people to get inspiration. You know, to get more effective and also to protect these ideas because it's like people need to work and get money for them… (P1)*

The participant (P1) maintains that the creation of an IP organisation that works similarly to patents organisations could benefit the AM industry. He suggests that such an ensure would ensure that people benefited from their works while also openly sharing their design.

Another participant provided the following suggestion:

> *…they need to develop a mechanism for selling intellectual property for things…they need to still have the incentive to design new things so it's important to have some money coming in somewhere along the line... (P9)*

The participant maintains that to ensure that designers continue to have the financial incentive to design for AM, there is a need to create a mechanism where 3D printing-related IP could be sold. This he suggests will help minimise the problems of intellectual property theft and devaluation of IP which the existing model appears to promote.

7.3.4 Technical Solutions

Technical solutions were proposed by some participants for several ethical or societal issues identified in this research. These solutions have been grouped into 4 subsections bordering on intellectual property, toxic particles, 3D printed weapons, and safety.

1. Technical Solution for Intellectual property

On intellectual property, one participant said:

> *If you can get a digital version of a design, copyright it, then you could in theory form a check against a similarly shaped item. Erm, but I'm just talking theory here, there's nothing I know of in practice about that… (P15)*

The participant (P15) suggests that the creation of software to check copyrighted digital designs against other similar designs ones to identify those that have infringed the IP rights of the original designs. He, however, was quick to admit that he wasn't sure this was practical as he was just theorising.

2. Technical Solution for Toxic particles

Participant P5 who advocates the use of filters to get rid of toxic particles from 3D printers said:

> *We've got to sort of… get rid of particles and that's comparatively easy with a filter, all you need is an air pump, and a filter of the appropriate erm... mesh size, erm, and you can filter your particles out of the atmosphere. So, the technical solution is from an engineering standpoint straight forward at least as far as that is concerned… (P5)*

The participant, himself an innovator maintains that the toxic particles can be removed from the atmosphere with the use of filters with the right mesh size and air pump. And another participant suggests that these sorts of pumps were already in existence:

> *For example, there are things like filters are being developed, we have one which is from a kick-starter that we are testing at the moment which advertises that they remove, I think 98% of these nanoparticles… it's possible that in the future when they become more stable, more reliable, we will have these filters permanently attached, it's definitely possible… (P3)*

P3 maintains that some filters are already being marketed and his company has even trialled one which the manufacturer's claim removes 98% of the airborne toxic particles and hopes that in future, they'd be permanently attached to the 3D printers.

3. Technical Solution: 3D printed weapons

To prevent 3D printers from creating weapons, P16 who had an interesting suggestion, said:

> *It's actually technically possible to have some modules eh, that means in the 3D printer as soon as you start to print a 3D weapon, this 3D printer stops to print... and this can be built into the software… (P16)*

The participant contends that modules software can be created in the 3D printers so that as soon as they detect that a gun is being printed, they stop working immediately.

4. Technical Solution: safety

Participant P9 suggested that safety instructions be included with the technology. He said:

> *… we were just saying some sort of symbol or set of symbols that go on packets of filaments to explain to the user erm the safety measures they need to take with that one. So, if you had ABS box, it might say on it, erm, yea, please make sure you... or you must print this in an enclosed printer… just that sort of thing… (P9)*

The participant was of the view that the safety instructions could be symbols on filaments or instructions on the printers that tell users what safety measures must be taken with the printers.

7.4 Conclusion

In this chapter, findings on ethical issues from empirical research have been presented. It highlights the ethical concerns of experts in the 3D printing industry. The findings were grouped into the following themes – health and safety, intellectual property rights, 3D printed guns, environmental issues, employment issues, information security, business ethics, offensive items, and liability. The narrative also covered features of responsibility in the additive manufacturing industry and recommendation from the participants for a more responsible industry. The significance of these findings is discussed in more detail in the discussion chapter.

Chapter 8 : Discussion of Findings

8.1 Introduction

In this chapter, the findings from the empirical study are discussed. It begins by describing the participants who volunteered to take part in this study and shows how they are connected to the industry and the 3D printing taxonomy developed in this work. Their views on the ethical issues of 3D printing are then highlighted and compared to the findings of the literature review. The chapter also explains what the findings mean in terms of participant selection for research and highlights other issues that have come to bear on the ethics of 3D printing.

8.2 Participants Involvement in Additive Manufacturing

As pointed out in section 4.2.1 all the participants for this research were selected from communities of 3D printing users around Europe. The participants are all involved with DIY 3D printing hacker collectives like hackerspaces, fabrication laboratories (fablabs), and makerspaces. Although it is recognised here that this population doesn't fully represent a true sample of the public, the point of this research is to understand the concerns of users of 3D printing in terms of ethics and the hacker community provides a good mix of relevant users of the technology. The study also provides an opportunity for those who use the technology to share their perspectives and knowledge on the other issues being investigated in this research.

The participants' professional association with 3D printing was also described In section 4.2.1. It was explained that in terms of their occupation, they may all be categorised into 2 broad groups i.e. academia and SMEs, to reflect their professional connection to 3D printing. Based on the data obtained in this study, 4 participants (P5, P8, P9, and P12) were grouped in the academia class (see Table 4-1) while all the others were grouped under the SME class as illustrated in Table 4-2. All these participants add a complex and interesting mix of perspectives and depth to the research.

Following the development of the taxonomy of 3D printing users in section 6.5, the participants have now been classified based on the new taxonomy as shown in Figure Figure 8-1. The figure shows that the participants are all in the class of 'direct users' of the technology. This is because they all participate in the manual operation of the 3D printers. It also shows that although they are all direct users, some of the participants can be classified in the 'generative services' category while others in the 'facilitative services' category. Those in the generative service category are those who generate 3D models and subsequently print them out on 3D printers, while those in the 'facilitative service' group are focused on 3D printing objects for people who already have 3D models.

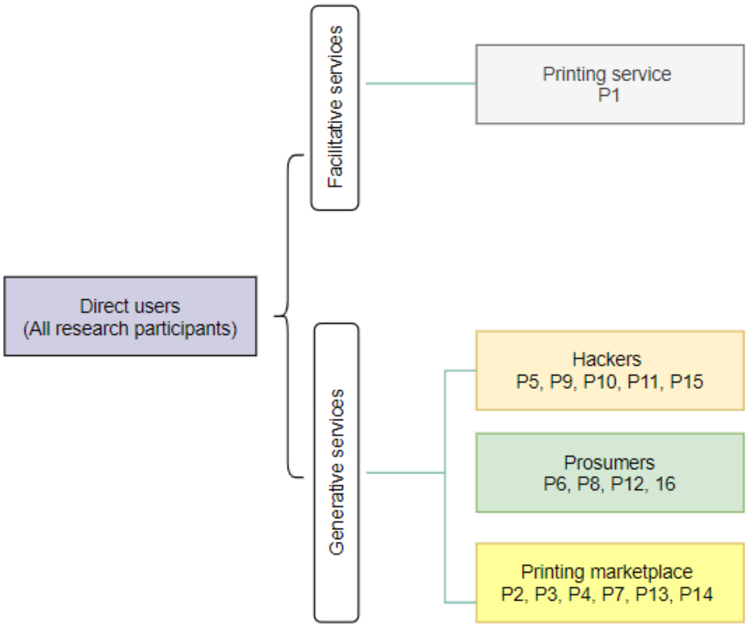


Figure 8-1 Classification of Participants based on the new taxonomy of 3D printing

In the classification shown in Figure 8-1, there is one relevant subclass to which those in the 'facilitative services' category can be classed. This is the 'printing service' category to which participant P1 has been placed as discussed in section 5.5. The generative services class has three relevant subclasses for hackers, prosumers, and the printing marketplace. Participants in the printing marketplace group include participants P2, P3, P4, P7, P13, and P14. These have been placed in this class because the participants provide services for creating 3D models and subsequently 3D printing them. The hacker category includes participants P5, P9, P10, P11, and P15. This category is composed of participants who are not just active members of the 3D printing hacker collectives and promote the hacker ethos but have also been actively involved in the development of these groups. Those in the prosumer category can be said to have evolved from being mere consumers of 3D printing artefacts to a point where they design and make products for themselves. This category includes participants P6, P8, P12, and P16.

8.3 On Ethical Issues of AM

The following discussion highlights the participants' views on ethical issues of additive manufacturing. It shows how some of the participants initially suggested that there are no ethical issues of additive manufacturing, and how many of the participants were able to point out at least one interesting societal concern promoted by the technology. Issues that were highlighted include concerns about data security and liability, the impact of AM on the environment, health and safety issues of 3D printing, as well as employment concerns resulting from 3D printing.

The findings of the participant's views on ethical issues of 3D printing are summarised in Table 8-1. The rows of the table represent participants while ethical issues are presented in the columns. The ethical issues listed in the columns are themes that have been developed from the findings of the empirical research and the next section describes these themes.

8.3.1 Description of Themes

In identifying themes during the analysis phase, as pointed out in section 4.2.3 the most important consideration was to capture terms, phrases, and sentences that contribute to answering the research questions. Thus, the themes which illustrate participants concerns about the problematic nature of 3D printing were developed inductively in such a way as to capture the important elements of 3D printing that highlights how the technology promotes societal issues. In some cases, subthemes were used to help demonstrate the hierarchy of meanings within the data and to give structure to themes that were considered large or complex.

For example, issues that relate to the effect of 3D Printing on the environment have all been grouped under the theme 'environment'. From the table, it can be seen that such issues as sustainability, biodegradability, recyclability, waste, energy, and the circular economy are in this category. Note that the circular economy is a relatively new concept related to environmental sustainability which aims to eliminate waste by improving the efficiency of resource utilisation. It does this through a model that encourages recycling, reuse, repair, refurbishment, maintenance etc. It is opposed to the make-use-dispose model which has a detrimental effect on the environment.

Issues around the environment form the second-largest theme of the findings with its six subthemes. The subtheme on sustainability mainly describes views from participants on how well 3D printing reduced the negative impact of manufacturing on the environment. The related terms biodegradability and recyclability are also important subthemes of the environmental risks of 3D printing as they reflect the participant's views on whether or not the materials used in 3D printing are biodegradable or recyclable. The subtheme 'waste' which is also related to the discourse on sustainability describes the participant's views on discarded materials from misprints as well as finished and unfinished objects of 3D printing.

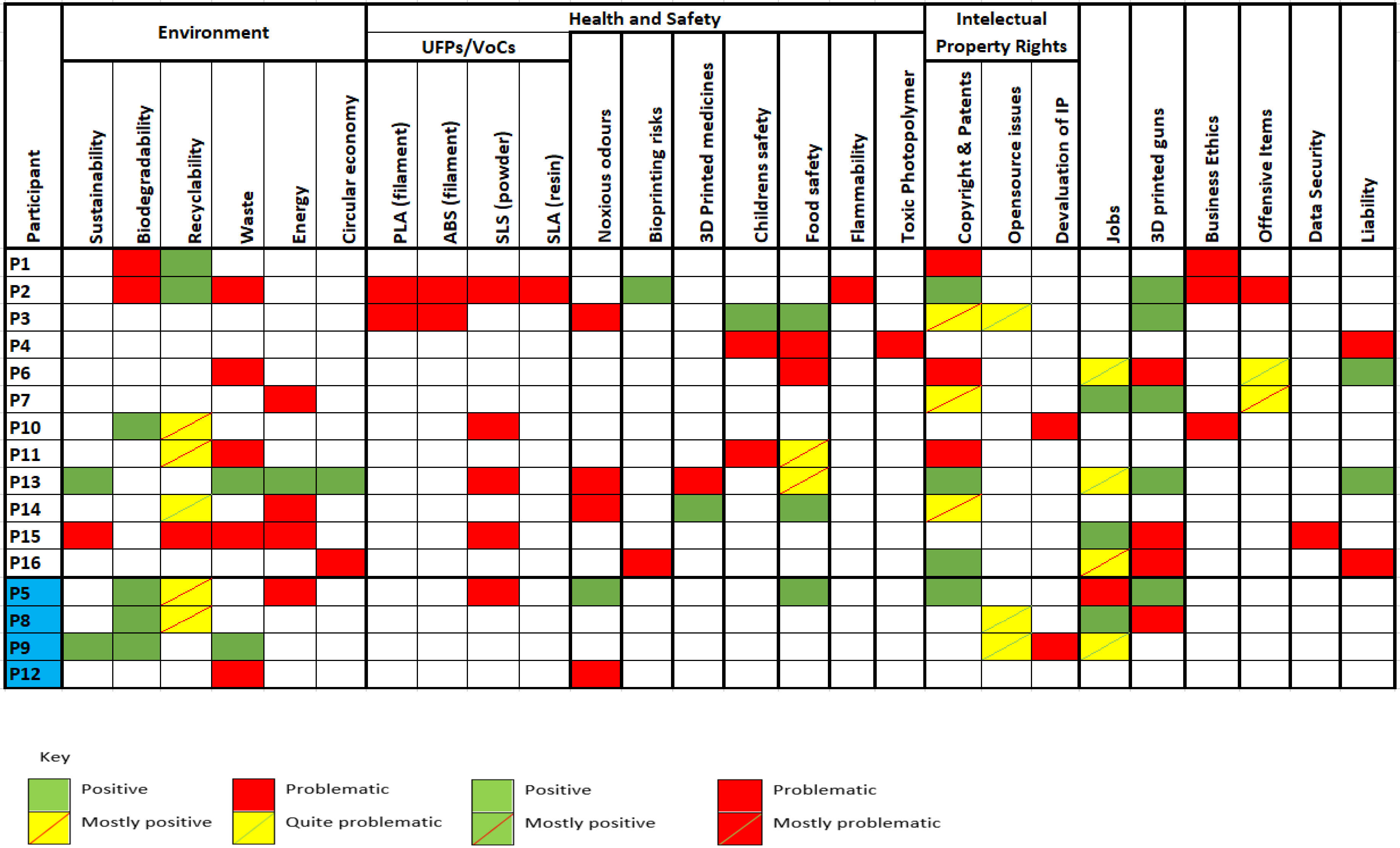
While ‘energy’ is the subtheme that describes participants’ views on energy consumption of 3D printers and the effect on the environment.

From Table 8-1 it can also be seen that over 40% of the themes developed for the ethical-issues columns are occupied by themes related to health and safety. This makes health and safety the theme with the most talked-about risks by the participants. The issues include a subtheme on ultrafine particles/ volatile organic compounds designed to highlight issues related to the emission of particles during 3D printing using materials like PLA, ABS, SLS, and SLA. Issues related to noxious odours have also been grouped within the health and safety-related risks as such issues could be detrimental to health. Bioprinting risk which is the subtheme discussing bioethical issues related to 3D printing has also been placed with the theme on health and safety risks. Rather than name this bioethical issues as was done in the literature review (section 2.6.6) the researcher felt that bioprinting was more appropriate and relatable to 3D printing users than the broader theme of bioethics.

Another relevant health and safety-related subtheme listed in the table is 3D printed medicines which refer to the use of additive manufacturing technology for the printing of medicines. Some participants discussed concerns related to this issue and the theme has been developed to capture such views. Children's safety is another health-and safety-related theme. It refers to safety concerns with the use of 3D printing for children's toys and the use of 3D printers around children. As issues around food safety are health and safety-related, the food safety subtheme has also been grouped under this related theme. It describes the issues related to food safety including food hygiene which can affect health. Other issues in the health and safety-related category are flammability and toxic photopolymer. While flammability describes participants views on metal powders used for 3D printing that are flammable and can ignite during some 3D printing processes, toxic photopolymer relates to 3D printing resins that are toxic when they come into contact with humans.

It came as no surprise that intellectual property issues of 3D printing were discussed by participants as this has been a very popular topic in the media and academic circles. The theme ‘intellectual property’ describes the participant's views on this matter. The theme is composed of three subthemes – copyrights and patents, opensource issues, and devaluation of intellectual property. The subtheme on ‘copyrights and patents’ describes the participant's view on this subject and relates to the ability of 3D printing users to copy almost every object with or without the authorisation of the rights holder. While the subtheme on ‘opensource issues’ characterises participants views on the ethics of freely available software and designs, the ‘devaluation of IP’ is a special subtheme describing views on how free software and designs affect IP.

Table 8-1 Charting participants views on the ethical issues of 3D printing



Still, on the columns of ethical issues in Table 8-1, other themes developed from participants' views include '3D printed guns' and 'offensive items'. The theme of '3D printed guns' describe participants views on issues related to the illegal use of 3D printing for creating guns. This is an illegal activity in most parts of the world (including the U.S) and yet 3D printing facilitates the easy development of such weapons outside of regulatory control and so it was important to understand the views of participants on this subject. The theme on 'offensive items' is a distinct theme that refers to the use of 3D printing for creating items which although are not illegal, might be considered offensive. For example, the swastika sign means different things in different cultures around the world and is not illegal in most. Nevertheless, many people find it offensive and react differently to it because of its association with Nazism. While this is just an example, some participants felt the use of 3D printing to create such items may constitute an ethical issue and the 'offensive items' theme highlights different views on this.

Another important theme in the columns of ethical issues in Table 8-1 is 'jobs' which describes participants views on the effect of 3D printing on employment. This theme is important considering the regular debates among academics and policymakers on the age-old question of the impact of technology on jobs. Business ethics is yet another theme in Table 8-1. This is a distinct theme that describes participants views on false advertising in the 3D printing industry. Some of the participants were concerned about the levels of false advertising in the industry and felt that it constitutes an ethical issue. Thus, the theme of 'business ethics' describes such views. Other themes include 'data security' and 'liability' where data security describes information security issues related to 3D printing and 'liability' describes the participant's concern on issues related to legal responsibility when something goes wrong with a 3D printing artefact.

8.3.2 Charting the Participants' Views

A traffic light system has been used in Table 8-1 to chart the participants' views on the ethical issues of 3D printing. In this table, green boxes signify positive comments from the participants about the 3D printing issues listed on the columns. Likewise, red boxes have been used to indicate that the participant feels that the issue in question is problematic. However, yellow boxes represent mixed views where participants appear to be torn between the potential benefit or harm of the issues concerned. In cases where the participant appears to lean more towards a positive view of any of the issues, the yellow boxes have been marked with a green diagonal line. On the other hand, a red diagonal has been placed on the yellow boxes where the participant appears to view the issue as mostly problematic even though they acknowledge some positive value. This information is summarised in the key for Table 8-1. Note, however, that the white boxes mean that the issues in the column corresponding to the white boxes were not discussed by the participant in the corresponding row.

The table can be read from left to right or top to bottom. For example, reading from left to right, the table can be used to answer questions such as ‘what are the ethical issues that participant P2 is concerned about?’. To answer this question, it can be seen that the information to the right of P2 shows that 9 of the columns are marked with red boxes. These correspond to the columns labelled biodegradability, waste, ultrafine particles from PLA, ABS, SLS, and SLA, flammability issues, business ethics, and offensive items. This then means that these are the issues that participant P2 appears to be concerned about. For example, as shown in 7.2.3 the issues around ultrafine particles were of significant concern to this participant that an important job offer was rejected to avoid health and safety issues. Also, P2 was very concerned about waste from 3D printing, particularly because there appears to be a lot of plastic materials that aren’t biodegradable being used as filaments hence red boxes for the waste and biodegradability subthemes.

As another example, to answer the same question as above regarding participant P13, the chart shows a mix of green boxes, yellow boxes, and red boxes to the right of P13. The red boxes correspond to SLS, noxious fumes, and 3D printed medicines. This means that the participant is concerned about ultrafine particles from SLS as they may have detrimental health and safety implications; similarly, the participant feels that noxious fumes emitted during 3D printing processes could be harmful; also, P13 is concerned about the use of 3D printing for creating medicines due to safety fears.

The yellow boxes correspond to food safety and jobs meaning that the participant has mentioned both positive and problematic effects of these issues and appears divided. However, the yellow box corresponding to food safety has a diagonal red line. This means that although P13 appears divided on food safety issues, the participant leans more towards the problematic effect of 3D printed food. Also, the yellow box corresponding to jobs has a green diagonal. This means that although the participant appears divided, P13 leans more towards 3D printing having a positive impact on jobs.

The chart can also be used to answer the question ‘How do participants view the environmental impact of 3D printing? To answer this question, the columns corresponding to the environment will be considered including all the subthemes from the findings. A look at the corresponding columns shows several red, green, and yellow boxes. The spread of these coloured boxes paints an interesting picture of the diverse views of the participants on this subject. For example, it can be seen that all the environment subthemes have at least one red box associated with them meaning that each issue had at least one participant who was concerned.

However, it can also be seen that some participants do not think 3D printing has a problematic impact on the environment. Among these are participants P13 who only had positive things to say about the environmental impact of 3D printing in the areas of sustainability, waste, energy consumption of 3D printers, and its effect on the circular economy. Likewise, participant P9 appears not to have any concerns regarding the effect of 3D printing on the environment as the participant mentioned only positive comments in the three subthemes considered by this participant i.e. sustainability, biodegradability, waste. Interestingly, however, the table shows that participants P3 and P4 did not comment about the environmental effect of 3D printing.

Also, it can be seen that out of 16 participants, 14 commented on issues around the environment. However, a breakdown of their opinions show that only 2 participants felt that 3D printed objects were not biodegradable, 1 participant appeared concerned about the recyclability of 3D printed materials, and 1 participant explicitly stated that 3D printing wasn't a sustainable technology. Interestingly, all the yellow boxes for the theme on the environment are on the recyclability subtheme. The spread of the yellow boxes indicates that although participants P10, P11, P5, and P8 appear divided about the recyclability of 3D printed materials, they lean more towards it being problematic i.e. the materials cannot be easily recycled. On the other hand, although participant P14 is also divided about the recyclability of 3D printed objects, the participant appears to lean more towards it not being a problem.

The spread of the red boxes in environmental subthemes also indicates that the most concerned participant about the effect of 3D printing on the environment was participant P15 who discussed concerns in 4 out of the 6 subthemes in the areas of sustainability, recyclability, waste and energy. It also shows that the least discussed issues related to the environment were those on sustainability and the circular economy where 2 participants each commented on these issues. Interestingly, in each of these cases, one participant each expressed concern about the effect of 3D printing. Also, in each case, the second participant who discussed the issue had a positive view concerning the effect of 3D printing on the environment. For example, on the circular economy, participant P16 felt that rather than promote a circular economy, 3D printing could be problematic as he feels it is not ecological. On the other hand, P13 felt that 3D printing could enable a circular economy because it can be used to increase the lifespan of products through the creation of replacement parts.

8.3.3 Applying the Framework for Classifying and Assessing Ethical Issues of 3D Printing

The framework for classifying and assessing the ethical issues of 3D printing developed in section 6.6 will be applied here. In that section, the application of the framework was demonstrated on data obtained from the literature review on ethical issues of 3D printing. The framework will now also be applied to the empirical findings. To demonstrate this, the framework will be used to assess the risk of ethical issues in a 3D printing business, risks to the environment, resources, and information.

1. Business concerns

To understand the concerns of a 3D business in terms of the ethical issues identified above, a risk assessment using the bottom-up approach of assessing and classifying risks developed in section 6.6.1 can be applied. This starts with the creation of either a persona or user profile depending on the level of detail required and then comparing back to the taxonomy developed in section 6.5 to determine the user class. Based on the class, an analysis of the risks involved can then be carried out. To demonstrate the application of this approach, a hypothetical business scenario will be created here and used to show what ethical concerns a 3D printing business might have.

In characterising the persona, the first step is to describe the product. For this discourse, it will be assumed that the business is involved in the 3D printing of keyholders like the one shown in Figure 4-1. It will also be assumed that this is a home-based business that also designs the 3D model for this artefact, prepares it for 3D printing, and subsequently 3D prints it in-house. This then means that in the 3D printing taxonomy, this business fits nicely in the 'printing marketplace' category. The next step is to visualise the user of this keyholder or the 'pure consumer' as described in the taxonomy. In this case, it will be assumed that the user is a father of 2 small children whose ages are all below 3 years. Based on the taxonomy, the 'pure consumer' is classed as an indirect user as they do not interact directly with 3D printers or participate in the design of digital models. Other relevant information can be added when building the persona, however, the information developed thus far is sufficient for the risk analysis.

Based on this scenario, therefore, and having identified 2 relevant user classes in the taxonomy of 3D printing users, the next step is to create the matrix of users and ethical issues which can then be used to access risks. The matrix for this scenario is shown in Table 8-2

Table 8-2 Assessing business risk concerning ethical issues

Users	Environment						Health and Safety								Intelectual Property								
	Sustainability	Biodegradability	Recyclability	Waste	Energy	Circular economy	Ultrafine Particles	Noxious odours	Bioprinting risks	3D Printed medicines	Childrens safety	Food safety	Flammability	Toxic Photopolymer	Copyright & Patents	Opensource issues	Devaluation of IP	Jobs	3D printed guns	Business Ethics	Offensive Items	Data Security	Liability
Direct	high	high	high	high	high	high	high	high	low	low	high	low	low	low	high	high	high	high	low	high	low	high	high
Intermediate																							
Indirect	med	med	med	med	low	med	low	low	low	low	high	low	low	low	low	low	low	med	med	med	med	med	high

Key			
	low	med	high

What this means is that the direct 3D printing user, in this scenario, the business, should be concerned about all the high-risk issues highlighted in red. For this business, all the environmental issues have been assessed to be high-risk. This is because the business is involved in the digital fabrication of plastic keyholders and participants in the empirical research have pointed out how each subtheme of the environment (sustainability, biodegradability, recyclability, waste, energy, and circular environment) pose risks to the environment particularly when plastic is used. For example, as shown in Table 8-1 five of the participants (P2, P6, P11, P15, and P12) all appear to agree that waste is a significant problem in the 3D printing industry due to print errors, use of scaffolding, and the experimental nature of 3D printing.

For this hypothetical business, three of the health and safety themes in Table 8-2 have also been highlighted as high-risk issues i.e. ultrafine particles, noxious odours, and children's safety. In this case, noxious odours and ultrafine particles are high-risk issues because the business is home-based meaning there is a high risk of being exposed to emissions from 3D printers all day long. Children's health and safety is a high-risk issue because the keyholders design with moving parts makes it quite fragile and an unsupervised child can easily break it apart and put bits in the mouth.

The opensource nature of 3D printing where models are easily available for download makes concerns related to intellectual property high-risk issues. Users must always ensure that they have the right permission or are the rights holders for the objects that they 3D print. On the issue of jobs, as one participant puts it, every 3D printed item means that someone in a traditional manufacturing role has likely lost some work. While this might be seen as an insignificant problem currently, factors such as the rapid growth of the industry, changing workflows and value chains means diminishing work in the manufacturing industry. Business ethics has also been flagged up here as a high-risk concern because of the problem of false advertising some participants in the empirical research have pointed out.

Data security is another high-risk concern here. Although it was just one participant who mentioned this issue in the pilot study, a growing body of work (as shown in the literature review) has pointed out how 3D printers are susceptible to malicious cyberattacks capable of putting personal data and business data at risk. Given the health and safety issues mentioned (e.g. concerning children's safety), the issue of liability has also been highlighted as high-risk in this case. Who becomes liable when something goes wrong and how to enforce liability, in this case, becomes problematic as current liabilities laws may not apply, and there's difficulty in determining the stage at which the defect happened as it could be from any number of sources e.g. the CAD software, the 3D printer, the filament, the model etc.

The other issues related to health and safety (bioprinting risks, food safety, flammability, and toxic photopolymer) are all low-risk issues for this business because there is no direct relationship with the business and these concerns. For example, the business is involved in the printing of plastic keyholders and this has little or nothing to do with bioprinting and food safety. For the same reason, 3D printed guns and offensive items are low risks issues for this business.

For the indirect user, in this case, the customer, several high risks concerns have been identified here. They include 5 environment-related themes i.e. sustainability, biodegradability, recyclability, waste, and the circular economy. These are high-risk issues because the keyholder is made from plastic material which is not easily recyclable or biodegradable and thus has consequences for sustainability and the circular economy. Other issues in the high-risk category are children's safety and liability. As it has already been pointed out, the customer in this hypothetical scenario has small children who might be at risk. This situation, as well as that of liability as explained in the case of the direct user above, also applies to this customer.

Energy has been given a low-risk concern for this customer as the product is a keyholder and its use doesn't require the consumption of energy. Likewise, all the other health and safety issues (apart from children's safety) have been highlighted as low risk because there is little or no direct relationship between these issues and the use of the keyholder. Other issues that have been designated low-risk due to little or no relationship to the use of the keyholder by the customer are 3D printed guns and offensive items.

Several medium risk concerns have been identified for the indirect user in the scenario painted above. These include the intellectual property related themes i.e. copyrights and patents, opensource issues, and devaluation of IP. These issues are of medium concern because by purchasing the keyholders, the consumer risks promoting IP issues, particularly in situations where the business hasn't carried out due diligence to ensure that IP rights are respected. Data security is also a medium risk concern because the customer also shares some risk in a situation of malicious cybersecurity issues on the business.

2. Environmental concerns

Environmental concerns related to 3D printing are based on the way the technology and its outputs are used. Therefore, to understand the issues that concern the environment, it is important to determine how the operations of the different users relate to environmental issues. To do this, the top-down approach for assessing the risks of 3D printing described in section 6.6.2 is applied here. A matrix of the ethical concerns already identified and the higher-up or top-level category of users is created. Higher-up users, in this case, refers to level 1 users (i.e. direct, intermediate, and indirect) in the 3D printing taxonomy shown in Figure 6-2. The matrix developed shown in Table 8-3 can then be used to match the concerns to each user group to understand how they impact the environment.

The matrix schema shows that several high risks issues concern the environment and that they mostly originate from direct users. This is because the direct users are involved in the manual operation of 3D printers and they influence the workings of the technology. The high-risk issues related to the direct users include all the concerns identified by the environment subthemes i.e. sustainability, biodegradability, recyclability, waste, energy, and the circular economy and two issues from the health and safety subthemes i.e. ultrafine particles and noxious odours.

While it is conceivable why all the environment subthemes are identified here as high risk, it might be less so for the health and safety-related themes. As the participants in the exploratory research have shown, the use of 3D printers can lead to the emission of ultrafine particles and noxious fumes which are environmental pollutants. Also, as shown in the literature review (section 2.6.2) these particles are in the range of nanoparticles and so can easily penetrate the human skin and get into organs where they can accumulate and cause health-related problems. So it can be said that ultrafine particles and noxious fumes are environmental issues as well as health-related issues.

As intermediate uses mainly specify requirements for the outputs of 3D printers and are involved in the design of 3D models, and also hosting of online content for 3D printing, their impact on the environment is mainly related to energy consumption. Hence, energy use is a high-risk issue for the environment with regards to intermediate users as shown in Table 8-3.

Indirect users are mainly consumers and their disposal of the artefacts from 3D printing can have a direct impact on the environment. Hence, it is shown in Table 8-3 that apart from energy, all the subthemes from the environment have been identified as high-risk concerns. As most 3D printed artefacts require little or no energy during their use, energy has been identified as a low-risk issue for indirect users. The other environmental themes i.e sustainability, biodegradability, recyclability, waste, and the circular economy all have a direct relationship with the disposal of artefacts after the consumer has finished with them. As the majority of 3D printing artefacts are made from plastic which is not recyclable, or biodegradable, they have an impact on the circular economy. All the other issues identified by the participants and included in the matrix in Table 8-3 do not have a direct connection with the environment, hence they have been identified as low-risk.

Table 8-3 Assessing environmental concerns of 3D printing users

Concerns		Users		
		Direct	Intermediate	Indirect
environment	Sustainability	high	low	high
	Biodegradability	high	low	high
	Recyclability	high	low	high
	Waste	high	low	high
	Energy	high	high	low
	Circular economy	high	low	high
Health & Safety	Ultrafine Particles	high	low	low
	Noxious odours	high	low	low
	Bioprinting risks	low	low	low
	3D Printed medicines	low	low	low
	Childrens safety	low	low	low
	Food safety	low	low	low
	Flammability	low	low	low
	Toxic Photopolymer	low	low	low
IP	Copyright & Patents	low	low	low
	Opensource issues	low	low	low
	Devaluation of IP	low	low	low
Jobs		low	low	low
3D printed guns		low	low	low
Business Ethics		low	low	low
Offensive Items		low	low	low
Data Security		low	low	low
Liability		low	low	low

Key	
yellow	low
red	high

3. Resource concerns

To understand how the ethical issues identified by the participants in this research concern natural resources, either the bottom-up or top-down approach for assessing the risk of 3D printing illustrated in sections 6.6.1and 6.6.2 respectively can be used. The difference lies in the level of specificity required and the type of details available for the assessment. For this discourse, however, it is sufficient to demonstrate the resource concerns of 3D printing by applying the top-down approach.

As shown in the section above, the top-down approach requires the creation of a matrix which interrelates the already identified ethical issues with the relevant category of users from the 3D printing taxonomy. The analysis can then proceed by comparing each issue with the different users to assess the risk posed by the users and to develop an understanding of the effect on resources. The matrix for this analysis is shown in Table 8-4.

Table 8-4 Assessing resource concerns of 3D printing users

Concerns		Users: Direct	Users: Intermediate	Users: Indirect
environment	Sustainability	high	low	high
	Biodegradability	low	low	high
	Recyclability	high	low	high
	Waste	high	low	high
	Energy	high	high	low
	Circular economy	high	low	high
Health & Safety	Ultrafine Particles	low	low	low
	Noxious odours	low	low	low
	Bioprinting risks	low	low	low
	3D Printed medicines	low	low	low
	Childrens safety	low	low	low
	Food safety	low	low	low
	Flammability	low	low	low
	Toxic Photopolymer	low	low	low
IP	Copyright & Patents	low	low	low
	Opensource issues	low	low	low
	Devaluation of IP	low	low	low
Jobs		low	low	low
3D printed guns		low	low	low
Business Ethics		low	low	low
Offensive Items		low	low	low
Data Security		low	low	low
Liability		low	low	low

Key	
(yellow)	low
(red)	high

It indicates that for the intermediate 3D printing users the most important concerns which can be related to resources is energy. This is because most of the energy generated currently are from non-renewable resources like fossil fuels and 3D printing requires a considerable amount of energy, especially for platforms hosting 3D models because of the constant need for energy to power online data servers and computers. Thus, the effect on energy is described as high-risk here.

For direct users, however, high-risk concerns that are relatable to resources include sustainability, recyclability, waste, energy, and the circular economy. When 3D printed objects are not recycled, they go to waste which means more resources need to be consumed to enable the fabrication of new objects. Cutting down waste, encouraging re-use, recovery and use of recyclable materials for 3D printing are all measures that can enable sustainability by reducing the consumption of natural resources. Interestingly, biodegradability is highlighted as low-risk in this case because of the limited impact on resources.

Apart from energy use which is highlighted as low-risk for indirect users, they have a similar risk concern on resource consumption as direct users. This is because indirect users have little or no impact on energy use as they are pure consumers and have little or no need for energy consumption in most cases for the use of 3D printed artefacts. Similarly, all the other issues in the matrix are highlighted as low-risk issues because they have little or no direct relationship with the consumption of resources.

4. Information concerns

The top-down approach can also be used for the analysis of concerns of 3D printing-related information. This also requires the creation of a matrix schema that can be used to interrelate the ethical issues identified against the high-level users defined in the 3D printing taxonomy (i.e. direct, indirect, and intermediate users). The analysis can then be done by comparing each issue against the different users to determine the risk posed by the users. This can then be used as a basis for developing an understanding of the effect on 3D printing related information.

The matrix shown in Table 8-5 indicates that direct, intermediate, and indirect users of 3D printing have similar levels of risk in terms of information in all areas but energy. As explained in the preceding sections, indirect users have little or no energy requirements in terms of the use of most 3D printing artefacts and therefore energy is a low-risk issue for them.

However, the situation is different for indirect and direct users whose risk levels for energy are described here as medium risk regarding information. This is because the majority of users of 3D printing technology likely rely on non-renewable energy for data transfers and for powering up their 3D printers. As energy has a direct impact on sustainability, this issue is also described here as a medium-risk concern for information.

It can also be seen that several other medium risk issues have also been identified. These are the intellectual property rights related subthemes namely copyright and patents, opensource issues, and devaluation of IP. These have been described as medium risk concerning information because of the tendency for IP theft to easily occur in the 3D printing arena even though it is not yet a common problem. IP theft, as well as the opensource nature of vast amounts of 3D printing information, can lead to devaluation of intellectual property which has also been highlighted as medium-risk here.

Table 8-5 Assessing information concerns of 3D printing users

Concerns		Users: Direct	Users: Intermediate	Users: Indirect
environment	Sustainability	med	med	med
	Biodegradability	low	low	low
	Recyclability	low	low	low
	Waste	low	low	low
	Energy	med	med	low
	Circular economy	low	low	low
Health & Safety	Ultrafine Particles	low	low	low
	Noxious odours	low	low	low
	Bioprinting risks	low	low	low
	3D Printed medicines	low	low	low
	Childrens safety	low	low	low
	Food safety	low	low	low
	Flammability	low	low	low
	Toxic Photopolymer	low	low	low
IP	Copyright & Patents	med	med	med
	Opensource issues	med	med	med
	Devaluation of IP	med	med	med
Jobs		low	low	low
3D printed guns		low	low	low
Business Ethics		low	low	low
Offensive Items		low	low	low
Data Security		high	high	high
Liability		low	low	low

Key	
(yellow)	low
(orange)	med
(red)	high

The table also shows that data security has been highlighted as the high-risk issue of relevance to information. As explained in section 2.6.7, 3D printers are easily susceptible to malicious cybersecurity attacks making data security an issue of high relevance to information concerns in 3D printing.

8.3.4 Comparing the Empirical Findings with Findings of the Literature Review

In this section, the findings from the empirical research will be compared against those from the literature review to highlight similarities and differences from the results.

1. Environmental Issues

On the environmental issues of 3D printing, the findings show that many of the conflicting views in literature with regards to the environmental impact of AM are also shared by the participants. The findings show that at least 14 of the 16 participants had something to say about the effect of 3D printing on the environment making this the most talked-about theme of the study. However, 5 of these participants didn't feel that 3D printing had any sort of problematic effect on the environment. The findings also show that although 6 subthemes on the environment have been identified, (i.e. sustainability, biodegradability, recyclability, waste, energy, and circular economy) there were just 2 participants who had views related to more than one subtheme. The others were only able to discuss one environmental concern each.

This result appears to mirror the general view found in the literature about the effect of 3D printing on the environment. Most of the articles published on this topic appear to paint 3D printing as a green technology. 3D printing has often been hailed as a sustainable method of manufacturing that can significantly reduce manufacturing waste. One of the more popular views in this regard suggests that the additive nature of 3D printing as opposed to subtraction (of materials) in traditional manufacturing, means that waste is eliminated. Interestingly, the issue of waste was the second most discussed subtheme in the interviews but what the findings show is that most participants who commented on this issue felt that 3D printing does have a waste problem. Like Keppner et al. (2018, p.24) quoted in section 2.6.1, these participants were able to point out that AM generates waste from misprints and from processes that require support structures. The participants appeared quite worried about this problem as one even suggested 20 – 40 % of the 3D printing material are wasted.

The findings also show that most of the participants who commented on the biodegradability of 3D printing felt that the materials used (especially PLA) would not harm the environment because they breakdown naturally. As shown in the discussion in the literature review, some environmentalists like Gadhave et al. (2018, pp.23 & 24) have also pointed to PLA's starch-based origins to further their argument that the material is 100% biodegradable.

But contrary opinions are beginning to emerge as studies are showing that this may not necessarily be the case with PLA as other factors need to be considered. Writing for the Smithsonian, Royte (2006) maintains that claims for the environmental virtues of PLA are downright misleading due to considerable drawbacks inherent in its biodegradability that are not being publicized. The article notes that a controlled composting environment where temperatures of up to 140 degrees and a huge supply of oxygen and microbes are required to breakdown PLA, otherwise, they take 100 to 1000 years to breakdown naturally in landfills or soil burial arrangements.

Similarly, analysis by Muniyasamy et al. (2016, p.143) appears to confirm that ‘microorganisms present in soil environment are unable to depolymerise PLA under soil burial conditions for an incubation period of 200 days’ and that industrial composting conditions where pH, moisture content, temperature, and thermophilic microorganisms are required to compost it. Similar arguments were also presented by some other participants during discussions on the biodegradability of PLA. Interestingly, one of the participants also conducted an experiment in which a piece of 3D printed PLA object was buried in earth under natural environments for 4 years and after it was dug up and washed, it looked as good as new. Nevertheless, many in the 3D printing scene appear to be oblivious of such facts as the study has shown.

The findings also show that another popular belief in the 3D printing arena is that the technology is green because materials like ABS are fully recyclable. As sown in the literature review (section 2.6.1) there is a popular belief that ABS is fully recyclable because it is a thermoplastic which means that it can be turned into liquid form when heated and then solidified again once cooled. It also showed how the likes of Krassenstein (2014) contend that 3D printing will ensure a safer environment around the world as the plastic material used can be recycled and turned into filaments for 3D printers.

Unfortunately, the properties of thermoplastics like the one used in 3D printing mean that even if plastics are being recycled, the mechanical properties degrade and make it impossible to continue recycling indefinitely. Also, the presence of additives and impurities create a challenging environment for recycling. Of the 16 participants, just one participant completely agreed that such materials could pose serious environmental problems and pointed out that recycling of 3D printed plastics is fraught with challenges due to degradation of the material and the presence of impurities.

Like many of the 3D printing-related issues, the literature on energy used by these machines is often conflicted as two opposite views exist. As shown in section 2.6.1, while one side claims 3D printing is more energy-efficient than traditional subtractive manufacturing, the other side claims that it isn’t the case. However, most of the participants that commented on this issue appear to have taken the latter position – maintaining that 3D printing isn’t as energy efficient as some claim.

Issues around the amount of energy consumed by machines have always been of concern to society generally and so it wasn’t a surprise that this topic came up in some of the interviews. Nevertheless, what did come as a surprise was that out of 16 participants, there were just 5 participants who felt that it was an issue worthy of mention. This could either mean that the other participants weren't aware of the energy debate, or weren't concerned about this problem. Whichever is the case, this isn't a very nice situation as energy consumption has a significant impact on environmental sustainability.

The findings show how muddled the discourse on the environmental impact of 3D printing is. The above discussion also illustrates how much misconception and confusion there is on the subject and illustrates how difficult getting the right answers can be. While AM might not be as environmentally friendly as some (especially those in the industry) might portray, on the balance, however, it may be said that the technology has great potentials as an environmentally friendly alternative to traditional manufacturing. Nevertheless, great challenges must be overcome for any real advantages to being derived from the technology in terms of sustainability, plastic waste pollution, biodegradability, recyclability, energy consumption, and the circular economy.

2. Health and Safety Issues

The findings on health-related risks of additive manufacturing reached two important conclusions. The first being that not enough is known about how using the technology may adversely impact health and secondly, that results of some studies conducted in this area are alarming. However, the literature review also indicates that some in the industry are sceptical about any negative impacts on health that additive manufacturing might have on users. It showed that this type of view was predominant with the use of PLA which many have pointed out is a derivative of starch and therefore inert. Interestingly, some participants expressed similar opinions mainly suggesting that it is harmless as it isn't very different from many materials used in kitchen equipment.

The literature review on health-related risks of AM found that only about a handful of studies have been conducted to determine any harmful effects of 3D printing and that the earliest known study was conducted only in 2013 despite the long history of additive manufacturing (see section 2.2.1). It should, therefore, be no surprise that not a lot is known about the health impact of AM. Some of the participants in this research also acknowledged that there is a dearth of information in the area of health-related risks.

Interestingly, research in this area all began because a student who had taken a job at a local 3D printing shop complained to his college professor, Dr Brent Stephens about 'funny' smells from the 3D printers (Lee, 2016). This prompted the first experiments in this area and since then, most of the studies have revolved around the sort of emissions that are given off during the operation of 3D printers. Surprisingly, the issue of noxious odours was one of the most talked-about subjects by participants in this research with 4 of them also admitting that the printers give off ‘funny’ smells (see Table 8-1). Similar to the advice of Webb (2018, p.39) who suggests that users of 3D printers must consider ways to vent out smells, smoke, and noxious gases emitted during the print process, one of the participants was concerned about keeping 3D printers in small spaces like the bedroom.

The suggestion to always vent out the working spaces where 3D printers are used is timely as the literature review has shown how these fumes, odours, and noxious gases in many cases, do indeed contain UFPs or nanoparticles. Their tiny sizes mean that they can penetrate the body and find their way into the bloodstream or get logged in organs like the lungs, liver, or even the brain where they can continue to accumulate until they cause serious problems. The fumes may also contain VOCs like styrene, ethylbenzene, acetaldehyde, formaldehyde, and 4-vinylcyclohexane, or laurolactame which are all classified as carcinogens, or irritants like caprolactam and methyl methacrylate.

Many of the participants in this research were unaware of these serious claims with only 6 of the 16 persons who participated in the study showed some awareness of problems that materials used in 3D printers could cause. Although most of the participants mentioned an issue each in this area, one participant appeared to be more knowledgeable than the others as this participant was able to identify problems linked to four of the materials – PLA, ABS, SLS, and SLA (see Table 8-1).

However, the issues expressed by the participants are similar to those discussed in the literature review (section 2.6.2) with the primary fear being the exposure to cancerous substances hidden in the fumes and gases given off by 3D printers. It was, however, interesting to see that PLA was one of the materials where there appeared to be strong disagreements between the participant about the health impacts. As the literature review also showed, many in the industry have assumed that because PLA is starch, it can only cause very little or no harm, yet studies have shown that it emits methyl methacrylate which recent research suggests may cause skin corrosion, and trigger asthma, and serious damage, as well kidney and liver lesions, and kidney necrosis (Acero, 2017). So, it is indeed worrying that, so little is known about the impact PLA might have on users’ years down the line as it is one of the most widely used materials along with ABS.

Two other related issues were raised concerning the medical use of 3D printers. The first of these issues was about bioprinting where 3D printing is used for the creation of human organs like livers – a growing area of application of 3D printing. However, just 2 participants discussed issues related to this, with one suggesting that it is safe and so doesn’t foresee any ethical issues with this sort of use. Like the controversies discussed in the literature review around bioprinting (see section 2.6.6), the other participant appeared to be quite concerned about this development and suggested that it could lead to ethical issues. He compared its use to issues raised when attempts were made to transplant modified organs of pigs and other animals to humans. It appears the comparison refers to the procedure referred to as xenotransplantation which has also been promoted as a means of remedying the problem of shortage of replacement for damaged human organs.

In xenotransplantation, pig cells, tissues, or organs are transplanted into humans to replace damaged organs. It is thought to be a viable means of solving the issue of shortages in available human organs, tissues and cells (Denner, 2017, p.1). However, the World Health Organisation has raised concerns about safety, quality, effectiveness, and unacceptable infectious public health risks that this sort of treatment might promote (WHO, 2005). Recent developments have shown that bioprinting is being seriously considered for use for organ replacement including heart transplants (Kuruvilla, 2019), as well as kidney and partial brain (Uyanik, 2019) which in reality is quite remarkable.

Nevertheless, serious concerns have also been raised about 3D bioprinting as shown in the literature review (see section 2.6.6) including safety risks as it is thought this could lead to cancers; issues of social stratification resulting from a tiered system of organ replacement; situations where 3D bioprinting or the more radical biohacking is used to extend human capabilities beyond what is normal making some humans less susceptible to injury, fatigue, or other types of illness and thus raising ethical issues akin to those in sports where performance-enhancing medical technology is heavily regulated; issues around justice in access to bio-printed organs, and dual-use possibilities of 3D bioprinting and biohacking where the technology could be used either for beneficial purposes or harmful purposes.

The other health-related issue that was raised by participants involves the use of 3D printers for printing medicines or drugs. As shown in Table 8-1 two contrasting opinions were presented – one for, and the other against the use of 3D printing in this way due to risks of contamination. This participant appeared to have worked with Prof. Lee Cronin and his group who since 2012 has been working on digitising chemistry to enable the printing of molecules on demand which can then be combined in reaction vessels to create medicines (Cronin, 2012). Recent improvements in the technology and design apparatus have shown that progress is being made in this field (Kitson et al., 2018, pp.318 & 319) and the technology would likely be out there sooner rather later.

However, like the participant rightly noted, this could lead to serious safety risks and as Service (2018) rightly points out, it could lower the barrier to synthesising dangerous drugs which means that more of the dangerous drugs could quite easily be printed much more cheaply and easily with 3D printers. The authorities already have difficulty dealing with the ever-growing drug problems in society and the ready availability of technology that could further remove barriers in the lucrative trade of illicit drugs is certainly a thing of serious concern.

The study highlights several other areas where safety is called into question including the use of 3D printers around children and for the creation of toys, the safety of 3D printed food, flammability of some of the materials, and safety issues with some photopolymers. Two of the safety issues (3D printed toys and food) are well documented in both the literature review and by the participants in the empirical study. However, the other issues were raised by a single participant in each case who appear to be the only ones familiar with these issues.

The literature review in section 2.6.2 notes a worrying trend where most desktop 3D printers have limited or no safety features and their manuals have little or no information about safety. One of the participants who appear to agree with this maintains that unlike other well-established technologies like laser cutting where the safety issues are well known, 3D printing is still emerging and only very little is known about any safety issues with the technology.

Despite the lack of safety information and general awareness about safety issues among users of AM technology, it was puzzling to see how some of the participants appeared unconcerned about the safety of 3D printers around children especially when they are used for toys. Instead, they mostly talked about the good that can come from children using 3D printers, for example, gaining new skills and creating their personalised toys. However, contrasting these sorts of upbeat positivity about 3D printed toys and the use of 3D printers by children, few other participants appeared to be worried about the safety of 3D printed items around children with one participant asking important questions about the impact on their health.

Such views are similar to those of Carlon (2017) mentioned in section 2.6.2 who also raised the question of the safety of 3D printed toys in terms of structural integrity, constituent additives, fragility, and sharp edges. This is why it is puzzling why very few participants appear concerned about the safety of 3D printers and 3D printed items around children because this appears to be a serious issue and yet, there appears to be only a little awareness of the risks they pose to children.

Also, as 3D printers are increasingly being used in the food industry, it was no surprise that the issue of safety has been raised both in the literature (see section 2.6.2) and by participants in this research. It was pointed out in the literature review that the media has paid more attention to the positive side of 3D printed foods focussing on the arty details of the foods and their taste while ignoring to a large extent any safety issues with the technology. This attitude appears to have caught on with the general public as the better half of the participants who spoke about 3D printed foods appear to be unperturbed about any safety issues with this technology.

This is also a puzzling issue as some evidence has been discussed in the literature about safety issues with 3D printed foods as they appear to promote harmful levels of microbial growth due to the heating and cooling process they go through as they pass through the nozzles of 3D printers. This could cause food poisoning or allergies. Also, the safety of 3D printed plates has been questioned as the layered nature of these items mean that they are also prone to bacterial growth because leftover foods easily get stuck in them. It was interesting to see that only a few participants felt this way about 3D printed food.

Thus while some of the views of the participants agree with the literature suggesting that 3D printing may adversely affect health and safety, the majority appear not to have a clue about this subject. This indicates that much more needs to be done to highlight the possible health effects of the technology and the provision of necessary safety information.

3. Intellectual Property Rights

Considering that 3D printing enables just about anyone with the digital file of any object to print out the physical artefact, it was no surprise that the issue of intellectual property came up in the discussions with participants and has also featured prominently in the literature review. The research found that while there is quite a lot of awareness of IP issues that may result from 3D printing, many in the industry appear unbothered about issues like copyright and patents likely due to the effect the DIY hacker community and the associated hacking culture has had on the development of AM technology. Interestingly, a related issue which has been described as the devaluation of intellectual property appears to be the main concern of some users of the technology.

One of the findings on this issue is that it appears those in the industry who feel that 3D printing has the potential to negatively impact IP rights are in the minority. Signs of this trend were already evident early on in the development of hacking communities with the culture on open sharing of software which was fuelled by the opensource movement of the 1990s (McGowan, Stephens and Gruber, 2007, p.409). Depoorter, (2014, p.1493) warned that a time will come when users of 3D printers will form beliefs and attitudes that support the liberal use of 3D printers and that legal ambiguities will foster activities that do not consider IP laws. It appears that time is already here from the attitudes of participants in this research to copyright and patents as many appear to be averse to these issues.

Some of the participants pointed out how AM has been around for so long, and how only the expiry of patents and the intervention of the opensource movement enabled rapid growth in the industry (see section 7.2.4). Rather than the restrictive rules of the current IP frameworks, these participants would prefer the opensource licence whose purpose is to deny exclusive rights to exploit work (St. Laurent, 2004, p.4) and allows modifications, derived works, and their distribution (Rosen, 2005, p.4). They eagerly pointed out that progress of the RepRap project – which essentially democratised 3D printing after about 3 decades of its existence under a closed licence system – has enabled over 3 million 3D printers (Jones et al., 2011, p.177; Zivkovic and Battaglia, 2017, p.661) to be developed in such a short period by simply allowing open access to its hardware, firmware, and software.

It should be pointed out that intellectual property issues like these are not entirely new (Machlup and Penrose, 1950, p.1; Baker, Jayadev and Stiglitz, 2017, p.12). However, as noted in section 2.4.3 and 2.4.5 certain characteristics of AM like the low entry cost, its appeal to the hacking culture, and the ease with which just about any object can be reproduced makes AM especially problematic in this area. Armed with a digital file obtained easily from the internet, 3D scans, or designed with Computer-Aided Design (CAD) software, an artefact can be printed with or without the consent of the rights holder in the bedroom or garage, basement etc with a 3D printer that costs as little as £100.

Even though the hacking movement has challenged attitudes towards IP rights and there are calls in some quarters for a move to the open license system, it appears that the likelihood of a major shift from the current IP regimes which are rooted in Locke's philosophies are unlikely anytime soon. Recall that John Locke's utilitarian theory of labour made a case for the private ownership of property acquired through labour, and for the right to enjoy some reward for that property:

> *The labour of his body, and the work of his hands, we may say are properly his. Whatsoever then he removes out of the state that nature hath provided, and left it in, he hath mixed his labour with, and joined to it something that is his own, and thereby makes it his property. It being by him removed from the common state Nature placed it in, hatch by his labour something annexed to it, that excludes the common right of other men. For this labour being unquestionable property of the labourer, no man but he can have a right to what that is once joined to, at least where there is enough and as good, left in common for others (Locke, 1690).*

The argument put forward by Locke suggests that labouring for an object gives the worker exclusive right to the object and taking that object or interfering with it in some other way would amount to a violation of the individual's natural right to that object. In that sense, it can be seen why major changes to current IP laws would be resisted by those who would like to derive financial benefit from their labour.

Nevertheless, some in the 3D printing arena appear to be unhappy about the impact that opensource and the DIY hacker culture is having on IP rights. Several participants suggested that open sharing is helping to devalue intellectual property and to deprive those who legitimately wish to derive financial benefit from their work from doing so. All of these go to show that there is some agreement between some of the literature and participants in this research that 3D printing raises some serious questions about ownership of intellectual property which is quite worrisome as the technology keeps developing rapidly.

4. 3D Printed Guns

A concern that AM raises is the creation of 3D printed guns. However, the findings of the literature review and the empirical research appear to agree that many in the additive manufacturing industry are quite sceptical of any real danger from these weapons. Only a small group appears to have a contrary view and feel that such guns pose a real threat to society.

As shown in Table 8-1 five participants were of the view that ongoing debates on this issue are playing to a false hype promoted by the media. They maintain that 3D printed weapons do not pose a serious threat to society as they are not effective and that 3D printing is not a practical technology for creating weapons.

However, the findings in section 2.6.4 of the literature review appear to contradict these sorts of opinions. It shows how the development of the 'Liberator' – the first 3D printed gun – has propelled further development in this area, such that more sophisticated weapons are now being made with the 3D printer. They include weapons like the Washbear revolver, described as an 8 shot self-loading revolver, and the EMG-01A coil gun. Interestingly, one of the participants who run a 3D printing business maintains that on 2 separate occasions, blueprints of the Liberator have been brought to his business for printing by customers in London.

To illustrate how much of a problem this might turn out to be, in March 2019, news outlets in the UK reported the case of 25-year-old Tendai Muswere who was charged to court for creating the frames of 2 types of 3D printed guns, items the prosecutors claim are prohibited under the Firearms Act of 1968 (Boyle, 2019; SkyNews, 2019; BBC, 2019b). It is quite worrying that many in the AM industry do not feel that 3D printed weapons pose a real threat to society. The pace of development of these weapons, the ease with which the files can be obtained online, and the cheap cost of creating such weapons should be a cause for concern.

Additive manufacturing technology will continue to improve and it appears that more powerful plastic weapons would continue to be developed. Such weapons can then be taken aboard flights because current security technologies at airports would be unable to identify them as weapons. And as a participant in this research pointed out, metal 3D printing is coming to the desktop. The schematics and designs of 3D printed weapons are often promoted by the 3D printing hacker community who share ideas on how to improve existing designs and then make these available freely online. All these suggest that more powerful and sophisticated 3D printed weapons will be created in the future, posing a threat to society.

5. Jobs

As noted in the literature review on the impact of 3D printing on employment in section 2.6.5, technological development has often stirred up emotive debates on its effect on jobs. This research finds that with the emergence of 3D printing such debates have continued. However, the findings appear to indicate that among 3D printing users, the debates appear to be skewed in favour of the technology with many of the users having a positive opinion on the impact of 3D printers on employment.

Only a small number of the participants held a view that contrasted with the favourable opinions expressed by the majority. Although these participants were few, their views, however, are quite persuasive as they adopted a common-sense approach to their arguments. They appear to echo the views of de Laubier et al. (2018, pp.13 & 14) referred to in the literature review who maintains that the digital nature of AM means that there is less need for manual labour in the manufacturing process and could therefore lead to significant reductions in workforce.

An example of the way technology may impact jobs in the future can be seen at the Amazon Go shop located in the basement of its Seattle Headquarters. This store does not employ any cashiers or checkout staff and operates what Amazon refers to as 'just walk out' shopping. This allows customers to make purchases simply by scanning their phones at the entrance, pick up items at the store and then just walk out. According to Elliot (2018) sensors in a new generation of machines can determine the items each customer picks up from the shelves and within a minute of leaving the shop, a receipt of items purchased is emailed to the customer. This is likely the direction of automation in the future. And the World Economic Forum (WEF) projects that by the year 2022 the proportion of companies likely to adopt 3D printing is 41% (World Economic Forum, 2018, p.7). As the technology continues to become mainstream, it should therefore not be surprising that AM will have far-reaching impacts on jobs.

Nevertheless, it appears that the impact of additive manufacturing on jobs will likely be influenced by how well the technology develops and to what extent it is adopted by society. Interestingly, like in the literature, participants appeared divided in their views about the trajectory of additive manufacturing as some suggest that it will get really popular and be available in most homes, while those with a contrary view suggest the opposite.

One aspect that a good number of participants seem to agree on is that although additive manufacturing is not suitable for mass manufacturing, it is changing workflows in many industries. This sort of impact was acknowledged in a Harvard Business Review article (McCue, 2015) which noted that the availability of 3D printers has opened people's minds to new ways of doing things and suggests that the manufacturing industry will be transformed as more people see new ways of making things.

For some participants, what they would like to see additive manufacturing do is to enable a Utopian society. Of course, this society isn't necessarily going to be a copy of the fictional utopian society that sir Thomas Moor (1516) proposed over 500 years ago. Rather, it appears closer to the holistic version of Utopia described by Levitas (2017, p.6) where 'social arrangements, means of livelihood, ways of life, and their accompanying ethics' thrive. Particularly, participants suggest they aspire for a society where the use of machinery like 3D printers empower people to have a better means of livelihood un-dictated by the constant work-earn-spend model of today's capitalism but one where social arrangement encourages a more caring and sharing society.

Although this society may appear far-fetched for now, other influences of additive manufacturing on employment that has been suggested by participants like changes to workflow, already appear to be the norm in many industries. At the moment, determining to what extent 3D printing will disrupt jobs is difficult and any dramatic reduction or increase in employment also appears to have been rebuffed. Thus there is strong agreement between the participants and the literature that rather than lead to a dramatic reduction in jobs, 3D printing will enable interesting changes in workflow.

6. Business Ethics

Issues about business ethics came up in the empirical research but not in the literature review. The research has found that like many other businesses, additive manufacturing isn't immune to unethical business practices promoted by some in the industry mainly for financial gain. Also, like many ethical issues, the unethical business practices highlighted by participants in this research are not necessarily illegal and sit in that grey arena that's neither completely black nor white. The issues raised all appear to be related to false advertising made by 3D printing businesses in their marketing of products like filaments.

A particularly interesting issue that was raised suggested that a 3D printing business was marketing filaments which they claim are recycled filaments in a bid to appear environmentally friendly and to appeal to the environmentalists. This appears to be an instance of actions commonly referred to as 'greenwashing' a term coined around 1989 from 'green' and 'brainwashing' (Mitchell and Ramey, 2011, p.41). It refers to situations where unsubstantiated or misleading claims of the attributes of an organisation's product or service on the environment are made in a bid to look more environmentally friendly (Aggarwal and Kadyan, 2011, p.61). Kubiak (2016, pp.96 & 97) maintains that greenwashing isn't a recent phenomenon and traces its roots to the 1960s and contends that it is so big a problem that in the U.S and Canada, up to 95% of products described as environmentally green feature some elements of greenwashing.

What comes to mind is the recent case where the Volkswagen Group was indicted by the US Environmental Protection Agency (EPA) for violating the Clean Air Act (CAA) by using technology to create false air quality control data for their vehicles (Majláth, 2016, p.113). Unfortunately, participants have pointed out that this issue has begun to creep into the 3D printing industry as some companies appear to be making misleading claims about being environmentally friendly.

7. Offensive Items

3D printing has been promoted as a tool for creating items that cannot be easily obtained in a store. It, however, was a bit of a surprise to find during this research that it is being used to create objects that some might consider offensive. One instance of this was mentioned by a participant in this research who discussed a situation in which Shapeways, a popular 3D printing service bureau, refused to print a model of the Swastika for a customer. The Swastika has become a well-known symbol primarily due to its association with the Nazi party of Germany and the race issues they promoted.

Interestingly this issue didn't come up in the literature review. However, Koslow (2016) a blogger discussed the refusal of Shapeways to print this object and how it led to protests by an American religious group called 'Raelians' who believe that the earth was created by extra-terrestrials. Although this group along with Hindus, Jains, and Buddhists view the hoked cross as an important religious symbol claiming it represents infinite time, the vast majority of the western world consider the hooked cross a symbol of violent racism and this is likely the reason behind Shapeways refusal to print this object.

Although this is not an isolated event as another participant pointed out that he has printed out items he felt were offensive for customers, the literature on 3D printers being used to create offensive items is scant and it didn't come up in the exploratory scan either.

However, these sorts of issues are particularly interesting as another participant points out that the UK additive manufacturing industry may find precedence in recent court cases in the country where cake makers refused to craft cakes for homosexual couples due to their religious beliefs and court cases were subsequently instituted against them. However, Bowcott (2018) notes that the ruling of the case which was dragged up to the Supreme Court was later in favour of the bakery.

All of these go to show that 3D printing of offensive items will likely become a bigger issue that the additive manufacturing industry might have to contend with as the technology gets more popular and yet not a lot of attention is being given to this matter currently.

8. Data Security

The research finds that like many other digital technologies, additive manufacturing is not immune to security issues and yet it appears these issues are not well known. The empirical research shows only 1 of the 16 that participated in this research discussed a connection between 3D printing and security – in this case, data security in terms of credit card skimming devices. In contrast, much of the findings of the literature on this issue (see section 2.6.7) refer to cybersecurity issues concerning cyberattacks on 3D printers which can result in files being maliciously altered or stolen.

The skimming devices that one of the participants referred to is a device that fits snugly over card slots on ATMs and point-of-sale (PoS) devices, criminals can read off credit card details and then use this information to steal money from the bank accounts of unsuspecting victims. Coyne (2013) reported on a case in which AU$100,000 was stolen from bank accounts across Australia after 15 ATMs were compromised with the use of 3D printed skimming devices. And Wagenseil (2014) shows how big a problem this is as he maintains that there is a thriving community that exists online whose sole purpose is to print as many of these devices for interested parties quickly and cheaply. Unfortunately, with 3D printing getting cheaper and more efficient, it appears that this problem would likely not go away soon.

Although the data security issues in the literature review can be said to be related, they are a different type of security issue. It is more to do with the security of 3D printer that is breached maliciously by hackers who can then go on to slightly change the way they work or alter the schematics of designs. A further discussion on this topic is provided in section 8.6.4 however, it is being pointed out here that the growing use of additive manufacturing for creating safety-critical infrastructure like part for aircraft, security breaches like this could result in a huge loss in terms of lives and property.

9. Liability

On the issue of liability, the literature review suggests that with 3D printing, liability is quite a complex issue because of the complicated nature of the value chain. The empirical study, on the other hand, shows that the participants appear to have a simplistic view of issues around this subject and just 2 of the 16 participants appear to see the complexities involved in determining liability when something goes wrong.

Many do not appear to appreciate how the complex nature of the 3D printing value chain creates new difficulties for issues around liability. This is because there are so many different people involved who might reside in far removed countries making it hard to apportion liability. Also, 3D printing enables amateur designers and hobbyists to take on similar risks as established manufacturers without necessarily having similar liability protection.

Describing a complex scenario, Eckstein and Brown (2016) suggest a hypothetical scenario where a company in China uploads schematics for printing an auto replacement part and it is bought by an individual in the United States, who prints it out in a 3D printing marketplace and sells the printed part to another person for use his car. In the event of an accident, where the 3D printed part has been proven to be the problem, determining what recourse the accident victim has to liability becomes a complex matter because of the complex value chain and the different legal jurisdictions involved.

As noted in the exploratory scan, liability laws in place today were created for an era where mass manufacturing was the norm, the retailer separated the producers from the consumers, and consumers were not required to understand the complexities inherent in consumables. Thus, in the hypothetical situation painted above, Eckstein and Brown (2016) suggest that the victim has few options under current legislation as per:

- Recovering damages against the individual that sold the 3D printed auto part would be almost impossible because strict liability does not apply where an item wasn't bought from 'commercial sellers' like manufacturers, distributors, and retailers, and it would be difficult to prove that this is a case of negligence because all the seller did was to download the file and have another person print it;
- It will also be difficult to recover against the local 3D printing marketplace in terms of strict liability, negligence, and or implied warranty because they provided the 3D printing service and were not engaged in the sale of goods;
- Equally, it will be difficult to find the manufacturer of the 3D printer liable because the accident victim will have to prove that the 3D printer was defective and that it

was defective when it left the possession and control of the manufacturer, and the defect caused the injuries;

- As product liability laws apply only to the sale of products, recovery against the Chinese company that uploaded the schematic is also unlikely because the laws only apply to the sale of products that are considered 'tangible'. Also, the question of jurisdiction then arises even if an adequate argument can be forward to show that the CAD files may be considered a tangible product.

Therefore, this study finds that while the literature appears to agree that the situation concerning the liability issues of 3D printing is quite complex, many of the participants are yet to appreciate the complexities. Also, the literature indicates that liability issues for 3D printing will become quite difficult to adjudicate under the current legal structures and yet most of the participants appear to have a very simplistic view of such issues.

10. Biohacking

Biohacking was one important issue highlighted in the literature review (see section 2.6.9). The review discussed the risky nature of the procedures that grinders and their DIY Bio counterparts perform and pointed out that these procedures usually lie on the fringes of the law. Curiously, none of the 16 participants in this research discussed biohacking. This was quite interesting because all the participants in this study are involved with DIY 3D printing hacker collectives like hackspaces, makerspaces, or fablabs and as shown in the literature review, biohackspaces are not only similar in terms of the DIY and opensource mentality, they are all offshoots of the hacker culture that have embraced 3D printing and other opensource hardware.

The fact that some of the participants in this research actively participated in the development of 3D printing by helping to bring it to the desktop, and yet appeared unaware of biohacking and the risks involved goes to show the difficulty of anticipating some of the societal implications of computing technology due to its malleability. Could it perhaps be that they are aware of the situation but just don't think this constitutes an ethical issue and so have decided not to raise it? Well if that is the case, then it goes to show why there is an urgent need to educate users of the technology on the seriousness of some of the risks of such use outside of the institutional framework.

8.4 Implications of the findings on expert participation in knowledge-making

Thus far, the findings have shown that the participants in this research have come up with an impressive array of issues related to the problematic effect of 3D printing in the society.

They have also provided insightful arguments that show how their experiences and history have moulded their views. However, a closer look at individual participants' responses (see Table 8-1) paints a different picture which appears to indicate that many of the participants are only aware of a small number of issues. Considering the ongoing debate on meritocracy and the use of technical experts as ethics experts (see section 2.7), as well as questions over the validity of professional community focus groups in ethical engagement research, it is important to understand how the findings of this research feed into these discourses.

It has previously been pointed out how participants were selected primarily because of their familiarity with 3D printing, the DIY hacker culture, and their expertise in using the technology. As part of the hermeneutic approach used in this research, the interview questions were asked in such a way as to enable responses that are based mostly on the participant's experiences. The researcher endeavoured to do this without leading them onto a set answer or attempting to put words in their mouth. This may likely explain why the findings of the research charted in Table 8-1 shows that individual participants did not comment on many of the ethical issues identified. Note that the white spaces in the chart represent issues that participants didn't discuss.

However, another reason why participants may not have mentioned these issues will also be explored here. That is the possibility that participants did not know about the issues that haven't been mentioned or didn't feel that they were problematic in terms of ethics. It should be pointed out here that all the participants were provided similar research information sheets with information describing the research and stating the objectives. Before each interview, this information was repeated and the aims and objectives of the research were explained again while ensuring that the participants understood what the research was about.

Interestingly, the total responses received from the participants (marked by the coloured boxes of the chart) make up only about 25% of the total volume of responses that would have been provided if all participants commented on every issue identified by subthemes. Again, going by the subthemes the chart also shows how the average participant had about 3 concerns related to 3D printing and only 2 participants (P2 and P15) discussing more than 4 issues. One important issue which only received a passing mention by one participant is the danger associated with resins used in SLA 3D printers which the participant describes as 'not the safest material to come into contact with'. As shown in the literature review this material is quite dangerous as zebrafish embryos exposed to printed parts from SLA suffered serious deformities or died within 7 days and yet only one participant was aware of the dangers.

This situation raises serious questions about ethics in the industry. Interestingly, one of the participants maintained that the ethical issues of 3D printing are ‘benign’ and the outcome of this research shows this participant appears to be speaking for the majority of 3D printing users. Interestingly, a look at the definition of benign in the Oxford Advanced Learners Dictionary (2015) indicates two meanings – the first, a formal form is ‘kind and gentle, not hurting anyone’ and the second, a medical form meaning ‘not dangerous or likely to cause death’. The findings of this study indicate that this appears to be the general attitude reflected in the industry in regards to the ethical issues of 3D printing.

It can also be seen how the views of some of the participants may have been shaped by their backgrounds. For example, many of those with an engineering background argued that 3D printing might have fewer ethical issues or issues that weren’t very different from those promoted by similar technologies including Laser cutting, large-print formatting, and CNC and so can be ignored. These participants all appear to have had extensive experience with such machinery before moving on to 3D printing. To understand how popular such views were either within or outside the industry, an extensive online search was conducted finding no explicitly published journal articles of this sort.

However, there were 3 interesting mentions in engineering related blogs comparing problematic issues of CNC with AM. One of the blogs argues that while the additive nature of 3D printing means that generally less waste is generated when compared with CNC, some forms of AM generates considerable waste due to support structures and materials that cannot be reused (Molitch-Hou, 2016). Similarly, the other suggests that AM has no waste and is more environmentally friendly than CNC where waste results from cutting material away from an original block to create an object (Jamie, 2018; Haoze, 2020). It thus appears that the general view amongst such ‘experts’ is that 3D printing has less ethical issues than similar technologies and therefore society shouldn't be concerned about this technology.

One other point worth mentioning is the difference between the responses of those from academia and those from SMEs. Note that in the participant column in Table 8-1 the academics have been highlighted in blue and clustered together at the bottom of the table. Of a total of 26 subthemes identified in this research, there was at least one academic who was concerned in only about a quarter of these (i.e. 7 subthemes). It can be seen that 2 of these subthemes (waste, energy) relate to the environment and 2 health and safety-related issues were identified(i.e. ultrafine particles resulting from SLS, and noxious odours). The other issues they were concerned about are the devaluation of IP, jobs, and 3D printed guns. They were only partially concerned about recyclability and opensource issues and were unconcerned about sustainability, biodegradability, food safety, as well as copyrights and patents. On the other hand, for those from SMEs, there was at least one participant who had an ethical concern in 25 of the 26 subthemes and a partial concern of the 26th subtheme (i.e. opensource issues).

This was quite an interesting finding because it shows that those from SMEs appear more knowledgeable about the ethical issues of 3D printing than the academics. Although one might argue that the number of academics is just about a quarter of the total population of participants, and so this result is not a fair comparison. However, a closer look shows that each academic came up with about 1.75 issues on average while those from SMEs came up with 3.7 issues on average. Thus, whichever way one looks at this, the academics appear to have suffered more from non-knowledge than those from SMEs. Could this be attributed to their proximity to the technology? This is quite likely because those from SMEs would likely use this technology on a more regular basis than those from academia.

It is, therefore, important to revisit the question of meritocracy and the use of technical experts as ethics experts and the validity of professional community focus groups in ethical engagement research. As pointed out in the literature review (section 2.7) there has been a growing trend to appoint technical experts into roles requiring ethics expertise and this situation is more evident in Silicon Valley where meritocracy infuses everything from hiring practices to policy positions.

It should be pointed out that the prevailing context in which the word ‘meritocracy’ is used today as a positive ideal is rather different from the pejorative context in which the term was coined over 60 years ago in the book ‘The Rise of Meritocracy 1870 – 2033 (Young, 1958). In this book, the author Michael Young, a British politician, socialist, and social reformer hoped to ‘inspire reflection’ on the folly of replacing egalitarianism with meritocracy. Young (2001) argued that while it is good to appoint people to jobs based on merit (intellectual ability plus effort), doing this based on ‘ability of a conventional kind’ risks creating a new social class’ that could disfranchise groups that no longer have their people to represent them.

Similarly, the situation in the tech-related industries where those with ‘conventional’ abilities i.e. engineers and tech experts, are appointed to ethics roles not only risks disfranchising those with a legitimate interest in the evaluation of value-laden technology but also risks promoting a narrow focus on ethical issues that would result in suboptimal solutions. This study has shown some of the pitfalls of relying on tech-experts to use personal judgment to evaluate hard ethical questions of products they are closely associated with. Similar to Moss and Metcalf (2019) argument on meritocracy, this study has provided some indication that ‘thinking hard’ about the potential harms of a product in the real world is not the same as thoroughly understanding how society is affected by the product. Tech experts by themselves cannot be said to possess socially robust knowledge of the effects of technology on those who might be affected by the technologies they promote.

Does this then mean that ethicists are presumed to be the ‘know it all’ of societal issues of technology? That is not necessarily the case because even though ethicists might be trained to ‘think hard’ and to reflect on the potential societal harms of technology, they too are not immune to the problem of non-knowledge. For example, it was pointed out how the problem of UFPs and VOCs was only discovered in 2013 by an Engineer even though 3D printers had been around for about 3 decades. This was one problem that even ethicists had missed for so long and it was only because of the intervention of technical experts that the problem was uncovered.

Thus, this study suggests that a more appropriate methodology would be one that involves a broad range of stakeholders through a community-based strategy that democratises expertise and is more egalitarian than those that privilege technical expertise. They enable communities to participate in technical decisions making which often results in more effective solutions than interventions that privilege expert-led technical fixes. As pointed out in the literature review (section 2.7) professional community-based approaches are better able to focus on the types of issues that expert-based studies seldom emphasise including the impact of technological developments on personal well-being, work ethics, and community life.

Rather than reduce the quality of expertise, the quality of knowledge and understanding can be increased through democratic participatory approaches. While this study has benefited from the different cultural and historical backgrounds of the participants, a better understanding of the issues and probably more issues may be generated through an approach that is not restricted to technical expertise alone. Nevertheless, it must be pointed out that for such approaches to be successful, implicit political and personal biases, as as well as precommitments must be acknowledged to avoid them serving as rubber stamps for political and personal agendas. Also, it is important to pay attention to the power dynamics in the group as those with technical expertise may wield much more power in such settings.

8.5 On Regulating 3D Printing

It was interesting to find that majority of the participants who commented about regulation, were averse to new governmental regulations in the industry. Others, however, who were not completely opposed to regulations suggested that a mechanism for regulating IP may be developed, and standards and certifications by non-governmental bodies could also be created. Yet some others suggest self-regulation via codes of conduct are a preferred means of regulating the industry.

Most of the participants in this study were against the idea of creating new regulations that specifically target the use of 3D printers. In fact, out of 16 participants in this study, 11 participants directly addressed the issue of regulation in the AM industry by a governmental authority. As discussed above, 5 of these suggested that additive manufacturing was adequately covered under existing regulation and maintained that any further regulation would harm the industry. Just one participant felt there was a need for government interference by creating regulation for specific applications, while 2 other suggested they'd prefer the creation of other types of mechanisms for regulating intellectual property. The others discussed standards, certifications, and codes of conduct as alternatives to government regulation.

As an example, one participant (P14) who doesn't favour any regulation maintains that copyright, patent, and trademarks are established protocols that cover 3D printing and so there is no further need for new laws in this area. However, legal experts like Goo (2018) have provided contrary views suggesting that IP laws will need to catch-up with the technology as it is way ahead of the current regulation. This appears to be similar to the situation when digitisation of music and videos allowed unfettered access to downloads and new laws like the Digital Millennium Copyright Act had to be introduced in the US (see section 1.3). Also, according to a recent European Commission report prepared by Bonneau et al. (2017, p.5), the jurisprudence with regards to legal regimes in the areas of copyright, patents, and trademarks is unclear and needs to be addressed.

Another issue that was highlighted relates to how the cost of compliance with regulations might hurt the AM industry. Participants pointed out that adhering to regulation may require the purchase of new equipment and redesign of building facilities to ensure that the health and safety standards are met and users protected. Such regulatory requirements may be too expensive for many SMEs involved in 3D printing and other users of the technology.

Thus, the cost of complying with regulation can also impede responsible actions in the industry as participant P7 and P5 have pointed out. The participants who used examples of waste disposal and air filtration equipment, to illustrate their point, suggest that many users of 3D printers will try to cut corners to avoid any expensive expenditure that new regulations might dictate. As an example of the cost of compliance, Mirsky, Baker and Baker (2013, p.4) and Ascent (2020) suggest that complying with new regulations make some industries less competitive because it is not only time consuming but also very expensive as average spending on compliance is more than 7% of total operating cost.

As many of these printers are used in homes and other private spaces like garages, this raises the question of how such regulations would be enforced in such places. For example, the research has shown how biohackers conduct their activities outside of regulated spaces such as garages and basements of private homes to sidestep many of the codes of ethical conduct already in place in regulated spaces like universities and corporations. It is therefore important to consider how any new regulations might be enforced in such private spaces.

Also, the possibility of regulations stifling the growth of the AM industry was highlighted by some participants (see section 7.3.1). Among other things, they were of the view that regulations tend to cover too wide an area which could lead to the industry struggling to comply with regulatory requirements. A similar point was made by Pierrakakis et al. (2014, p.15) who suggested that tightening existing IP protections would likely discourage innovation in the AM industry. Other examples of industry players with such an opinion include Davis (2017) and Eu-reporter (2018) who maintain that the European Parliament risks stifling innovation in the AM industry with new regulations.

Another participant points out that because laws are slow to catch up with the pace of development, their usefulness is quite limited in the context of 3D printing which is developing rapidly. An indication of the fast pace of development of these technologies can be seen in how quickly the technology for 3D printed guns has improved from 2012 when the debate over regulation had just begun as shown in the literature review. All of these illustrate how much of an issue regulation could be in the 3D printing industry.

Outside the 3D printing industry, some professionals have begun to argue for regulation of the industry include Adedira and Oyedele (2017) who maintains that there is a need for government regulation and inspection in the areas of quality and safety standards for additive manufacturing. They also suggest that the regulations should specifically address the performance of 3D printed materials over time, including their quality and consistency, and the types of materials used with the technology. And Bhargav (2017) who contends that in the case medical use of additive manufacturing for procedures like orthopaedic implants, heart valves, and dental implants, there is need to regulate both the 3D printer, materials used, manufacturing process, and the final application.

Nevertheless, some participants like P9 suggest that what is lacking in the 3D printing industry are mechanisms for selling IP protected items likely in a bid to mitigate against any devaluation of IP caused by free opensource file sharing (see section 3). Interestingly, companies like Fabulonia, a UK based company, have attempted to offer such a solution and created an online marketplace for original design right holders to sell customized 3D originals with a choice of copyright protection types including fully paid licences or free unlimited ones (Kuneinen, 2013). However, the company which registered with a lot of fanfare in 2013 appears to have gone bust as the company went dormant in February 2019 and a notice of compulsory strike-off was issued by Companies House (2019). This likely illustrates how difficult it is to get such solutions to satisfy users of the technology.

Some participants proposed the creation of standards for 3D printing insisting that having standards that are followed by the industry would help build trust as clients can see that they are providing products and services correctly. They have therefore chosen to get certifications like those offered by the International Standards Organisation (ISO) as they feel this could help promote their business. Interestingly, some additive manufacturing-specific standards are already being developed for the industry in a collaboration between the American Society for Testing and Materials (ASTM International) and ISO.

The ASTM/ISO Standards for 3D printing that have been created include 14 in the area of materials and processes, 2 for design, 3 for test methods, and 1 for additive manufacturing terminology (ASTM, 2018). An example of the standard terminology promoted in the ASTM standards is discussed in section 2.2.2. What would likely follow will be some industry certification processes that will give recognition to those who follow the standards. For now, though, the efforts of ASTM and ISO do not appear not to have been well recognised in the industry as not none of the participants were aware of them and not much is being done to ensure that they are being adhered to.

8.6 Unique issues indicating the effect of the Hacking Culture and the need for regulation 3D printing

The findings of this research indicate that 3D printing has several unique factors that can be linked to the hacking culture and also indicate the need for regulating the use of technology. This is because these factors all come together in such a way as to create distinctive ethical issues for use of the technology as the following discourse shall show.

8.6.1 The ethically distinct nature of 3D printing

3D printing can be said to have an ethically unique nature brought about mostly by the hacking culture and the context in which the technology is used. Recall that in the literature review it was shown how a common theme that runs through the hacking ethos is a culture of open sharing, the objective of which is the democratisation of technology with the intention that anyone and everyone can participate and benefit equally. They believe the ability to participate creates new opportunities and feel that institutional rules and regulations only create barriers for participation.

Thus, it was shown that to achieve their aim of decentralising information, the hacking culture appears to promote 'a wilful blindness' of the societal ills that could result from pursuing a dogma of total openness. This attitude prevents effective deliberation and reflection of the problematic societal impacts of a completely open science and technology. Although the growth and development of 3D printing can be ascribed to the spirit of openness promoted by the hacker culture, an indication of how this 'willful blindness' can result in societal issues can be seen in what 2 participants in this study have referred to as a 'devaluation of intellectual property'. This refers to a situation where those with a need to benefit financially from their intellectual property are unable to because of the free and open availability of their products on the internet.

The number of participants who suggested that they do not consider the effect of 3D printing on copyrights to be problematic also mirrors the general perception of hackers. Like much of the hacker movement, they generally feel that intellectual property rights have been used as a weapon to oppress progressives who wanted to improve the technology. They also feel that rather than promote knowledge-making, IP rights have rather impacted the entire AM industry negatively as it takes too long for patent ownership to expire before others can work towards improving technology. They also fail to see that the dogma of total and complete open sharing means that technology could very easily get into wrong hands from where it can be used for all sorts of nefarious activities that are contrary to commonly held societal values.

8.6.2 Hacking versus regulated manufacturing

The hacking culture with its ethos for open sharing, collaborative working, and use of technology in ways that others haven't imagined, has enabled a proliferation of cheap, easy to access 3D printers. By the removal of financial and technical barriers, it has facilitated greater accessibility to manufacturing technology which was initially designed to be used under institutional supervision in places like corporations and universities. As a result, just about anyone with a few hundred pounds can purchase a 3D printer and begin manufacturing without restrictions with the touch of a button using 3-dimensional models that have been downloaded freely online or for a small fee.

This creates interesting dilemmas in the areas of health and safety, liability, and intellectual property rights. 'Health and safety' has become an issue because by producing artefacts in homes and garages, many of these small scale manufacturers easily circumvent institutional safety rules and regulations. In many countries, such manufacturers are not bound by the same safety standards that established manufacturing companies are required to follow. Thus, their products are less likely to have undergone rigorous safety checks and may result in serious harm to users.

With 3D printers, guns can now be created in homes and private spaces with files freely downloaded over the internet and although some say that such weapons currently don't pose a threat to society, as the technology improves, there is a greater risk that such guns would pose problems for society. Currently, guns have distinct characteristic that makes them identifiable when used to commit crimes. However, with 3D printed guns, all such unique identifiers are not present in designs making it more difficult to identify criminals that use them.

Intellectual property rights issues may also abound because of the ease with which object can be copied either by scanning them or using computer-aided software to design them. The open availability of designs could harm IP rights in the sense that they cause a devaluation of the intellectual property of those who wish to make a living from their work.

Also, this creates liability issues as such independent manufacturers usually do not have similar liability protection as the established companies and making it difficult to apportion appropriate compensation to those who may have been harmed. The problem of liability is compounded by the distributed nature of 3D printing which as shown in the literature review, creates unusual value chains that current liability regulations aren't designed for.

8.6.3 Biohacking issues

One of the highlights of the literature review was the section on biohacking which showed how 3D printing has enabled the convergence of life sciences and information systems in spaces outside of the regulated environment of institutional science. This convergence redefines the relationship between science, research, and the DIY movement. It promotes the democratisation of science in profound ways and enables people with no formal training in biology and medicine to participate actively in science in ways that traditional science would not permit.

For example, the activities of grinders, a subgroup of the biohacker community that seeks to optimise their bodies and mind with the use of openly sourced science and technology tools. They are closely related to the transhumanist movement who actively seek to use technology to augment and evolve the human species. The literature review has shown how, along with other advanced science tools like protein inhibitors of CRISPR-cas9, 3D printing is quickly becoming a favourite tool for the activities of biohackers due to its versatility. Grinders are part of the subculture of 3D biohackers and usually operate outside the realm of traditional science and medicine in private spaces like basements and garages where they can sidestep the rules of ethics review boards.

This, therefore, raises ethical issues including safety of the procedures they carry out which could result in unintended health complications, infections, and immunological diseases. It could also lead to reliance on medication for the rest of one's life. Like in the case of bioprinting (see section 2.6.6 and 8.3.4), it could also create moral dilemmas around issues of justice and access to human enhancement. Even then, it appears the participants in this study were either unaware of the biohacking issues or didn't feel that it has any ethical issues of concern as none of the 16 participants discussed anything related to biohacking.

8.6.4 Relationship of the physical to the digital

3D printing is a digital technology with an ability to transform physical things into data and data into things. This digital nature of 3D printing creates peculiar problems in terms of the materialisation of malicious cybersecurity activity. With previous technologies, the effect of a cybersecurity attack remains in the digital domain, but 3D printing makes it possible for such issues to transfer from the digital world into the physical. Thus, apart from issues of intellectual property theft which might happen in the case of a cyberattack, or damage to the digital files of a 3D printer, it is now possible to maliciously alter design files such that the structural integrity of the 3D printed object is damaged. If this happens on safety-critical infrastructure like aircraft or in the electric power grid, this could result in damage not only to the infrastructure in question but also members of the society could be harmed.

Likewise, as the participants in this research have shown, the open sharing culture of digital 3D printing models may result in a devaluation of intellectual property rights meaning that those wishing to benefit from their IP rights would find it difficult to do so. Also, 3D printing makes it easy to copy just about any item either by scanning, use of Computer-Aided Design software, or simply downloading it, thus promoting infringement on the IP rights of others.

8.6.5 Consumer manufacturing and customisation

3D printing enhances consumer manufacturing like no other technology before it. Consumers with little or no formal training can use the technology in the comfort of their homes or similar spaces to manufacturing just about any object they desire. As a result of the digital nature of the fabricated objects, it allows for designs of the greatest intricacy and customisation. As shown in the literature review, it also benefits traditional manufacturers as it gives them the ability to rapidly go from design to production, to create customizable one-off parts, as well as mass-customisation to meet ever ever-changing customer demands.

Nevertheless, as most of these new entrants into the manufacturing scene may be unfamiliar with safety procedures for product design, or regulations for the minimisation of hazards, this might lead to the development of unsafe products. The quality and consistency of products are also affected as there is currently only very limited legal frameworks for regulating the standards of feedstocks and other materials used in 3D printing. Thus, 3D printed objects could be affected by such reliability issues including anisotropy and porosity which are usually not detectable by merely looking at the external surface of the object. And as some of the participants in this research has shown, the fact that 3D printing is being used for food and children's toys means that there is an ever-present likelihood of a microbial contamination hazard occurring in these circumstances.

8.6.6 Agile manufacturing and the tinkerers waste problem

The hacking culture also promotes tinkering and experimentation in such a way that it has enabled 3D printing to implement agile manufacturing principles making it possible to respond quickly to rapidly changing needs (see section 2.4.1). However, this agile nature means that there are unprecedented levels of experimentation going on with 3D printers than with almost any other technology. It has often been pointed out how the most popular use of 3D printing is in prototyping. This level of experimentation results in the generation of a lot of waste.

Participants in this research have pointed out that waste could be as much as 40% of the total material used in 3D printers. Bearing in mind that much of this waste is not recycled mostly because the materials are not easily recyclable, and where they are recyclable, impurities mean that the cycle cannot go on indefinitely. Also, the study has shown that claims about the biodegradability of 3D printing filaments like PLA are mostly a misconception of the true nature of biodegradation. Under standard temperature, experiments have shown that it will take about 100 years for PLA to degrade. Thus, while the agile nature of 3D printing is great for rapid production, the unprecedented levels of waste generated as a result of experimentation mean an ever-increasing waste problem.

8.6.7 Concept, perceptions and expectations of responsibility

As pointed out in the literature review, one of the ethic that underlies the hacker culture is the idea that computers can change life for the better. Even though the hack value attached to hacking often means that they perform feats simply for the sake of showing off or doing things differently, the fundamental ethic can still be said to be a desire to change the world for the better. That is why it is perplexing to see that within this hack culture, the notion of responsibility is usually only confined to the promotion of hacker ideals rather than altruism.

For example, when asked about their expectation of the responsibility of 3D printing, many of the responses from the participants were directed towards factors that can promote 3D printing rather than those that can rid society of the ethical issues identified. It is noteworthy that there was a participant who suggested there was no further need to promote the notion of responsible 3D printing in the industry.

The participant (P13) explained that he felt this way because 3D printing isn't a new technology and it isn't very different from other manufacturing technologies. He suggested that 3D printing simply does what other manufacturing technologies do, and therefore doesn't have an ethical impact.

Although this viewpoint was quite clear, the participant used the peculiar expression 'orthogonal' in referring to the nature of responsibility already existing in the industry. The Oxford Living Dictionary (2019) defines 'orthogonal' in 2 ways – the first suggests something at right-angles or involving right angles, and the second describes statistically independent variables. Both definitions thus imply separateness, independence, or having nothing to do with each other. It thus appears that the point the participant has made is that responsibility and manufacturing are independent of each other, or, that they have nothing to do with each other. If that is the case, this would be quite alarming.

Despite all the positives of manufacturing and industrialisation, humans have over the years, had a hard time dealing with the negative social and environmental impacts of manufacturing. Since the first industrial revolution, air and water pollution, soil contamination, and destruction of habitat have all been consequences of manufacturing (Abdul-Rashid et al., 2017; Folk, 2018). In one instance, the National Geographic (2009) described how waste from manufacturing and related industries contain chemicals, heavy metals, radiation, dangerous pathogens and toxins, and this is just a tip of the problem illustrating the impact of irresponsible waste disposal.

However, if on the other hand, the point P13 intends to convey with the use of the expression 'orthogonal' is the opposite, suggesting that responsibility is an integral part of the manufacturing process and therefore there's no further need to encourage responsibility, this too may be considered a naïve proposition. The ever-growing negative environmental and societal impacts of manufacturing is evidence that the manufacturing and other industries have not shown enough responsibility.

For example, since one of the earliest environmental and societal impacts of the ever-growing demand for manufactured plastic was highlighted in the 1950s by Harris (1959, pp.221 & 229), more and more studies have shown that the problems have now grown to crisis levels (Thompson et al., 2009, pp.2156–2159; Pavani and Rajeswari, 2014, pp.90–92; UN Environment, 2017; UN Environment, 2017). This situation also extends to the IT sector where a recent report notes how widespread the lack of responsible manufacturing is (TCO Development, 2014). Professor Robert Spekman once said, 'making money is certainly one of our obligations, but it needs to done in a moral and ethical way' (McClenahen, 2005), likewise, it can be said that making things is important, but it must be done responsibly – morally and ethically.

The need for greater responsibility cannot be over overemphasized – even in additive manufacturing – and whether it is a new technology or old, whether it is innovative, or not, is immaterial and should not be considered criteria for determining this need. Like Lee (2016) said of additive manufacturing, 'we have a responsibility to make sure that we create an industry and a community that is safe, productive, and beneficial to society at large. The greater the number of people that understand this need, the better it is for society.

8.7 Towards a More Responsible AM Industry

This research has found that although many in the additive manufacturing industry are averse to regulation, there is a need for some sort of regulation particularly as 3D printing is being used outside of the regulatory framework currently in place in regulated institutions like universities and corporations. However, developing appropriate regulation does take time and yet it would be risky to allow the continued use of 3D printers without specific provisions to encourage more responsible use of the technology.

The rest of the discussion, therefore, will focus on the views of participants who appear to have understood this need for greater responsibility in the AM sector as they discussed interesting ways in which responsibility can be further encouraged. Their suggestions have been grouped into themes on education, eco-friendliness, sensitive to IP, transparency, regulation, and technical solutions.

8.7.1 Sensitivity (to Intellectual Property)

The study has highlighted how issues with intellectual property right violations are easily promoted by 3D printing as the model of physical objects can easily be created either by downloading, scanning or with the use of computer-aided design (CAD) software. The study has also shown that many in the additive manufacturing industry do not care very much about such IP rights because they feel that they are restrictive and detrimental to the growth of the industry. In the literature review, it was shown how this attitude closely follows the fundamental principle of the hacker ethic which is that all information should be freely available.

However, some feel that left unchecked, incidences of IP rights infringement will continue to grow and become a problem to the industry particularly concerning devaluation of intellectual property. Such participants have suggested that users of 3D printers need to be sensitive to the rights of intellectual property owners. For example, participant P9 made a more general statement about being conscious of IP theft. Seemingly agreeing with this, Cassaignau (2016) suggests that there is a need for users of the technology to have respect for intellectual property rights as this is crucial to the growth of the industry.

8.7.2 Enviro-friendliness

Given the problematic impact of additive manufacturing on the environment, participants proposed several interesting enviro-friendly actions to help minimise damage to the environment. The recommendations discussed covered such topics as recycling, waste management, the use of biodegradable materials, minimising air pollution, conservation of energy, and helping to ensure a more circular economy.

Having identified that waste was one of the more serious problems facing the 3D printing industry, participants appeared to agree that waste management was one way to ensure a more responsible industry. One of the participants (P15) who recognised that 3D printing generates a lot of waste due to print-errors suggests that one way to reduce this waste is to try not to reprint objects so many times. He also suggests that having an industry where the waste materials are recognised and disposed of safely can help reduce the waste problem. Taylor (2019) appears to agree with this suggestion as he maintains that while there are challenges with dealing with 3D printing waste, it presents new opportunities for the waste management industry and so there should be positive engagement between these two industries to ensure that waste is dealt with appropriately

Among other things, participants also suggested that recycling is a good way of getting rid of waste material from 3D printing. However, the study has shown how achieving sustainable recycling is fraught with challenges including the problem of degradation of the mechanical properties of recycled plastic which makes it impossible to continue to recycle indefinitely. Also, the presence of additives and impurities makes recycling difficult.

Despite these challenges, however, recycling must be encouraged where feasible, and as far as possible as this would help limit the problem of waste from 3D printing. As participant P2 pointed out, it is the most practical option for minimising the effect of waste plastic in the environment. Other participants that appear to agree with this include participant P7 who suggests that companies can responsibly get rid of plastic by recycling, and P9 who maintains that his 3D printing shop was working towards purchasing a filament recycling machine to help with the huge amount of waste they produce.

While admitting that no suitable waste management approach is capable of handling all types of waste materials, the United States Environmental Protection Agency (2017) proposes a waste management hierarchy that emphasizes reduction and reuse. It suggests recycling as the next most preferred alternative, followed by energy recovery and then treatment and disposal (Figure 8-2).

Figure 8-2 Waste management hierarchy

No wonder participant P15 argues that helping people to understand the importance of buying or printing only what they need is a great way to avoid environmental problems due to waste. Together, both the suggestion to reduce and to recycle are part of the basic concept of the 3 R's – Reduce, reuse, recycle being promoted by environmentalist (Thompson et al., 2009, p.2159) and according to Wilkins (2018) are all part of the bigger picture of a circular economy model where waste is minimised, and materials are reused or recycled at the end of a products life. It appears that this is what participant P7 had in mind when he suggested that 3D printing can help to increase the lifespan of products which are no longer supported by manufacturers.

Another interesting suggestion in the area of waste management made by participants is regarding biodegradability. The participant maintains that it is the responsibility of users of AM technology to ensure that they use materials that can return to nature. Although it has been shown in this research that biodegradability is extremely difficult under standard environmental conditions, it is important to note that there are newer 3D printing materials already being developed that have better biodegradability properties. For example, using highly biodegradable cellulose, Sanandiya et al. (2018) developed a material they call Fungal-like Adhesive Material (FLAM) which they produce by introducing small amounts of chitin between cellulose. Therefore, as technology improves it is believed that advancement will lead to the development of materials that can biodegrade naturally.

Ensuring that the air remains clean and fresh is vital given the health challenges that UFPs and VOCs given off by 3D printers may cause. One of the participants, therefore, suggested that users of the technology have a responsibility to ensure that the air remains clean by limiting pollution caused by fumes and particles given off while 3D printing. One way to do this is with the use of filtration equipment and the use of air extractors and air conditioning equipment (Katz et al., 2020). Another important suggestion in this regard is for the use of nanofiber-based membranes which Rao et al. (2017) maintain offers the promise of minimising air pollution from 3D printing.

Energy is another area where users of additive manufacturing can improve to better benefit the environment. As it has been suggested some types of 3D printers are energy hogs (Parraman and Segovia, 2018). One participant, therefore, maintained that in his business, they endeavour to put the machines off when not in use to help save energy. In the future, however, using more environmentally friendly energy sources like participant P7 suggested would likely offer a more sustainable solution for energy problems. Already progress is being made in this area as Gwamuri et al. (2016) and Khan et al. (2018) have developed opensource 3D printers that derive power from solar energy. This suggests improved efficiencies and wider acceptance of these solar-powered 3D printers will enable a more environmentally friendly industry in terms of energy consumption.

8.7.3 Awareness (of ethical issues)

A low level of awareness of the ethical issues of 3D printing and the societal implications by the users of the technology has been illustrated in this study. Interestingly, a fundamental principle of the hacker ethic which many of the users of the technology follow is that knowledge should be shared with other people to enable everyone to benefit from such information. It is no wonder then that education was the most prominent element that participants discussed with regards to factors that can help entrench greater responsibility in additive manufacturing. Of the 16 participants, 5 felt that there is a need to educate people in the industry of the impact additive manufacturing has in terms of ethical issues and societal impacts.

One of the participants (P8) suggested that open 3D printing spaces – the type of spaces used by DIY hacker collectives – where people go to talk about and learn about additive manufacturing are a great place to teach about responsibility and safety in 3D printing. He maintained that there is an onus on those doing training in such places to imbibe this culture in their students. The DIY hacker community through hackspaces, makerspaces and fablabs have an excellent track record of opening up discussions on the advancement of additive manufacturing, they have, however, failed to equally promote issues around ethics and moral responsibility with the use of the technology.

A similar point was also made by another participant (P4) who argued that it is incumbent upon those who know to teach and correct others. In like manner, Toombs, Bardzell and Bardzell, (2015, p.633) contends that in the spaces created by the opensource hacker communities, there is strong motivation to teach, learn, and participate in activities that directly benefit the community, demonstrating the responsibility of members to care not only for each other but also for their community. This suggests that the willingness of members to teach and learn about activities that benefit their community, could easily be extended to education on ethical activities that benefit not just their community, but mankind in general.

Likewise, a call was made by another participant (P2) for an educational process for businesses to teach about such things as reusability of materials, health and safety with an emphasis on how to deal with materials in a safe manner etc. – issues which have all been highlighted as problematic in this research. The use of avenues like tradeshows was suggested by the participant. Other such avenues that might be useful include workshops, conventions, and exhibitions – events where business people and professionals come together to advance findings and inventions as well as their products and services. This is likely what Maskell, Bathelt and Malmberg (2006, p.997) meant when they suggested that temporary clusters are great avenues for interaction and the building of knowledge. Agreeing with this, Jago and Deery (2009, p.12) maintain that the face-to-face interaction that such business events enable is a stimulating environment for learning. As the participant suggests, these sorts of events provide great opportunities for teaching and learning about ethical practice and responsibility in the industry.

Another participant (P2) recommends orientating people towards the positive through positive actions. By developing the right culture while using 3D printers and teaching others to use them, learners can be oriented towards using the technology responsibly. According to the Institution of Occupational Safety and Health (2015), culture is a way of doing things that are shared, taught, or copied, and maintains that everyone in a particular culture tends to do things similarly. Thus, one way to motivate people towards the positive as P2 suggests is for the organisation to adopt a responsible culture with regards to the ethical issues of additive manufacturing.

8.7.4 Transparency (in the AM industry)

Transparency implies openness and accountability. As shown in the literature review, the hacker movement operates on a premise that all information should be freely accessible because systems can only benefit from free access to information. However, it appears that some 3D printing businesses are not being as transparent as they ought to be. Some of the participants in this research pointed out how misleading advertising is promoting irresponsible business practices in the industry. It was therefore quite interesting to see that some participants wanted to see a change of attitude in this aspect. Participants suggested that they would like to see greater transparency in the AM industry particularly in the way printing materials are advertised and in the areas of health and safety.

Turilli and Floridi (2009, pp.105 & 107) suggest that transparency is an ethics 'enabling' factor when it provides information necessary for endorsement of ethical principles. Similarly, Guénéheux and Bottomley (2014, p.8) suggest that transparency requires a high level of openness and disclosure. However, Lee (2016) points out that some in the industry have expressed their anxiety that an open discussion of ethical issues like those related to health impacts of VOCs and UFPs by 3D printers may hurt the development of the technology.

With that in mind, the comments of participant P3 are particularly important as they suggest that being transparent would instead have a positive impact on issues around ethics as it will help the community to self-regulate. This is because others would be able to easily see where mistakes are being made and can provide advice on better approaches. Likewise, the Digital Advertising Alliance (2018) describes transparency as self-regulatory, and Bothwell (2000) maintains that disclosure or transparency has become the most important means of self-regulation. This indicates that rather than acting as a mitigating factor to the development of the technology, transparency is a vital element that is needed to effectively move the AM industry forward.

8.7.5 Technical solution

Participants in this research also recommended several technical solutions that could help ensure a more responsible industry. They proposed 4 areas that technology may be used to minimise ethical issues including the use of technology to identify models protected by copyrighted; use of filters to clean the air of toxic particles and fumes; use of software to detect 3D printed guns; and creating technical symbols that provide information about safety which can be attached to 3D printing materials and objects.

Interestingly, the idea of preventing copyright of digital files as proposed by one of the participants isn't entirely new or far-fetched. For example, a patent for a similar digital right management system was applied for and granted to Isbjornssund and Vedeshin (2014). The patent titled 'Method and system for enforcing 3D restricted rights in a rapid manufacturing and prototyping environment' would enable schematics of 3D printing to be compared to a database of such items to determine how much of the design was copied from pre-existing copyrighted items. This would likely operate in a similar form as current plagiarism detection tools. However, it appears the actual invention is yet to be made as no such applications can be found online. On the other hand, Goo (2018) also suggests the use of encryption and tracking systems to make it more difficult for unauthorised use of 3D design files. This goes to show that great ideas for discouraging copyright infringement based on the use of technology are already being considered in the AM community. Yet, what remains to be seen are practical applications that work.

Concerning 3D printed weapons, the solution proposed by one of the participants was for a software to detect when a weapon was being 3D printed which then stops the printer automatically. This solution rhymes with a relatively new digital rights management system called C3PO developed by Li et al. (2018) where a 3D printer is preinstalled with a database of thousands of images that allows the printer to compare print jobs and stop printing soon as it detects that a weapon is being made. However, this idea has been criticised (BB, 2018) as being impractical because of the difficulty to completely obfuscate the operations of the software from users by locking down its bootloader to prevent any form of alteration.

Participants also discussed the use of filters to minimise the number of nanoparticles given off during 3D printing. And as P3 indicates, such filters already exist and are being trialled in 3D printing shops with many claiming to eliminate between 95% - 99% of these nanoparticles. However, Fabbaloo (2017) points out that many of these filters use industry-standard filters (e.g. High-Efficiency Particulate Air HEPA) which are said to filter up 0.3 microns. Yet, many of the nanoparticles that these filters are required for are in the range of 0.012 to 0.0116 microns which means that would only trap some of the harmful particles.

Interestingly, a more recent study by Katz et al. (2020) which compared the emission rates of 3D printers using filters against those without filters concluded supports the view that such filtration devices are not effective. The study concluded that the HEPA filtration devices helped in reducing the mass spectrum, emission rate, and less aromatic influence during ABS printing. Crucially, however, this conclusion means only a reduction was achieved and not total elimination of UFPs and VOCs. Therefore, such filters may not be effective in preventing problematic health effects due to dangerous particles and gasses emitted by 3D printers.

Issues relating to the safety of materials and instructions on how to use them may, according to another participant, be minimised through the use of technical symbols placed on packs of materials and possibly printed objects to always remind users of safety issues with the products. This is likely in response to the issue noted in the literature review where it was pointed out that King (2015) suggested a dearth of information on most aspects of the safety of 3D printers currently exists. Many desktop 3D printers contain only limited or no safety features, and even their manuals have little or no information about safety. The challenge in this case, however, will be getting users in the additive manufacturing community to agree to a set of symbols that could be easily understood by the majority. Perhaps these types of technical fixes are the sort of things that the hacking culture should pay more attention to rather than simply doing things in more interesting ways.

8.8 Conclusion

Among other things, this chapter has provided an overview of the ethical issues that 3D printing experts are concerned about. It has also shown that the overreliance of technical experts to generate ethical issues of emerging technologies could impoverish research findings due to a narrow focus on issues. Also, tech experts may have difficulty identifying the broad spectrum of ethical issues that such a study would require. It has also shown that the hacking culture could be said to have a double-edged effect on 3D printing because although it has promoted the democratisation of the technology, it has also passively promoted ethical issues by enabling unrestricted access to a powerful technology that was originally designed to be used under institutional control.

Chapter 9 Reflecting on the Research and Conclusion

9.1 Introduction

This chapter provides the summary and concluding remarks for this study. It also discusses how the research has made an original contribution to knowledge and outlines the plans for further research in this area.

9.2 Reflecting on the Research Approach

This research is an attempt to contribute to the ongoing debate among policymakers, ethicists, philosophers, and academics about the ethical issues of emerging technologies. It considers the dilemma of science and technology where they are thought to deliver many benefits – efficiency, increased productivity, and convenience etc – and yet promote serious ethical and societal concern.

Of particular focus in this research is 3D printing otherwise referred to as additive manufacturing. The study set out to understand what the ethical issues of the technology are from the perspective of expert users of 3D printing in DIY hacking communities like hackspaces, makerspaces, and fablabs. 16 expert interviews were conducted, then transcribed verbatim and analysed thematically with the aid of NVIVO – a qualitative data analysis software which helps in the organisation and analysis of data. An interpretive hermeneutic approach was applied during the analysis to understand and explain the outcome of the interviews.

This was done by asking questions of the text, and seeking clarification when the answers weren't quite clear as if engaging in a conversation with the interviewer all over again, then letting all the transcripts 'talk to each other' to get a fuller picture of the text. This approach helped the researcher to understand how the life experiences of the participants and the hacker culture they have adopted have shaped their perception of the ethical issues of 3D printing. The hermeneutic approach also helped the researcher to understand how personal prejudices can form the basis of understanding and allowed the researcher to build on previous knowledge and to dismiss false biases.

9.3 Reflecting on the Research Questions and Outcomes

As pointed out earlier, this study set out to understand the ethical issues of additive manufacturing from the perspective of expert users of the technology who are associated with 3D printing DIY hacking communities like hackspaces, makerspaces, and fablabs.

To this end, the following are the research questions that guided this study and a summary of the outcomes:

I. **What are the ethical issues of additive manufacturing?**

The study has uncovered several ethical concerns that additive manufacturing appears to promote. These issues have been highlighted by breaking them into 26 subthemes. The main themes, however, are in the areas of environmental issues due to waste from 3D printers; health and safety-related issues due to harmful nanoparticles and VOCs emitted from 3D printers; issues with intellectual property rights such as copyright and patents and the devaluation of intellectual property; possible job losses, and problems with 3D printed weapons. It also includes data security issues, business ethics, offensive items, and difficulties in determining liability.

To make it easy to visualise all 26 ethical concerns identified by the research participants and to see the distribution amongst them, a chart has been created by plotting the issues against the participants. A traffic light system has then been used in the chart to highlight each participant's views on the ethical issues of 3D printing. A demonstration of how to use this chart has been provided in this thesis. It shows how the chart can be used to answer questions such as 'what are the ethical issues that participant P2 is concerned about?' or 'How do participants view the environmental impact of 3D printing?

The chart formed the basis of a framework for classifying and assessing the ethical issues of 3D printing developed in this work. This framework was predicated on a novel taxonomy of 3D printing users also developed in this work. The taxonomy is novel because it goes beyond any other taxonomy of 3D printing users developed and incorporates users that have been ignored in previous taxonomies such as prosumers, hackers, and consumers. This is useful because it now makes it possible to consider the risks of 3D printing to such users.

II. **What effect does the hacking culture have on the ethics of additive manufacturing?**

This study has also found that the hacking culture has had a double-edged effect on 3D printing. It has actively promoted the democratisation of the 3D printing by enabling anyone and everyone to participate and benefit equally. However, it has also passively promoted ethical issues of the technology by making it possible to use the technology so easily in spaces outside of institutional control. For example, in garages and basements where ethical approval isn't required to perform any type of operation with the technology. This has encouraged anarchic use of the technology by biohackers such as grinders and members of the DIY bio community;

promoted DIY groups like Defense Distributed who seek to enable anyone and everyone to own a 3D printed gun; exacerbated IP rights issues, and have led to an increase in environmental problems due to manufacturing.

Consequently, participants volunteered recommendations for a more responsible industry include such actions as greater sensitivity to intellectual property, and more awareness on ethical issues, better environmentally friendly practices, and a higher level of transparency in the industry. Other recommendations made include the development of more standards for use of the technology and certifications to recognise those who abide by such standards; regulatory mechanisms for intellectual property to ensure that those who want to benefit financially from their design are better protected from open sharing and yet allowing the community to learn from such designs; as we all better technical solutions for waste management and determining property ownership.

III. What are the implications of expert participation in knowledge-making?

It has been shown in this study that many expert users of 3D printing have a limited understanding of the ethical issues the technology promotes. For example, just one of the 16 participants appeared to understand that data security issues of 3D printers could have far-reaching consequences. Similarly, in some cases, a sole participant recognised potentially serious issues related to sustainability, and the potential health and safety implications of 3D printed medicines, bioprinting, risks of flammability of some 3D printing powders, and the toxicity of some photopolymers.

Interestingly, none of the participants identified any concerns with biohacking which is an important issue because of the ability for individuals lacking in formal training to use readily available 3D printers in non-traditional settings like basements and garages while taking little or no ethical considerations. Its growing use by biohackers and grinders and the growing possibility of serious harm resulting from such technologies especially when used in combination with other inexpensive and easily accessible tools like CRISPR-Cas 9, shows there's urgent need to take a closer look at such concerns.

The study also showed that on average academics identified an average of 1.7 of the 26 subthemes that the collective identified, as opposed to an average of 3.7 issues by those from SMEs. This raises important questions about the reliability and validity of expert participation in knowledge-making for ethics-related research as the issue of non-knowledge and narrow focus could mean that important issues of concern could be missed resulting in impoverished conclusions.

It has, therefore, been suggested here that community-based participatory approaches may be more suitable for unpacking ethical issues of emerging technologies. This is because they tend to better democratise expertise and consider the views of a broader variety of stakeholders. It has also been pointed out here that for such approaches to be successful, implicit political and personal biases, as as well as precommitments must be acknowledged to avoid them serving as rubber stamps for political and personal agendas. Also, it is important to pay attention to the power dynamics in such groups as those with technical expertise may wield much more power in such settings.

9.4 Original Contribution to Knowledge

This thesis makes an original contribution to knowledge in the following ways.

1. The study has developed a taxonomy of 3D printing users which goes beyond existing taxonomies to recognises not only those who manually operate 3D printers and design 3D models, but also include indirect users who are 'pure' consumers – those whose contact with the technology is limited to the outputs they consume – in the taxonomy. Importantly, this new taxonomy of 3D printing also includes prosumers and other types of users of the technology whose activities lie on the periphery of the regulated environment i.e. biohackers and their subcategories like DIY Bio and Grinders. It also includes DIY hacker collectives like makerspaces, hackspaces, and fablabs. By including these types of users in the taxonomy of 3D printing users, it enables a more holistic assessment of the impact of 3D printing on all types of users.
2. This study has also created a framework for assessing the risk of 3D printing based on the new taxonomy of 3D printing users. This new framework has 2 approaches i.e. a bottom-up approach which is useful for assessing the likelihood of 3D printing users to be affected by issues already identified; and a top-down approach that can be used to determine the types of users that are at risks of problematic issues of 3D printing. The use of this framework has been demonstrated in this research showing how it can be successfully applied to assess the risk of 3D printing to different user groups.
3. An understanding of the ethical concerns of 3D printing has been developed from the perspectives of experts from DIY hacking communities. It shows how individual users in these groups have a very limited number of concerns in terms of the problematic effect of 3D printing but as a collective, they share an impressive number of concerns which have been broken down into 26 subthemes in this research. None of the 16 participants mentioned some important issues like those related to biohackers and several issues like those related to bioprinting and data security were identified by sole

participants. Therefore, the findings have important ramifications for the use of expert participation in knowledge-making research particularly in the area of ethics which require critical thinking of problematic aspects of technology. It shows how limiting participation in research to tech experts can impoverish research findings which can then go on to affect relevant policies. This thesis thus finds that participatory approaches that promote the democratisation of expertise to a more diverse group of stakeholders rather than simply relying on tech experts may be more appropriate for such studies.

4. An explanation of how the hacking culture has helped to promote some of the ethical issues of 3D printing has also been provided in this thesis. It has shown that although the democratisation of 3D printing has brought many benefits, it also means that the technology can be used so easily by everyone and anyone in places where there is no institutional control on what one can and cannot do with 3D printers. This exacerbates ethical concerns like those related to health and safety due to anarchic use by biohackers, safety concerns of 3D printed guns, and the rise in concerns of intellectual property rights abuses.

9.5 Future Research

The findings of this research are largely based on outcomes of interviews with tech experts associated with hacker collectives like makerspaces, hackspaces, and fablabs. This can be considered a limitation because it means the findings may have had a narrow focus. The thesis could benefit from opening the discussion on the ethics of 3D printing to a wider group of stakeholders. In future, therefore, it would be necessary to carry out a similar study with a wider group of stakeholder in such a way that the findings can be comparable to this thesis to determine how community-based participatory approaches might enhance the findings on ethical issues.

In future also, the framework for classifying and assessing the ethical issues of 3D printing developed in this research may be made more attractive to the tech world by extending it further through the automation of some of the processes. This can be done by integrating it into an application or software with a user-friendly interface that allows easy input or selection of relevant data. Based on such data, an automated report would then be generated that shows the classification and assessment of the 3D printing risks.

9.6 Conclusion

The research has explained what the societal concerns of additive manufacturing are from the perspective of experts who are closely associated with 3D printing hacker collectives. It has also shown how limiting participation in ethics-related research to tech experts can impoverish research findings and therefore calls for approaches that promote greater collaboration with relevant stakeholders. The research has developed a taxonomy of 3D printing users which can be used to establish a more holistic understanding of the associated societal risks. Also, the research finds that there is a need to rethink the regulation of 3D printing as there is currently no specific laws targeting this technology. This is important because of the anarchic use of 3D printers in places like basements and garages where there is no institution control.

The ever-improving capabilities of AM which have brought about the seamless transition from consumer-to-manufacturer-to-retailer means that current regulations are unable to deal with the host of societal concerns of AM that this study has highlighted. Along with regulations targeting the use of 3D printers in locations outside of traditional institutions and corporations, the research finds that other actions that may help promote the more responsible use of 3D printing include: raising awareness of the ethical issues that 3D printing promotes; encouraging users to be sensitive to intellectual property rights, fostering transparency, and promoting more environmentally-friendly materials as well as waste minimisation.

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Appendix I

Participant Information Sheet

Dear ______

I would like to ask you to participate in the data collection for a study on “ethical issues of additive manufacturing”. I am an Information Systems research student at De Montfort University, Leicester. You will find more information about the study on the attached project outline.

I hope to better understand the following issues:

I. What are the ethical issues of additive manufacturing?
II. What effect does the hacking culture have on the ethics of additive manufacturing?
III. What are the implications of expert participation in knowledge-making?

Participation in this study is entirely voluntary. It will involve responding to a short set of interview questions. You may decide not to answer any of the interview questions if you wish. You may also withdraw from this study at any time by directly advising the researcher interviewing you, by email, or by using the contact detail at the end of this document. If you notify me of your withdrawal, all identifiable data will be destroyed. Once data has been anonymised it will be impossible to identify the origin and cannot be destroyed.

I may ask for clarification of issues raised in the interview sometime after it has taken place, but you will not be obliged in any way to clarify or participate further.

The information you provide is confidential, except that with your permission anonymised quotes may be used. If you request confidentiality, beyond anonymised quotes, the information you provide will be treated only as a source of background information, alongside literature-based research and interviews with others.

Your name or any other personal identifying information will not appear in any publications resulting from this study; neither will there be anything to identify your current position at your place of work. The information gained from this interview will only be used for research purposes and will not be recorded in excess of what is required for the research.

Even though the study findings will be published in international conferences and journals, only the research team will have access to the interview data itself. There are no known or anticipated risks to you as a participant in this study.

If you have any questions regarding this study or would like additional information please ask the researcher before, during, or after the interview.

Yours Sincerely,

George Ogoh

Appendix II

Consent Form

Issue	Initials
I have read the information presented in the information letter about the study " ethical issues of additive manufacturing"	
I have had the opportunity to ask any questions related to this study and received satisfactory answers to my questions, and any additional details I wanted.	
I am also aware that excerpts from the interview may be included in publications to come from this research. Quotations will be kept anonymous.	
I understand that the interview will be recorded and give permission.	
I understand that relevant sections of the data collected during the study may be looked at by the researchers and/or supervisors. I permit these individuals to have access to my responses.	
I understand that I can withdraw from this study at any time, with no penalty, and all data that has been collected from me will be destroyed.	

With full knowledge of all foregoing, I agree to participate in this study.

I agree to be contacted again by the researchers if my responses give rise to interesting findings or cross-references.

☐ no

☐ yes

if yes, my preferred method of being contacted is:

☐ telephone ………………………………………………………..

☐ email …………………………………………………………..

☐ other …………………………………………………………..

Participant Name:		Consent was taken by	
Signature:		Signature	
Date		Date	

Appendix III

Sample Transcript (with Initial Coding)

***I* –** All right let's go. What's your involvement in the industry?

P2 – Yea, so ah, my background is Mechanical Engineering and I got involved in 3D-Printing while I was doing my thesis and my university was about… in 3D-Printing and yea, then I just eh... I moved to, I moved to London to find... start a career in this, eh...

***I* –** You mind, you mind if asked what, what your thesis was on? How it relates to in 3D-Printing?

P2 – Basically ah... yes, it was ah, assembling an Ultimaker tool, ah... testing slicing parameters, and also design, design something... design like a part of a drawing eh, in solid works for... it was for a graphic card competition during that time.

***I* –** Cool, cool...so, right now, how are you in, in it?

P2 – So, here I started as the production coordinator of the, of the 3D printing firm and then ah, and then, yea you now it's very easy to just, to switch to erm, consulting, like ah... because you are using the printers, and ah, as long as you print you know what it can do, how far you can go, your limitations, so... and also you are... of course you are testing and you experiment with things and also you are pushing... you are pushing some limits, ah... yea, limits that you don't always know unless you try...

***I* –** Cool. Yea, so, so what you're doing at the moment is cons... some sort of consultancy right?

P2 – Eh, yea, basically I... yea, like... I'm doing consultancy like eh, like **P3** we're, we are able to see the file and choose the right process… or, ah, direct the customer towards the right notifications of his design in, in order to… to be printable or recreate his design from point zero basically... ah, another thing that we also... that I'm dealing with is 3D-Scanning which is the reverse process of getting the digital file, and this is something also that ah, you can experiment a lot because there are, there are significant limitations concerning the the safest finishing of the part that you are going to scan or the size... so ah, yea this is something that we... am, am trying to experiment and see how far we can go on there also...

***I* –** Okay, lovely...

P2 – And, yea, right now basically I'm, I'm managing the store of the company so that means that yea, I'm offering... I'm consulting the customers eh, also I manage the production and I prioritise and plan the production basically and eh, doing the maintenance on the machine's that we have here at the store.

***I* –** Nice, nice that ah, means you are involved in the whole thing from... yea...

P2 – Yea, like from the eh...

***I* –** Cool from the scratch to finish, yea?

P2 – From scratch to finish.

***I* –** That's eh, that's an interesting one. So, who would you say, are your erm, stakeholders when you erm, do your work? Who are your stakeholders like, who do you, people that get involved in your work?

P2 – Basically, eh, architect's, product designers, eh jewellery designers, eh just, and just people that they want to print parts that they cannot find, you know, like...

***I* –** In the market?

P2 – You know, they cannot find anymore in the market, and they want to try with us to scan something, or, that they have and then try to get the digital file modified a bit or eh like many, there are many cases like that.

***I* –** Hmm, interesting. Erm, so, have you come across situations in your work where someone is suggesting to print or to do some work that is... you've thought it, and you've thought it might not be something you'd want to get involved in? Have you had any situation like that?

P2 – Eh...

***I* –** I'm not asking to name specific names or situation's... but you know...

P2 – No, no, no.... like ah, personally I, I didn't have like eh, you know an ethical talent on this... but eh, I mean, is eh, yea, I know the story that Shapeways once... somebody wanted to print a Swastika...

I – Oh!

P2 – Yea!

***I* –** I've never heard of that one (laughs)

P2 – And then Sageways refused to that...

***I* –** Okay... cool, cool... that's interesting.

P2 – And also, and also yea, when the first 3D-Printed gun eh... when they upload the design on the internet and like the American government just completely...

***I* –** Went bonkers (laughs)...

P2 – Yea...

***I* –** Right...(laughs) .... and, and, and... yes, I also, I was just talking with him... In Japan at the moment, I think there's... they're beginning to create new laws, erm because of that gun issue. You know Japan seems a very... they call it pacifist society, they don't war, they don't want to get involved in anything that has got to do with harm, you know so eh, they are trying to create new laws around in 3D-Printing eh, to limit what people can do with it because they are beginning to get worried if it's so easy... from what we've read online, what... some of the YouTube videos we've seen online... they've made it look as if it's so easy to produce guns, and, and stuff like that you know, and so Japan is beginning to, to worry and to create new laws. Do you think that's something other parts of the world should be doing?

P2 – Well, yea, you... is always good to direct people to eh, a proper... to a nice... to a good direction because like... to orientate them...

***I* –** Yea... (laughs)...

P2 – Towards positive, not towards negative...

***I* –** Negative...

P2 – But I think it's the nature of the people that if you don't have it in Japan, you gonna have it in America. But still, I don't know how much... how this is feasible like the 3D-Printed guns...

***I* –** (Laughs)

P2 – Because I can tell you, this... this plastic, it melts at 240ºC and when you have something like a bullet inside...

***I* –** Right...

P2 – So then, this temperature... it exceeds this temperature so that means that ...

***I* –** It would melt...

P2 – Would melt... should melt. So, I don't really know that this... this...

***I* –** Is possible at the moment.

P2 – Yea...

***I* –** So, 10 years from now, 20 years from now? Do you think? Well with the metal 3D printing thing coming up... what, what's... cos even if, if, if you are able to use metal to print so much stuff, cos I heard that's where the technology is moving towards right now... you know printing in metals and stuff like that. Do you see that happening first all? That we could print everyday objects in metal, and then if we are able to print everyday objects in metal, is it possible that guns would be an issue an at that time?

P2 – Yea, is possible but... and, I, I don't know if you know there is already, I think that it's the university of Birmingham that they const... they construct... they constructed a device that can ah, I... that can recognise 3D-Printed guns in ah...

***I* –** Lovely, I'll just write that down...

P2 – Yea...

***I* –** Cos that's interesting.

P2 – This is something that they were, they were an experiment with this device, I don't know if you know you have it as a finished product right now, but for sure they... because it's always like that, you have the bad, but you have also the good, and it's the same with the technology. There are people that they're gonna invent the bad, but there are also the people that gonna invent something that is gonna ah... is going to balance that.

***I* –** Yea...

P2 – Unfortunately! ____ **inaudible** 08:39

***I* –** Yea, that's true... erm, good... so, now that...

P2 – Is like, yea you have the virus... like you have, you have hackers, but you have also the strong ah, anti **–** virus and whatever... security... so both are evolving...

***I* –** Right, so good... so, you, you brought an interesting one... the way the anti-viruses are.... antiviruses for the computers, and other people are creating... you know people keep creating viruses and anti-viruses, it's unfortunate but that's the way the world is. So there will always be people who try to do negative things with technology.

P2 – Yep

***I* –** Will there be any way to minimise? I mean... it's going to become very difficult to limit... to stop them, it's going to become very difficult to stop them, but do you think there will... it's possible to … you know, add something to the technology? Or add something to the law's or you know… is there something we can do to at least minimise how fast you can do these things? So, you think there's anything we can do or anything anybody can do?

P2 – I don't know like... I want people to be free and create whatever they like. Is like, you know is like, is like when you... is like silk road, you know? Silk road gave freedom to people. You can find eh, like, okay many bad things and many, many things, but you know...

***I* –** (Laughs)...That freedom gives you...

P2 – And some, some people believe that the owner of Silk Road is the biggest criminal on the earth. Some people believe also that he gave the true freedom to people. So, to me I would like too... people to be free to create whatever they want.

***I* –** Cool. Cool. Sorry, I'm just... I don't want to forget some of these things so I'm just giving some small... bit of notes here and there. Erm, so erm...

P2 – But eh, you can... like... am worrying too... it's better not to ban things... you know, it's better to motivate people towards the direction... because this does really make sense and don't, don't say to people you can't do that! Because with this kind of attitude, people will do that. It's like you know, its action/reaction sometimes.

***I* –** Yea... if you try to suppress them, they... people will be getting to...

P2 – Yea... I believe in motivating instead of suppressing. So, you will try to eh, to push them to cultivate and improve towards something positive without mentioning the negative... because if you mention and if you, if you stand on the negative, then this is gonna attract attention to some, some, you know like to a group of people you'd say.

***I* –** Yea, that's true. There'll always be people who would always try to fight against you know whatever it is.

P2 – Eh... seriously, me as a person I don't like somebody to tell me not to do...

***I* –** Not to do this (laughs)...

P2 – to do that...

***I* –** Yea, I get that point, I get that. Yea, it's true... erm, all right, so that brings me to this issue now about erm, the consequences... do you, do you sometimes... erm... well from your work so far, or from your involvement in the industry, what ethical issues do you think may come up?

P2 – So I... my biggest ethical issue is that ah, am printing so much plastic and that… eh also am throwing so much plastic which I don't know... like one of my issue was that the filament... the... you couldn't... you couldn't manufacture eh... recycle... recycle with filaments...

***I* –** So environmental problems, right?

P2 – Yea...

***I* –** Cool...

P2 – Well, my biggest issue was like eh, envi... environmental issues.

***I* –** Cool

P2 – I don't care about the copyright of the design... I don't care about that. My biggest issue is the things that we are doing like... while we are prototyping.

***I* –** Yea, because that's one of the argument's people say that in 3D-Printing is environmentally safe and all that stuff, but if you're printing plastic, see, it becomes a problem isn't it?

P2 – It is.

***I* –** I like that...

P2 – And like, they say okay eh, PLA is biodegradable, okay, a plastic bag can be biodegradable, but it needs 100 years to melt... what does this mean? It doesn't make sense.

***I* –** (Laughs)

P2 – But, however, I can tell you that we have just received eh, a series of filaments that they can come from recyclable eh, PLA and they manage to do that... some people manage to do that. But what I don't like, is that first you have this... you know this bomb with the… in 3D-Printing, you print, you print, you print plastic, and then okay ah, now I remember that I have to recycle it.... okay, I'll do it.

***I* –** Yea... yea, and that's, that's, that's the thing about technology you see... and I was given example of what's happened in nanotechnology, you know... erm, where they use these little... tiny particles, erm turns out the technology is supposed to be very useful to us... they've used it to you know create walls that erm... paints... when a particular type of paint... you... it cannot get... you can't have dirt on the paint on the... on your wall. It's impossible to have dirt, it's impossible to germs... eh bacteria... it's impossible, it kills the bacteria immediately. But then the problems is, 10 years later, if I'm breathing from it... if am inhaling, you know the stuff coming from that wall, how does it affect my health, you know? And so some of the technology that people bring out it's, it's... the problem is they don't think about what's going to happen 10, 20 years from now and that's why we are trying to look at this issue of in 3D-Printing and how it affects, you know, humanity generally, it's not just one particular issue but generally, you know. Yea, so you've... I, I like the fact that you've mentioned the environmental issues...

P2 – No I believe in the future, in the future you could never eh, you know like evolve something without being sustainable. I would, I, I believe that we gonna reach that point that if, if... you can like... you can suggest only this innovation... but you have, on parallel develop something sustainable for what you have invented. Like I believe it's going to be like parallel.

***I* –** Yea...

P2 – I think this is what the government should legislate...

***I* –** Okay, okay, please just eh, say that again... what the government should be legislating should be on how to develop ...

P2 – Basically, if you, if you develop an innovation, you need to develop also something that would make that sustainable as an idea for the environment. This is what eh, this is what government should legislate basically.

***I* –** Cool...

P2 – And for example, you have, you have... let's say you have a factory that produces those eh, 100 Tonnes of eh.... yea Carbon on your site, then, then you need to have also you know the eh, a specific amount of forest in order to balance that, you know? Something like that

***I* –** If you cut the trees down, you have to plant another tree

P2 – Yes...

***I* –** Right. I like that... cool

P2 – You destroy something, you create something else...

***I* –** So, so with the… in 3D-Printing, we could create laws that say, well, you don't just... if you're going to use plastic, you have to use plastic that probably is biodegradable, or...

P2 – Recyclable...

***I* –** Recyclable, recyclable at least...

P2 – At least recyclable

***I* –** Even if not biodegradable .... yea... Even if not biodegradable... at least recyclable... thank you. All right so, let’s look at another issue, erm... good... so that basically, that answers the question about how you think we could encourage responsibility instead of creating laws, we could just erm... okay, so.... yea, because we… the next question would have been, how should we encourage responsibility you know, in, in... besides, besides the laws, besides creating say a law say to encourage people to be environmental... more environmentally friendly, do you think there is any other way we could at least encourage responsibility? At least, at least responsibility... that is people should be responsible.

P2 – Hmm... what else is… should Is say... well except… go... ah, from... they are recycling the filament, and also... I don't know...

***I* – All** right that's fine, that's fine... that's fine... that's fair enough... eh, recycling the filaments... cool...so yea I think that's about it for...

P2 – Yea, I think the most realistic is just to start at least from recycling...

***I* –** Okay... cool... erm, so you don't really see the intellectual property as a big issue? And you don't see the health issues?

P2 – Yea...

***I* –** We've not talked about that, have we?

P2 – No, no, no...we haven't

***I* – All** right, let's talk about health issues....

P2 – The health issues, yea... like eh, you know I... if you print with ABS the fumes are some substances are 100% cancerous

***I* –** Hmmm!

P2 – (Laughs) It's like there is no doubt about that...

***I* –** Wow... I didn't even know that really...

P2 – Yea, well... you have some machines that they, they, they have a filter to filter these substances... but again like, we are experiments... even PLA we don't know what these fumes can cause and... but eh, what I can really say is that, I've concerning like... so to have many processes of in 3D-Printing, so for FDM, ABS, the fumes of ABS are cancerous. For resin, if you inhale resins, resin is toxic. It's toxic for your lungs. Ah, for SLS process, the powder... the powder, this powder can go very deep inside your pores, it go inside your lungs, and also, eh, is... and also is very flammable in high, you know... in high concentration if I can say that. So ...

***I* –** I like the fact that you are raising all these issues because these are things, a lot of them I have even thought about them...

P2 – Yea like, to be honest, I I had like a job offer to, to move from FDM printing to SLS printing and I didn't do it because...

***I* –** Your health first, right?

P2 – Yes... because I have, I have to sacrifice my lungs and there was a 2 years commitment contract, and I said to them, how... because you live your phone there, and then after 3 minutes you are touching the phone and it has a layer of dust and this is everywhere... like everywhere. And, I, I ask them like, how, how many of these would I have inside my lungs after 2 years? And he said to me, if you pose it this way, I can't tell you something. But, no like... and I try, I try to search that on the internet and they don't say something, they say... some respiratory problems.... but no men, this is... would, would fill every single particle of your lungs... it's so small, it's like 10 times smaller than your pores... And yea, then there... you have eh... these are the 3 processes that I know that you know that, you know.... at least you need to learn...

***I* –** Yea... cool... now that brings me to another question, you know the RepRap erm... I, I have an interview with the guy who designed the thing... that's on the 6th like I said to you earlier erm, do you think there any issues with one, because I'd like to ask him particularly about those... the rep... you know the RepRap machine right?

P2 – Yea, that, that can print itself, but...

***I* –** Yea, the self **–** replicating machine...

P2 – Yea...

***I* –** Good... do you have... do you think there are any issues with that one? So that when I see him I can specifically ask him about that one....

P2 – No these are not the real issues... my issue is that you have 2 big companies on additive manufacturing that they hold... that they were holding the patents. And ah, this whole revolution about he in 3D-Printing is because after 30 or 20 years, the, the patent set free... my question is why this company should hold that all these years... and why this didn't happen before? And because... and now is you know, is the property of something, but if something can really helps...

***I* –** Speed up the process right?

P2 – Speed up the process of evolving something and make it better, why you have to keep it on these closed bound, boundaries of the... of the companies?

***I* –** That's an important one actually, cos I would... I'd speak to him about that one particularly.

P2 – Yea, like again, yea, of course, it's their copyright...

***I* –** What I've noticed about him particularly is, his technology, all of his technology... or most of his technology are open source... that's the RepRap guy. Yea, he doesn't see any reason why you stifle... stifle development. He just creates his technology and he puts it out there and says, you know...

***P2* –** No like am... I like his ethics. His ethics were… they're wide, open source... these are the pure ethics, ethics of in 3D-Printing... but you know, then... now, I see companies that they try to create something else... for example like want.... you know because they are looking for am, long term customers.... they want to be with them and spend on them, like they want devotion, that's what they... what... that's what the...

***I* –** Like when you buy the 2D **–** printer and then you keep going back to buy the, the ink (Laughs) isn't that...i that's not right, right?

P2 – Is basically this one like... is... what you have on the, on the 2D **–** Printers and now you gonna have it on the 3D-Printers basically, like you have a machine that doesn't cost that much, but then if you want to print with materials, you have to pay... but... and also you need to, you need to use specifically the raw materials... specifically the round slicer, and this is not true because it works, I can see like I have so many closed sourced machines but, I can tell you, all of them are working with 3rd party filaments and this is a huge lie...

***I* –** Cool...

P2 – Of course, I'm not telling that to the customers but, okay....

***I* – All** right, thank you so much. I am grateful. I think we can actually just stop here for today...

P2 – Okay...