Creating and Capturing Sustainable Value for Additive Manufacturing

WEN LIU

DOWNING COLLEGE

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Declaration

This thesis is the result of my own work and includes nothing which is the outcome of work done in collaboration except as declared in the Preface and specified in the text. It is not substantially the same as any that I have submitted or is being concurrently submitted for a degree or diploma or other qualification at the University of Cambridge or any other University or similar institution except as declared in the Preface and specified in the text. I further state that no substantial part of my thesis has already been submitted, or, is being concurrently submitted for any such degree, diploma or other qualification at the University of Cambridge or any other University or similar institution except as declared in the Preface and specified in the text.

It does not exceed the prescribed word limit for the Degree Committee of the Engineering, as it has been submitted with words 64604 (including tables, footnotes and appendices, but excluding the bibliography). This thesis contains 33 figures and 51 tables.

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Abstract

This research has explored the business model and sustainable value in the context of *additive manufacturing* (AM). In terms of the sustainable value of AM business models, it indicates that the AM business models not only generate monetary revenue through selling machines, materials, and other products but also create value for the environment and society via using environmental-friendly materials, recycling, reusing, achieving resource efficiency and improving social wellbeing. However, sustainable value is surprisingly overlooked in incumbent AM companies, and the profitable business models are yet to be identified. The research revealed that AM companies typically still set a one-dimensional profit maximization goal without considering the consequences for the broader social and ecological contexts. Most AM companies do not know how to maximize the sustainable value of AM technologies through business model innovation which creates a significant knowledge gap for the industry.

The research seeks to address the central question: how can AM companies develop business models to create and capture sustainable value? The purpose of this research is to help AM companies identify opportunities to create and capture sustainable value outcomes. One objective of the research is to contribute to knowledge about business models and sustainability concepts. Another objective is to contribute to practice and offer the frameworks that can facilitate strategic planning and sustainable business model development. The research adopts a qualitative approach and involves six case studies and two focus groups, representing seven sectors and companies from three countries with 43 participants in total at the exploratory stage and descriptive stage, respectively. The research has generated empirical insights,

theoretical models and practical frameworks that help AM scholars and practitioners better understand AM business models as well as create and capture sustainable value. The research has filled the literature gap and met the industrial need and made contributions to both academic knowledge and industrial practice.

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Paper Publications

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Chapter 1 Introduction

1.1 Research Background

Additive manufacturing (AM), also known as 3D printing, has evolved and blossomed into different additive processes since its inception in the mid-1980s. Significant technology progress has been made since then. Different to traditional machining process of subtracting materials, AM systems draw on computer-aided design models to create 3D objects by adding successive layers of the materials (Oettmeier, K., & Hofmann, E., 2017). ASTM (2012) has classified different AM processes into seven categories respectively: materials extrusion, powder bed fusion, vat photopolymerization, material jetting, binder jetting, sheet lamination, and directed energy deposition (ASTM, 2012). In parallel to the technology development, a significant market trend is the increasing demands of mass-customization, low-volume and individualized products (Oettmeier, K., & Hofmann, E., 2017). The industrial applications of AM technologies have been gradually shifting from rapid prototyping and product customization towards direct production that scales in volume, size, and availability. The development and commercialization of AM processes have made significant progress and obtained a variety of practical applications in different industries.

AM presents significant potentials to enable companies to develop new methods of creating objects and better deal with global manufacturing challenges. There is an expectation that AM technologies have the potential to revolutionize much of the manufacturing industry, and the advantages over traditional manufacturing (e.g., milling, casting, injection molding) have captivated the imagination of the public. It is commonly noted that AM’s impact is so significant that it is referred to as a paradigm shift in manufacturing that brings numerous social, economic and environmental benefits (Huang et al., 2013). However, to achieve broad adoption for AM technologies, some limitations and challenges including prohibitive costs of machines and production, narrow product range, low part strength, few material choices, size limitation, low printing speed, and low surface precision need to be overcome;

particularly the market demands for 3D printed objects remain weak and uncertain (Liu and Rong, 2015). Many researchers have been working on these improvements in AM processes for decades (Huang et al., 2013). Mainly, how companies can implement AM technologies to support innovation, to gain competitiveness and to improve sustainability performance are commonly recognized as worthy of researching (Petrovic et al., 2011).

Separately, the business model has attracted much attention from both academics and practitioners (Zott et al., 2011). Business model innovation is widely recognized as a critical enabler for companies gaining competitiveness and sustainability performance (Boons and Lüdeke-Freund, 2013). Research has shown that business model innovation helps firms create and capture value. However, the purpose of the traditional business model is to seek short term and revenue-oriented value, which fails in achieving sustainability. Notably, sustainable business models intentionally go beyond this to deliver economic value and simultaneously create the environment and social value. Sustainable business models have been shown to enable the company to gain a competitive advantage and make positive contributions to the environment and society (Boons and Lüdeke-Freund, 2013). However, the way of achieving sustainability through business model innovation in practice is inadequately addressed in the literature (Boons & Lüdeke-Freund, 2013). More in-depth research is needed on whether strong new business models can help create positive effects for the environment and society (Boons & Lüdeke-Freund, 2013; Hansen, Große-Dunker, & Reichwald, 2009; Schaltegger et al., 2012; Stubbs & Cocklin, 2008). This chapter introduces the research background by revealing the academic gap and industry needs. The motivation of this research is to bridge the knowledge gap. The research structure is also outlined.

1.2 Problem Statement

Much work has been carried out to make significant advances on the technical side of AM technologies; however, the research on AM business models and AM management studies is nascent, and the literature regarding these issues are relatively limited (Mojtaba and Fabio, 2016). The AM industry, however, is still at an early stage of formation and profitable business models are yet to be identified and developed (Liu and Rong, 2015). The AM companies may not fully understand how to maximize value and whether AM is environmentally or socially beneficial. *'AM companies*' refer to the companies, including all size business entities that focus on the development and use of AM technologies, processes, services, and set AM products/services as their core businesses. This creates a significant knowledge gap for industry because of the lack of studies on how to maximize the sustainable value of AM technologies through business model innovation.

Equally, the sustainability performance of AM has often attracted positive writing in the grey literature, which emphasizes the reduction in raw materials needed, and the reduction in distance travelled when using AM. However, whether AM always generates a positive impact on environmental sustainability, has only limited research focus to date (Ford and Despeisse, 2016). No firm conclusion has yet been made that AM is more energy-efficient or environmentally friendly than subtractive manufacturing processes overall (Huang et al., 2013). The implications of AM on resource use and materials toxicity remain unclear even though the process itself is material efficient. From a social perspective, potential health hazards might be generated in the process of dealing with printed and unprinted materials. Research into the social and environmental implications of AM technologies is still in its earliest stage (Ford and Despeisse, 2016; Huang et al., 2013).

In terms of the sustainable value of AM business model, it indicates that it not only generates monetary revenue through selling AM machines, AM materials, products or services, but also creates value for the environment and society via using environmental-friendly materials, recycling, reusing, achieving resource efficiency and improving social wellbeing. However, the way of achieving sustainable value for AM companies are poorly addressed in the existing literature. As a result, profitable AM business models for sustainability have yet to be constructed (Liu and Rong, 2015). Conventional AM business models need to be adapted and extended to incorporate sustainability concepts. There is, therefore, a gap in our knowledge about how the AM business models create and capture sustainable value. This study aims to narrow the gap between theory and practice and improve the understanding of this field.

1.3 Research Aims and Objectives

The research intends to draw insights from empirical evidence to contribute to knowledge that can be applied to practice. The research aims to make theoretical and practical contributions to the concepts of the business model and sustainable business model in the context of AM and fill the knowledge gap between theory and practice. The overall research objectives are to understand better how AM companies can improve their business models to create and capture sustainable value.

Notably, the research objectives (RO) are to gain the theoretical and empirical perspectives of:
Research objective 1: to develop a better understanding of AM sustainability, particularly in the environment and society perspectives;
Research objective 2: to analyze AM business models, identify failed value exchanges and uncover value opportunities;
Research objective 3: to develop frameworks that enable AM companies to develop sustainable business models.

The research aims and objectives help determine the main research question that is proposed:

RQ: How can AM companies develop business models to create and capture sustainable value?

1.4 Thesis Structure

This thesis is comprised of eight chapters, and the detailed schematic of the thesis structure is shown in Figure 1.1. The figure presents the objectives and outcomes to achieve for each chapter. This is somewhat iterative than a linear, involving the redesigning, rethinking and revision of the research process.

Chapter 1 introduces the research background, the identified research problems, the research aims, and objectives. The main research question is proposed based on the research aims. The overview of the research is presented along with the illustration of the thesis structure.

Chapter 2 reviews the relevant literature and addresses the knowledge gap. The research questions are confirmed and validated. This chapter prioritizes the types of literature pertinent to review and presents the literature framework. This chapter examines three bodies of literature and identifies the critical concepts for this research. The key concepts are structured into three analysis processes. It also proposes a conceptual framework as the theoretical foundation to help analyze data and answer research questions.

Chapter 3 comprehensively articulates the research strategy and research design. The chapter also describes the taxonomy of different methodological approaches, identifies appropriate research methods, justifies the research strategy, and discusses the data analysis and collection techniques.

Chapter 4 presents each case at the exploratory stage, illustrates the analysis and initial findings of each case study. It provides empirical evidence for the research.

Chapter 5 presents each case at the descriptive stage, illustrates the analysis and findings of each case study. The chapter aims to reject, shape and confirm the high-level themes and look across the case studies for patterns.

Chapter 6 presents an in-depth analysis and synthesis across all the case studies and the findings and patterns that emerge. The models and frameworks are developed and synthesized based on the results.

Chapter 7 discusses the findings concerning the models and frameworks in relation to existing literature. It also presents the limitations of the research.

Chapter 8 provides an overview of the research and demonstrates that the research questions have been addressed. This chapter identifies theoretical and practical contributions. It also presents opportunities for future work.

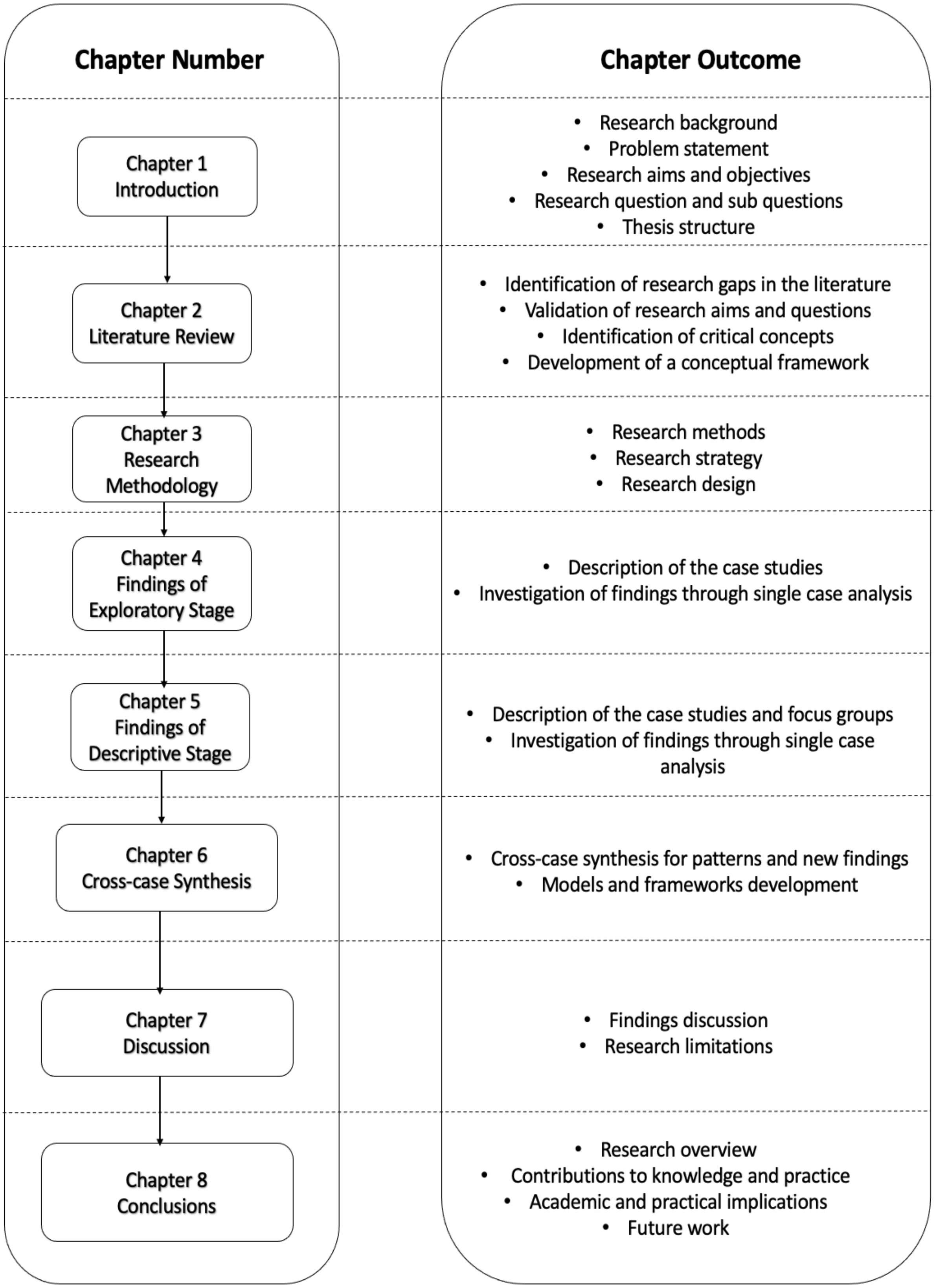

Figure 1.1: Thesis structure (Author generated)

Chapter 2 Literature Review

This chapter is presented to identify the research gap, confirm the research questions, and illustrate the process of reviewing the relevant literature in detail. This chapter also prioritizes the types of literature pertinent to review, present the literature framework and illustrates the knowledge gap in the existing literature. Initially, the literature framework is proposed, and research questions are confirmed.

This research explores three fields of literature shown in Figure 2.1: a) AM technologies, b) sustainability and c) business model. The three research fields were chosen because they are the most relevant to the research question: *how can AM companies develop business models to create and capture sustainable value?* The three fields of literature generate three knowledge intersections, namely: AM business model, AM sustainability, and sustainable business model.

Given that there is limited established body of literature on sustainable AM business models, the chapter provides a detailed account of the general business model and sustainability literature, and overviews of other relevant fields of literature. This chapter mainly conducts the review of the relevant literature on the intersecting fields.

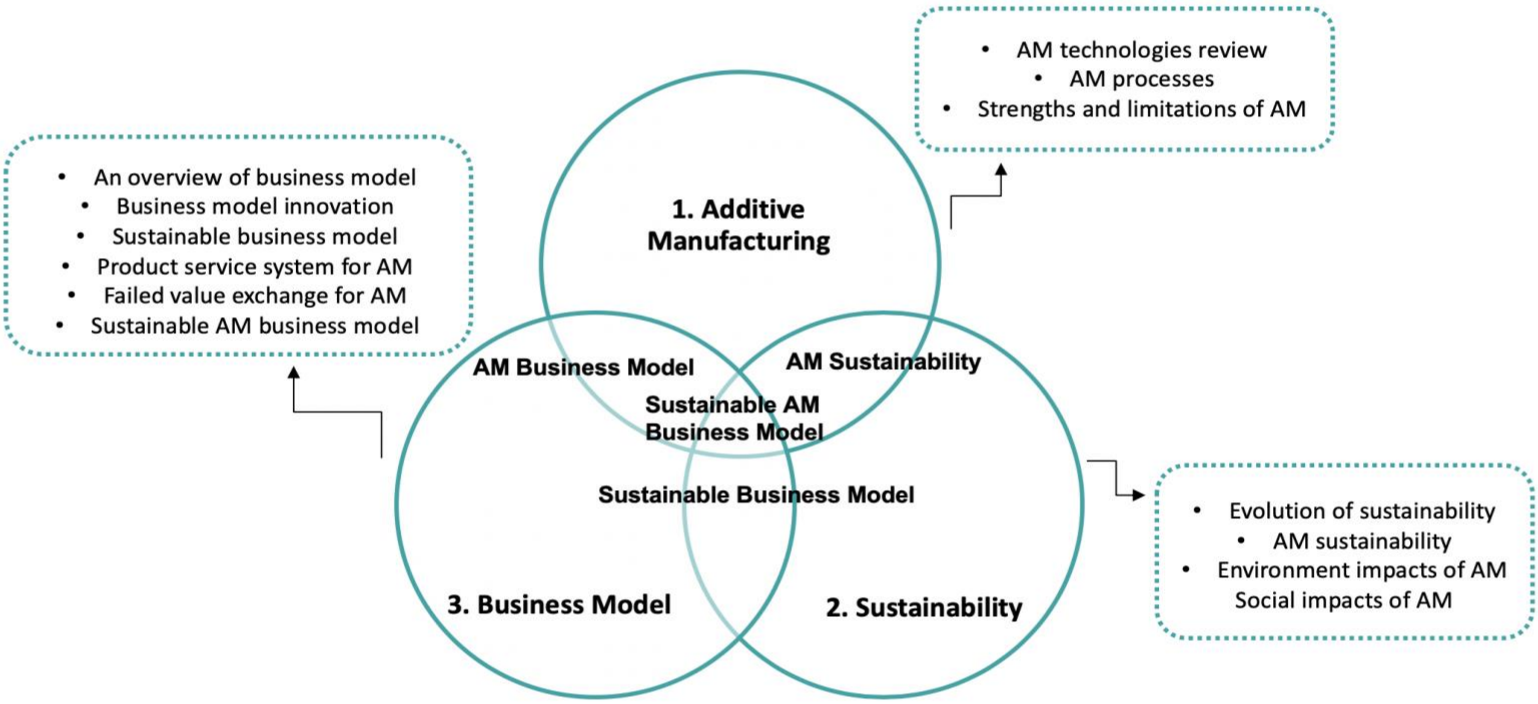

Figure 2.1: Mapping the literature review fields (Author generated)

2.1 How the Relevant Literature was Reviewed

The author conducted a systematic database search and pursued cross-reference snowballing technique, following the process shown in Figure 2.2. First, a structured literature search was conducted in the overlaps of additive manufacturing, sustainability and business model literature. This was done by searching the Topic/Titles, Abstracts and Keywords respectively. The author developed the search terms including “additive manufacturing” AND “sustainability”, “additive manufacturing” AND “business model”, “sustainable business model”, “additive manufacturing” AND “sustainable business model”, “additive manufacturing” AND “business model*” AND “sustainab*”. The terms were used to search for publications by relevance in English on the Thomson Reuters Web-of-Science, Elsevier Scopus and ScienceDirect databases. Some other terms including “sustainable value creation”, “value uncaptured” and “product-service systems”, were searched and used to complement the research topic. Table 2.1 displays the numbers of results that were generated from the initial research. It could be argued that the research in the field of sustainable business model is quite abundant and robust. But the research areas in the knowledge intersections of AM business models and AM sustainability are limited by comparison. It should be noted that there are very few publications of sustainable AM business models which lie in the overlap area of the three fields of literature (See Figure 2.1).

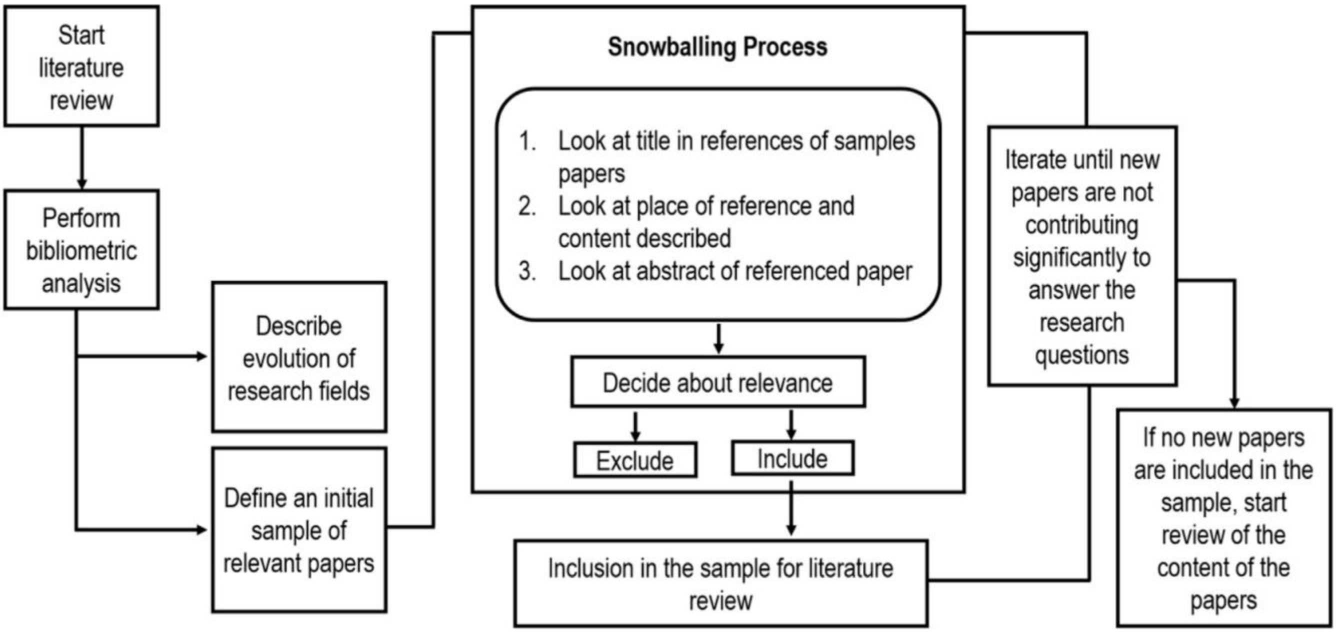

Figure 2.2: Literature review process (Geissdoerfer et al., 2017b)

The abstracts of the identified publications were scanned to define the initial sample of relevant articles based on the inclusion and exclusion criteria. The selection criteria encompass the degree of relevance to the research scope, the research influence and the novelty of research ideas. Notably, if the papers related to the AM business models, AM sustainability or other AM business models for sustainability, the papers were included; otherwise, the papers were excluded. Thus, the author determined 50 papers that were selected as the sample of relevant papers to be used as the start point for the snowballing process. Then the titles in the reference section and cited contents of the sample papers were scanned and filtered to decide the relevant cross-references. The additional publications were then identified, and the abstracts of referenced papers were scanned to determine whether the articles were relevant or not. The author screened out overlapping and irrelevant results.

Additional related references were included in the sample and again scanned for cross-references based on the correlation to the research question, the novelty of the research ideas, the impact and rigor of the studies. The process was iterated until we find no new papers relevant to the research. Thus, the sample was confirmed, and the content of the selected papers was reviewed for this research.

Table 2.1: Results of systematic literature review

Search Terms	**Total Number of Results**		
Topic/Title, Abstract, Keywords	**Web of Science**	**Scopus**	**ScienceDirect**
"sustainable business model"	291	692	2352
"additive manufacturing" AND "sustainability"	226	267	316
"additive manufacturing" AND "business model"	20	79	31
"additive manufacturing" AND "sustainable business model"	14	1	10
"additive manufacturing" AND "business model*" AND "sustainab*"	15	23	10

Furthermore, the author examined the full contents of the selected papers published by highly cited journals and academics. The relevant publications were extracted and synthesized to address the research issues based on the similarity of the research propositions. The key findings and contributions of literature were compared, evaluated and interpreted to address the research questions. The author concentrated on peer-reviewed journal papers in English to guarantee the quality of literature. Some of the peer-reviewed resources and critical journals most frequently monitored including *International Journal of Additive Manufacturing Technology, International Journal of Production Research, Journal of Cleaner Production, Technological Forecasting & Social Change, Business Strategy and the Environment, and Academy of Management*.

It should be noted that some influential reports and articles were also reviewed from sources such as technical reports, corporate annual reports, newspapers and government reports to select the most relevant ones using the same snowballing criteria to enlarge the "snowball". The author was critical in the review of all publications (peer-reviewed and not). However, the snowballing method may be biased due to the author's personal research preference and selection criteria for filtering papers. Therefore, the author continually reviewed the latest publications, following up relevant papers and key conferences, discussing the work frequently with other researchers to mitigate the partiality of the body of literature and ensure the comprehensiveness of the literature review. This chapter grounds the research in the literature to identify the key fields of knowledge that help investigate the research problem and confirm the presence of a gap in knowledge.

2.2 Additive Manufacturing Review

This section reviews the latest literature in the field of AM technologies, with the discussion of the AM processes, the strengths and weaknesses. The landscape of AM processes and the main findings in these research fields are then explored. This section does not include the intersections with business model and sustainability, which will be presented later, shown in Figure 2.1.

Additive manufacturing (AM), also known as 3D printing, has evolved and blossomed into different additive processes since its inception in the mid-1980s. Significant technical progress has been made since then. According to the American Society for Testing and Materials (ASTM) standard, it defines AM as the "*process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining*" (ASTM, 2012). AM process is quite different from the conventional manufacturing processes, e.g. casting, milling, forming, and machining. AM can print out physical and solid 3D objects layer-by-layer using powders, liquids or filaments as raw materials (ASTM, 2012). Plastic, ceramics, polymer, metal, and a mixture of alloys or even sugar and chocolate can also be used as the base materials to print 3D end-use parts (Diegel et al., 2010). AM can transform the design in the form of a 3D robust model to a finished product without using additional fixtures and cutting tools.

Furthermore, AM can make use of raw materials to produce minimal waste and generate satisfactory geometric accuracy (Diegel et al., 2010). AM may bring about a paradigm shift to manufacturing for design and embrace more market opportunities and industrial applications (Huang et al., 2015). The author has classified all the AM's synonyms from the literature including rapid manufacturing, freeform fabrication, solid freeform fabrication, direct digital manufacturing, additive layer manufacturing, additive fabrication, additive processes, additive techniques.

2.2.1 The AM Processes

AM has emerged as a flexible and powerful technique in advanced manufacturing industry (Shahrubudin et al., 2019). Unlike traditional machining process of subtracting materials from a large stock of sheet metal (e.g. milling, casting, molding, or drilling), general AM processes begin with a computer-aided design (CAD) model or a scan of an existing artefact. The 3D model will be subsequently converted into a readable STL format. The STL (Standard Tessellation Language) file format is a standard for the AM and was first created by 3D Systems company in 1987. The software slices the CAD model into cross-sectional layers, and then the digital file is sent to the printer for manufacturing. Next, the printing machine is set up, and the build parameters are prepared appropriately (Baumers et al., 2016). The AM machine then creates 3D objects automatically by adding successive ultrathin layers of materials until the final object finishes without necessary supervision (Gibson et al., 2010). In the following steps, the printed parts need to be removed from the machine and cleaned up in the post-processing to meet the surface standard (Gibson et al., 2010). However, Gibson et al. (2010) take the build failure into account where a situation that the printing process needs to start all over again due to the process discontinues and failure. The generalized steps of AM are illustrated in Figure 2.3 showing the process of creating a 3D object using AM.

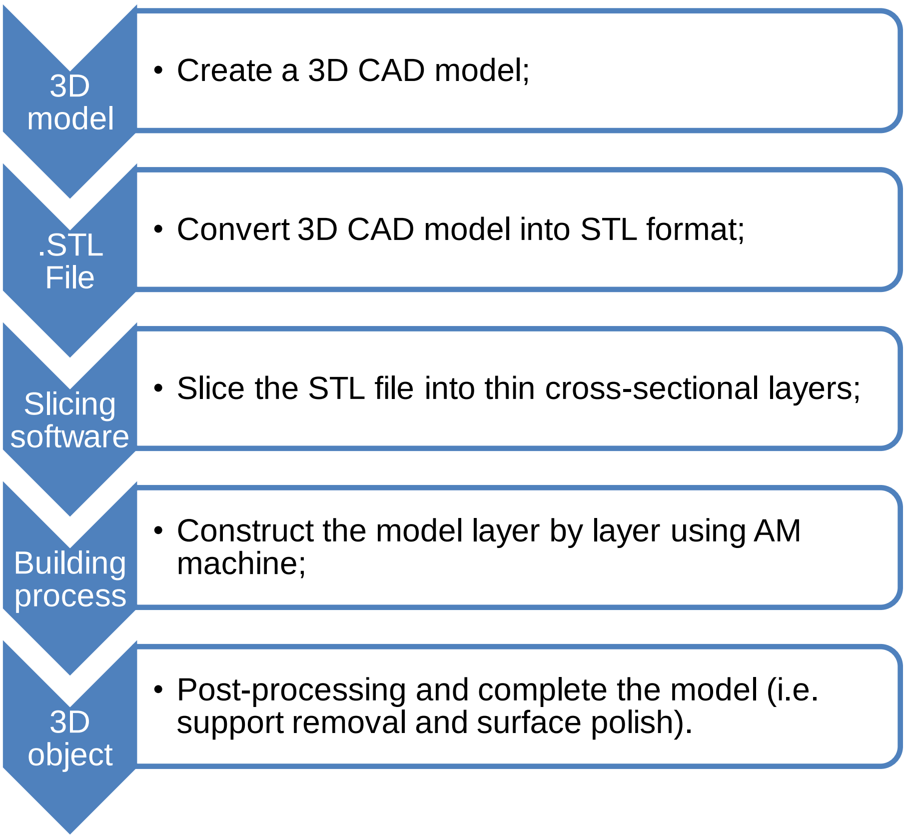

Figure 2.3: Generalized AM process (modified from Costabile et al., 2017)

There are different AM classification standards since its emergence in the 1980s (Weller et al., 2015). Essentially, different AM processes construct and consolidate raw materials layer upon layer in different ways (ASTM, 2012). For instance, some processes use electron beams to melt filaments; some processes use laser beams to sinter or melt plastic and metal powders to produce layers. While, other processes use inkjet printing heads to accurately spray binder onto polymer or ceramic to build physical objects (Jeroen and Erik, 2013). Based on the materials characteristics and raw material states, AM processes are classified into four categories: 1) liquid; 2) filament; 3) powder and 4) solid sheet (Kruth J P et al., 1998). Notably, ASTM has updated an extensive list of AM standard categories. The AM processes are classified into seven categories including *materials extrusion, powder bed fusion, vat photopolymerization, material jetting, binder jetting, sheet lamination, and directed energy deposition* (ASTM, 2012). These seven categories have been widely recognized and adopted. The terminology of each AM category is described, shown in Table 2.2.

Upon these seven categories, the author further explored the characteristics of AM processes for each category and comprehensively reviewed the principles of AM processes from the perspectives of printing materials, power sources, implementation challenges/downsides, applications, strength and opportunities. Table 2.3 shows the characteristics and principles of AM processes for each category. There is an expectation that AM technologies have the potential to revolutionize the manufacturing industry. The superior advantages over traditional manufacturing have captivated the imagination of the public which reflected in the mainstream publication: the April 2012 issue of the *Economist* that quote AM as "*the third industrial revolution*". The ongoing research mainly focuses on the various AM processing technologies; however, quite limited research covers the AM management, operational and strategic dimensions. J. Savolainen and M. Collan (2020) emphasize that AM remains a complementing manufacturing technology and the economic value of AM is still based on the conceptual studies.

Table 2.2: The definitions of each AM process (Author generated)

AM Process	Definition
VAT photopolymerization	It is a process that a liquid photopolymer (i.e. photosensitive resin) or a radiation-curable resin as the primary material in a vat is selectively cured by a UV light (Gibson et al., 2010). Notably, 3D System company developed the first commercial AM technology using stereolithography (SLA) method, which is the first vat photopolymerization process (Hull, 2012). Due to it relies on photopolymerization, this technology is inherently limited to photopolymer. Stereolithography is generally one of the most accurate AM processes with the excellent surface finish.
Directed energy deposition	This technology process uses laser and electron beam as the directed energy sources to fuse materials usually metal powders layer upon layer as the materials are being deposited (Gibson et al., 2010). Multiple-materials can be deposited simultaneously, making functionally graded parts possible.
Powder bed fusion	It is a process that uses a laser or electron beam to fuse and melt material powder in the selective regions of a powder bed. Metal and polymer powders can be used as the primary materials in the powder bed fusion process. However, there are some potentially significant problems during the thermal process for materials build-up such as warping, heat-induced distortion, and stresses (N. Guo and Ming C. Leu, 2013) Selective laser sintering (SLS), selective laser melting (SLM), direct metal laser sintering (DMLS), and electron beam melting (EBM) are prevalent powder bed fusion processes.
Material extrusion	Fused deposition modelling (FDM) is a well-adopted extrusion-based technology that was initially invented by Stratasys company in 1989 (N. Guo and Ming C. Leu, 2013). This technology process builds up materials layer upon layer by extruding molten thermoplastic onto a substrate through a nozzle.
Material jetting	This technique uses inkjet-printing heads to deposit wax or polymer droplets onto a substrate while the layers are constructed on the top of each other (ASTM, 2012). The materials are cured by UV light, and multi-nozzle print heads are applied to increase the speed. It is also possible to print two different materials simultaneously with excellent structure and surface accuracy.
Binder jetting	This process is to selectively deposit a liquid bonding agent onto a bed of powder through inkjet printing head nozzles to join powder materials. The binder plays a significant role in adhesively gluing each powder layer together. In this AM process, printed objects consist of bound powder, and require infiltration to have sufficient strength during post-processing. A variety of materials can be processed using this technology, such as metal, ceramic, and polymer.
Sheet lamination	Laminated object manufacturing (LOM) and ultrasonic additive manufacturing (UAM) are typical sheet lamination processes. The process is a rapid prototyping system that the layers of adhesive-coated paper, plastic and metal laminates are bonded together to form an object (ASTM, 2012). The dimensional accuracy is less than stereolithography and selective laser sintering. The stair-step effect needs to be minimized after the processes.

In general, AM technologies have been rapidly developed over three decades. The number of literature articles on the exploration of AM technologies is abundant. While the research on AM business model and management studies are nascent and the literature regarding these issues are relatively limited. While it could be argued that the research on AM management is increasing and receives significant attention. For instance, Holzmann et al. (2019) demonstrate the relationship between business model and AM technology with the identification of two business model patterns. This confirms that the empirical study on the business models of AM manufacturers is quite scarce. Mojtaba and Fabio (2016) explore the structure of the AM research domains in the scope of management, business and economics. Eight research streams are characterized as the common themes, which include technology selection, supply chain, product design, production cost models, environmental aspects, strategic challenges, manufacturing systems, open-source innovation, business models and AM economics (Mojtaba and Fabio, 2016). It should be noted that the research streams are not consolidated, and more efforts are required to offer reliable insights into building theoretical and practical foundations in these management perspectives.

Table 2.3: Characteristics and principles of AM processes for each category (adapted from Nannan Guo and Ming C. Leu, 2013, Gao et al., 2015; ASTM, 2012; Gibson et al., 2010)

Categories	Processes	Printing Materials	Power Sources	Implementation Challenges/Downsides	Strengthes/Opportunities	Applications
Vat photopolymerization	Stereolithography; Digital light processing (DLP); Masked stereolithography (MSLA)	Photopolymer resin; Ceramic suspension	Ultraviolet laser	Brittle quality, not suitable for mechanical parts; high costs for materials	Smooth surface finish; Fine feature details; High resolution and accurary; High printing speed	Injection mold-like prototypes; Casting patterns; Soft tooling; Investment casting; Jewelry and dental applications; Hearing aids
Directed energy deposition	Laser engineered net shaping (LENS); Directed light fabrication (DLF); Direct metal deposition (DMD); Direct laser deposition (DLD)	Polymer; Ceramics; Metal powder (cobalt chrome, titanium)	Laser beam	Post processing required to achieve desired effect; Limited material use	High quality for repair work; Good balance between surface quality and speed	Prototypes; Repairing and maintaining parts; Tooling; Functional parts
Powder bed fusion	Selective laser sintering (SLS); Direct metal laser sintering (DMLS); Selective laser melting (SLM); Electron beam melting (EBM)	Thermoplastic powder (Nylon 6, Nylon 11, Nylon 12); Metal powder (aluminum, stainless steel, titanium Ti6Al-4V; cobalt chromium); Ceramic powder	Laser/electron beam	Longer lead times; Higher cost than other printing processes; Small build sizes	Functional dense parts; High mechanical properties; Complex geometries; High accurary; High strength and stiffness; Strong functional parts; Powder recycling; Fine feature details	Complex ducting (hollow designs); Casting patterns; Tooling; Functional metal parts (aerospace and automotive); Medical and dental parts
Materials extrusion	Fused deposition modeling (FDM); Fused filament fabrication (FFF)	Thermoplastic filament (PLA, ABS, PET, PETG, TPU); Wax	Thermal energy	Brittle quality, not suitable for mechanical parts; Higher cost than SLA/DLP for visual purposes; Poor surface finish; Limited part resolution	Full color and multi-material printing; Machine relatively low cost	Prototypes; Jigs and fixtures; Casting patterns
Material jetting	Polyjet; Wax casting technology; Drop on demand (DOD)	Photopolymer resin; Wax	Thermal energy	Brittle quality, not suitable for mechanical parts; Higher cost than SLA/DLP for visual purposes	High surface finish; Full color and multi-material printing	Full-color product prototypes; Injection mold-like prototypes; Medical and dental models; Tooling
Binder jetting	Inkjet 3D printing; Sand binder jetting; Metal binder jetting	Sand or metal powder; Ceramic powder; Polymer powder	Thermal energy	Low mechanical properties; High porosity	Low cost; Large build volumes; Wide material selection; Full color printing	Casting patterns; Functional metal parts; Full-color objects; Sand casting
Sheet lamination	Laminated object manufacturing (LOM); Ultrasonic additive manufacturing (UAM)	Paper; Plastic film; Sheet metal (aluminium, copper, stainless steel and titanium)	Laser beam	Post processing required; Limited material use	High speed; High surface finish; Low cost for material and machine; Ease of material handling	Injection mold-like prototypes; Casting models

2.2.2 Strengths and Limitations of AM

The demand for AM is growing due to some of the superior benefits that AM can provide. AM technologies have demonstrated their abilities in producing customized, functional and sophisticated products in aerospace, automotive, biomedical and many other industries. However, technology has its own drawbacks that need considering. For some applications, it may be not the case that AM is always resource-efficient and environment-friendly. AM still cannot fully compete with traditional manufacturing in different perspectives. The implementation of AM technologies is only in its infancy with several challenges of applying AM in the direct production contexts. It is doubtful that AM technologies would make conventional manufacturing processes obsolete (Huang et al., 2013). In order to achieve wide industrial adoption, AM technologies require further development in the critical perspectives of design capability, materials properties, process modelling and control, machine quality and sustainability applications (Bourell D L et al., 2009).

This section aims to better understand the strengths and limitations of AM. The author investigated the notable differences compared to traditional manufacturing. Table 2.4 describes both the strengths of AM and the limitations to its development and implementation.

Table 2.4: Strengths and limitations of AM (adapted from Petrick and Simpson, 2013; Petrovic et al., 2011; Tabone, 2010; Tao et al., 2018; Chen et al., 2015; Baumers et al., 2011; Kohtala C, 2015; Berman, 2012)

Strengths	Limitations
Enable manufacturers to build products with lower labor requirements;	High costs remain a significant barrier to widely adopt AM technologies;
Design and develop new products more effectively before committing to expensive manufacturing process and tooling;	Lack of designers and engineers skilled in designing 3D models and R&D;

Opens up the possibility of producing parts with very complex geometry;	Printing speed process slower than conventional manufacturing processes, which make it difficult for high-volume production;
Efficiently prototype the design to test the viability and feasibility of physical parts;	Legal issues about who should be responsible should the component design and manufacturing process goes wrong;
Transform consumer to the manufacturer and encourage user innovation and maker movement;	Photopolymers/plastics unable to produce large-sized objects due to lack of materials strength;
Increase supply chain proficiency through shortening time-to-market, decreasing manufacturing lead time and transportation costs;	3D printed parts show rough and imperfect surface finish;
Improve resource efficiency in ways through implementing efficient manufacturing systems;	Limitations of materials include materials standardization, dimension accuracy, process productivity and prohibitive costs;
The product can be manufactured at a location close to the customer;	Poor surface accuracy caused by residual stress and stair-stepping;
Produce highly customized and complex low-volume products;	Process qualification and certification need to be improved;
Potential to save materials as some typical filaments or resins can be recycled;	3D printed parts repeatability and consistency need to be improved;
Metal powders during SLS or melting processes can be recycled up to 95%;	Full industry acceptance and adoption in many sectors are not achieved;
Enables design freedom and design optimization for product development;	The extensive industrial applications need to be identified and broadened;
Not impose the additional expenses	Material properties for a given AM

of creating new physical tools;	process cannot be guaranteed;
Trigger efficient and flexible model design and part production with better function;	Many manufactured parts fail to meet the particular application needs
Reduce the volume of materials required and weight of transport-related products in the supply chain;	Limitations relating to high cost, low strength and short material, need to be overcome;
Generate a decentralized manufacturing process, closer to the point of consumption;	Support structure materials cannot be recycled so need to be minimized through a good build-up orientation;
Decrease large-scale investment in factories and machinery to reduce costs;	Need post-processing afterwards due to "stair-stepping" effects;
Help manufacturer and designer to get feedback faster due to rapid prototyping;	Existing AM systems still predominantly rely on rapid prototyping not direct manufacturing;
Trigger new business model development with an improved carbon footprint.	Size limitation, low printing speed and low precision of product need to be improved.

Furthermore, Huang et al. (2015) identify four crucial AM technology components that the materials, design, process innovation, characterization and certification need to be addressed in Figure 2.4.

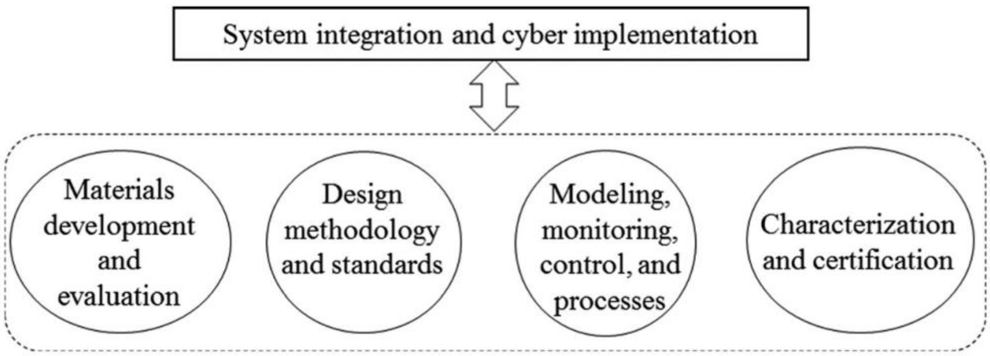

Figure 2.4: Four essential technology elements and system integration for AM (Huang et al., 2015)

The strengths and limitations addressed in the literature provide valuable insights into AM technologies. Researchers and engineers are continually working on the improvement of AM processes to overcome the abovementioned barriers for decades. It is significant to develop a method and framework to guide the adoption of AM technologies in a well informed and sustainable manner (Despeisse et al., 2017). The full adoption of AM would disrupt the ways that manufacturing companies operate business and capture value. It is evident that AM has the potential to pave the way for a new era of sustainable manufacturing and has an impact on a paradigm shift in manufacturing. There is a need for empirical studies to investigate the challenges confronted by AM companies and the barriers of widely implementing AM in practice. The empirical evidence will be discussed in the research finding chapter to address the sub-research questions.

2.3 Sustainability

This section reviews the literature in the field of sustainability as it relates to AM. Notably, the sub RQ1 is addressed to understand the AM sustainability better, and the research in the business model will be explored in the next section.

The term '*sustainable development*' was initially coined by the World Conservation Strategy (WCS) in 1980 to correlate with sustainability. The World Commission on Environment and Development (i.e. The Brundtland Commission) provided one of the most widely accepted definitions of sustainability as "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" (World Commission on Environmental Development, 1987, p. 41).

In the business context, Bansal & DesJardine (2014) explain that the definition of business sustainability is "*the ability of firms to respond to their short-term financial needs without compromising their (or others') ability to meet their future needs*". In the future, companies that make sustainability a goal will be more likely to achieve competitive advantage (Evans at el., 2009). Sustainable development is considered as a holistic principle to shape, improve and optimize the business activities and strategies to achieve the goal of prosperity. However, the concept of sustainability remains limited in the business applications of the majority of companies.

Elkington (1998) proposes the framework of the Triple Bottom Line (TBL), which is comprised of three different pillars: namely economic, environmental and social 'bottom lines'. The three pillars substantially intertwine and affect each other to maintain the balanced and systemic integration of economic, environmental and social performance. The three dimensions referred to 'profit, planet and people' around sustainability concepts for measuring an organizational success. The TBL extends the primary bottom line of a single dimension of profits to a broader network integrating social and environmental perspectives of performance.

The fundamental essence of the TBL concept for the business is to evaluate the corporate performance from not only the financial return but also the social and environmental responsibility. This TBL concept act as "interdependent and mutually reinforcing pillars" and plays a significant role in the business model towards sustainability (UN General Assembly, 2005). In the business world, companies need to develop sustainable solutions incorporating economic, social and environmental dimensions simultaneously to gain long-term competitive advantages.

To achieve sustainability, it is essential to understand interconnections and manage complex systems (Metcalf and Benn, 2013). Senge (1990) argues that system thinking is a technique, a discipline, a framework for seeing wholes and interrelationships. System thinking is the ability to understand the entire systems, investigate the relationships and the interactions among interconnected parts in systems (Senge et al., 2008). Notably, Holling (2001) presents that system thinking is a way to understand the complexity of whole systems from economic, social and environmental perspectives.

Furthermore, Gaziulusoy et al. (2003) indicate that sustainability is not static but a dynamic sate that is continuously changing and improving. From a system perspective, sustainability is the ability of systems to design, adapt, transform in the face of changing conditions and cannot be achieved without whole system thinking (Anarow et al., 2003; Williams et al., 2017). From a sustainability perspective, system thinking approaches encourage managers not just concentrate on one economic component of that system but also understand the interconnected systems of businesses in the environmental and social dimensions.

2.3.1 AM Sustainability

Sustainable manufacturing is defined as the employment of manufacturing processes to fabricate products that simultaneously minimize negative environmental impacts, provide social well-being for employees, communities, and consumers as well as make economic profits (DOC, 2014). The global market for AM is expected to grow, which may increase the prominence of aspects of sustainability in the manufacturing process. Research into the sustainability implications of AM would, therefore, be very valuable before the market matures on a global scale (Wohlers, 2013). Researchers argue that AM can bring several benefits from the sustainability perspective and would become a key manufacturing technology in the sustainable society of the future (Chen et al., 2015; Huang et al., 2013; Ford and Despeisse, 2016). In the context of a sustainable manufacturing paradigm, investigating and estimating the environmental and social impacts of AM processes becomes necessary.

The nascent research has focused on the resource efficiency of different AM processes (e.g. FDM, SLS, SLM) (Baumers et al., 2011; Sreenivasan and Bourell, 2009). Some researchers monitor the AM production processes and quantifying the environmental impacts of AM (e.g. Baumers et al., 2011, Gebler et al., 2014, Yoon HS et al., 2014). Other studies have investigated the AM materials consumption and energy use in comparison with the conventional manufacturing, e.g. injection molding and casting (Chen D at el., 2015; Yoon HS et al., 2014). For instance, Frazier (2014) conduct a review on metal AM processes to illustrate the AM performance in reducing energy, materials and other resource consumptions. Tao et al. (2018) provide an overview of the sustainability of AM evaluating the energy and environmental impacts of AM. It should be noted that due to the power sources of AM are heat and power; it would lead to an overall increase in energy demand and the number of unrecyclable wastes (Rogers et al., 2018).

Furthermore, regarding the role of sustainability benefits in AM adoption, it is acknowledged that companies typically consider adopting AM mainly due to the economic factors of cost reduction and time savings (M.K. Niaki et al., 2019). The economic benefits are the key determinants, while, environmental and social motives have a minor influence on the decision to adopt (M.K. Niaki et al., 2019). The author summarized an overview of the sustainability implications of AM from economic, environmental and social dimensions shown in Table 2.5.

Table 2.5: Sustainability implications of AM processes (modified from Chen et al., 2015; Y. Long et al., 2017; Zanetti et al., 2015)

Economic	Environmental	Social
Higher material utilization, less material consumption	Unclear impact on water quality and acidification	Equal possibilities to all participants in markets and societies
More efficient supply chains with fewer transportation efforts and shorter lead times	Less carbon footprint and greenhouse emission	Bridge technological, educational and cultural gaps between developing and developed countries
Less material and energy losses due to less inventory	Ambivalent studies in terms of an environmental impact or eco-efficiency	User-oriented products, more customer satisfaction

Economic	Environmental	Social
Less waste and better waste management	Unclear impact on handling, using, and the disposal of the materials	Potential benefits on human health and work condition
Less over-production in stocks and small production batches	Possibility to reduce waste and energy consumption	Unclear impact on the employment situation of the industry
No molds, casting, tooling necessary and lower production ramp-up time	Possibility to recycle and reuse waste. materials	Democratization for manufacturing and consumption
Potentially higher profit and lower costs	No scrap, milling or sanding needed	Customer involvement/ maker innovation
Profitability could be proved in selected cases	Customer proximity and digital movement	Local expertise endorsement development

In general, until today, the technological characteristics of AM (e.g. mechanical properties, materials) have been highly focused on achieving growth in volume of use and growth in profit. In comparison, sustainability, lifecycle cost, and business model have been less focused on (Costabile et al., 2017). To what extent these sustainability benefits have been realized in practice has not been quite clarified (M.K. Niaki et al., 2019). The research on AM business models is nascent, and the literature regarding these issues are relatively limited (Mojtaba and Fabio, 2016). It should be noted that the existing research in this area still lacks consistency and continuity with the absence of a strategic plan (Tao et al., 2018). Therefore, understanding and characterizing AM processes for sustainability becomes significant and worthy of investigation.

2.3.2 Environmental Impacts of AM

The environmental impacts of AM were initially studied in 1999, and a widening to AM sustainability has been paid attention to in 2010 (Tao et al., 2018). The primary resource consumptions in AM include energy and material use. Several research tools and methodologies have been developed to deal with the environmental impact such as Life cycle assessment (LCA) (ISO14040), Design for Environment (Vargas Hernandez N et al., 2012), and Carbon Assessment (ADEME, 2009). The LCA was established in the 1990s to accurately evaluating the environmental impacts of the manufacturing process, product, and other activities with different criterion (S. Nimbalkar et al., 2014; ISO 2006; Mehrpouya et al., 2019). The energy/material consumption and transportation/packaging systems of AM processes have been analyzed using LCA methods (Mehrpouya et al., 2019). For instance, Baumers et al. (2011) measure the energy consumption rate and conclude that the energy consumption of SLS process is higher than expected as extra energy consumptions occurred in the equipment warm-up and cool-down processes. Gebler et al. (2014) elaborate that the research into the sustainability implications of AM technologies has been done at a broad level. The energy and environment impact of AM from the life cycle perspective has been quantified that illustrates that AM has the potential of reducing the energy demand by 2.54–9.30 EJ and CO_2 emissions by 130.5–525.5 million tons by 2025 (Gebler et al., 2014).

Outside of using LCA to measure the wider environmental impact within the additive production process, some studies focus on the comparison only of energy and material consumptions between different AM processes (e.g. SLS, FDM and SLM). For instance, J. Faludi et al. (2015) investigate different AM machines with different materials and show that energy consumptions largely correspond to AM machine variations. Other studies analyze the environmental impacts between AM and conventional manufacturing processes (e.g. milling, injection molding). For instance, Yoon HS et al. (2014) investigate the AM process and conventional bulk-forming to compare the energy consumptions. Surprisingly, the findings illustrate that the AM process surpasses conventional bulk-forming process with around 100 times higher of the specific energy consumption. A more detailed study by Telenko and Seepersad (2012) presents that SLS would consume more energy than injection molding process regardless of the mold production stage.

From the product service system (PSS) view, Nopparat and Kianian (2012) use the result-oriented PSS approach to evaluate the AM technologies in the scale model kit industry. It shows that AM processes generate higher energy consumption compared to traditional manufacturing, but maintain higher efficiency concerning raw materials consumption. However, it is not always true. For instance, Tang et al. (2016) compare computer numerical control (CNC) milling and binder-jetting fabrication process. It indicates that the CNC milling process consumes more energy and generates more CO_2 than binder-jetting technology to manufacture the same product.

In general, energy consumption during the printing process would be higher than the theoretical estimation because of the low productivity and time-consuming process (Tao et al., 2018). The public perception that AM processes consume less energy than traditional manufacturing processes is inappropriate. It could be argued that AM processes generate more energy consumption than that of casting and injection molding, although AM holds apparent advantages (Huang et al., 2013; Tao et al., 2018). In fact, AM processes generate considerable wastes that bring about environmental concern.

What's more, some studies focus on material recycling perspectives. The AM wastes are derived from the non-recyclable material powders, scraps with unexpected defects, and support structures. Dotchev and Yussof (2009) investigate the recycling of unused polyamide powders in the laser sintering process. Their research indicates that using AM can significantly reduce by 40% the specific types of materials and save over 90% of unused powders for reuse (Petrovic et al., 2011). While Peng et al. (2018) highlight the significance of part quality and powder reuse in achieving the maximal lifecycle impact-saving. The research shows that the current AM processes can guarantee the part quality and printing repeatability, yet the mechanical properties of powders and dimensional accuracy cannot be guaranteed after reusing several times. Furthermore, some researchers have reported that the emissions of ultra-fine particles may pose adverse operator health effects when the particles are handled and operated in an unvented or unfiltered indoor environment (Stephens et al., 2013; Tao et al., 2018). The author identified that the materials toxicity and harmful effects of AM materials have been rarely investigated in the literature, and the relevant research remains limited.

In general, there is minimal research on the environmental impacts of AM technologies. Understanding and evaluating the environmental impacts of AM from a life cycle perspective is still challenging. This early study has shown that AM is not as sustainable as many have suggested as it generates more energy consumption than that of casting and injection molding. No firm conclusion has yet been made that AM is more energy-efficient or environmentally friendly than subtractive manufacturing processes overall (Huang et al., 2013). It could be argued that collecting the data of material and energy consumptions for AM processes are still challenging. Based on the literature, finalizing a conclusion that AM processes have lower environmental impacts than traditional manufacturing is biased and complicated as the total amounts of waste data are missing, and many uncertainties exist (Huang et al., 2013; Dotchev and Yussof, 2009).

Several researchers have developed quantitative models for LCA or EIA (environmental impact assessment), but the results remain limited to measuring the actual environmental impacts directly. Notably, using LCA to systemically analyze the environmental impacts of AM continues to hold methodological difficulties including insufficient data inventory and limited direct measurements (R. Sreenivasan et al., 2010). Baumers et al. (2011) point out that the impact of AM on sustainability are still unclear. Conclusions about AM sustainability, especially environmental sustainability, varies under different circumstances and on a case-by-case basis (Liu et al., 2016). More sustainability evaluation is needed to determine the performance, correctness and practicality of the environmental impacts.

Finally, resource consumption data for AM processes has been recognized as very significant for the evaluation of environmental impacts; however, different parties refer to their difficulties in sourcing sufficient lifecycle data inventory and conducting an accurate sustainability assessment for AM technologies (R. Sreenivasan et al., 2010; J. Faludi et al., 2015; Y. Tang et al., 2016). The author identified that some material suppliers or machine manufacturers are highly concerned about disclosing and sharing essential information and data related to resource consumption, production process, and recycling/disposal. The author, therefore, analyzed that the environmental impacts need further attention from two perspectives: 1: accurately evaluate the resource efficiency of different AM processes; 2: accurately evaluate the lifecycle energy and material consumptions of fabricated products between AM and traditional manufacturing considering design optimization.

2.3.3 Social Impacts of AM

The term, 'social impacts', is defined by the United Nations Environment Programme as *"consequences of positive or negative pressures on social endpoints (i.e., the well-being of stakeholders)*" (UNEP). It is noted that the literature on the social impacts of AM is very much under-explored (Huang et al., 2013; Chen et al., 2015; Matos et al., 2019). In general, the social aspects are most often related to work safety, health condition, employment schemes, quality of life and human well-being, etc. Several researchers argue that AM technologies mainly create some positive social impacts on health and safety (Matos et al., 2019). For instance, some studies indicate that AM technologies have the capability of fabricating customized products such as surgical implants and assistive devices for improved health and well-being (Huang et al., 2013). The safety products producing by AM processes can fit the medical need of an individualized human body and therefore deliver higher personal comfort, e.g. prostheses, teeth that improving people's quality of life. Some studies pinpoint that AM can create positive impacts on education and cultural aspects. Particularly, AM can be applied in museums and cultural events. It also can be used to improve the students' learning process (Matos et al., 2019).

On the other hand, some significant issues for AM processes lie in health conditions and occupational hazards. AM processes may have less health risk compared to traditional manufacturing process since the worker can avoid working in hazardous environments (Mehrpouya et al., 2019). However, in the process of handling, using and disposing of the printed materials, potential health hazards become highly recognized (Huang et al., 2013). Some of the printed materials would potentially generate adverse effects on the health condition. Mainly, harsh skin reaction, eye irritation, and allergies may occur if the powder or liquid materials are accidentally in contact with skin. Prolonged exposure to some materials and chemicals is likely to influence the health and lead to chronic allergies (Huang et al., 2013). Notably, the detrimental effects of the chemical solvents used for the removal of support structure after post-processing in SLA such as propylene carbonate, isopropanol remain primarily unknown except some symptoms including skin burns and respiratory uneasiness (Huang et al., 2013).

Education and training for correctly operating AM machines, handling and disposal of AM materials, as well as handling of high-intensity laser systems, are needed for the health protection (Huang et al., 2013). Notably, once handling and dealing with the materials and chemicals, wearing protective equipment such as masks, goggles and gloves are necessary to avoid potential occupational hazards (Huang et al., 2013). Long term effects of the particles released from laser sintering and powder bed processes are primarily unknown, which raise possible health issue (Stephens et al., 2013). The adverse effects of some AM materials are still not well understood (Huang et al., 2013). It is needed to better understand the potential health and occupation hazards of AM. Further investigation of the health hazards and potential toxicities is needed.

Much of the literature addresses the significant technology development issues, including materials characteristics and preparation, process control and monitoring, along with machine and part quality (Ruffo and Hague, 2007; Huang et al., 2015; Petrovic et al., 2011). However, the issue of AM sustainability remains largely unexplored. Very few conclusions have been made to elaborate on its sustainability implications from the environment and society dimensions. Therefore, the author summarizes that AM is likely to achieve more significant sustainability impact once 1) closer integration and deeper cross-disciplinary collaboration are implemented; 2) timely and comprehensive research is conducted to grasp the opportunities of energy-efficient and environmentally benign improvements. AM is expected to become a key manufacturing technology in a sustainable future.

2.4 The Business Model and Value

As shown in Figure 2.1, this section reviews the literature in the fields of business model, sustainable business model and sustainable AM business model. Notably, the research in the concepts of business model innovation, product-service system and failed value exchange is discussed respectively.

The concept of a BM was initially proposed in the 1950s and started to become widely accepted in the 1990s, along with the advent of the internet (Yip, 2004). Both academics and practitioners have recently paid substantial attention to the BM (Zott et al., 2011). There are more than 1,177 articles published to address the notion of a BM in the academic journals; however, there is no agreement about what a BM is (Zott et al., 2011; Teece, 2010). Some authors do not define a BM but refer to it (Bambury, 1998; Saloner and Spence, 2003). Scholars have variously referred to a BM as a profit formula, as processes (Johnson et al. 2008); a description (Weill P., and Vitale M. R., 2001), a representation (Shafer et al., 2005); activities (Amit and Zott, 2012); architecture (Dubosson-Torbay et al., 2002); a conceptual tool or model (George and Bock, 2009) and as a framework (Afuah, 2004; Zott et al., 2011).

Table 2.6 provides descriptions of BM that demonstrate the definitional diversity that BM entails. The author lists some key implications derived from BMs for this research which help identify the key concepts for building sustainable business models.

Table 2.6: Descriptions of BM and key implications for building BMs

Description	Source	Key Implications
Value creation function for a BM refers to economic and customer benefits;	Teece (2010)	Customer-centric value
BM should be considered as a network-centric rather than a single firm-centric perspective;	Zott and Amit (2010)	Network-centric value
Value should not only focus on customers and the firm itself but for all stakeholders within the value network;	Magretta (2002)	Multi-stakeholder perspective
The elements of a BM include value proposition, value creation and delivery and value capture system;	Amit and Zott, (2001); Teece (2010); Richardson (2008)	Organizational logic of value systems
BM describes the rationale of how an organization creates, delivers and captures value;	Osterwalder and Pigneur (2010)	A model of an organizational system
The role of BM link to strategy and innovation;	Osterwalder and Pigneur (2010); Chesbrough and Rosenbloom (2002); Magretta (2002)	Management concept
BM converts companies' resource and competency into economic value;	Chesbrough and Rosenbloom (2002)	Core competencies and critical resources for profits
Technological innovation requires a BM to create value for the company and create needs for the target market	Teece (2010)	Integration of BM and technology for value creation and customer needs

segments;		fulfillment
Technology innovation and business model innovation are the key enablers for companies gaining competitiveness and sustainability performance;	Boons and Lüdeke-Freund (2013)	Competitiveness and sustainable value creation
BM elements are not static; instead, they are changeable once organizations identify new opportunities and resources;	Demil and Lecoq (2010); Druilhe and Garnsey (2004)	Changeable value systems
BM elements interrelate dynamically and develop in a dynamic process.	Johnson et al. (2008)	Dynamic development of value systems

The author developed the key implications of the BM based on the literature. Reviewing and analyzing BM's characteristics indicates that the BM is a management concept, an organizational system, not only creates value for customers but also for all stakeholders. It describes the logic of doing business in a dynamic process and aims to achieve competitiveness and commercial potential. Alongside the attention, the business model literature lies in three research domains such as strategic management (Amit and Zott, 2001), technology and innovation management (Chesbrough, 2007), or information systems (Gordijn and Akkermans, 2001). Furthermore, value can be defined as valuable resources from a resource-based perspective that enables customers to be better satisfied (Bogner and Thomas, 1994; Verdin and Williamson, 1994). Value can also be seen as the firm offers customers the product/service that contains attractive attributes/price relationships compared to substitutes or selling a similar product/service at lower costs than competitors (Conner, 1991; Barney, 1986a). Rayna and Striukova (2016) provide a business model framework from a value perspective. The 360° business model framework includes all the value-based components such as value proposition, value creation, value capture, value delivery and value communication, shown in Figure 2.5.

The overall framework highly focuses on the concept of value. The value proposition is what the firm offers to the customer and brings product/service to the market. Value creation addresses core competencies and critical resources that are needed to deliver the value. Complementary assets are also significant elements to make the company success (Rayna and Striukova, 2016). Value delivery addresses how to deliver the value to target customers through different distribution channels (Osterwalder, Pigneur, and Tucci, 2005; Abdelkafi, Makhotin, and Posselt, 2013). Value capture concerns a firm's ability to capture the value created, which includes profit allocation and revenue model (Chesbrough, 2007). Lastly, value communication, which is also a critical element of a business model, describes the ways firms communicating their offerings and values with target market segments (Abdelkafi, Makhotin, and Posselt 2013). However, research on BMs is still in search of a robust theoretical foundation. The lack of standard theoretical foundations has led to a different understanding of BMs (Zott at el., 2011; Teece, 2010). The lack of consensus and unifying the BM concept's language demonstrates the need for more in-depth studies on BM. It is expected that more focus would be on empirical research on BMs.

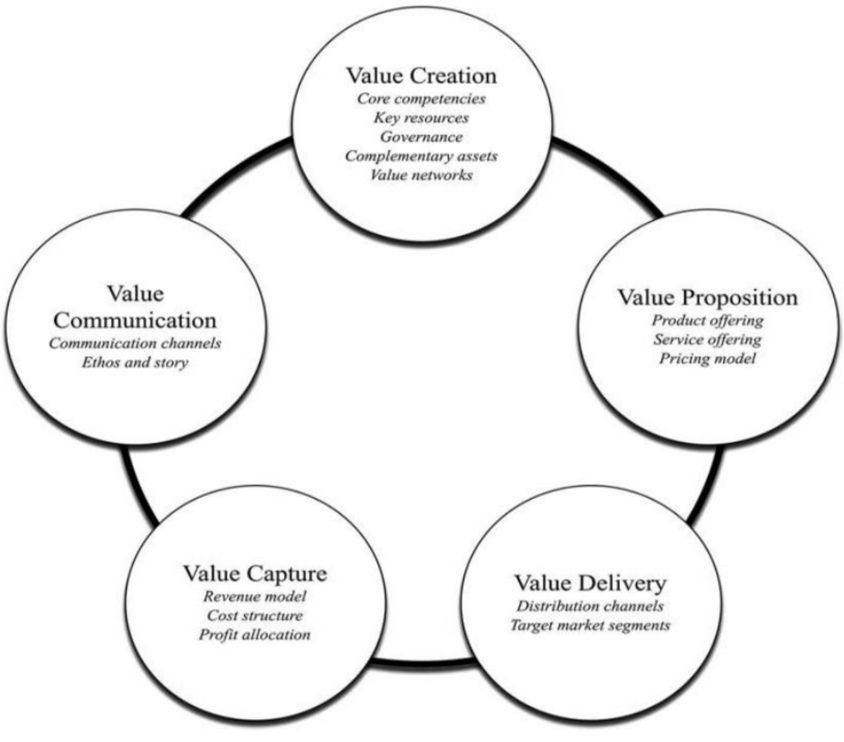

Figure 2.5: 360° Business Model Framework (Rayna and Striukova, 2016)

While much research has focused on printing techniques, material processing, and applications of AM, little analysis has been done on the development of AM business models. It can be argued that the AM business model is an emerging area of research that lack case-based evidence (Savolainen and Collan, 2020). Also, studies on the impact of AM on business models are scarce and need more empirical work (Oberg et al., 2018). In this research, the author examined AM business models from the value perspective and linked them to value systems. Henceforth, the author refers to the BM components as four 'value systems' (value proposition, value creation, value capture and value delivery) (Richardson, 2008). The dominant perspectives of AM business models employed in this study refer to the organizational logic of value exchanges for all stakeholders, particularly the environment and society (Amit and Zott, 2001; Teece, 2010; Bocken et al., 2013).

2.4.1 Business Model Innovation (BMI)

The research into BMI started becoming prevalent in the 1990s, which corresponded to the increasing study into BMs (Magretta, 2002; Zott et al., 2011). The concept of BMI has become of great interest, partly because scholars consider it as a source of competitive advantage and a way of generating valuable outcomes (Kindström, 2010; Mitchell & Coles, 2003, Yunus et al., 2010). According to the research of business model elements, scholars have different statements about what constitutes a business model. In principle, four types of components have mainly been agreed by the scholars, which are value proposition (Chesbrough and Rosenbloom, 2002; Shafer et al., 2005; Teece, 2010; Richardson, 2008), value creation (Zott and Amit, 2002; Chesbrough and Rosenbloom, 2002; Richardson, 2008), value capture (Chesbrough and Rosenbloom, 2002; Zott and Amit, 2002; Richardson, 2008) and value delivery (Osterwalder et al., 2005; Richardson, 2008). In this context, some researchers regard BMI is to make significant changes to the four business model elements (e.g. Johnson et al., 2008). Some researchers believe that BMI is an incremental change in BM components and their relationships (Osterwalder & Pigneur, 2005); or a fundamental change in BM components (Markides 2006); or ranging from incremental to radical of where incremental involves minor changes and radical refers to fundamental changes to any business components (Velu & Jacob, 2014). The author reviewed the academic literature of BMI and developed significant implications for BMI in this research, shown in Table 2.7.

Table 2.7: Characteristics of BMI and key implications for BMI

Source	Characteristics	Key Implications
Zott et al. (2011); Chesbrough (2010)	BMI has become increasingly significant to firm performance and business success;	Firm performance
Doganova and Eyquem-Renault (2009)	Technological innovation is significant for the company; however, it cannot guarantee a company to achieve success;	Critical driver of firm success
Demil and Lecocq (2010); Ireland et al. (2001); Johnson et al. (2008)	BMI can help company transformation and renewal;	Value transformation
Bouchikhi and Kimberly (2003)	Companies struggle for the configuration of assets and are lack of sufficient understanding of the potential value of a novel business model;	Asset configuration for economic value
Casadesus-Masanell and Zhu (2013)	BMI is to search for new ways of creating and capturing value for the stakeholders;	Value creation and capture for multi-stakeholders
Chesbrough (2007)	A unique business model to realize its value and commercial potential is significant for a firm;	A way of generating valuable outcomes
Markides (2006)	BMI is to discover a fundamentally	Entirely new

	different BM in an existing business;	business model
Velu and Khanna (2014)	BMI can redefine a product/service, the way of providing it to the customer and the way of monetizing the offerings;	Change of business model components
Amit & Zott (2012)	The logic of BMI is to change how to do business instead of what to do;	Underlying logic of doing business
Casadesus-Masanell and Zhu (2013)	BMI changes the ways to deliver products or services to customers that do not necessarily offer new ones;	A process of transformation of value delivery
Girotra and Netessine (2013)	The essence of BMI is a novel way of the delivery of existing products and services to existing market using existing technology;	Incremental change of value delivery of existing offerings
Hayashi (2009)	Firms in different competitive landscapes shape business models differently;	A process of experimentation and innovation
Foss and Saebi (2016)	BMI refers to the process of developing these novel replacements that provide product or service offerings to customers that were not previously available;	Process and outcome
Foss and Saebi (2016)	Conceptualizing BMI is ambiguous, describe BMI as an outcome of the organizational change process.	Conceptual ambiguity and disconnected research streams

The author made comprehensive observations from reading across the BMI literature and explored the key implications from BMI literature on AM. Reviewing and analyzing the characteristics of BMI illustrates that BMI is a process of experimentation and innovation, a novel way of generating value for stakeholders, and a critical driver for firm performance and success. The author has drawn inspiration from the scholars' conceptions of the related activities about BMI and found out that many BMI studies highly focus on the economic value return and the new ways of monetizing the offerings. However, drawing the concepts of sustainability and sustainable value creation is a lack of focus in current BMI research.

In the context of AM, it is indicated that AM has the potential to impact BMI through changes of different BM components profoundly (Rayna and Striukova, 2015; Hämäläinen and Ojala, 2017). AM allows releasing products/services offering more efficiently, thereby affecting the value proposition process (Rayna and Striukova, 2015). Another significant way of AM leading to business model innovation is to integrate crowdsourcing into direct manufacturing. The crowdsourcing platforms (e.g. Kickstarter and Threadless) mainly deal with the conceptual ideas and initial design issues. Direct manufacturing can extend crowdsourcing to the manufacturing process and efficiently print out 3D models, which can impact the value creation process (Rayna and Striukova, 2015).

Companies (e.g. Ponoko and Shapeways) adopt AM to provide online services, which can reduce the physical storage and transport costs. When the customers use online printing service, products can be directly printed and shipped to the consumer, thereby changing the value delivery process. Furthermore, Tapscott and William (2006) highlight that AM can transform people from consumers to '*prosumers*', which describes the situation where consumers are in charge of the design, manufacture, delivery and consumer products, usually through AM in a nearby location. AM has an impact on the distribution channels by enabling customers to manufacture objects at home.

However, Rayna and Striukova (2015) fail to address in detail how AM companies can develop new BMs instead of how AM influence the current BMs. Their studies also do not focus on the AM business model itself and lack empirical evidence. Oberg et al. (2018) systematically review the current knowledge on AM within business and management research. Their review examines how the emergence of AM affects existing BMs rather than how companies transform business models to adopt AM technologies or how AM companies develop novel business models towards sustainability.

The author presumes it is evident by this point that AM has potentials to impact the BMs through changing the *value proposition, value creation, and value delivery processes*. This also confirms the author's arguments that draw from the source there is a need for in-depth case studies into BMs, particular AM business models, with the intention of better understanding value transformation, creation and capture from both theoretical and practical perspectives. Furthermore, the measurement of the performance of AM business models is worthy of investigation (Roger et al., 2018). In general, BMI is an emerging research topic and current research is not yet mature, particularly in the AM aspects. In this new area, more sound and empirical research are expected.

2.4.2 Sustainable Business Model (SBM)

The business model was introduced in the previous section as a concept that is to mainly seek revenue-oriented economic value, which fails in achieving sustainability. The author's review of the literature has identified that there is still a lack of agreed concept of the SBM itself. SBM is under-exploited (Schaltegger et al., 2011). The literature on SBM is still emerging (Evans et al., 2017). The way of achieving sustainability in practice is also inadequately addressed. It should be noted that more in-depth research is needed on whether strongly new business models can help develop integrative and competitive solutions through creating positive effects for the environment and society. (Boons & Lüdeke-Freund, 2013; Hansen et al., 2009; Schaltegger et al., 2012; Stubbs & Cocklin, 2008).

To achieve industrial sustainability, Evans et al. (2009) highlight some available sustainable models such as industrial ecology model (Graedel, 1996), corporate social responsibility (Holme and Watts, 2000), cradle to cradle (McDonough and Braungart, 2002), sustainability by design (Ehrenfeld, 2008), and eco-innovation (Reid and Miedzinski, 2008). Short (2014) articulates some BM types that embrace higher sustainability attributes including product-service systems, industrial symbiosis, socially inclusive models, green business model and resource stewardship councils. The author describes the characteristics of SBMs that demonstrate the definitional diversity and identifies some key concepts for building SBMs, shown in Table 2.8.

Table 2.8: Theoretical description of SBM and key concepts

Source	Description	Key concepts
Bocken et al. (2013); Schaltegger et al. (2012)	Deliver economic value and contribute to the sustainability of the company, the environment and society;	Triple bottom line
Bocken et al. (2013)	Embed sustainability into BMI to achieve social, environmental and economic benefits for a wide range of stakeholders;	Multi-stakeholder perspective/Triple bottom line
Schaltegger et al. (2016)	Describe, analyze, manage, and communicate a company's sustainable value proposition in relation to its customers, and all other stakeholders;	Sustainable value creation for multi-stakeholders
Schaltegger et al. (2016)	Capture economic value while maintaining or regenerating natural, social, and economic capital beyond organizational boundaries;	Triple bottom line
Bocken et al. (2013); Lüdeke-Freund (2010)	Minimize energy consumptions and wastes, at the same time encourage reuse, re-manufacture and recycle throughout the whole product life cycle;	Close loop/environmental sustainability
Lüdeke-Freund (2010)	Innovate BM through generating competitive advantage while minimizing harm and wastes;	Competitive advantage/ environmental

		sustainability
Schaltegger et al. (2011)	Create value for the whole range of stakeholders, including the natural environment inside and outside the company;	Multi-stakeholder perspective
Bocken et al. (2013)	Maximize environmental and societal benefits, and stimulate co-creation and co-innovation;	Triple bottom line
Bocken et al. (2014)	Reduce negative impacts and delivers positive benefits for the environment and society through changes in the way the companies propose, create, deliver, capture value;	Triple bottom line
Schaltegger et al. (2012)	No sustainable value can be created and captured without creating value for a broader range of stakeholders, including the environment and society;	Sustainable value creation and capture for multi-stakeholders
Valdimirova (2012)	Companies should understand the existing BMs, embrace sustainability vision, and understand the internal and external environment required for the change to sustainable BMs;	BM transformation towards sustainability
Manzini and Vezzoli (2003)	Imply the need for shifting from product-oriented thinking to system thinking for sustainability.	System thinking

The author identified the key concepts for building SBMs which help select the concepts to analyze sustainable AM business models. The selected key concepts will be discussed in Section 2.4.5. Reviewing and analyzing the characteristics of SBM from the literature indicates that SBM encompasses the concepts of the triple bottom line, sustainable value creation and capture, multi-stakeholder perspective, system thinking, and competitive advantage.

In general, many scholars agree that SBMs are still under-researched. The author acknowledges that there is a need for a more detailed and comprehensive investigation of the logic and features of an SBM. Particularly, some challenges need to be overcome, e.g., lack of clarity and conceptual consensus of BM, BMI and SBM (Boons and Lüdeke-Freund, 2013; Magretta, 2002; Osterwalder and Pigneur, 2005; Zott et al. 2011); lack of empirical studies and evidence (Stubbs & Cocklin 2008; Schaltegger et al. 2012); and lack of grounded theory (Teece 2010; Boons et al., 2013). The challenges for SBM development have been summarized by Evans et al. (2017) shown in Table 2.9.

Table 2.9: Challenges for the development of SBMs (Evans et al., 2017)

Challenges	Authors
Triple bottom line The co-creation of profits, social and environmental benefits and the balance among them are challenging for moving towards SBMs.	Hart and Milstein, 2003; Stubbs and Cocklin, 2008; Schaltegger *et al.*, 2012
Mind-set The business rules, guidelines, behavioural norms and performance metrics prevail in the mind-set of firms and inhibit the introduction of new business models.	Johnson *et al.*, 2008; Yu and Hang, 2010; Boons and Lüdeke-Freund, 2013
Resources Reluctance to allocate resources to business model innovation and reconfigure resources and processes for new business models.	Chesbrough, 2010; Zott *et al.*, 2011; Björkdahl and Holmén, 2013
Technology innovation Integrating technology innovation, e.g. clean technology, with business model innovation is multidimensional and complex.	Hart and Milstein, 2003; Yu and Hang, 2010; Zott *et al.*, 2011
External relationships Engaging in extensive interaction with external stakeholders and business environment requires extra efforts.	Stubbs and Cocklin, 2008; Vladimirova, 2012; Boons and Lüdeke-Freund, 2013
Business modelling methods and tools Existing business modelling methods and tools, e.g. Osterwalder and Pigneur (2010) and Johnson *et al.* (2008), are few and rarely sustainability driven.	Björkdahl and Holmén, 2013; Girotra and Netessine, 2013; Yang *et al.*, 2014

These prominent challenges suggest that creation of SBM is a significant business transformation issue, with identified challenges in the articulation of the potential solutions through the balance of triple bottom line, cultivation of business mind-set, reconfiguration of resources, integration of technology innovation with BMI, external relationships engagement, and development of methods and tools. It should be noted that there is still a lack of empirical studies and practical insights to help companies achieve BMI transformation towards sustainability (Stubbs and Cocklin, 2008; Schaltegger et al., 2012). The creation of or transform to an SBM still confront multidimensional challenges. There is a lack of a holistic approach to achieve SBM in practice (Short, 2014). In the context of AM, the unsustainable business model can be identified as excessive materials and energy used, highly adverse ecological and social outcomes generated, and failure in gaining competitive advantage. Thus, the AM business model process needs to better consider sustainability. A typical example of an SBM is PSS, which delivers functionality rather than selling ownership of a product to fulfil customers' needs. PSS has demonstrated the attributes of resource efficiency, environmental performance benefits as well as become a significant determinant of the economy's overall performance (Schaltegger et al., 2011). For instance, car-sharing service allows better utilization of cars and reduces the need for owning a car, thereby delivering more significant environmental and social benefits. However, the extant studies on AM business model only touch on the economic value and cost model without a deep understanding of sustainable value creation and capture. The studies suggest the need for more empirical studies on AM business models to better understand the sustainable value of AM. The PSS model for AM is discussed in the following section.

2.4.3 Product Service Systems (PSS) for AM

Researchers and practitioners' interests in PSS have risen significantly in recent years. Scholars hold different theoretical emphasis of PSS along with a variety of definitions. The mainstream concept of PSS is a combination of product and service to fulfilling customer' need (Goedkoop et al., 1999; Tukker, 2004; Baines et al., 2007). Goedkoop et al. (1999) define the critical elements of a PSS as follows: (i) *the product: a tangible commodity manufactured to be sold*; (ii) *the service, an activity is performed without the need for a tangible good or without the need for the system*; (iii) *a collection of elements including products, services and their relationships*. In light of this, Tukker (2004) presents the widely accepted classification of PSS, namely product-oriented service, use-oriented service, and result-oriented service, which are mainly based on the relationships between the provider, customer and value model. The three generic types of PSS models are described in Table 2.10.

Table 2.10: Discussions of three types of PSS models

PSS Model	Discussion
Product-oriented PSS	The customer owns the product, and the value is created by adding service to product (Tukker, 2004). Examples of such a system are related to monitoring, installation, and maintenance of the physical product through services (Anderson, J. and Narus, J. 1995). Mainly, examples include using a solar panel on a roof to generate electricity or using a rainwater tank to capture water as opposed to purchasing the product from the utility company (Baines et al., 2007).
Use-oriented PSS	The customer does not need to own the product, and the value is created by providing access to the product and the function (Tukker, 2004). The product remains the property of the company. It comprises product rental, leasing, subscription and sharing. Examples of such a system are related to selling the use or availability of a product without customer ownership (Anderson, J. and Narus, J. 1995). In particular, the car-sharing system or rental service is the growing use-oriented PSS models. Therefore, high priced items and items used infrequently are better for the user-oriented PSS model (Goedkoop, 1999).
Result-oriented PSS	The customer pays for functionality and competency rather than having the ownership of a particular product (Tukker, 2004). The value is created by providing a function or selling a result instead of providing a physical product to the customer. Examples of such a system would be selling washed clothes instead of washing machines (Baines et al., 2007; Tukker, 2004). Outsourcing activities and pay per service units are also well-known examples. In this type of PSS, products are entirely replaced by services, and products remain the property of the company, thereby reducing the need for customer ownership (Baines et al., 2007).

As a specific BM, the central focus of PSS is to sell the result of a combination of products and services to customers in terms of function fulfilment and value generation (Baines et al., 2007; Tukker 2015). From the sustainability perspective, PSS is considered as an innovative model to reduce the effects of negative externalities and add value to environmental performance (Baines et al., 2007; Tukker and Tishner, 2006a; Manzini and Vezzoli, 2003). Some authors emphasize the economic value of PSS that regard it as a significant determinant of the economy’s overall performance that can make a significant contribution to a more sustainable economy (e.g. Baines et al., 2007). Some consider PSS as a market proposition that incorporates additional services by extending the traditional functionality (e.g. Mont, 2002). Others combine the concepts of sustainability and BM within the definitions to indicate that PSS can not only generate value for customer satisfaction, but also fulfils the sustainability requirements (e.g. Creusen, 2011).

Furthermore, the research on PSS has been advanced in the business value focus and studied in different practical fields such as manufacturing, chemistry, electricity, and computer science. While it should be noted that there is minimal research on PSS for AM and on how traditional AM companies can shift to the service providers and gain environmental and social benefits from their service operations. There is a driving paradigm for the current industrial interest in AM of which a BM paradigm shift from selling physical products to PSS in AM (J. Savolainen and M. Collan, 2020). It is worth researching on the PSS for AM and figure how PSS can generate value for customer satisfaction, at the same time, meet the sustainability requirements. Notably, some PSS examples introduced by Jegou and Manzini (2008) can be learned and implemented by AM companies (e.g. the multi-user laundry service and home nursery service).

In terms of sustainable PSS, Tukker and Tischner (2006a) define sustainable PSS as "*a PSS generating minimum negative environmental in the meantime maximizing economic value and social well-being*". There are two essential criteria to justify PSS performance, namely product-service value and sustainability assessment (Creusen, 2011). Product-service value is business-oriented to fulfil customer's need and generate economic value. Regarding sustainability assessment, the environmental impact is a significant factor to evaluate PSS performance. The company should go beyond the schemes of production and consumption to extend the scope of PSS to a broader sustainability issue and generate environmental benefits (Creusen, 2011; Tukker 2015; Manzini and Vezzoli 2003).

It should be noted that sustainable PSS has significant potential for the resource efficiency and environmental protection through some successful examples (e.g. car-sharing services, chemical management systems and solar leasing (Tukker, 2015; Manzini and Vezzoli, 2003). However, this does not necessarily imply that PSS would inherently deliver sustainability and some PSS solutions designed to be sustainable but, in the end, failed in generating business value (Tukker and Tischner, 2006a; Tukker, 2004). Even though it has

tremendous benefits, knowledge about how companies can implement sustainable PSS has remained limited (Baines et al., 2007). Existing methods and tools for the development of sustainable PSS are still under-researched.
In this research, the author regards sustainable PSS as a strategy and a solution where it offers greater sustainability and help capture sustainable value to not only satisfy customers' needs, but also a wider range of stakeholders. In the context of AM business model, the available services that AM companies provide are machine installation, objects repair, and machine maintenance considered as the product-service business models (Despeisse and Ford, 2015). Therefore, how to increase resource and energy efficiency in the use of AM materials and machines, how to improve machine remanufacturing, material recycling and reuse, and how to reduce customers' ownership responsibilities for AM hardware are worthy of investigation.

Besides, outsourcing as a result-oriented PSS model allows people to use AM technologies without the initial high investment of the equipment. Some other used-oriented PSS models could be developed and implemented such as machine sharing, subscription and leasing that can improve the equipment utilization showing the contribution to sustainability benefits (Despeisse and Ford, 2015). However, almost all AM companies are only selling their printers (Holzmann et al., 2019). Leasing and renting are quite typical in other industries but is rare in AM companies. It could be argued that such revenue sources might also be applicable to AM. Software-as-a-service could be used as inspiration for "printer-as-a-service" or other PSS models (Holzmann et al., 2019). In general, the literature review indicates a lack of research on PSS for AM in practice. No academic literature has been uncovered that address the implementation of PSS in AM companies. The lack of industrial case studies and empirical evidence suggests the need for more in-depth research on sustainable PSS for AM.

2.4.4 Failed Value Exchange for AM

Failed value exchange is a quite new concept that presents the negative aspects of BM in order to stimulate BMI. Rana et al. (2013) discuss the value exchanges among multiple stakeholders and propose the concepts of value destroyed and value missed. Yang et al. (2014) extend Rana et al.'s (2013) value system research and incorporate two new value forms into the system, namely value surplus and value absence. Yang et al. (2016) further propose the wider value uncaptured perspective, which is defined as the potential value that could be captured but has failed to be captured in companies. Value uncaptured perspective represents failed value exchange in the business model, which is not related to the concept of value capture in most business model literature (Yang et al., 2016; Richardson, 2008). The four forms of value uncaptured include value surplus *(value exists, but is not required*), value absence (*value required, but does not exist*), value missed (*value exists and is required, but is not explored*), and value destroyed (*value comes with adverse outcomes*) (Yang et al., 2016). Furthermore, Fernando (2016) proposes four failed value types in the value network including Type A (*I give, but don't get a return*), Type B (*I give, but you don't want*), Type C (*I don't give, but you want*), Type D (*I give or have too much*), which set the company as "I" to give value to the customer as "you" that "you" can also apply to any stakeholder which the focal firm is exchanging with.

The concept of failed value exchange can be used as a novel perspective for studying BMI across the product life cycle (Yang et al., 2016). Failed value exchange exists in almost all companies. Some failed value is visible, e.g., waste streams in production, under-utilized resources, and reusable components of broken products; some is invisible, e.g. overcapacity of labor, insufficient use of expertise and knowledge (Yang et al., 2016). Reducing any kinds of uncaptured value would create value opportunities (Yang et al., 2016). Yang et al. (2014) further elaborate that value refers to a broad set of benefits derived by a stakeholder from an exchange, which in the context of sustainability, include not only monetary profit, but also include social and environmental value. All the values being created and captured in companies are for all stakeholders, not only for customers but also investors, government, suppliers, environment, society and other parties (Bocken et al., 2014).

In the context of AM, the technologies develop rapidly to address the limitations regarding materials, printing speed, product quality, and process monitoring. However, understanding and identifying failed value exchanges in AM business models have not been addressed so far. It is worth investigating the current AM business models to understand the failed value exchange. The author considers the concept of failed value exchange as a strategy and a system. The author uses value uncaptured to understand failed value exchanges among multi-stakeholders and create value opportunities within AM business models.

In practice, Osterwalder and Pigneur (2010) develop a popular tool "*business model canvas*" that gives substantial insights on the components of a business model with a focus on the value proposition and details the business modelling process. However, the canvas maintains a quite narrow view of the value proposition, which poorly addresses the sustainability issues across the full stakeholder network. Furthermore, Bocken et al. (2014) develop the sustainable business model archetypes that can be used to accelerate the development of SBMs in research and practice. The archetypes are known as '*create value from waste'* which means turn wastes into a valuable input to create value and to contribute to the circular economy. However, the archetypes are quite general and conceptual without detailing the sustainable business modelling process. The archetypes also fail to address the particularities of BM and BMI. Except for listing out the relevant terminologies towards sustainability, the archetypes do not accordingly detail the mechanisms and reflect the logic of how companies create, capture and deliver sustainable value from waste.

A more recent tool is the Cambridge Value Mapping Tool, shown in Figure 2.6. The rationale behind the tool is that by analyzing the value systems, identifying failed value exchange among multi-stakeholders across the industrial network, companies can uncover value creation opportunities (Bocken et al., 2013; Evans et al., 2017; Yang et al., 2016). Notably, the value captured means that stakeholders capture positive value benefits. Value missed represents that stakeholders fail to receive benefits due to low quality designed value creation systems. Value destroyed describes the negative impacts of business activities on the environment and society with depletion of non-renewables and ecological damages. Value opportunities represent new value and offer benefits for existing/new stakeholders (Bocken et al., 2014; Yang et al., 2016).

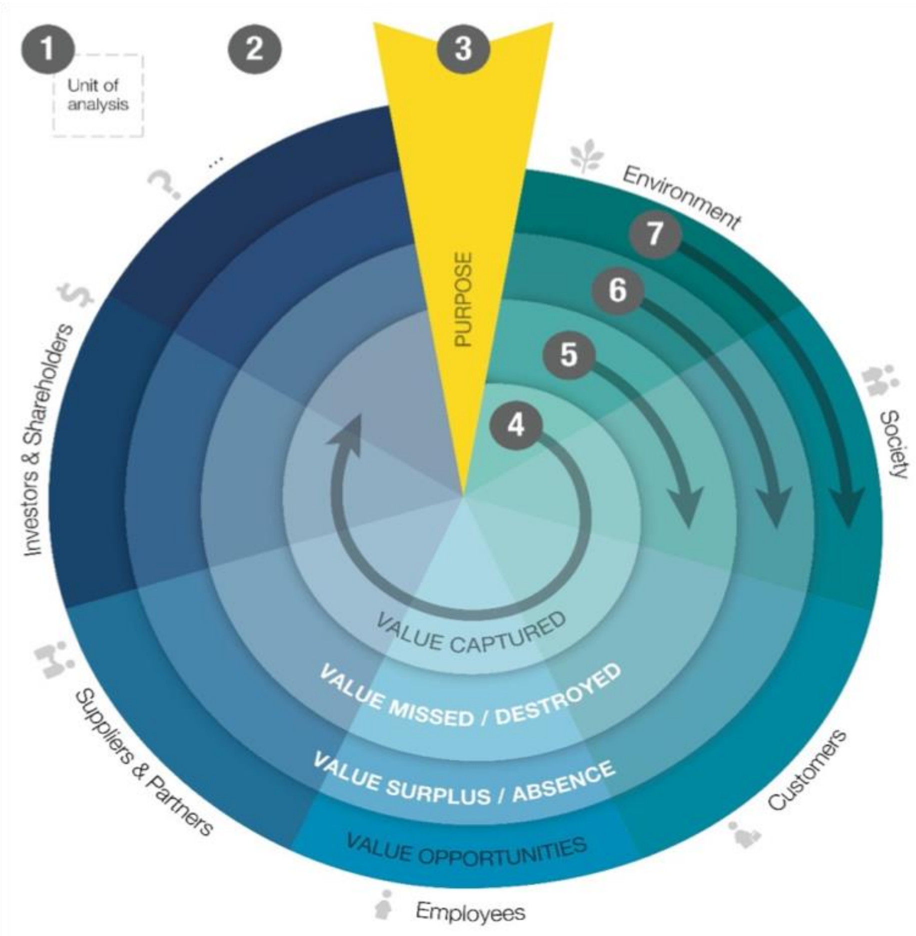

Figure 2.6: Cambridge Value Mapping Tool (CIS, 2016)

The Cambridge Value Mapping tool is widely used to guide practitioners in a structured step-by-step process through the following questions (Evans et al., 2017; Yang et al., 2016):

- What is the unit of analysis is?
- Who are the stakeholders for the unit of analysis?
- What is the purpose of the unit of analysis?
- What is the current value captured?
- What is the value missed and/or destroyed?
- What is the value surplus and/or absence?
- What are the new value opportunities?

It should be noted that this tool obtains a holistic perspective of the value proposition and facilitates sustainable value creation opportunities for a wide range of stakeholders (Bocken et al., 2013; Evans et al., 2017; Yang et al., 2016). Thus, the author decided to implement this tool to analyze AM business models, because this tool takes sustainability and multi-stakeholders into consideration which could assist AM companies in analyzing and designing sustainable business models.

2.4.5 Sustainable AM Business Model

There is a growing research interest in developing business models for AM; for instance, the proposal for consumer-centric business models for AM (Bogers et al., 2016). Previous research has identified the business model canvas (Osterwalder, 2010). However, the business model canvas fails in considering sustainability and not including a wide range of stakeholders. The sustainable business model archetypes are developed by Bocken et al. (2014) with the full consideration of economic, social and environmental benefits. Still, neither tool is widely adopted in AM companies and they fail to show the business modelling process and value creation/capture mechanisms. There is still limited research linking AM with a sustainable business model.

The review of literature enables the author to understand that AM technologies have great potential to generate fewer wastes than traditional subtractive methods of production and hold many potential sustainability benefits (Ford and Despeisse, 2016). It should be noted that AM has not been sufficiently explored from the perspective of a sustainable business model. Moreover, the author has identified that the current tools and methods are either too conceptual and general, or not used in practicing AM companies. Scholars and practitioners' understanding of the social and environmental perspectives of AM still lags (Ford and Despeisse, 2016; Huang et al., 2013). There are no systematic and holistic methods to support AM companies considering the sustainability perspectives and to facilitate the value creation process. Mainly, understanding AM business models and achieving sustainable value are poorly addressed in the existing literature. The author has identified a need for a more comprehensive understanding of sustainable AM business model.

However, the wide implementation of AM may lead to higher demands for customized goods, higher rates of product obsolescence and increasing resource consumption (Ford and Despeisse, 2016). Given the potential for growing negative consequences, there is a need to increase our knowledge and empirical evidence for AM companies to integrate sustainability considerations into business model innovation via a systematic approach. The sustainable business model can help AM companies improve sustainability performance and competitiveness. Correspondingly, it should be noted that the failed value exchange can be used as a novel approach to study AM business models. However, understanding of AM business models through the lens of failed value exchange has not been investigated in the literature.

Based on the literature, the author has selected four key concepts for building sustainable AM business model for this research. The four key concepts are derived from the analysis of SBM in Section 2.4.2 (See Table 2.8). These concepts are chosen mainly because of their relevance, significance and applicability that other ones would not make the same contribution. The selected concepts thus provide the basis of the analysis that help investigate the research question: *how can AM companies develop business models to create and capture sustainable value?* The key concepts are respectively 1) triple bottom line (TBL); 2) system thinking; 3) multi-stakeholders; and 4) sustainable value creation. The key concepts thus play a significant role in helping understand AM business models and analyze value systems of each AM business model. The key concepts also inspire the author to develop a conceptual framework which will be discussed in the next section.

Triple Bottom Line

As discussed in Section 2.3, TBL comprises of three different pillars: economic, environmental, and social dimensions. The TBL extends the fundamental bottom line of profit-oriented dimension to a sustainability perspective with a broader network. This concept requires a significant change in business focus from single economic value to a broader view encompassing social and environmental value. Notably, the integration of TBL into BM to develop SBM is significant for AM companies. AM practitioners need to change the mindsets to think about sustainable value, not only the financial return, but also the social and environmental responsibilities. There is a need for AM companies to embed TBL perspective into the core of AM business models to gain long-term competitive advantages.

System thinking

Senge et al. (2008) present that system thinking is to understand the entire systems, and investigate the relationships, the interactions among parts of systems rather than things. System thinking is a technique, a discipline, a framework for seeing wholes, seeing interrelationships, and seeing patterns of change rather than static perspectives (Senge, 1990). It is evident that system thinking does not apply a linear methodology; instead, it applies the iterative technique and stimulates the investigation, discussion, and amendment. It should be noted that system thinking would be constructive for companies to understand complex, non-linear, and interconnected systems of businesses (Senge et al., 2008; Charnley at al., 2011) from the sustainability perspective. Thus, system thinking would enable AM practitioners to take the whole picture to look at the interrelationships among different parts of a system, rather than on isolated parts to achieve sustainability.

Multi-stakeholder perspective

Stubbs and Cocklin (2008) emphasize that the multi-stakeholder perspective is a crucial concept in SBMs. SBMs embed sustainability perspectives into the business modelling process and treat society, environment as critical stakeholders. SBMs aim to create value for all stakeholders and develop collaborative partnerships among stakeholders (Stubbs & Cocklin, 2008). The traditional BM process is to get an economic return for the company and creates customer value. While SBMs take multi-stakeholders as the priority, consider multi-stakeholder engagement as the critical component for the whole system. In the case of AM business model, the sustainability issues, particularly environment and society, are not the main focus for most AM companies. Therefore, the concept of multi-stakeholders needs to be incorporated into the business purpose and modelling process to consider a wide range of stakeholders.

Value creation and sustainable value

The concept of value creation is derived from the BM literature as a critical component (Amit & Zott 2001; Chesbrough 2007; Richardson 2008). In the context of sustainability, value creation is not just to consider the monetary value and requires a more comprehensive view of value, particularly social and environmental benefits. Sustainable value is regarded as a key concept for integrating sustainability issues in the environment and generates economic, social and ecological value simultaneously (Wheeler et al., 2003; Hart and Milstein, 2003). Bocken et al. (2015) state a need for a more holistic view of value that integrates social and environmental dimensions of sustainability to balance all stakeholder interests for sustainable value creation.

Furthermore, Rana et al. (2012) present that the sustainable value is broadly defined as a 'set of benefits derived by a stakeholder from an exchange'. However, the concept of sustainable value is still underdeveloped (Cardoni et al., 2020). In terms of AM business model, the sustainable value indicates that the AM firms not only generate monetary revenue through selling AM machines, AM materials, AM products or services, but also create and capture value for the environment and society via using environmental-friendly materials, recycling, reusing, achieving resource efficiency and improving social wellbeing. Therefore, there is a need for AM companies to develop business models to consider all three dimensions of sustainability for sustainable value creation. The four concepts were chosen because of their relevance, significance, and novelty. These concepts do not stand alone; instead, they are interrelated to each other.

2.5 Building the Conceptual Framework

The author considered these vital concepts as the most relevant ones to help develop an AM sustainable business model. The chosen four concepts were synthesized to propose a conceptual framework based on the literature review, shown in Figure 2.7. The author explained three analysis processes as the underlying logic of the conceptual framework through the lens of value system, failed value exchange and sustainable value.

Analysis 1: analysis of business models using system thinking

This analysis is based on the concepts of system thinking, multi-stakeholders, and business model. System thinking enables AM practitioners to study the whole picture to look at the interrelationships among different parts of a system, rather than on isolated parts to achieve sustainability. System thinking may help understand the complicated and interconnected systems of business, thereby better analyzing the business models of crucial AM stakeholders. Mainly, AM practitioners can use system thinking to analyze value systems, namely, *value proposition, value creation, value capture and delivery* (Richardson, 2008).

Analysis 2: multi-stakeholder analysis of failed value exchanges

This analysis is based on the concepts of multi-stakeholders, system thinking, and failed value exchange. Multi-stakeholder perspective is a key concept in SBM development. Particularly, AM companies need to treat society and environment as the key stakeholders not just focus on monetary profits. In terms of failed value exchange, *value surplus, value absence, value missed, and value destroyed* were incorporated into the framework (Yang et al., 2016). AM companies need to consider the failed value for all stakeholders, not only for customers and firms itself but also for government, suppliers, environment, society and other parties. This analysis process explains that the multi-stakeholder analysis of failed value exchanges using system thinking could lead to sustainable BMI.

Analysis 3: development of an SBM

This analysis process is based on the concepts of TBL and sustainable value creation. AM is still under development, and for some applications, it may be not the case that AM is always resource-efficient and environmentally friendly. Notably, some prominent failed value in AM companies could be waste streams in the printing process (powders, polymers, metals and other materials), deficits in skilled engineers and designers, structure support parts and materials that yet are reused and recycled, along with the excessive energy consumptions. The core idea for AM sustainable business model is to minimize energy consumptions and wastes, at the same time encourage reuse, remanufacture and recycle. The social and environmental aspects need to be considered to create the sustainable value of AM. Thus, this analysis process incorporates TBL into the AM business modelling process to create sustainable value.

The purpose of the conceptual framework is to direct the research process, link the theoretical and empirical aspects, and answer the research questions. In essence, the proposed framework includes three constructs connected based on their interdependencies. It highlights the significance of sustainability concept as the bedrock and links with the AM business model. It should be noted that the conceptual framework uses the failed value exchange as the novel perspective to study the AM business model. It depicts the business modelling process by identifying value systems and failed value exchanges within the AM companies to create and capture sustainable value.

In general, as shown in Figure 2.7, the conceptual framework follows the proposed three analysis processes by which first understanding AM business model, second using system thinking to analyze value systems and identify failed value exchanges, not only considering economic value but also social and environmental value, ultimately creating and capturing sustainable value. Notably, “S1, S2…Sn” represent the key stakeholders involving in AM business models such as supplier, government, customer, employee, society, environment, among others. S1, S2, S3 in Figure 2.7 could represent the environment, society, and customer, respectively. The AM business model exchanges with “S1, S2…Sn” to generate failed value. For instance, AM business model exchange with the “S1” environment generates waste streams in the printing process (materials, scraps, printing support, etc.), which is considered value destroyed. The conceptual framework is used in the case studies, which lays the foundation for data collection in Chapter 4 and 5.

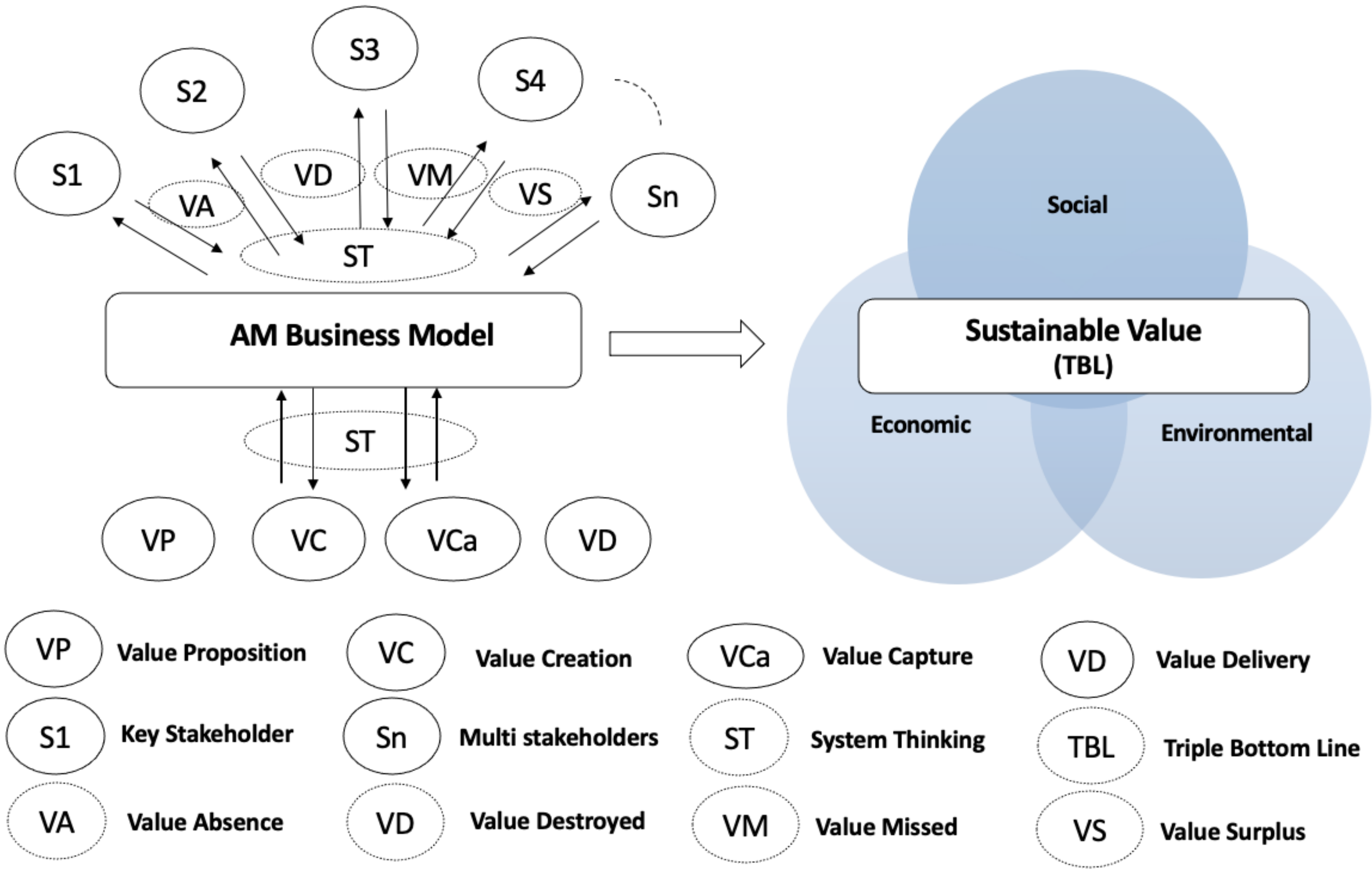

Figure 2.7: Conceptual framework (Author generated)

2.6 Research Gap and Confirmed Research Questions

This chapter presents a literature review covering three bodies of literature: AM technologies, sustainability, and business model. The research shows that the theoretical and empirical studies in the fields of sustainable AM business models are still immature. The research identifies the need for better understanding of AM business models and the sustainability implications (Ford and Despeisse, 2016). Notably, understanding and identifying failed value exchanges in AM companies has not been addressed. There is a lack of studies of AM business model that draw on the key concepts of TBL, multi-stakeholders, failed value exchange, system thinking and sustainable value creation. There are also very few studies on identifying critical factors, value opportunities and potential solutions that help AM companies create and capture sustainable value. Thus, the main research question proposed is checked against the literature and confirmed by the author.

How can AM companies develop business models to create and capture sustainable value?

The research aims and the main research question determine and confirm the sub-questions (RQ) as follows:

RQ1: What are the sustainability implications of AM from environmental and social perspectives?

RQ2: What are the current business models within AM companies?

RQ3: What are the failed value exchanges among multi-stakeholders?

RQ4: What are the challenges that prevent the adoption of AM?

RQ5: What are the critical factors that help AM companies develop sustainable business models?

RQ6: How can AM companies identify opportunities for sustainable value creation and capture?

The sub RQ1 was answered in the literature review part (Section 2.3) and the remaining RQ2-6 will be addressed in the research findings part. The gap in the current literature is therefore elaborated, and the research aims for answering the research questions are confirmed to fill the knowledge gap.

2.7 Chapter Summary

This chapter systematically presents a literature review covering three bodies of literature: AM technologies, sustainability, and business model, which are the most significant and relevant to the research inquiry. The literature illustrates that both theoretical and empirical studies in the fields of sustainable AM business models are still immature. Various researchers have shown extensive interests in AM business model. Still, little empirical evidence is found on how AM companies can better create and capture sustainable value from AM technologies.

There is so far no consistency and agreed definitions of a BM, BMI, SBM and sustainable value. The few published literature is mainly based on the researchers' perceptions and fail to offer empirical evidence. Due to the emergent nature of the topic, there is a need for in-depth case studies research into business models within AM companies. AM is regarded as a promising green technology that can bring several advantages, but it does not seem to bring sustainable effects automatically and inherently. The development of sustainable AM business model is still challenging.

The literature analysis helped the author identify four key concepts: triple bottom line, system thinking, multi-stakeholder perspective, value creation, and sustainable value used in analyzing AM companies to build sustainable business models. Based on that, three analysis processes are developed as the underlying logic to construct the conceptual framework. The framework thus lays the foundation for the data collection and analysis in the research finding parts. This chapter also confirms the research gap and research questions.

Chapter 3 Research Methodology

This chapter comprehensively articulates the research strategy and the decision made by the author to develop an appropriate approach to carry out the research, answer the research questions, and achieve the research aims and objectives. The philosophical assumptions, procedures of inquiry (research design), and research methods of data collection, analysis and interpretation are explained, which involve the determination of an appropriate methodological approach and an underlying philosophical position. The chapter also describes the taxonomy of different methodological approaches, justifies the research strategy, and discusses data collection techniques.

This chapter aims to present and justify the methodological strategy, including the philosophical paradigms, the research design, and the methods of data collection, analysis and interpretation. The literature review part in the previous chapter has justified the meaningfulness of the research questions by demonstrating the knowledge gap and research motivations. The nature of the meaningful research question is to use a proper solution known as the research method to find appropriate answers to address the questions.

The broad research approach involves the intersection of philosophy, research designs, and specific research methods (Creswell & Creswell, 2018). The framework clearly explains the interaction of these three components involved in an approach, shown in Figure 3.1. Therefore, the research approaches are selected for conducting the research-based upon the justification of philosophical paradigms, detailed research designs, and research methods as well as the justification of their interconnections.

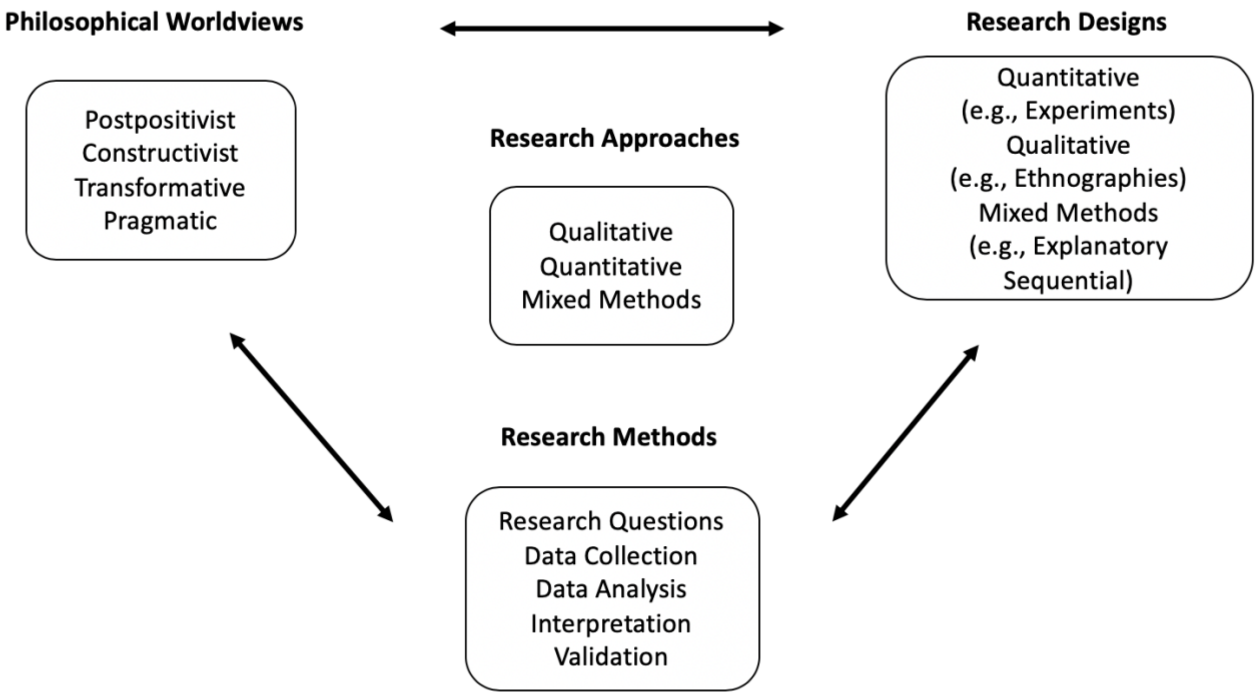

Figure 3.1: Intersection of philosophical worldviews, research designs, and research methods (adapted from Creswell & Creswell, 2018)

3.1 Philosophical Worldview

Creswell & Creswell (2018) use the term *worldview* instead of *paradigm* to describe “*a basic set of beliefs that guide action*” (Guba, 1990). Creswell & Creswell (2018) consider worldview as a general philosophical orientation about the world and the nature of research. Other researchers claimed philosophical worldview as epistemologies and ontologies (Crotty, 1998), or research methodologies (Neuman, 2006). The worldview is held to be the set of beliefs which will lead to implementing qualitative, quantitative, or mixed methods in the research. Philosophical paradigms as a general philosophical orientation about the world, even though they remain profoundly hidden in research, they still influence the practice of research and need to be identified (Slife & Williams, 1995). The philosophical assumptions made by the inquirers consist of ontology (nature of reality), epistemology (how the researcher knows about it), axiology (the role of values in the research), rhetoric (the language of research), and methodology (the methods used in the research) (Creswell, 2013). The underlying philosophical paradigms can be revealed by each philosophical assumption and can find its position in the spectrum of these assumptions. The philosophical assumptions, including ontology, epistemology, axiology, rhetoric, and methodology, are illustrated in Table 3.1, which direct the research process in a logical sequence.

Table 3.1: Philosophical assumptions (Creswell, 2013)

Philosophical Assumptions	
Assumption	Question
Ontological	What is the nature of reality?
Epistemological	What is the relationship between the researcher and that being researched?
Axiological	What is the role of values?
Rhetorical	What is the language of research?
Methodological	What is the process of research?

Four widely discussed philosophical worldview or beliefs arise based upon discipline orientations, research communities, and past research experiences, namely postpositivism, constructivism, transformative, and pragmatism. The significant elements of four philosophical paradigms are highlighted in Table 3.2.

Table 3.2: Major elements of four characterized philosophical worldview (Creswell, J. W., & Creswell, J. D., 2018)

Postpositivism	Constructivism
• Determination • Reductionism • Empirical obervation and measurement • Theory verification	• Understanding • Multiple participant meanings • Social and historical construction • Theory generation
Transformative	**Pragmatism**
• Political • Power and justice oriented • Collaborative • Change-oriented	• Consequences of actions • Problem-centered • Pluralistic • Real-world practice oriented

3.1.1 Choosing a Philosophical Paradigm

This research addresses a real-world problem and contributes to both academic and practical knowledge. The purpose of the research is to explore how sustainability concepts can be embedded in the implementation of AM technologies and to develop AM business models to create sustainable value. The research aims to explore how AM companies could develop sustainable business models to create value from AM technologies. This is a real-world practical oriented research question with a focus on AM business models. This research primarily relies on practitioners' opinions, experiences, and perspectives of a particular type of social activities. The author analyses the selection of philosophical paradigms from the perspectives of ontology, epistemology, and methodology.

Considering the ontology, two essential aspects of dealing with the nature of reality and existence are namely objectivism and subjectivism (Easterby-Smith et al., 2002). In the case of objectivism, the researcher receives an objective view of a social phenomenon. In term of subjectivism, as each individual perceives social phenomenon in different ways, the researchers get more diverse answers instead of straight answers (Saunders et al., 2009). The research meanings derive from the interaction with others. Crotty (1998) presents that participants seek to understand the world and develop meanings based upon their own experiences and personal background. The researchers work and interact with participants base upon cultural and historical experiences to co-construct the social realities. Constructivists interpret the world where people live and work, mainly to understand meanings that others have about the world from a subjective perspective in which the researcher and the researched are inseparable.

This research seeks to investigate each individual company to yield different answers rather than make general assumptions. Therefore, the ontological approach is in line with the subjectivistic perspective. Once subjective views are obtained from different AM companies, the author will take an objective stance in interpreting the different sources of data to reduce the subjectivity. In terms of methodology, constructivism involves an inductive process “from the ‘bottom-up’ to build theory” which the fundamental consideration is from the particular to the general or grounded theory. Furthermore, the constructivism perspective is to understand the subjective meaning of individual experiences and to seek the complexity of views instead of narrowing meanings. Thus, constructivism is selected as a better choice than other paradigms as it takes account into multiple social constructed realities, and the co-construction perspective indicates the suitability of constructivism in guiding the research.

This research addresses two main problems: inadequate understanding of AM business models (theoretical problem); and the lack of practical guidance for helping AM companies to develop sustainable business models (practical problem). The author discussed the concept of the business model and the great need for increased understanding of the sustainability implications of AM technologies. The research outlined the need for empirical studies on AM business models and justified reasoning to conduct the research for increased understanding. The research also attempts to understand the sustainable value of AM technologies and how AM companies could develop sustainable business models to create value. Apart from exploring the existing AM business models, this research also attempts to identify the failed value exchanges with multi-stakeholders and the critical factors which can guide AM companies in innovating and transforming business models toward sustainability. Through the literature review, the author explored AM sustainability issues and the challenges of AM technologies.

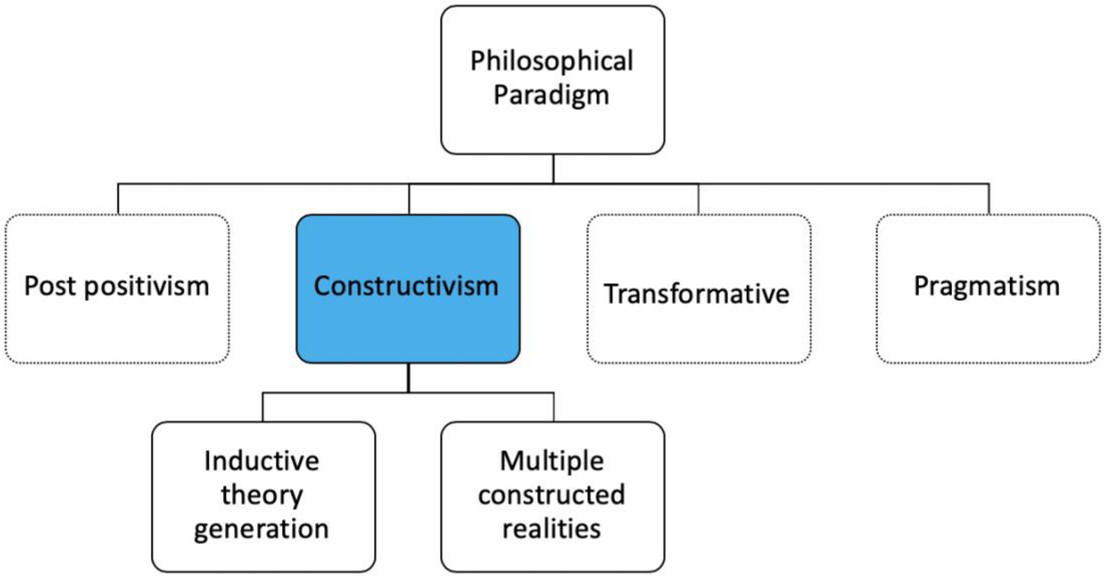

Figure 3.2: Constructivism as the chosen philosophical worldview for this research (Author generated)

Besides this, the research needs to collect participants' opinions and experiences about the current AM business models and the failed value exchanges to build new knowledge from empirical evidence. The conceptual model based on the understanding of the phenomenon and the possible solutions to the research question is constructed, shown in Figure 3.2. However, there are no existing theories based on influential empirical studies to answer the research questions; thereby, a theory is established from the bottom-up approach in an inductive process, rather than to be tested deductively. The research requires subjective descriptions of AM business models and explores the new possible ways of using AM technologies in different AM firms. The exploratory and interpretive nature of this research justifies that the philosophical positioning of constructivism and inductive research approach is more suitable than other philosophical paradigms as a basic set of beliefs. Figure 3.2 depicts the constructivism as the chosen philosophical paradigm for this research.

3.2 Research Design

This section aims to explain the research design and seek to select a research approach for this research. The research design refers to procedures for addressing a research question through the collection, analysis, interpretation of data in a research study. It also directs method decisions made by researchers and sets the logic of interpreting research data. Research designs are claimed as *strategies of inquiry* (Denzin & Lincoln, 2005), *approaches to enquiry* (Creswell & Plano, 2011) or *research methodologies* (Mertens, 2010). Primarily, three research approaches are conceived as prominent research design, namely quantitative, qualitative, and mixed methods. In light of this, qualitative and quantitative represent different ends on a spectrum, while mixed-methods reside in the middle of the spectrum. The main elements of the three types of research are shown in Table 3.3.

Table 3.3: Main elements of alternative research designs (Creswell, J. W., & Creswell, J. D., 2018)

Quantitative	Qualitative	Mixed Methods
• Experimental designs • Nonexperimental designs • Longitudinal designs	• Narrative research • Phenomenology • Grounded theory • Ethnographies • Case study	• Convergent • Explanatory sequential • Exploratory sequential • Complex designs with embedded core designs

Quantitative Research

Quantitative research has been widely used in social sciences since the late 19th century until the mid-20th century. Mainly, quantitative research involves *experiments, quasi-experiments, applied behavioral analysis* or *single-subject* *experiments* (Neuman & McCormick, 1995). This approach to inquiry involves justifying assumptions to deductively test objective theories by examining the variables and analyzing numbered data within statistical procedures. The experiment seeks to identify the function of treatment and test the impact of a treatment on an outcome by controlling all other factors that could bring a different outcome (Keppel, 1991). Quantitative designs hold complex experiments with different variables and involve techniques of structural equation modelling, hierarchical linear modelling, and logistical regression.

The quantitative design also includes non-experimental designs, e.g. *causal-comparative research*, *correlational design* (Creswell, 2012). Notably, the causal-comparative design seeks to compare two or more classes referring to an actual cause. The quantitative research holds the philosophical assumptions of the postpositivist worldview and derives mainly from psychology. In this scenario, the researchers collected information and data to justify or refute the hypotheses to test the theory by calculating specific patterns of perceptions to a social phenomenon and examining relationships among variables. Furthermore, a longitudinal design is also a typical quantitative approach with data collection over time to investigate the development of ideas. Creswell, J. W., & Creswell, J. D. (2018) particularly highlight two quantitative approaches namely: 1: experiment and 2: survey; the definitions of the approaches are 1: determining if a specific treatment has an impact on an outcome through actual experiments and quasi-experiments; 2: offering a numeric description of trends, attitudes, or opinions of a population by examining a sample of that population which involves cross-sectional and longitudinal designs through questionnaires or structured interviews to collect data.

Qualitative Research

Qualitative research intends to understand and establish the meaning of a social phenomenon or human problem from the various perspectives of participants (Creswell, J. W., 2010). It takes a holistic approach to study the phenomenon and is suitable for research fields where little knowledge has yet been generated (Corbin and Strauss, 2007). As explained in Table 3.3, qualitative research as a constructivist worldview tends to build theory inductively from particulars to general themes. This approach specializes in verifying explanations and validating the accuracy of findings. Furthermore, qualitative research provides expertise in exploring the meaning of an untapped social phenomenon and examining the significant variables that are not known. In light of this, the strategy of inquiry involves several specific approaches, including ethnography, historical research, grounded theory, phenomenological research, case studies, among others (Creswell, 2013).

Mainly, ethnography is a research design that researchers collect primary data through observation and interview with a cultural group, organization, or community in a natural setting to over a certain period to explain how they live, experience and make sense of their lives and culture (Creswell, 2011). Narrative research is a strategy of inquiry that the lives of researchers and stories about participants' lives are explored and retold into a narrative chronology (Clandinin & Connelly, 2000). The grounded theory involves discovering and forming a general, abstract theory of a process and action grounded in the views of participants through using different stages of data collection (Strauss and Corbin, 1998). Phenomenological research explores the human experiences about a phenomenon through extensive engagement to develop patterns and relationships of meaning (Moustakas, 1994). A case study research method involves investigating an event, an activity, a process, or a program in depth to collect detailed information within its real-life context over a period of time (Yin, 2003).

Mixed Methods

The mixed methods research as a pragmatic worldview involves systematic integration or combination of qualitative and quantitative research techniques, methods, approaches into a single study (Johnson et al., 2007). Tashakkori and Teddlie (1998) define the mixed methods research as "*a type of research design in which QUAL (qualitative research) and QUAN (quantitative research) approaches are used in the type of questions, methods, data collection, and analysis procedures, or in inferences*." Mixed methods research refers to the use of data collection methods to collect both qualitative and quantitative data.

Qualitative research includes the collection of open-ended data without pre-determined responses; while quantitative data holds close-ended responses from questionnaires or in a psychological study. As all methods have inherent biases and weakness, the combination of qualitative and quantitative data can, therefore, neutralize the weakness and reduce the biases of each type of data; thus, triangulating data sources is to seek convergence to integrate both methods (Jick, 1979). The distinctive differences between qualitative and quantitative research lie in the forms of data respectively text/image (qualitative) and number (quantitative), open-ended questions and closed-ended questions, emerging approaches, and pre-determined approaches.

3.2.1 Choosing a Research Approach

Selection of research approaches depends on the suitability of using qualitative or quantitative methods and understanding the strengths, limitations of each method. A deductive approach that sometimes called a "top-down" approach begins with thinking theory and involves the use of hypotheses, then collects observation data to test the hypotheses (Saunders et al., 2009). On the contrary, the inductive approach, which is a "bottom-up" approach, works the other way moving from specific observations to broader generalizations (Saunders et al., 2009). Strengths of using the inductive approach by its nature are more open-ended and exploratory to look at how human interpret the social world. On the other hand, the deduction is relatively narrow and involves testing and confirming hypotheses to make clear theoretical significance (Saunders et al., 2009). As this research seeks to gather rich insights into subjective views to make a broad generalization and contribute to theory from research data, this research will mainly execute inductively.

Furthermore, an exploratory approach is well suited for this research, as empirical support is limited; Thus, the research will shed light on the matter. Despite the increasing amount of literature on AM technologies, few offer insights into the AM value generation based on empirical evidence, and few provide theoretical foundations for this research. This research aims to understand how AM companies could create sustainable value through business model innovation. The research aims to address the complex, real-world problem identified in the AM industry and provide new knowledge to help AM companies develop sustainable business models. The research question "*How can AM companies develop business models to create and capture sustainable value*?" requires a close examination of the AM business models and failed value exchanges amongst multi-stakeholders. The critical factors that guide AM companies to develop business models toward sustainability also need to be identified. In light of this, the research intends to understand a practical problem in which the detailed understanding can be obtained by talking directly with people, going to workplaces, and doing fieldwork.

However, qualitative methods inherently hold several limitations. In this research, qualitative approaches focus on capturing subjective perspectives on business models and sustainability associated with AM processes. The precise measurement of energy saving implications, materials consumption, and waste reduction could not be assessed and more difficult to analyze using qualitative method. Notably, the data collection process is relatively time-consuming, and the findings could not be generalized. Additionally, the research involves asking open-ended questions, collecting individual opinions, and different AM practitioners' viewpoints need to be analyzed associated with their background. Thus, the results could not be verified objectively as the participants have more control over the data content.

Furthermore, the existing theories do not adequately capture the research problem's complexity; the quantitative measures and the statistical analysis do not fit the problem. Thus, the qualitative approach demonstrates a better fit for this research. Using a qualitative approach is adequate for addressing the research questions through inductively building theory from the bottom up and from particular to general themes. The richness of data would be a significant key for this qualitative study. Therefore, a qualitative approach is proposed as the primary method, which enhances the understanding of the research question and the research findings, as shown in Figure 3.3.

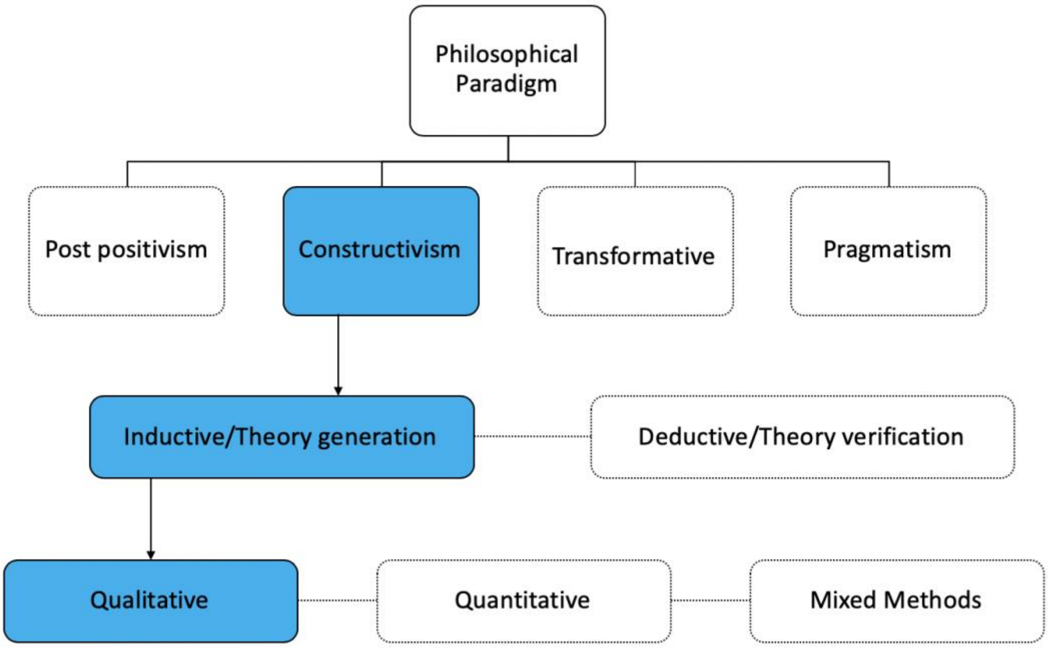

Figure 3.3: Qualitative research as the chosen research approach for this research (Author generated)

3.3 Choosing a Qualitative Approach to Inquiry

As qualitative research is chosen as a proper approach for conducting the research, this section intends to identify the specific approach to the qualitative enquiry for this research. The qualitative approach to inquiry involves five specific approaches including ethnography, historical research, grounded theory, phenomenological research and case studies (Creswell, 2013). All five approaches involve similar research process and employ similar data collection process, including interviews, observations, documents, and audiovisual materials. In order to choose the best qualitative research approach for this research, the author studies the overview table that contrasts the characteristics of focus, the type of problem addressed, the discipline background, the unit of analysis, data collection forms, data analysis strategies, and the written report (Creswell, 2013), shown in Table 3.4.

Table 3.4: Comparison of the characteristics of five qualitative research approaches (Creswell, 2013)

Characteristics	*Narrative Research*	*Phenomenology*	*Grounded Theory*	*Ethnography*	*Case Study*
Focus	Exploring the life of an individual	Understanding the essence of the experience	Developing a theory grounded in data from the field	Describing and interpreting a culture-sharing group	Developing an in-depth description and analysis of a case or multiple cases
Type of Problem Best Suited for Design	Needing to tell stories of individual experiences	Needing to describe the essence of a lived phenomenon	Grounding a theory in the views of participants	Describing and interpreting the shared patterns of culture of a group	Providing an in-depth understanding of a case or cases
Discipline Background	Drawing from the humanities including anthropology, literature, history, psychology, and sociology	Drawing from philosophy, psychology, and education	Drawing from sociology	Drawing from anthropology and sociology	Drawing from psychology, law, political science, and medicine
Unit of Analysis	Studying one or more individuals	Studying several individuals who have shared the experience	Studying a process, an action, or an interaction involving many individuals	Studying a group that shares the same culture	Studying an event, a program, an activity, or more than one individual
Data Collection Forms	Using primarily interviews and documents	Using primarily interviews with individuals, although documents, observations, and art may also be considered	Using primarily interviews with 20–60 individuals	Using primarily observations and interviews, but perhaps collecting other sources during extended time in field	Using multiple sources, such as interviews, observations, documents, and artifacts
Data Analysis Strategies	Analyzing data for stories, "restorying" stories, and developing themes, often using a chronology	Analyzing data for significant statements, meaning units, textual and structural description, and description of the "essence"	Analyzing data through open coding, axial coding, and selective coding	Analyzing data through description of the culture-sharing group and themes about the group	Analyzing data through description of the case and themes of the case as well as cross-case themes
Written Report	Developing a narrative about the stories of an individual's life	Describing the "essence" of the experience	Generating a theory illustrated in a figure	Describing how a culture-sharing group works	Developing a detailed analysis of one or more cases

This research aims to understand how AM companies could develop sustainable business models to create value from AM technologies. The main research focus is to understand a practical problem and develop an in-depth description of multiple cases with different AM companies. However, the main focus of this research is not exploring an individual's life, understanding the essence of the experience, developing a theory or interpreting a cultural-sharing group. Therefore, the case study is more suitable than other approaches for this research.

Regarding the type of problem suited for design, this research mainly intends to understand what critical factors can guide AM companies to develop sustainable business models. These research questions are mostly ‘what’ and ‘how’ questions in unexplored research areas and understanding of cases instead of telling stories of individual experiences or interpreting a shared pattern of culture. Case study refers to studying a social phenomenon and is more likely to have significant strengths such as novelty, testability, and empirical validity (Eisenhardt, 1989). Furthermore, the theory developed from case study results in new insights with an understanding and an explanation of a social phenomenon. Thus, the case study is more suitable than other approaches for this research.

In terms of the unit of analysis, this research is studying AM business models through primary interviews, observations and documents analysis. In light of this, the data strategies of this research are to describe the cases in-depth and develop themes of the cases along with cross-case themes rather than re-storying stories and describing the culture sharing group. Concerning the written report, the research intends to develop an in-depth analysis of one or multiple cases instead of a narrative about stories of an individual’s life, a theory or a culture-sharing group. This research needs to collect participants’ opinions and experiences about AM business models and failed value exchanges with multiple stakeholders. Hence, the case study is more appropriate than other approaches for conducting qualitative research. Case studies are chosen as a fundamental data collection method because this research studies a sophisticated, contemporary phenomenon with few existing theories. Also, case studies can provide significant novelty, testability, and empirical validity to build theory (Eisenhardt, 1989).

This research begins with a regular literature review covering three bodies of literature: AM technologies, sustainability, and business model, and then builds a theoretical, conceptual model using AM business model as the unit of analysis. The main research question “*How can AM companies develop business models to create and capture sustainable value*?” is a “how” type question. It studies a sophisticated, contemporary phenomenon which the author has no control of behavioral events (Yin, 2013). The research investigates the emerging AM industry and attempts to gain exploratory, real-life insights that help better develop sustainable AM business models. Therefore, the lack of viable theory and empirical evidence and the emerging nature of the research topic justify case study as a suitable approach for this research in Figure 3.4.

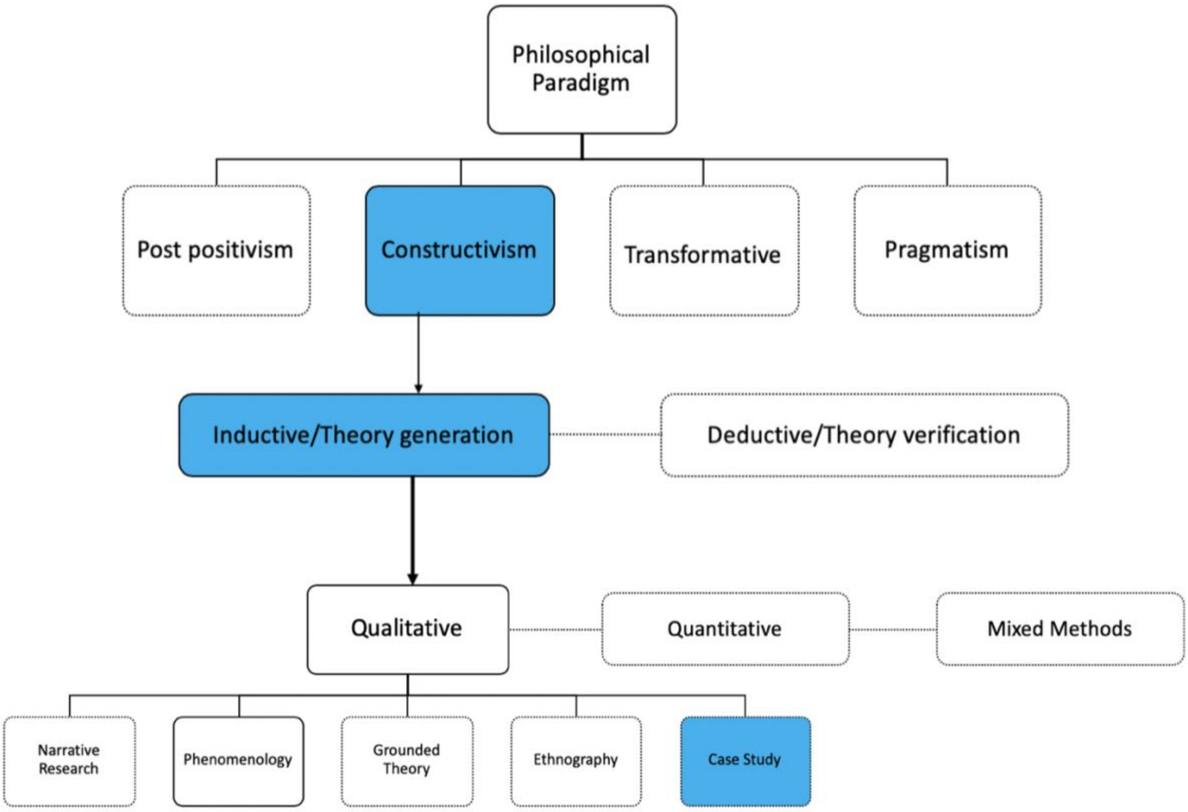

Figure 3.4: Case study as the chosen qualitative approach for this research (Author generated)

3.4 Designing Qualitative Research

The research employs the philosophical paradigm of constructionism and chooses qualitative case studies as the principal qualitative approach. The author developed a flowchart based on a qualitative constructivist format to explain the research design (Creswell, 2009). The flowchart of designing the research is shown in Figure 3.5. The flowchart begins with the introduction part, including the statement of the problem, review of the literature, purpose of the study, research questions, delimitations and limitations, as well as research methodology. Notably, the statement of the problem is to identify a situation beyond the existing range of experience and knowledge with no concrete solutions in which follows a review of the relevant literature to understand the research problem.

The second part of the flowchart is part of the procedure that depicts the overall design of the qualitative research methodology to address the research problem. This procedures part provides different methodological choices, characteristics of qualitative research and philosophical assumptions. The part also includes data collection and analysis and research strategies for validating findings (Creswell, 2009). The third part presents the significance of the study to reflect on the effects of the solution. The fourth part is to show the preliminary pilot findings through the proper solution, and the last part is to get the expected outcomes to answer the research question.

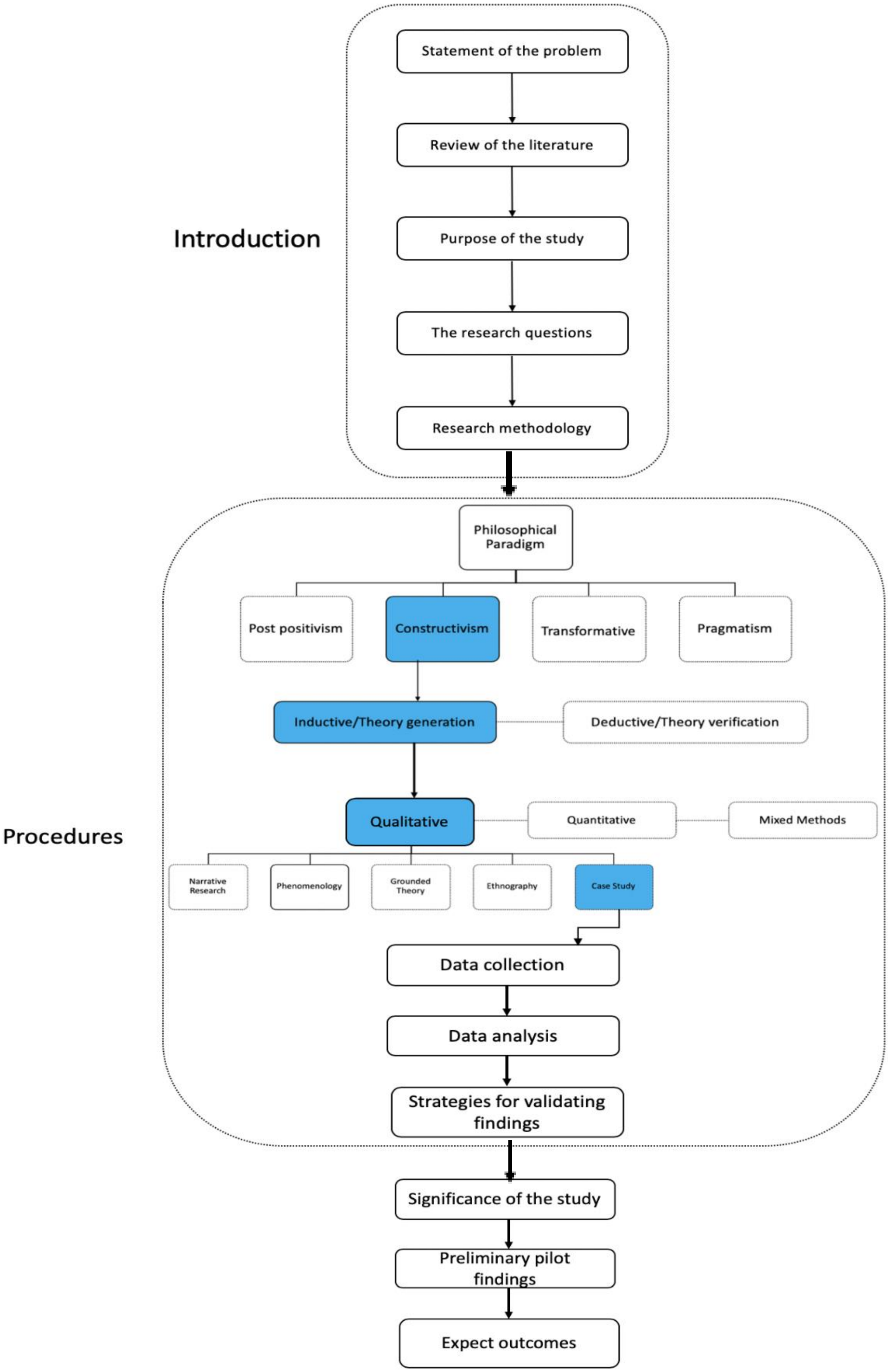

Figure 3.5: Process of research design (generated based on Creswell, 2009)

3.5 Data Collection and Analysis

Guba and Lincoln (1989) present data collection methods that concentrate on the procedures of data collections, analysis, and interpretation. Case study research involves studying a case within a real-life, contemporary context (Yin, 2003). The case study is considered as a strategy of inquiry, a methodology, a research strategy or a type of design in qualitative research (Creswell, 2013; Yin, 2003; Denzin and Lincoln, 2005; Merriam, 1998). Yin (2003) claim that the case study is an effective empirical method to gain explorative, real-life insight that allows the researcher to build theory. Case studies are used widely in exploratory, descriptive, and explanatory research (Yin, 2003). There are three types of qualitative case studies that distinguished by the intent of the case analysis namely the single instrumental case study, the multiple case study, and the intrinsic case study (Creswell, 2013).

Notably, in a single case study, the researcher concentrates on an issue and selects one case to explain the issue (Stake, 1995). In a multiple case study, the researcher might select multiple cases and study several programs to illustrate different perspectives on the issue. While an intrinsic case study is to focus on the case itself rather than an issue or a concern as the case presents an unusual or unique situation (Stake, 1995). Furthermore, the data collection in case study research derives from different sources of information such as documents, interviews, observations, and archival records (Yin, 2003).

This research involves an in-depth examination of sustainable AM business models. The case study approach is suitable for this research in light of the limited work that has been undertaken into business models. Also, this approach is apposite in studying a sophisticated, contemporary phenomenon with few existing theories (Bryman and Bell, 2015; Yin, 2003). Yin (2003) indicates that a case study is identified as an empirical inquiry that the boundaries between phenomenon and context are not evident. The case study investigates a contemporary phenomenon in depth within its real-life context when the phenomenon is not sufficiently theorized and complex (Yin, 2003). Single-case design help researchers generate thorough insights, and multi-cases design allows researchers to compare different variables. Multiple-cases design is particularly relevant for avoiding extraneous variation and providing a broad picture of a complex phenomenon (Yin, 2003). Conducting only a single-case study is far from enough to illustrate the features of whole AM ecosystems. Mainly, this research involves multiple and comparative case studies as it supports generalization better (Yin, 2003). Thus, a multiple-case study is chosen to mitigate the weakness of a single case study. The unit of analysis for this research is the AM business model, and the data collection protocol is designed. Qualitative data is collected, and single case analysis is conducted. The single case findings are compared across all the cases for cross-case analysis. Then, the findings are synthesized, and the themes are generated. The author identifies the cases with boundaries and seeks to understand the cases and compare multi-cases comprehensively. The author provides a detailed description of each selected case, followed by a cross-case analysis which interprets the themes and meaning across the cases.

The overall procedures start from the review of the literature to collect the secondary data. In this research, the literature review was adopted to investigate sub RQ1. Literature review delivers constructs to lay a foundation of building theory in qualitative research (Eisenhardt, 1989). The key concepts from the literature were synthesized and used to build up the conceptual framework. The general literature review intends to have a better understanding of the overview of AM technologies, AM business models and sustainability perspectives, thus setting the base for the development of the conceptual framework as discussed in the previous chapter.

The purpose of research can be classified into three categories in social science, namely: exploratory, descriptive, and explanatory (Robson, 2002). Exploratory research aims to seek new insights, assess new phenomenon, and figure out what is happening. It can be used in research when little is known at the beginning of the study (Robson, 2002). The information collected in an exploratory stage can be used to lay the foundation of descriptive research. Descriptive research aims to portray an accurate profile of the situations and define critical variables. However, analytical research intends to seek an explanation of situations or phenomenon in the form of causal relationships, preferably using the quantitative approach. In light of this, analytical research could be used to explain the key relationships and test the theories generated by the first two stages.

This research purpose encompasses two categories, exploratory and descriptive. In the exploratory stage, the research seeks to understand AM business models better, failed value exchanges with multi-stakeholders and the challenges of AM to find out what is happening, which are lack of prior theory, and identify critical factors and value opportunities, therefore exploratory. Data is collected in phase one to identify initial findings and generate themes as critical factors to help AM companies develop sustainable business models. Based on the analysis and initial themes from the exploratory stage, new data is collected in phase two of descriptive research to confirm, reject, or shape codes to the identified themes and validate them. This stage aims to provide an accurate description of the phenomena. In the third phase, several theoretical and practical models are developed based on the comparative analysis and synthesis of data across multi-cases; the practical frameworks are proposed and developed in the final stage to solve the research problem better. New literature is reviewed throughout the data collection and analysis phases for strengthening the understanding of the cases.

3.5.1 Case Selection

AM technologies are developing rapidly and are presumably too far away to reach the full adoption situation. The investigation cases for this research were selected following a sampling strategy selected by considering strategy, access, and representativeness (A Bryman, 2012), where the AM business model is the unit of analysis. The author used two criteria to identify cases among manufacturing companies. The first criterion is that the target companies are AM companies as the decisive factor that AM technologies/products/services are their core business/focus rather than traditional manufacturing companies that use AM technologies or intend to adopt AM. The second criterion is that the selected AM companies are market leaders and have a significant market impact and share with substantial business experiences.

The selected AM companies in this research embrace different AM functions and business orientations, including 3D model design, materials, machine, software development, online printing service, education platform, consulting service, among others. There are 30 companies targeted at first that ensuring the data collected are sufficient and robust. The author decided to select 6 cases in total that are the most representative ones encompassing different AM sectors. Six cases were chosen is due to the degree of theoretical saturation reached when the incremental improvement is minimal and gathering new data no longer sparks new insights (Eisenhardt, 1989; Charmaz, 2006). Furthermore, Eisenhardt (1989) suggest that 4-10 cases selected in case studies are desirable and usually work well. Six cases selected for this research provide sufficiently new perspectives, elaborate emergent phenomenon and replicate findings across cases (Eisenhardt & Craebner, 2007).

In terms of selecting proper interviewees, the author considered CEOs, senior managers (e.g. sales, marketing, operation directors), designers, and engineers. Those interviewees are expected to provide attractive opinions for data collection. The criteria are set for the identification of potential interviewees to enhance the validity and reliability of this research. For the industry-related interviewees, all the CEOs and senior managers are required to have five years' working experiences in the AM industry; engineers and designers are required to have a strong technical background and design capabilities with three years' experiences working in the AM industry. The interview questions follow a conversational approach and are tested before approaching to interviewees for data collection. The questions follow a typical structure including company introduction, current business models and value systems, sustainability issues, products/services, significant challenges for AM adoption, failed value exchanges, PSS, sustainable value creation, policy and regulation, and future development.

All interview processes were audiotaped with prior consent for later transcription and analysis. Consent can be withdrawn before or during the interview process. The interviewee can leave at any time and has the right to withdraw without penalty from the study before letting the author know he/she wishes to withdraw. The author may ask the interviewee for reasons for withdrawal for evaluation purpose. The time and date for an interview were agreed upon with interviewees to fit their schedules best. The interviews typically lasted among 1 - 3 hours and were conducted in English. The author travelled to Japan, United States, China, to collect data. Most of the interviews were conducted at the company sites, industry conferences, and expos. Notably, the author spent four months in Japan and four months in the US to conduct in-depth interviews with the case companies. Data were collected between October 2016 and November 2018, over 24 months. Data were collected from multiple sources, including a documentation (e.g. company reports, website articles, newspapers, and project documents), observation, presentations, and transcripts of interviews and workshops. A detailed list of interview questions is attached as an appendix (see Appendix A).

In summary, following the sampling guidance, six cases were selected from three countries including China, USA, and Japan during two data collection phases. These cases cover all identified AM business models, ensuring the research validity and reliability.

3.5.2 Qualitative Data Collection

Qualitative data analysis method (Miles and Huberman, 1994) is used to collect and analyze the data. The analysis process is conducted through three stages of coding namely open coding (i.e. read the data, note down codes for related statements, and assign them to categories), axial coding (i.e. re-read data, confirm the concepts and categories accurately), and thematic coding until saturation to explore how the concepts and categories are related. Furthermore, the data collection forms of the case study are to use multiple sources of evidence to reduce bias and increase validity. Table 3.5 describes different data collection forms and data sources that the author used for this research.

The author considers the interview as an essential source of case study information and seeks to choose well-informed interviewees in AM companies to provide meaningful information and insights. Hence, the interview is selected to collect primary data for this research. There are three types of interview, i.e. fully structured, semi-structured, and unstructured interview. The order of the questions of a structured interview is predefined, and the verbal interactions between participants for each question are to be the same; the order of the questions of the semi-structured interview can be modified depending on what is the most appropriate for finding better answers; for unstructured interview, however, there is no predefined order of questions. It is using open-ended questions to encourage free expression and verbal interaction with no predetermined set of expectations for the researcher (Robson, 2002; McQueen and Knussen, 2002).

Table 3.5: Data collection methods and sources (Author generated)

Data collection methods	Sources
Interview: semi-structured and unstructured and focus group	Leading AM firms' leaders; CEOs; senior managers; engineers; designers
Observation	Fieldwork
Document analysis	Annual reports of AM companies; technology reports; consultancy articles; official government documents, newspaper articles and websites

This research attempts to explore authoritative interviewees' opinions about AM business models and failed value exchanges within AM companies. It requires respondents to provide new ideas and significant insights into affairs and actions to improve the validity and reliability of this research (Yin, 2003). Therefore, semi-structured and unstructured interviews are used to collect data more flexibly than a structured interview. The interviews protocol follows a systematic structure to ensure the reliability and quality of the data.

Focus group is regarded as an effective and highly interactive data collection method to obtain information from participants with different perspectives about a problem that is rarely offered by other data collection methods; for instance, individual interviews or survey (Van de Ven and Johnson, 2006). The author used focus groups to identify significant facts and gain exciting insights into a group setting. The research organized industry workshops with the participation of senior managers, engineers, designers, and other experts in the AM industry. Thereby, the author conducted face-to-face interviews with participants and engaged in focus group interviews with a wide range of interviewees in each group.

Participant observation is used as the complementary data collection method in this research to attain the opinions of participants inside the case studies (Yin, 2003). The author used observations to watch what participants do, record and analyze what is observed in a natural setting on the behavior, which not interfere with anything that is being observed, and not influences the behavior to be observed. The author observed and took field notes at the research site. It provides a better understanding of the context and phenomenon and rich information about the subject.

Documentation is perceived as a common source of evidence in a case study. The interview data is complemented by data from other sources: particularly, academic papers, company reports, consultancy reports, technical reports, press release, presentation, government publications, and industry newspapers. Thus, the data in this research are collected through multiple sources of interviews, documents analysis, and observations, including interview transcripts, observation memos, documents summary, emails and literature.

The survey is used to collect information in the format of the questionnaire and a structured interview for this research. The research is highly exploratory, and all the identified variables for survey method does not yet exist. Therefore, due to the lack of theoretical propositions, it is challenging to develop a structured questionnaire to conduct the survey for this research. Other alternative methods such as action research are not adopted, because this research is not targeted at understanding and planning of change in social systems (Easterby-Smith et al., 2002). However, the research has the potential to adopt an action research method when the research aim is to bring about change. Thus, the survey is likely to use once the phenomenon is better understood, and the variables are identified in the future.

3.5.3 Exploratory Stage Data Collection

In the exploratory stage of data collection, three case studies (Table 3.6) were conducted to observe and understand different AM business models, failed value exchanges, challenges of AM development and critical factors as well as valuable opportunities for each case. The author conducts significant focal firm engagement where spend a large amount of time with the senior management team of strategy and operation in the companies. The case companies are selected in various sectors, including design, machine, material, and service-oriented. These case companies are AM focus and have acknowledged leadership in the AM industry. The findings are based on 15 semi-structured interviews with 11 participants (interviews with a mean duration of approximately 100 minutes) and supported by observation, site visits, and documents analysis (industry reports, practitioner-oriented articles, news). The interviews include senior management with comprehensive experiences in AM management and technology implementation. Those interviews mainly focus on the general questions such as customer and product/service-related questions and seek to understand the particular experiences of participants. With the interviewee’s permission, all interviews were recorded and later transcribed to produce over 100 pages of text-based data. All the interviews were recorded and transcribed word by word to avoid bias. (Chapter 4 presents the findings). A detailed list of interview questions is attached as an appendix (see Appendix A). Table 3.6 presents the details of case companies in the exploratory stage, including three companies, 15 interviews, and 11 participants.

Table 3.6: Interviews in the exploratory stage (Author generated)

Company	AM Sector	Interviewee/Job Position	Methods	Time (mins)	Location
Case A:	Design service; data management; AM coffee shop; AM museum	A1: CEO	Face to face interview; emails follow up; observations; phone call; document analysis	100+80	China
		A2: Design Director		60	
		A3: CMO		70	
Case B:	Machine; printing service; software; materials	B1: Business Development Director	Face to face interview; emails follow up; phone call; observations; document analysis	100+100	USA
		B2: Product Manager		100+60	
		B3: HR		80	
		B4: Sales Manager		80	
		B5: Market Representative		60	
Case C:	Materials; printing process; design service	C1: CTO	Face to face interview; emails follow up; phone call; observations;	100+60	Japan
		C2: Business Development Director		100	

Company	AM Sector	Interviewee/Job Position	Methods	Time (mins)	Location
		C3: Sales Manager	document analysis	60	

3.5.4 Descriptive Stage Data Collection

The descriptive stage of data collection is to gain significant insights into AM business models, failed value exchanges within AM companies, challenges of AM development, barriers of implementing AM, critical factors for sustainable value creation, and value opportunities. New data are collected to reject, shape and confirm the themes identified in the exploratory stage. In this stage, three companies and 19 semi-structured interviews with a total of 14 participants (Table 3.7), two focus groups with a total 18 participants (Table 3.8), and two site visits are used to collect data. At the descriptive stage, the interviews mainly focus on the multi-stakeholders, future development, and other open related questions (see Appendix A). With the interviewee's permission, each interview was recorded with a mean duration of approximately 100 minutes and later transcribed to produce over 120 pages of text-based data. All the interviews were recorded and transcribed word by word to avoid bias. Each interview has listened, and the transcripts were read five times to avoid missing interesting constructs and themes. An iterative interview mode is adopted that requires the correcting and re-planning of interview questions. The author intends to provide an accurate description of the identified themes where the themes are applied to the development of frameworks and models (will be discussed in Chapter 6).

Table 3.7: Interviews in the descriptive stage (Author generated)

Company	AM Sector	Interviewee/Job Position	Methods	Time (mins)	Location
Case D:		D1: CEO		100+100	China

Company	AM Sector	Interviewee/Job Position	Methods	Time (mins)	Location
	Machine; printing service; design service; ODM	D2: Sales Manager	Face to face interview; emails follow up; phone call; observations; document analysis; site visits	90	
		D3: COO		80	
		D4: CTO		100	
		D5: Project Engineer		100	
Case E:	Printing service; machine; education; online information service	E1: CEO	Face to face interview; emails follow up; phone call observations; document analysis; site visits	120+100	China
		E2: COO		80+90	
		F3: CTO		90+100	
		E3: Sales Manager		80	
		E4: HR		60	
		E5: Business Development Director		60	
Case F:	Consulting service	F1: Consultant 1	Face to face interview; emails follow up; phone call; observations; document analysis; site visits	120+100	Japan
		F2: Consultant 2		100	
		F3: Consultant 3		120	

The author conducts two focus groups to collect data by observing workshops. The workshop involves 18 participants to discuss the interview questions. The critical factors and root causes identified at the exploratory stage and descriptive stage were introduced to the focus groups in the workshops to facilitate discussion and idea generation. Their opinions and reactions were observed and documented. The focus groups (Table 3.8) include the participation of the CEOs, senior-level managers, designers, and engineers to get feedback from a broader range of people with different perspectives. Table 3.8 shows the focus groups with Company G and Company H with 18 participants in total.

Table 3.8: Focus groups in the descriptive stage (Author generated)

Company	AM Sector	Participant Number/Job Position	Methods	Time (mins)	Location
Case G:	Education; E-commerce platform	10 participants/ CEO; CMO; operation; sales; marketing; R&D; strategy; finance; general management	Focus group; presentation observations; workshop; document analysis; site visits	180	China
Case H:	Service platform; online printing	8 participants/ CEO; CTO; CMO; strategy; business development; manufacturing; sales; operation	Focus group; presentation; workshop; observations; document analysis; site visits	160	China

3.5.5 Qualitative Data Analysis

A linear and hierarchical approach building from the bottom to the top is developed and used to guide the qualitative data analysis (Creswell, 2013), shown in Figure 3.6. Firstly, the computer-assisted qualitative data analysis software was used to organize and prepare the data that involves storing, transcribing, structuring, and analyzing all data. Second, all data were coded into categories, methods and rules used were extracted and classified. The single-case findings were analyzed to describe, understanding and explain what happened in each case. Each case study was carried out to identify emerging patterns relevant to the research questions. The cross-case analysis was then implemented to interpret different forms of data and to look for patterns across different cases. Multiple case studies were conducted to generate robust theory and to validate the theory through replication in various situations (Eisenhardt 1989; Yin 2003). The interviewees were asked to provide opinions of current business models (value proposition, value capture, value creation, value delivery), technical challenges, failed value exchanges, product and service, customer problems, supplier problems, future development, and sustainability issues. The author aimed to report with high fidelity what the interviewees said. The single-case findings were then analyzed across all the cases for cross-case synthesis.

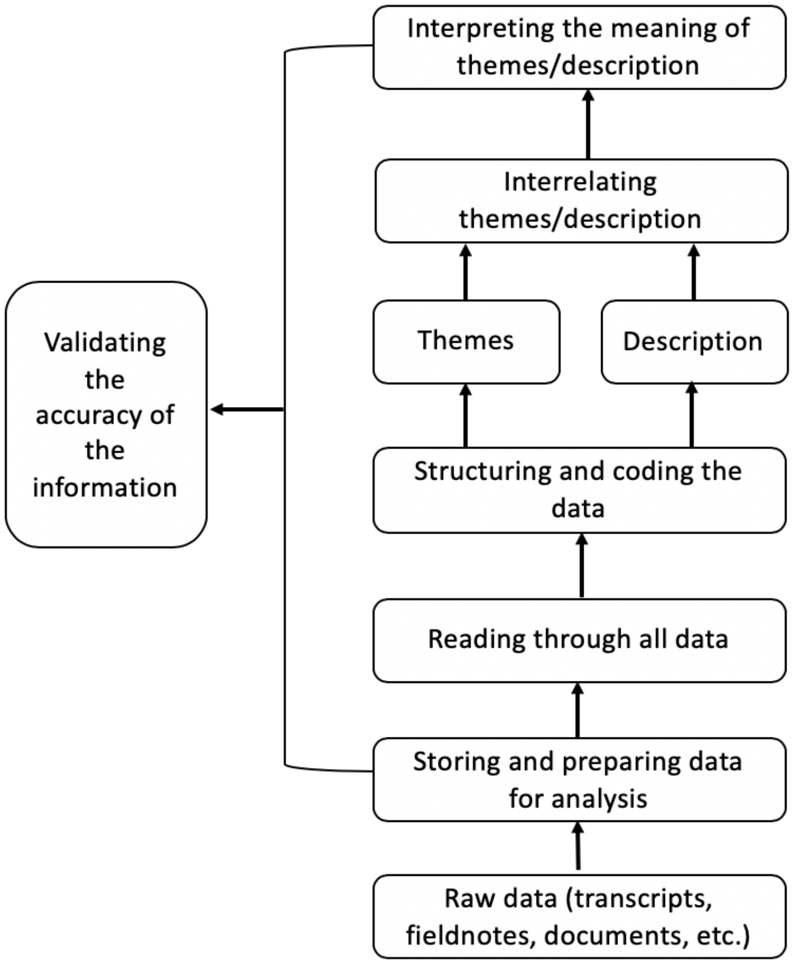

Figure 3.6: Structured qualitative data analysis process (Creswell, 2013)

The author uses thematic analysis to identify, analyze, and report patterns within data (Braun and Clarke, 2006). Themes are patterns to describe a phenomenon and answer particular research questions. The author follows a typical process for conducting thematic analysis: 1) transcribing data (read data, note down codes); 2) generating initial codes (generate related statements and transform them to different categories); 3) search for themes (re-read data, and identify similar codes or categories); 4) reviewing themes (identify patterns in coding and cluster codes into common themes); 5) defining and naming themes (Braun and Clarke, 2006). Several different themes that display multiple perspectives and a description of the setting for analysis were produced. The themes are the significant findings in this study, which will be further discussed in the findings section.

In the exploratory stage, the interviews, observations, and document analysis are conducted. Interesting quotes across different cases are highlighted and clustered into generic groups to generate initial themes and description to build layers of complex analysis. In the descriptive stage, interviews, focus groups, observations, site visits, and document analysis are conducted. Data is analyzed and coded to confirm, reject and shape the initial themes. Thus, the themes are established, rejected and shaped to form complex theme connections and convey descriptive information about each interviewee. The revised themes are compared against existing literature to check whether it confirms, rejects, or adds detail to the knowledge. The final step involves interpreting the meaning of themes and description to capture the essence of the findings (Lincoln & Guba, 1985). It follows the building theory process from case studies to generate conclusions for two functions: contribution to knowledge, and contribution to practice. Furthermore, the author uses a theoretical lens to develop several conceptual models based upon a comparison and synthesis of the findings.

3.6 Quality of the Research

The author actively incorporated different strategies to improve the accuracy of the findings in this research. The research used multiple sources of evidence, particularly, triangulate different sources of data, including literature review, documentation, observations, and interviews, to build a coherent justification for themes. The following-up interviews were conducted to allow participants to check the accuracy of the significant findings, the themes and to comment on the results. A detailed description of the settings and different perspectives about the themes were produced to convey the results to enhance validity. The convergence of evidence helped avoid single-source bias and the research clarified the bias through self-reflection by the author. On the other hand, this research presents some contrary information and negative evidence to contradict the data, thereby increasing the accuracy and validity of the findings.

Furthermore, the author got involved in the AM fields for several years, regularly engaging with the AM practitioners for a prolonged time which helped in developing a better understanding of the phenomenon. The profound experiences that the author had with the participants in AM companies provided more accurate findings for this research. To enhance the research quality and maintain the reliability, the author documented the procedures of the case studies to check the reliability and looked over the accuracy of transcriptions to avoid the misconception. The cases were selected to be as diverse as possible, including various AM business models and orientations. The cases then were analyzed following the conceptual framework to make research generalization. The replication logic in the selection and analysis of the case highly ensured the research validity. Particularly, the interview processes can be replicated. The fieldwork, workshops and seminars are a bit difficult to replicate due to the factors of personal experience and expertise.

Furthermore, the author listened and analyzed the transcripts until saturation to avoid the bias caused by the author's varying data analysis skills at different stages of the research. The structured qualitative data analysis process was presented to ensure the consistency of research results so that anyone conducted the same case studies would draw the same findings and conclusions. Data triangulation was implemented. The author also stepped back to look for the features and patterns in the irrelevant data during data analysis. The results of the study remain limited in terms of generalizability.

3.7 Chapter Summary

This chapter comprehensively describes each methodological consideration, philosophical assumption, procedures of inquiry, and research methods to answer the research questions better and achieve the research aim. The chapter also presents the taxonomy of different methodological approaches, justifies the research strategy, and discusses data collection techniques. The research stands at the philosophical paradigm of constructivism and adopts a qualitative research approach. It implies a two-phase data collection procedure with exploratory and descriptive stages, respectively. The qualitative data are collected through multi-case studies with different data collection approaches.

Chapter 4 Findings of the Exploratory Stage

This chapter presents the research findings through three cases studies at the exploratory stage. The objective of this chapter is to understand different AM business models and understand how AM companies are developing BMs to create and capture value. At the exploratory stage, the author investigates each case to present a comprehensive picture of all elements within each AM business model, including value proposition, value creates, value capture, value delivery using system thinking. Furthermore, failed value exchanges with the major stakeholders in each case are analyzed. A new type of failed value called *value unsupported* is identified from case studies. The logic of data analysis of the individual case study is based on the conceptual framework developed in Section 2.5 to help identify business opportunities through analyzing value systems and failed value exchanges with multiple stakeholders across the industrial network.

The author seeks to understand more about the sustainability implications of AM and gain significant insights into how companies take advantage of AM to develop business models for value creation and capture. The author also identifies the negative root causes in the aspects of AM design, AM machine, and AM material and then categorizes the negative root causes into the key challenges for broad AM adoption prevention. In light of this, the initial themes are identified as critical factors to help AM companies understand the factors that are significant for sustainable business model development. The themes are also compared against existing literature to check whether to contribute to the knowledge. Furthermore, the value opportunities are investigated for turning failed value into value opportunities in each case.

4.1 Case Study A

4.1.1 Introduction to Company A

Company A is an internationally renowned 3D-printing design company and provides 3D design product and service. The company was founded in 2008 and become one of the most professional 3D-printing design brands around the world. The company dedicates to customized design and 3D-printing related research, development and professional training. Company A specializes in 3D-printing design across multiple scales, ranging from small objects to large installations, interior design and architecture. They aim to create objects using AM technologies to maintain a refined balance between theoretical and aesthetic perspectives, functionality and beauty to achieve long-lasting value.

The reason for choosing this company is that it provides a variety of AM products and services, not only it concentrates on AM design products, but also involves in innovation research, AM cultural museum, and retail café store. Besides this, they offer diversified service to different stakeholders, including data management service, technologies outsourcing, educational training, customized design service, intellectual property trade and sale, among others. This company engages closely with multi-stakeholders to create and capture value. In this case study, in-depth interviews were conducted with the CEO, CMO and Design Director. The interviews were transcribed, and observations were made combining with secondary data from documentary analysis.

4.1.2 Business Model of Company A

The business model for Company A is to provide 3D-printing related products and services to the end-customers and corporations through online and offline sales. The target customers are two types: one is the end-users who are not priced sensitive and pursuing individualism and differentiation; the other one is the corporations who require design data service. The customer value propositions of Company A lie in five perspectives. The first is the professional 3D-printing design products, such as fashion clothing, jewelry, food, lifestyle objects, museum and exhibition derivatives. The products are sold through online and offline shops such as pop shops, retail stores and museum art shops. The second value proposition is the customized data service, working with over 100 companies for design data management. As commented by the CEO:

"*AM is like the television and the TV programs are the 3D models made by the* *designers. If go back to 1970s, in China, at that time, we do have TV, but we have no interesting TV programs*".

The company takes advantage of different types of 3D software to create 3D models for printing and uses different 3D printers such as FDM, SLS, and SLM to produce the objects. The CEO also said:

"*In the AM industry, we do have a lot of advanced 3D printers. However, professional design data is insufficient. Therefore, we are creating the contents, creating the design data instead of developing the AM machines, materials or any hardware*."

The third value proposition is an Innovation Design Center for AM designer's training and technology research. The CEO emphasized:

"*We want to offer the 3D-printing professional design training program, AM industry employment certification, conduct research and development, build up 3D-printing designer platform and database, and manage 3D design IPs*".

The fourth one is the 3D café, which is a 3D-printing café store owned by Company A to make a deep combination between café culture and AM culture. The café store creates a relaxed and youthful place for people who are interested in AM and want to have an AM experience. The fifth value proposition is that company A collaborates with the local government to establish the first AM Cultural Museum in China. The museum holds AM objects, architecture, an exhibition with the combination of traditional education, cultural experience, IP derivatives store, and other functions.

The value creation is that Company A has the abilities to manage different resources and work with different stakeholders closely to adaptively match the technology, customer, and market. As commented by the CEO:

"*We make the decision based on qualitative research like the interview, questionnaire and literature reading to get the feedback from potential* *customers using system thinking to figure out what they want*."

Company A established the 3D design research center to focus on industry-university-research collaboration. One of the core competencies is that the 3D-printing design models can be printed with no defects and flaws on top of that the models can maintain the aesthetic feeling and functionality. Mainly the company has developed the robot arms to print the large-scale objects.

Another unique value creation is that as the data service provider, the company has zero inventory and cost-effectively outsource all the materials supplying 3D models printing, and post-processing parts. Also, the company maintains a close partnership with the downstream and upstream suppliers, including raw materials providers, machine manufacturers, printing service providers, among others. The core capabilities are the design methodology and the fundamental design principles, "*We call it digital baroque style*." The company has developed 3D-printing design training programs to educate potential employees.

"*Our training program is better than the ones available in the market as we have the design methodology, teaching materials and professional experiences, therefore, we can outweigh other training programs and educate our employees more effectively*."

The company takes active engagement with the designers and perceives them as a significant asset. Those designers enable the company to create high value based on the creativity, individual initiative and aesthetic perception. Furthermore, the company makes profits from selling 3D-printing products, providing customized design service and education programs through the online and offline distribution channels.

4.1.3 Value Systems and PSS Solutions in Company A

The business model of Company A is identified through analyzing the value systems using system thinking. System thinking helps better understand the complicated and interconnected systems of company business. The relationship between Company A, customers and value systems has determined the PSS solutions. The company has extended the business to incorporate the sale of integrated 3D-printing products and customized data service as a product-service solution. Mainly, Company A sells the café, lifestyle objects, and museum derivatives along with the technical services including 3D model design, testing and consulting. There are two PSS solutions; one is the product-oriented PSS because the ownership of the product belongs to the customer, and the technical service is included as part of the original sales. The other one is the result-oriented PSS in which the company does not manufacture the 3D printer, nor provide materials instead of outsourcing all the physical equipment, materials, technologies, and sell the 3D design service.

Company A collaborates with different suppliers to help test the design models and ensure all the data can be printed flawlessly. It enlists the services of printing technologies in the market to help realize the design models for the customers. The evidence of economic, environmental and social benefits provided by the PSS solutions within Company A have been identified. Table 4.1 summaries the value systems including value proposition, value creation, value capture, value delivery, social value, environmental value and economic value. The information in this table was mainly generalized from interview data. The codes of economic, environmental and social value emerged and were grouped into the categories as the main findings in Table 4.1.

Table 4.1: Value system analysis for Company A

Valve System	**Main Findings**
Value Proposition	Professional 3D-printing design products; customized 3D-printing data service and data management; IP trade, management and protection; Innovation Design Center; 3D-printing café store; AM Cultural Museum
Value Creation	Industry-university-research collaboration; zero inventory; close partnerships with the downstream and upstream suppliers; design

	methodology and principles; design guidance that considers AM process characteristics; leverage the advantages of AM for direct manufacturing; know AM capabilities and limitations
Value Capture	Different pricing models for the customized design service and data management; charging for different AM products
Value Delivery	The products are sold through online and offline shops such as pop shops, retail stores and museum art shops; one-off payment for the AM design service
Social Value	Improved customer relationships; close partnership with suppliers; improved service efficiency; a museum for education and science popularization
Environmental Value	Product life extension; no machine and materials needed; waste reduction
Economic Value	Outsource hard equipment and technologies; reduced initial investment; diversified products and services for customers; 3D designer training for human resource reserve; innovation design centre for research and development; café shop, museum and exhibition for brand publicity and promotion; IP protection and management

4.1.4 Failed Value Exchanges in Company A

The author implemented the conceptual framework to analyze the business model elements, which takes sustainability and multi-stakeholders into consideration. In this section, the failed value exchanges were identified and analyzed with the consideration of multiple forms of values from a multi-stakeholder perspective. Hundreds of codes of failed value exchanges from the interviews and workshops emerged and were grouped into 48 examples of bullet points in Table 4.2.

Table 4.2: Failed value exchange analysis in Company A

Failed Value Exchanges	Examples/Explanations
Value Missed	•Lack of understanding our design style/concept for customers •Products not well received by end-users •Customers lack understanding of how to use AM for daily lives •Narrow target segmentation •Failed to improve the business to customers •Not focus on general customers' demands
Value Absence	•Data model scarce •Not focus on general customers •Narrow customer segmentation •Lack of human resources •Not provide 3D printer and AM service •Not conduct user experience evaluation and optimization •Few predictions for potential customers and markets •Need research into material science and AM technology •Insufficient design for sustainability consideration •Insufficient design for recycling, remanufacturing, reuse •Insufficient communication between designers and manufacturers •Insufficient communication between customers and designers

	•Insufficient IP knowledge operation and management •Rely too much on technology suppliers for product manufacturing, maintenance and post-processing •Lack of awareness and experience of recycling and remanufacturing •Need for low-cost remanufacturing technology •Need for designers with the experience of sustainability •Need for managers with the knowledge of sustainability •Restricted market view and marketing strategy •Lack of new design thinking (lifecycle thinking, circular economy) •Lack of knowledge of AM capabilities & AM printing for designers •Lack of knowledge of AM material properties for designers •Lack of IP knowledge for designers •Failed to achieve mass customization •Poor understanding of mechanical properties for designers •Lack of certification of new component design and repair process
Value Destroyed	•Not care about design copyright for designers •Printed materials wasted •Limited recycling and reusing printed materials and scraps •Waste streams in the printing process (materials, scraps, printing support) •Challenges of the conceptual design stage to

	cause printed objects failed due to process-related factors
Value Surplus	• Insufficient 3D printer usage in the café shop and museum • 3D printers redundant in the café shops • AM products idle in the café shop and museum • Under-utilized design resources
Value Unsupported	• Lack of IP protection in the AM industry • Lack of IP trade environment and regulation • Lack of financial investment for the AM industry • Lack of the 3D design education system • Lack of qualified 3D design professionals • Lack of unified design principles and rules • Lack of unified guidelines and global standards to optimize product designs

4.1.5 Challenges of AM Design Process

The author identified and summarized the negative root causes in the AM design processes encountered by the AM design companies. More importantly, the root causes could help identify the AM design process's challenges and understand the barriers to wide AM adoption. The author interviewed multiple AM designers and collected data from different design companies from which the root causes were drawn at the exploratory stage. The root causes were also analyzed from the existing literature in the AM design research field, as summarized in Table 4.3.

Table 4.3 Root cause analysis in AM design

★ denotes that this finding is already in the literature and that this research CONFIRMS this. All other findings are original.

Key Challenge	Root Cause Analysis in AM Design

Design guidance	Lack of design guidance for embodiment and detail design
	Lack of design guidance that considers AM process characteristics★
	Suitability of AM process for conceptual, embodiment and detail design
	Lack of design guidelines, rules and influential factors★
	The difficulty of leveraging the advantages of AM for direct manufacturing
Design quality	Need improved dimensional accuracy and surface quality
	Insufficient of proper build-up orientation to reduce support structure materials in the design process
	Weak process consistency leading to printed parts having significant dimensional deviations
	Cautions of overhangs, abrupt thickness transitions, trapped volumes, layering
	Need improved composite simulation capabilities for primitive shapes, material compositions, functionally gradient materials
	Limitations of anisotropy, discretization, post-processing issues
Design factors	Challenges of conceptual design stage for AM due to the process-related factors; for instance, part consolidation, part accuracy, part strength, materials properties, materials shrinkage, mechanical properties, ease of printing and assembly, post-processing, printing costs, shape and size of each key feature, printing quality, lamination effects, anisotropy, product functionality (adding mounting points and pivot points)

	Wall thickness, outer and inner edges, slot depth, width and length, and overhang length
	Lack of focus on build orientation, layer thickness, support structure and removal, machining method for post-processing and inspection procedures
	Lack of factors for impact on design, manufacturing and post-processing★
Design methods	Lack of methods for design process considering AM capabilities, limitations and resulting design freedoms and constraints★
	Lack of methods for new design★
	Lack of conceptual design methods to aid designers in defining and exploring design spaces enabled by AM for representations of shape, property, process, and other variations
	Methods for simultaneous product and process design and multifunctional design
	Lack of methods of assessing lifecycle costs and environmental impacts of AM fabricated components and products
	Lack of methods for simultaneous multifunctional product design and AM process design
Design rules	Lack of a comprehensive set of AM design rules and materials data sheets that designers can rely on★
	Design rules missed including wall thickness, printable feature size, fillet radius, hole diameters, support structures, wear characteristics, clearances and tolerance
	AM design to be compatible with a traditional process

Design sustainability	Lack of sustainability considerations into AM design
	Lack of new design thinking (e.g. life cycle thinking, sustainability)
Design tools	Lack of development of various AM-oriented design tools★
	Lack of tools for representing complex geometries with repetitive features (e.g., cellular structures), multiple and gradient materials, and other variations
	Need improved design optimisation and simulation tools for minimising material and maximising process efficiency★
Design software	Need improved CAD systems to overcome the limitations of parametric, boundary representations, and solid modelling in representing very complex geometries and multiple materials
	Lack of improved finite element analysis software for 3D model design
Design IP	Lack of IP and design rights protection (copyright) ★
	IP security is a significant concern★
Design certification	Lack of certification of new components and repair process
Design standards	Lack of AM standards including design and equipment standards, application-specific standards, finished AM part standards, feedstock material standards, general standards (terminology, test methods, safety)★

The data was analyzed and produced into 36 root causes during the interviews and workshops. Some of the root causes are generic; others are specific.

Similar root causes were categorized into groups according to the kinds of key challenges in the 3D design process which help understand the barriers of wide AM adoption due to the design problems. The key challenges were identified and grouped into 11 categories including *design guidance, factors, methods, quality, rules, design for sustainability, tools, knowledge, software, IP protection, human resource, certification and standards*. The negative root causes in the AM design process impede the broad adoption of AM in different industries and sectors for the incoming AM practitioners and traditional manufacturers. For instance, the lack of qualified designers in the market has negatively impacted the development of AM design and value creation for Company A. These findings show the challenges of AM design that Company A faced. The author also identified failed exchanged value with different stakeholders in Section 4.1.4, which have not been considered before in AM design companies.

The author indicated that the failed exchanged value and the root causes were hidden within the existing business models and were uncovered through the analysis of value systems within the business models. The identification of the failed value exchanges within Company A helped uncover value opportunities to create sustainable value for customer, environment, and society. Company A needs to have the ability to see failed value exchanges, then transform the failed value into value opportunities and realize them. However, the identification of failed value exchanges in 3D design company has rarely been investigated by researchers and practitioners. This implies a gap in this research field and further confirms the need for this research.

4.1.6 Critical Factors Identified in Company A

The author investigated what critical factors can help Company A develop a sustainable business model. The author first looked for patterns within the data of what Company A was doing to create value. Then, the author identified the patterns within the data of what the failed value exchanges with multi-stakeholders were in Company A. The attractive and similar codes derived from the qualitative data were clustered into generic groups. The author has gone through all the codes and concluded names given to the themes which seemed to have the commonality. The title of the theme emerged out of the grouped codes is to represent critical factors that might be needed for the transition towards a sustainable business model for Company A. The author identified codes/patterns step by step to generate several high-level themes through thematic analysis that are critical to create sustainable value. Simplified thematic analysis findings are presented in Table 4.4.

Table 4.4 Simplified thematic analysis findings for Company A

Initial Quotes (Clustering)	Similar Codes	First Order Theme	Second Order Theme
"We have 11G data model; if you move too fast, it is not that easy to print because of the software program and limitation is not the hardware technology […] There are a lot of software but there is no good content. Content matters!"	Design contents; data models scarce; contents scarce	Data service	**PSS for AM**
"Digital design is not very commercial and not many people know the concepts and understand digital sculpturalism."	Digital design; design style; design concept	Design service	
"We define ourselves as the data service provider."	Data service provider	Data service	
"We find out that 3D printing is very high value-added and focus on applications and design services."	Personalised printing and services; AM applications	Design service	
"We designed a 3D printed crown model, and we needed to print out the crown. But there was no available 3D printing	Design service scarce/professional service inadequate;	Design service	

company can help us print it using the powder. Only Yuerui have the nylon to realise the 3D printing object […] At that time, we found that there is no company doing design and applications."			
"How to improve data management, how to better educate our employees, government policy following related to the development strategy."	Data management; employee education	Data management and service	
"One of our urgent company development issues is the human resource. There are not enough and sufficient people in the market that can directly work for us."	Professional designers scarce	Human resource	**Qualified AM professionals**
"We are looking for the people that are skilful and familiar with 3D printing […] However, in the current market, skilled professionals are scarce."	Skilled people scarce	Skilled employee	
"How to improve data management, how to better educate our employees, government policy following related to the development strategy."	Employee education; data management	Education service	
"Therefore, we develop a training program to educate them and let them work for us."	Training program; design education	Training program	

"All the printer manufacturers can sell their printers to our coffee shops. For instance, we have our own 3D printing coffee shop, in the shop we bought six different brands printers […] Then we test which one is the best, which one is the most competitive."	Printers wastes; printed materials recycling; under-utilised resources; waste streams in the printing process	Waste recycling	**Design for sustainability**
"It's all about service and […] it's sustainable corporate development."	Corporate strategy development	Corporate sustainability	
"Immediately, we asked them to sign the paper for the NDA to protect the IP. We are very familiar with the whole industry [...] We are very sensitive and cautious about the IP."	Care about IP protection	IP protection	**IP management**
"We focus on improving our technology barriers to prevent IP infringement."	IP infringement prevention	IP protection	
"That depends on whether the designers care about the design copyright and whether they have the relevant IP knowledge and knowledge of the business operation."	Not care copyright; IP knowledge; business operation	IP knowledge	
"The prerequisite of the IP trade platform is the 3D model evaluation [...] to decide whether a design model/copyright can be traded is the 3D model	3D model evaluation and testing systems; IP and copyright trade	IP trade	

evaluation and the systems."			
"B to C business model is to consider the general and basic customer demands not just the narrow high-class level […] 3D printing should apply to the whole market for most of the people."	Failed to capture general market value; business to customer failed	Personalised demands	**Mass customisation**
"We focus on the custom-made groups. Actually, they are the customised segmentation which will be the mass customisation for the public."	Custom-made group; not focus on general customers	Custom-made service	
"We are doing well with business partners but is not well received by the general customers […] Because all the 3D printing ideas and the advantages do not focus on the general customers' demands. It's very tough to do to C business."	Narrow target segmentation; failed business models for the general public	Customer segmentation	
"But for customisation, all the design models focus on specific target customer groups […] not for the general public […] our customers require unique and not repetitiveness and large volume."	Personalised demands; non-repetitiveness	Personalised service	
"In terms of chocolate printing, we have all the printers in the market […] So, we have the user experiences for all printing	User experience evaluation	User experience	**Stakeholder management**

machines, we can generate the user experience report."			
"For the lamp we design, this style and shape are not attractive to the ordinary family, and our 3D printing design is not to that type of general customers."	Customer segmentation; market differentiation	Customer engagement	
"The active engagement of a designer is very important […] The design model shapes either good or bad are depended on the designer creation connected to the subjective initiative."	Active engagement; the subjective initiative of designer	Designer engagement	
"We have all the capabilities including the suppliers downstream and upstream that work with us to print the personalised and customised products for the specific customer segmentation."	Relationship with suppliers, distributors and end-users	Business partnership	
"[…] if the data has not been expansion, it's very difficult for both top and down sites and markets to connect."	Data connecting market and customers	Systemic data connection	**System thinking**
"[…] to get the feedback using system thinking and we make the decision based on that information to figure out the customer demands."	Decision making based on key information	System thinking for decision making	

The author identified seven factors that are critical to Company A's business model development for sustainable value creation. The critical factors identified for Company A are *PSS for AM, qualified AM professionals, design for sustainability, IP management, mass customization, stakeholder management, system thinking*. Notably, the data suggests that Company A is a service leader in the AM design sector offering the result-oriented PSS solution in which the company provides the 3D design and data service. However, there is a lack of qualified AM professionals with AM design experiences in the current market, and the company does not set sustainability as the priority for 3D model design and AM products. There is no evidence for wastes recycling, and unprinted materials reuse for AM products in Company A. The company needs to incorporate the sustainability concepts into the design process and embed the sustainability considerations into the AM business modelling process.

Another example is IP management which is very significant for AM company, particularly for the design company as the 3D models are the fundamental value. Also, the intellectual values and design ideas should be highly protected. Furthermore, the company currently targets for the upper-level class customers and fails to cater to general customers. The company identifies a market trend of the increasing of consumer needs for AM, which requires the manufacture of mass-customization and individualized products. Therefore, to scale up the printing volume and to achieve mass customization can enable the company to cater to the general customers and create sustainable value.

The interview data suggested that system thinking is regarded as a significant and valuable factor for sustainable business model innovation; mainly, the senior managers use system thinking to make a strategic decision for business development and figure out specific consumer demands based on information collected through market research, literature review and industry interview.

4.1.7 Value Opportunities Identified in Company A

Researchers including Rana et al. (2013); Yang et al. (2016); Bocken et al. (2014) have contributed towards understanding new value opportunities, particularly new value creation and capture through new activities and relationships. By analyzing the identified failed value exchanges, a number of value opportunities were identified during the interviews and workshops. It is necessary for Company A to understand where the value failed exchanges with the multi-stakeholders are and rethink the value proposition to capture the value opportunities. The identified value opportunities were analyzed based on the assessment of failed value exchanges. The selected examples of failed value exchanges include *customer failed value, no IP management, lack of sustainability, human resource scarce, and data management problem*. The identified value opportunities helped gain a better understanding of the logic underlying how the failed value was turned into value opportunities and how the opportunities could be realized. Similar value opportunities were categorized and clustered into groups based on the types of failed value. 23 examples of value opportunities were provided, shown in Table 4.5.

Table 4.5: Selected examples of value opportunities in Company A

Failed Value Exchange	**Examples of Failed Value**	**Identified Value Opportunities**
Customer failed value	Not cater to general customers' demands and narrow target segmentation	Expand the product line to launch the 3D-printing products that cater to different levels of customers
		Provide a more customized design service for general customers not just for the high-class level
	Failed to improve the business to the customer	Lower the product/service prices to some extent to enable more people to use AM for daily lives
	Unknown customer needs (hidden needs and future needs)	Improve communication between customers and designers

		Listen carefully to the feedback from customers
	Products not well received by end-users	Analyze and make predictions concerning the future and hidden needs of general customers
No IP management	Not care about design copyright	Improve IP management and protection
	Lack of IP knowledge for designers	Educate designers about the IP knowledge and copyright protection
	Lack of IP protection and management	A proper legal framework and policy to protect IP rights need to be developed in the AM industry
Lack of sustainability	Insufficient design for sustainability	Incorporate sustainability concepts into product design
	Lack of lifecycle thinking and circular economy consideration	Integrate sustainable considerations and design thinking into the design process
		leverage the advantages of AM for direct manufacturing
	Lack of awareness of recycling and remanufacturing	Improve the design knowledge of AM process characteristics and limitations
	Need designers and managers with the	Strengthen the communication between

	sustainability knowledge	designers and manufacturers
		Provide a training program to improve the awareness of wasted and printed materials recycling and reuse
	Lack of recycling for printed materials and scraps	Optimize design models for recycling and design for sustainability
Human resource scarce	Lack of qualified 3D design professionals	Develop AM education system particularly design education needs to be established in the AM industry
	Educating professional designers costs a lot	Reduce costs for the design training program
	Inadequate knowledge of material properties for direct production	Educate designers with knowledge of material properties, machine operation, printing processing, post-processing and other AM processes
Data management problem	Poor data management	Build up the data management system, configure the data, troubleshoot the abnormal data
	Data-scarce for general customers	Increase the volume of design models and achieve the satisfaction of different customers'

		demands using sufficient data services
	Insufficient data models for printing	Expand the data pool to have more design models that can be printed with no flaws and defect
	Poor data utilization	Improve the efficiency of data utilization through data management and configuration

4.2 Case study B

4.2.1 Introduction to Company B

Company B is an internationally renowned 3D-printing company that provides professional 3D printers to engineers, designers, manufacturers, and decision-makers. The company was founded in 2011 and headquartered in the US with offices all over the world. The company dedicates to the development of an AM platform that enables the users to use stereolithography (SLA) technology to print parts with complex geometries and professional quality. Company B is continually expanding access to digital fabrication and obtains qualified AM professionals experienced in design development and manufacturing processes. Notably, the company offers diversified products/services including a variety of SLA printers, manufacturing solutions, post-process solutions, high-performance materials and AM software.

The reason for choosing this company is that it is one of the first companies developing the SLA and SLS printers, and it also provides standard materials, software, post-processing machine, and other consumables. This company continually optimizes the AM process, particularly the SLA technology and engages closely with multi-stakeholders to create and capture value. In this case study, in-depth interviews were conducted with several senior managers, including Director of Business Development, Product Manager, HR, Sales

Manager, and Market Representative.

4.2.2 Business Model of Company B

The business model for Company B is to develop 3D printers and related software and consumables to the target customers through online store and intermediaries. The customer value propositions of Company B lie in four perspectives. The first value proposition is the reliable and affordable 3D printers. Notably, Company B offers two professional AM technologies, respectively, SLA and SLS. The company has launched four different types of printers in which some use a UV light to solidify liquid resin into hardened plastic, as well as others, use a laser to fuse polymer powder to build parts. Furthermore, they provide two accessories for parts clean to remove any uncured resin from the surface and post-curing to get the maximum mechanical properties. As commented by the Product Manager:

"*We provide extremely high-quality parts and capabilities in a very affordable package. This is our competitive advantage* […] *we make the machine as much simple to use as possible*."

The second value proposition is the high-performance materials in-house. The company offers a group of photopolymer resin with great detail, smooth surface finish and no post-curing for engineering, manufacturing and product design. These functional materials hold outstanding characteristics such as high precision, excellent elongation, high heat resistance, superior impact strength, stability, deformation resistance, durable, robust, high-temperature resistance, high tear strength, rigid, and flexible. The Sales Manager said:

"*We provide the resin which can withstand very high temperature […] we also provide easy to use, removable resin tank and good quality resin cartridge."*
The Sales Manager said: *"We want to differentiate ourselves with other potential competitors by providing a variety of resins with affordable prices."*

The third value proposition is the AM software for printing setup, data management, and process monitoring. Notably, the company offers two types of software in which the first one can be used to set up the print's layout, orientation, supports for the print preparation; the other one is the management-oriented software which is used to manage printers, monitor materials, receive notifications, track printing and manage teams efficiently. The fourth one is the AM-related service and warranty packages, including professional support service, customized training sessions, email and phone support, installation, maintenance. Mainly, the service engineer is available to help customer integrate SLA into the work environment effectively. The Sales Manager said:

"*We want our customers to have good experiences of using our printers, but if the machine breaks down, we will send a replacement machine to resolve the issue as soon as possible […] we want to keep production downtime to a minimum; that's not good experiences, and we want to avoid that*."

The value creation is that Company B always develops the affordable, professional-grade desktop AM solutions, mainly keep decreasing the prices and increasing the quality. Company B has developed the first SLA desktop 3D printer and first large format resin 3D printer in a more affordable setup with a wide range of print materials. As the Sales Manager indicated:

"*We can print out parts with the incredible detail at the incredibly low price*."

The core capabilities are that the company can push the boundary of AM to make it accessible for a variety of applications such as manufacturing, healthcare, entertainment, education, jewelry, architecture, and many others. While the company is not just a machine manufacturer, it provides an integrated printing solution, including the high-resolution printers, rinsing and post-curing accessories, in-house materials, printing preparation and management software, as well as professional service to build up the AM ecosystem. The company has expanded the business to different markets and set up several branches in Europe, Asia, and North America to uncover new opportunities for value creation. The Sales Manager said:

“We have more than 220 employees in different branches, including 35 employees in Berlin and distributors all over the world.

The company have more than a hundred engineers concentrating on research & development for the innovation of the materials, SLA and SLS technologies. Furthermore, the company manages to capture value through offering desktop SLA instead of industrial SLA as the industrial SLA can cost up to $80,000 and the desktop SLA is starting only at $2000. Furthermore, the company maintains close partnerships with the resellers all over the world to promote the business and make AM more accessible. The Director of Business Development commented:

“*We must work closely with our trustworthy partners and distributors […] our resellers can provide good service to the customers and they represent us in the different market; therefore, we choose our partners very carefully.*”

4.2.3 Value Systems and PSS Solutions in Company B

The business model of Company B is identified through analyzing the value systems using system thinking. The relationship between Company B, customers and value systems has determined the PSS solutions. The company has extended the business to incorporate the sale of 3D printers, materials, print software and customized service as a product-service solution. Mainly, the company sells the SLA printers with individual desktop level and industrial level as well as launches SLS printer to build more prominent parts and higher throughput. The company also develops a range of photopolymer resin with high quality and features applied to different circumstances; for instance, in dental, jewelry and healthcare areas. The company implements the typical product-oriented PSS solution as the customer owns the product, and the value is created by adding service to product (Tukker, 2004).

The main profits came from the sale of physical 3D printers, materials, software along with associated service, including monitoring, installation, maintenance, technical support, and warranty coverage. The use-oriented and result-oriented

PSS do not apply to the company. The company only adopts the product-oriented PSS solution. The author analyzed the value systems and the sustainable value, including economic, environmental and social value based on the interview data, observations, company reports, and other documentation. The codes of sustainable value emerged and were grouped into the categories with the combination of business model attributes in Table 4.6.

Table 4.6: Value system analysis for Company B

Valve System	Main Findings
Value Proposition	High-resolution SLA and SLS printers; parts rinsing machine; post-curing machine; high-performance materials in-house for engineering, manufacturing and product design; print preparation software; process management-oriented software; removable resin tank; resin cartridge; after-sales service and warranty packages including technical support, customized training sessions, email and phone support, installation, maintenance, etc.
Value Creation	Launch the first affordable desktop SLA printer to keep the prices lower than any other competitors; have the capabilities of developing printing solutions to serve different market sectors including engineering, manufacturing, healthcare, entertainment, education, jewellery, architecture; strong research abilities on material development and technology innovation; have the resources and capabilities to penetrate a different market and sell the AM products/service all over the world; build up AM ecosystem

Value Capture	Different price levels of 3D printers, materials, and customized service to cater to target customers; affordable printers in the market to capture the customer value
Value Delivery	Sales strategy through online store and resellers; partnership with resellers in different countries; one-off payment for the printers, materials, software and other services
Social Value	Improved customer relationships; a strong relationship with resellers and suppliers; close engagement with multi-stakeholders; help doctors deliver treatments customized to serve each unique patient better; ability to produce custom products at low costs to improve patient care in the dental application; efficiently printing the products while saving customer significant time and costs; printers can encourage creativity, support immersive learning and maker education
Environmental Value	Product life extension; waste reduction; less material consumption; less over-production in stocks to save energy; improved material efficiency; reduced environmental impacts
Economic Value	Professional and customized service; affordable desktop SLA printer; reduced costs for customers; higher material utilization; no moulds, casting, the tooling necessary

4.2.4 Failed Value Exchanges in Company B

In this section, the failed value exchanges were identified and analyzed with the consideration of multiple forms of values from a multi-stakeholder perspective. The identification of failed value exchanges involved value missed, value absence, value destroyed, value unsupported and value surplus. Over a hundred codes of failed value exchanges from the interviews and workshops emerged and were grouped into 54 examples of failed value in Table 4.7.

Table 4.7: Failed value exchange analysis in Company B

Failed Value Exchanges	Examples/Explanations
Value Missed	•Inventory caused by delays in clients' payments •Competition from cheaper machines and materials •Implementing sustainability efforts maybe pose negative impact on making profits and cause economic downside •Over competition for desktop printer market including FDM, SLA, etc. •Previous generation machine cause cannibalization with the newly released printers •Challenge of managing China and Japan market due to the difference between culture, language and customer demands
Value Absence	•Only have single product-oriented PSS solution •Not consider leasing, sharing or subscribing 3D printers and materials to customers •Failed to produce and deliver large scale printer for customer •Incapable of printing large-size objects using SLA printer •Hard to retrieve and remanufacture the old printers •Lack of design service for customer with no design knowledge and experience •Set economic profits as priority •Lack of reuse and recycle printers

	•Resin cartridge cannot be reused and refilled •Resin materials cannot be recyclable and reused •Challenges of keeping product lower cost and higher quality •Functions limitation of SLA printers for customer •Lack of AM and subtractive manufacturing integration solution •Challenge of achieving mass customization •Lack of highly recyclable new materials •Lack of an open standard for AM industry development •Service scheduling problems •Costs increasing caused by excessive inventory •Difficulty of machine and material recycling and reuse •Insufficient communication between customers and manufacturers •Resellers in some countries cannot provide high quality after-sales service and compromise reputation •Manager's reduced abilities to identify failed value •Cost of printer maintenance too high
Value Destroyed	•Limited recycling and reusing printed materials •Waste streams in the printing process (materials, scraps, printing support, etc.) •Materials generate uncomfortable smell and may cause health issue •Challenge of using software and complicated to operate for a customer •Hard to balance economic and environmental

	value •Machine damage caused by improper use of cartridge •Cartridges get clogged due to too much resin flow out •Machine risk brought by too much resin spill out •Challenge of using software to manage the printers and monitor workflow •Replacement of broken printers takes time too long •Challenge of managing customer expectation if the supply is constrained •Machine crash down sometimes •Lack of used cartridges, canisters, spools, print engines and containers for return and recycle •Limited strength, rigidity and heat resistance for 3D printed parts which are not conducive to long-term preservation
Value Surplus	•Customers' unclear needs to purchase SLA printer •Printers idle in some research institutes and schools only for display •Insufficient machine usage within distributed networks and at home •Too much resin in the tank that causes the machine damage risk •Challenge of cleaning the resin tank due to materials spill out
Value Unsupported	•Lack of external supporting environment for leasing a new product •Need open and unified standards for AM industry development

	•Lack of unified printing principles, rules, guideline and standardization •Need to leverage and manage the relationships with the government and partners •Lack of AM education system in the AM industry •Need strategic framework and business tool for decision making, idea generation, and business management

The author identified the above-failed value in detail using the same coding and categorization process. These failed exchanged value and value captured help develop the initial themes which will be discussed in Section 4.2.6.

4.2.5 Challenges of AM Machine Development

The author identified and summarized the negative root causes in the AM machine development, which the AM machine manufacturers encountered. More importantly, the root causes could help identify AM machine development challenges and understand the barriers to wide AM adoption. Notably, these root causes were extracted from the qualitative interview data with different machine manufacturers and analyzed from the existing literature in the AM research field, as summarized in Table 4.8.

Table 4.8: Root cause analysis in AM machine development

Key Challenge	Root Cause Analysis in AM Machine Development
Printer speed	Low printer speed due to the machine limitation★
	Need for research in machine design and dynamics to achieve a drastic increase in fabrication speed and a reduction in costs★
Printer development	Lack of R&D in industrial printers for high speed and strength

	Lack of development of multi-materials and multi-colour printing systems
	Lack of modelling, sensing, control and process innovation for printer
	Lack of talents and qualified engineers in printer development★
	Incapable of printing large-size objects using SLA printer
Printing quality	Low machine reliability
	Low-quality consistency
	Lack of repeatability and consistency of the manufactured parts★
	Need for process sensing and feedback control to improve part performance and consistency
	Uncertainties of part quality and mechanical properties to make functional parts★
	Limited strength, rigidity and heat resistance for 3D printed parts which is not conducive to long-term preservation★
	Lack of integrating control algorithms with existing AM machine through machines' proprietary controllers
	Clogging resulting from the support structure
	Lack of manufacturing efficiency through improved automation of AM systems and process planning
	Precision and stability of the parts need improvement★
	Lack of intensity with exposure to high stresses for produced parts
Printer cost	High investment for industrial printer development★

	High industrial machine costs★
	High costs for machine maintenance and downtime
Printing sustainability	No or little recycling for the broken printer, used printer and print accessories
	Lack of awareness of the conversion of waste and by-products into products
	Need for capacity and capital to undertake to remanufacture
	Lack of awareness and knowledge of remanufacturing
	Noise from the printing process
	Potential health issues of handing glue or resin★
	Waste streams in the printing process (materials, scraps, printing support, etc.) ★
	Lack of equitable indicators and measurement metrics for measuring sustainability in printing processes and products★
	Lack of sustainability metrics and the corresponding measurement science
	Limited reclaimed and reused of waste materials, misprint and undesired outputs
	Challenge of educating the customer about the recycling of plastics and other materials
	Unawareness of sustainability concepts to integrate into printing practices
	Hard to retrieve and remanufacture the old printers
	Limitations of recycling due to quality and purity issues★

The data were analyzed, and root causes were categorized into 35 groups for 3D printer development, which helped identify the challenges of 3D printer development and understand the barriers of AM adoption due to the machine problems. The key challenges were identified and grouped into 5 categories including *printer knowledge, printing speed, printer market, printing development, printing quality, printer cost, printing sustainability*. The negative root causes in the AM machine development impede the broad adoption of AM in different industries and sectors for the incoming AM practitioners and traditional manufacturers.

The author identified failed exchanged value with different stakeholders in Section 4.2.4, which have not been considered before by the AM manufacturers. The author presented that the failed value exchanges and the root causes were hidden within the existing business model and were uncovered through the analysis of value systems. The identification of the failed value exchanges within Company B helped uncover value opportunities for company, environment, and society. However, the identification of failed value exchanges in the company has rarely been investigated by researchers and practitioners. This implies a gap in this research field and confirms the need for this research.

4.2.6 Critical Factors Identified in Company B

This section is to identify the critical factors that might help Company B develop a business model to create sustainable value. The author has already analyzed the value systems and the failed value exchanges with multi-stakeholders in Company B. Furthermore, the author identified codes/patterns step by step to generate several high-level themes based on the analysis of similar codes that were clustered into the groups. The third order themes identified were the critical factors that were needed for the transition towards a sustainable business model for Company B in Table 4.9 as follows.

Table 4.9: Simplified thematic analysis findings for Company B

Initial Quotes (Clustering)	Similar Codes	First Order Theme	Second Order Theme

"Whenever we try to implement something, if there are sustainable benefits with no economic downside, we will implement that […] if there is an economic downside, we will pause to figure out if it is worth doing."	Economic profits oriented; monetary profits emphasis	Economic Sustainability	**Printing for sustainability**
"We try to bring back machines, but I have a hard time to see this and figure out a way to get all the machines back to recycle."	Hard for machine recycling; recycling limitation	Close loop	
"In terms of reuse, recycle and remanufacture, we do not do that right now."	Hard for machine recycling; recycling limitation	Close loop	
"The resin cannot be recycled. We throw them away […] some metal can be recycled, but for resin, I do not think so."	No recycling for resin	Close loop	
"We want to make it environment-friendly to be the sustainable package."	Sustainable product packaging	Sustainable packaging	
"Customers want to refill the cartridge, but they cannot do it right now […] the cartridge is only good for one life and use."	No cartridge reuse	Close loop	
"We do not consider the leasing and subscription business models […] we	Single sales strategy; limited PSS models	Product-oriented PSS	**PSS for AM**

now just sell the machine."			
"We do not consider lease and other service models."	Limited-service model	Product-oriented PSS	
"We do not provide the design model […] the design is not our choice."	Design service scarce	Design service	
"I think there is a need for the strategic framework and tool in 3D printing companies."	Framework and tool scarce	Consulting service	
"People want a big machine, which is the number one customer request […] It is not easy for us."	Incapable of producing large-size machine; machine size limitation	Machine problem	**Technology innovation**
"If you want to make the objects bigger, it is not just a matter of increasing the size of the printer."	Challenge of producing large-size objects; machine limitation	Machine problem	
"[…] if we can get a bigger machine using other technology, then we will do that."	Machine size limitation; SLA limitation	Machine problem	
"That would bring in the risks to the machine […] Risks come from the cartridge not working properly."	Machine risk	Machine problem	
"They would have the issue with the resins, and maybe it does not flow up in the cartridge correctly."	Resin limitation	Materials problem	

"The risk is that you may have too much resin in the tank […] some materials spill out, and it is challenging to clean the tank."	Materials spill out	Materials problem	
"Because the customers want to have certain machine functions […] we do not have that ability to implement that over the life cycle."	Incapable of implementing certain functions; function limitation	Customer management	**Stakeholder management**
"Customers want different functionalities […] they may wait until we can provide that. However, we cannot. There are opportunities costs there."	Opportunities costs; function limitation	Customer management	
"When we announce a new product, we do not know what the support issue that was going to be."	Unknown external supporting environment	Supporting environment	
"It can be managing customer expectations, particularly when supply is constrained."	Customer supporting system	Customer support	
"We want customers to have good user experiences, and if the machine breaks down, that is not good experiences, and we will not avoid that."	Pay attention to customer experience	User experience	

"It is important that we work with our partner that is trustworthy."	Trustworthy partnership; supplier relationship	Partnership	

The author identified four factors through thematic coding and pattern analysis including *printing for sustainability, PSS for AM, technology innovation, and stakeholder management*. Notably, the data suggests that Company B is an SLA printer leader among AM manufacturers with the product-oriented PSS solution in which the company sell printers along with the after-sales service. However, to gain environmental benefits and improve social wellbeing, Company B may benefit from the implementation of PSS such as use-oriented and result-oriented models. Particularly, the data suggested that the use-oriented business model such as machine sharing, subscribing and leasing could improve machine utilization and may bring sustainable benefits.

4.2.7 Value Opportunities Identified in Company B

In terms of value opportunities, the author needs to evaluate the identified failed value and negative root causes; therefore, to understand how failed value could be turned into value opportunities and how the value opportunities could be realized. The author analyzed the typical failed value and developed several constructs for value opportunities where the similar ones were categorized and clustered into groups. Based on the critical factors, the author analyzed the failed value in terms of *customer failed value, lack of sustainability, technology immature, and lack of PSS solution* and provided recommendations to realize the value opportunities. Similar value opportunities were categorized and clustered into groups. 19 examples of value opportunities were provided, shown in Table 4.10.

Table 4.10: Selected examples of value opportunities in Company B

Failed Value Exchange	Examples of Failed Value	Identified Value Opportunities

Customer failed value	Insufficient communication between customers and manufacturers	Listen carefully to the feedback from customers
		Make predictions concerning the future and hidden needs of customers
	Lack of design service for customer with no design knowledge and experience	Provide customized design service for customers with no design knowledge
	Service scheduling problems	Use management software to improve the efficiency of maintenance and other after-sales services
	Challenge of using software for the customer	Make the software more user-friendly control
	Printer functions limitation	Keep developing the printer to incorporate more functions without mainly increasing the price
Lack of sustainability	Set economic profits as a priority	Improve the awareness and knowledge of sustainability concepts
	Lack of reuse and recycle printers	Develop a recycling plan for broken and used printers
	Resin cartridge cannot be reused and refilled	Consider biodegradable cartridge and fully clean cartridge for reuse
	Resin materials cannot be recyclable and reused	Develop environmentally friendly materials for printing
	No recycling and reuse for printed materials and scraps	Develop recycling and reuse technology for wasted and printed materials, broken and failed parts

	Materials generate uncomfortable smell and may cause health issue	Use biodegradable and environmentally friendly materials like PLA
Technology immature	Incapable of manufacturing large scale printer and product	Develop scale-up solutions for manufacturing; explore the open-source approach and establish local and replicable production network
	Lack of an open standard for printing	Work with ASTM and government to develop printing standards and requirements
	Limited strength of 3D printed parts	Develop new materials with better strength, rigidity, and heat resistance
	Lack of unified printing principles, rules and guidelines	Coordinate with AM researchers and practitioners to accelerate the development of AM standards and specifications
Lack of servitization	Only have product-oriented PSS solution	Implement sustainable PSS such as user-oriented and result-oriented models
	Not consider the service-oriented business model	Provide the machine sharing, subscription, and leasing service
		Deliver functionality rather than ownership

4.3 Case study C

4.3.1 Introduction to Company C

Company C is a global 3D-printing materials company which offer a diverse portfolio of AM materials and printing accessories. The company is headquartered in China with distribution centers in North America, Europe and Asia. The company dedicates to produce a wide range of materials including plastic, resin, nylon, fiber, polymer, among many others. The materials range from high-performance plastics to unique aesthetic solutions. They are committed to innovation, quality and aim to realize AM as an ultimate production tool and develop AM into a mainstream manufacturing method.

The reason for choosing this company is that it concentrates on AM material research and development and produce high-quality materials for different industries and sectors. Besides this, the company implements a rigorous quality control check on all materials to make sure the good quality. This company also maintains close relationships with local distributors, resellers, partners and other stakeholders. In this case study, in-depth interviews were conducted with the CTO, Director of Business Development, and Sales Manager. The interviews were then transcribed, and observations were conducted with the combination of secondary data from documentation analysis.

4.3.2 Business Model of Company C

The business model for Company C is to develop and manufacture high-quality, reliable AM materials and printing accessories to the target customers through online store and intermediaries. The customer value propositions of Company C lie in four perspectives. The first value proposition is a broad and growing portfolio of AM filaments as the core products for desktop printers to deliver high quality and reliability for a wide range of industrial applications. The company produces advanced filaments with the raw materials of PLA, PC, ABS, TPU, and Nylon. Notably, the AM materials can achieve high printing quality, strong mechanical properties, improved strength, high heat resistance, excellent stiffness and toughness to fulfil customer needs in design and prototyping. As commented by the CTO:

"*We have better quality and reliable materials with a relatively high price because we spend a lot of research and development, quality control and quality assurance."*

The second value proposition is the custom material service, which is to design and customize the particular materials to suit personalized needs. Mainly, if the customer requires a specific material that is not yet available in the market, the company can design and develop the needed material to best meet the user needs. The Sales Manager said:

"We are a very research-oriented company and largely focus on material research and development to enable the customer unique application."

The third value proposition is the AM facilities for post-processing and application development. The company provides three AM accessories to optimize the user experience with the materials, including a storage box for filaments, a desktop post-processing device, and a nebulizer. As the CTO said: "*We design and manufacturing filaments and also manufacture polymer surface polishing machine to do polish based on the different model sizes."*

The fourth value proposition is the materials testing and characterization for thermal characterization, mechanical testing, and optical microscopy analysis. The company pays significant attention to materials research and provides the materials with the combination of excellent properties/functions that are optimized for AM. Notably, the company established the research lab to test the mechanical, heat, and chemical properties to make sure that all the AM materials have relatively better quality and superior features than others in the current market. The CTO commented:

"*Our filaments are not only guaranteed to have the best quality standards but also provide innovative properties that help yield a better overall printing experience.*"

Furthermore, the company has invested a lot in the construction of a large manufacturing facility and equipment to scale up the production capacity and empowered the manufacturing capability. The value created for the customer is the research capability of producing high-quality AM filaments portfolio for different industrial applications, including PC, PLA, Nylon, TPU, and ABS. The company also has set up an R&D lab to test, characterize the materials to enable customer applications. The company positions itself as the materials pioneer and works hard to integrate materials, AM technologies and design to meet the customers' needs. One of the interviewees emphasized:

"*We are committed to innovation, quality and sustainability and […] we work hard to research new materials characteristics to produce safe, high-quality materials for the 3D printing industry*."

The company is expanding the materials production line to develop the industrial level materials for industrial printers for value creation. As one of the interviewees explained:

"*We mainly research and develop the FDM materials, and now we have our first ceramics materials and will develop more industrial level materials to expand our material portfolio."*

Furthermore, the company has expanded the business to the different markets and set up the branches in China, Japan, USA, and the Netherlands to uncover new opportunities for value creation. "*We set up the manufacturing factory and produce our materials in China […] we sell the materials through resellers all over the world*." Surprisingly, over 80% of profits come from the international market, particularly in the US and Europe rather than the domestic sales for value capture.

The company maintains a close relationship with the resellers to promote business and make the materials more accessible for value delivery. More importantly, the company initiated the Printer Manufacturers Partnership Program to develop a strategic partnership with the printer companies to deliver customized AM solutions to the customers. Notably, the value delivered for partner and company to team up is the custom development of materials with the integration of printer to optimize the material profiles and obtain technical datasheets for solutions delivery.

The Sales Manager commented: "*Particularly in China, we need the networking and business relationship with the manufacturers and other industries*."

4.3.3 Value Systems and PSS Solutions in Company C

The business model of Company C was identified by analyzing the value systems using system thinking. The relationships between Company C, customers and value systems have determined the PSS solutions. The company is an AM solution provider by offering high-performance materials, AM accessories and custom material service as a product-service solution. The use-oriented and result-oriented PSS models do not apply to the company. The company only adopts the product-oriented PSS model. The evidence of economic, environmental and social benefits provided by the PSS solution within Company C have been identified. Table 4.11 summaries the value systems and the information in this table was mainly generalized from the interview data. The codes of sustainable value emerged and were grouped into the categories with the combination of business model attributes.

Table 4.11: Value system analysis for Company

Valve System	**Main Findings**
Value Proposition	High quality and advanced filaments; materials portfolio including PC, PLA, Nylon, TPU, ABS; custom material service; AM facilities for post-processing and application development; storage box for filaments; desktop post-processing device; nebulizer; materials testing and characterization; manufacturing and research facilities

Value Creation	Strong research abilities on material development; AM technology innovation; capability of scaling up the production capacity; materials customization; ability to increase the materials production line; integration of materials, AM technologies and design; different international market penetration; sell materials all over the world
Value Capture	Different revenue models for materials and customized service; gain much more profits internationally; direct sales online; overseas market-oriented
Value Delivery	Sales strategy through online store and resellers; partnership with resellers in different countries; Printer Manufacturers Partnership Program; networking and business relationship; available to ship directly to the US and the Europe regions; online customer community for information exchange; an online customer forum for discussion and suggestion
Social Value	Improved customer relationships; a strong relationship with resellers and suppliers; close engagement with multi-stakeholders; Printer Manufacturers Partnership Program; online customer community; an open forum for communication and suggestion; materials customization
Environmental Value	Biodegradable materials; soluble support material (Nylon) for waste reduction; improved material efficiency; reduced environmental impacts; ABS with reduced odour during printing

Economic Value	Custom material service; a wide range of material selections; convenient printing accessories; materials testing and characterization; scaling up manufacturing capacity; extensive manufacturing facilities and equipment; materials customization; team up with printer manufacturer

4.3.4 Failed Value Exchanges in Company C

In this section, the author considered and identified the failed value exchanges with multi-stakeholders. The codes of failed value exchanges from the interviews and workshops emerged and were grouped into 45 bullet points as the failed value examples in Table 4.12.

Table 4.12: Failed value exchange analysis in Company C

Failed Value Exchanges	Examples/Explanations
Value Missed	• High initial investment in material development and manufacturing facilities • Fierce competition from cheaper materials • Challenge of managing Asia, US and Europe market due to the difference between culture, language and customer demands
Value Absence	• Lack of multi-color machine for printing different materials • Only have single product-oriented PSS solution • Not consider leasing, sharing or subscribing materials to customers • Challenge of achieving mass customization • Lack of highly recyclable new materials • Low strength object for poly-jet printing

	• Challenge of material properties customization • Machine and material compatibility • Specific demands of material properties not easy to meet • Lack of machine that can work with different types of materials • Limited materials recycling and reuse, only for PLA • Recycled materials not mechanically strong • Recycled materials have a safety issue • Hard to balance environmental protection and profits making • Lack of material certification for the biomedical industry • Materials quality and safety approval for the biomedical industry • AM software is not easy to use • Uncertainties of materials costs in the future • Lack of knowledge and experience of using software • Recycled filaments with porosity and dust inside • PLA and ABS are not polishable with alcohol • Target customer is quite narrow without caring about the low-end market • Lack of professional human resource in 3D printing materials
Value Destroyed	• Limited recycling and reusing printed materials • Waste streams generated in the printing process (materials, scraps, support materials) • Low-quality materials with lower prices negatively affect the market

	• Hard to balance economic and environmental value • No recycling for ABS, TPU, PC. • Recycled the materials negatively affect material properties • Wastes generation from prototyping • Materials recycling limited in the AM market • Materials recycling and reuse not being paid attention by managers • Sometimes isopropyl leek from the machine • Challenge of separating objects with multiple materials for recycling • Difficulty of material recycling and reuse
Value Surplus	• Need to remove the support materials • Materials overflow in the market with low quality and lower price
Value Unsupported	• Lack of certification and standards for AM materials • Lack of AM material education in the AM industry • Lack of high-quality FDM machine that can print the company's materials • Shipping costs are a bit high and need to negotiate with the logistics partner

The author identified the above-failed value in detail using the same coding and categorization process. The failed value exchanges were analyzed with different stakeholders including customers, partners, suppliers, environment and society. These failed exchanged value and value captured help develop the categories to form the initial themes in Section 4.3.6.

4.3.5 Challenges of AM Material Development

The author identified and summarized the negative root causes in AM material development. More importantly, the negative root causes could help identify the challenges of AM material development and understand the barriers for broad AM adoption from the material perspective. The author also reviewed the relevant academic literature in AM material to identify the challenges of AM materials, shown in Table 4.13.

Table 4.13: Root cause analysis in AM material development

Key Challenge	**Root Cause Analysis in AM Material Development**
Material properties	Low physical properties of polymers to achieve better fabrication
	Weak strength of materials properties particularly for resin and PLA
	Materials toxicity such as ABS and resin★
	Uncured PolyJet model materials cannot be recycled
	Uncured model materials require special handling, packaging, transportation, and disposal
	Relatively poor part accuracy caused by the stair-stepping effect and residual stresses★
	Challenges of forming and mixing of materials with desired properties in desired forms
	Unclear about how the process parameters affect the material properties and part performance under the extremely high material deposition rate
	Adhesion and thermal mismatch between heterogeneous materials and functionally gradient materials
	Lack of understanding of melting and recrystallisation in polymers to develop robust mathematical models

	The toxic smell produced when printing ABS★
	Reduction in the material properties and color contamination of materials
Material recycling and reuse	Limited recycling and reusing printed materials and scraps★
	Insufficient use of broken printed parts and waste materials
	Materials generate uncomfortable smell and may cause health issue★
	Lack of awareness and knowledge of recycling and reuse★
	Lack of awareness and knowledge of material sustainability
	Wastes of energy (electricity, cooling system, heat) with more energy-intensive per unit produced
	Limited recyclability due to mixed materials
	The low percentage of recycled materials percentage in materials inputs
	Non-recyclability of multi-materials products
	Challenges of separating wood-polymer composites for recycling
	Only certain materials can be recycled, but the recycling result is not valid, e.g., PLA★
	Lack of recycling support and method★
	Materials waste generation★
	Limited recyclability of materials due to quality loss★

Material quality	Incompatibility between non-standardized and non-recyclable materials
	Critical material quality loss during the recycling process
	Recycled materials may cause contamination of other materials
	Need new regimes of materials transformation due to extreme heating and cooling rates
	Plastic parts are fragile along with the layer lamination
	Weak adhesion of plastics, ceramics and wax
	Different degrees of distortion of parts and materials
Material standard	Lack of recycling and remanufacturing guidance and standard★
	Lack of standardisation of material development★
	Lack of standards in material data reported by various companies★
Material costs	Need for low-cost remanufacturing technology
	Relatively high materials costs★
	Costs of recycling and reuse are very high
Material selection	Overall limited material availability and selection in the AM industry
	Limited materials available for use in AM processes★
	Lack of development of new materials for AM processes★
Material development	Challenges of coordinating material flow control with machine motion control in the AM processing within each layer and between layers

	Lack of standards in material data reported by various companies is not comparable★
	Challenges of realizing more material options, better resolution, faster production, more reliable operation, robust certification, and lower costs★
	Lack of development of new materials for AM processes★
	The disconnection between high-fidelity modelling research and real-time online process control efforts

The root causes were categorized into 47 groups according to the kinds of key challenges in AM material development, which help understand the barriers of wide AM adoption due to the material problems. The key challenges were identified and summarized into 7 categories, including *material properties, material recycling and reuse, material quality, material standard, material costs, material selection, material development.* The negative root causes in AM material development impede the broad adoption of AM for the AM practitioners and traditional manufacturers.

These findings present the overall challenges of AM material development that Company C faced. The author identified the failed value exchanges and the root causes which were hidden within the existing business model and were uncovered through the analysis of value systems and failed value. Company C needs to have the ability to see failed value exchanges, then transform the failed value into value opportunities and realize them.

4.3.6 Critical Factors Identified in Company C

The author transcribed the data and identified codes/patterns to generate initial high-level themes based on the analysis of similar codes. Simplified thematic analysis findings are presented in Table 4.14 as follows.

Table 4.14: Simplified thematic analysis findings for Company C

Initial Quotes (Clustering)	Similar Codes	First Order Theme	Second Order Theme
"We produce excellent materials, but there are not many FDM machines that can print them out."	Low-quality AM machine; lack of machine can work with different materials	Machine problem	**Technology innovation**
"If the nozzle path can be redesigned to incorporate more nozzles […] it can realize the multicolor printing for FDM machine."	Multi-colour printing unavailable	Machine problem	
"Sometimes, materials might stop in the middle of the printing process and clog the nozzle to cause low quality object."	Printing bug; material defect	Machine problem	
"Some materials cannot be recycled […] if it is the object with multiple materials; it would be tough to separate."	Challenge of recycling multi-materials; low quality of recycled materials	Material problem	
"We will not put the recycled materials into our new materials production process which would negatively affect the properties of the materials."	Low quality recycled materials; mixed materials have low quality and characteristics	Material problem	
"The poly-jet printer can use resin materials to print object but is not strong enough and only for rapid prototyping."	Low strength poly-jet printing; material not strong	Machine problem	

"These polymers are typically not mechanically strong. Moreover, they are quite weak mechanically."	Recycled materials not mechanically strong	Material problem	
"It needs to go through some very specifically approval […] the full materials have to go through the certification."	Lack of material certification for healthcare; quality and safety approval	Material certification	
"It takes a lot of work and time for customization, such as fitting some types of machinery and producing these types of properties."	Material properties customisation; machine and material compatibility	Material customisation	**Mass customisation**
"[…] we supply the information for recycling, but we do not do it by ourselves."	Wastes generation; no recycling	Material recycling	**Materials for sustainability**
"If you would make the car parts, using these recycled materials would be more sustainable and good for nature [...] but these materials would be dangerous for people."	Low quality of recycled materials; safety issue	Material recycling	
"We have not considered the recycling issue."	No recycling; environmental pollution	Material recycling	
"People use our materials to prototype different models and then just throw them away when printing the wrong one."	No recycling; waste generation	Material recycling	
"The sales problem in China is that there are not so many	Price sensitive; customer unwilling	Customer management	**Stakeholder management**

high-quality customers willing to pay for good quality and service.	to purchase high price product and service		
"The Taobao have tremendous low-quality products with low prices; such system cultivates a large number of customers that are more likely to buy cheap and low-quality products."	Customer unwilling to pay for high-quality product and service	Customer management	
"We have a good relationship with customers to know what their expectations, then we can evolve our products in a good direction."	Maintain good relationship with customers	Customer management	
"In China, we need networking and business relationship in education and other industries."	Social networking; business relationship with government and industry	Stakeholder networking	
"We have our resellers and distributors in China, US, Japan, Korea and Europe."	Collaboration with distributors and resellers; trustworthy partnership	Partnership	
"The 3D printing software is not easy to use, which require special knowledge […] only a small number of employees know how to use the software."	Lack of software knowledge; lack of human resource in the AM industry	Human resource	**Qualified AM professionals**

"We have a training program to educate our employee."	Training and education program	Education service	
“We designed the polishing device from scratch through conception, design iterations, prototypes, feasibility study, optimization, trial production, compliance testing, final de-bugs, production, and worked with product development companies.”	Product development from scratch; collaborate to development product	Product management	**System thinking**
“We want to create a polishing machine with a combination of aesthetics, function and reliability.”	Balance of different functions	System design	

The author identified six factors that are critical to Company C’s business model development including *technology innovation, mass customization, materials for sustainability, stakeholder management, qualified AM professionals, and system thinking*. Therefore, the high-level themes can be used to help Company C transform towards a sustainable business model and capture not only the monetary profits but also the environment and social benefits.

4.3.7 Value Opportunities Identified in Company C

The author selected and evaluated the examples of the failed exchanged value in Company C to help identify the value opportunities. The similar constructs for value opportunities were clustered into groups, shown in Table 4.15. Based on the critical factors identified in the previous section, the author analyzed the examples of failed value in terms of *customer failed value, lack of sustainability, technology immature,* and provided recommendations to realize the value opportunities. 11 examples of value opportunities were presented.

Table 4.15: Selected examples of value opportunities in Company C

Failed Value Exchange	Examples of Failed Value	Identified Value Opportunities
Customer failed value	Customer unwilling to pay for high-quality product and service	Develop advanced materials to incorporate more functions without mainly increasing the price
	Lack of providing service to customers	Implement sustainable PSS such as use-oriented and result-oriented models
		Deliver functionality rather than ownership
	Target customers are quite narrow without caring about the low-end market	Cater to a general customer with the offering of multi-level products with relatively low price
	Lack of human resource in the AM industry	Collaborate with universities and vocational schools for AM education to cultivate qualified professionals for AM industry
Lack of sustainability	Lack of recycling and reusing printed materials and scraps	Develop recycling and reuse technologies for mixed materials and multi-color materials
	Materials generate uncomfortable smell and may cause health issue	improve the recycled material quality for regular use
		Develop environmentally friendly materials for printing
Technology immature	Multi-colour printing unavailable	Develop advanced printer that can print multi-color materials with good quality

	Lack of machine can work with different materials	Work with machine company to develop advanced printer with the compatibility of various materials
	Challenge of recycling mixed materials	Develop recycling technology to separate recycled mixed materials without compromising quality and characteristics as well as increasing the costs

4.4 Uncovering A New Value Form – Value Unsupported

A new failed value is identified from the analysis of the empirical data collected at the exploratory stage, and the definition is first provided by the author. The new failed value form is called *value unsupported* corresponding to the current value uncaptured perspective (Yang et al., 2016), but lies at a different level and stakeholder dynamic mechanism.

The author defines *value unsupported* as *"A mechanism, a system, a platform, or an architecture, which are required but has not been established externally for the focal firm to support value creation and capture."* The value unsupported is different from the value absence (*the value which is required but has not been created for the customer*). Value absence indicates that the company fails to create customer value (e.g. products, services, convenience, functionality, or happiness) and internally deliver it to the customer (Richardson 2008; Teece 2010; Osterwalder & Pigneur 2010; Zott & Amit 2010; Yang et al., 2016).

However, value unsupported indicates that the company fails to create and capture customer value due to the lack of external support such as policy, regulation, system, platform, environment, government, and other stakeholders. Therefore, the author proposes the Type E of failed value, "*I want, but you don't give*" based on Fernando (2016) that "you" refer to other external stakeholders instead of the customer and "I" refer to the focal firm. The author also generates the description of the value unsupported based on Yang et al. (2016), "*the value required but is not created by other stakeholders for the focal firm*" to differentiate with the previous four failed value forms.

The value unsupported indicates a stakeholder dynamic mechanism that the three-side of relationships among the focal firm, customer, and external stakeholder instead of bilateral interaction correlate each other to create and capture value. The novelty of the value unsupported is that it generates a new understanding of the failed value at a different level. Notably, it supplements the established failed value exchange perspective (Yang et al., 2016; Rana et al., 2013) with the significant identification of the three-side relationships of the stakeholders. The strength of this new failed value is that it emerged and was developed from the empirical data rather than a conceptual idea derived from the literature.

For example, in terms of Case A, the company looks for financial investment eagerly in recruiting more employees and expanding the business faster. However, the venture capital (VC) firms do less likely to set AM sector as the priority to invest in, and the depression of AM market has made the VCs feel less confident in investment than other sectors such as artificial intelligence, blockchain, and the driverless car. Therefore, the lack of capital investment due to the AM technologies immature and AM market depression made the company fail to get financial support from external stakeholders. Furthermore, there is no universal AM design rules, guidelines and standardization in the AM industry. The ASTM is striving for the development of unified AM standards and regulations, particularly for the design and materials process. Therefore, they are the value unsupported for Company A not being able to develop the technology further and capture more value.

In terms of the intellectual property (IP) protection issues, the emergence of open-source AM service has brought several challenges and risks to the IP, patents and design protections. The nature of open-source AM models makes it hard to control and limit sharing of IP. The applications of AM data are often compared with the situations of the copyrights of music or movies on the Internet. Typically, consumers are much likely to use or copy digital files for free. The intellectual values and design ideas should be highly protected. The company sometimes confronts with the IP infringement by the competitors and share with other companies illegally. Therefore, a proper legal framework and policy are needed to protect IP rights and improve the economic incentives for business to generate new ideas and develop a distinctive design. More importantly, government policymakers need to take measures to ensure appropriate IP protection and figure out how IP rights will be protected, and also assign legal liability for any problems that may be caused by 3D-printed products. Hence, it is the value unsupported for companies that there is no sufficient legal framework and policy for IP design rights protection in the AM industry. More empirical data are collected and analyzed to showcase and validate value unsupported perspective at the descriptive stage in Chapter 5.

4.5 Chapter Summary

This chapter uses three case studies to comprehensively discuss the AM business models, analyzed the value systems and PSS solutions, identified the failed value exchanges with multi-stakeholders, presented the negative roots causes, identified the critical factors for sustainable AM business model development, and also provide tactics to help turn failed value into value opportunities in each case.

The definition of value unsupported as a new failed value form is given to indicate "*value required but is not provided by external stakeholders*" and "*I want, but you do not give*", which is different with the value absence. At the exploratory stage, initial themes are identified to help companies gain an understanding of sustainable business models, and to turn the failed value into the value opportunities. At the descriptive stage, value unsupported will be used in the descriptive analysis and further data is coded to confirm, reject and shape the critical factors for sustainable business model development to form complex theme connections.

Chapter 5 Findings of the Descriptive Stage

This chapter presents the research findings through three further case studies and two focus groups with two site visits at the descriptive stage. Each set of results is presented, respectively. The objectives of this chapter are to gain deep insights into AM business models about what value is currently available, how value is extracted and captured through the business model view of value innovation and transformation, how the AM firms deliver value, thereby discovering new value opportunities within the AM business ecosystem. Furthermore, the author investigated the failed value exchanges, root causes as the challenges of AM, and critical factors for sustainable value creation.

At the exploratory stage, the author identified the initial themes *including PSS for AM, qualified AM professionals, IP management, mass customization, design, printing and materials for sustainability, stakeholder management, system thinking, and technology innovation*. In this chapter, new data are collected to reject, shape and confirm the initial themes. The themes are validated and established as critical factors for helping AM companies develop sustainable business models. The author intends to provide an accurate description of the failed exchanged value and the root causes as the barriers for AM adoption where they are applied into the development of frameworks and models (see Chapter 6). Furthermore, the focus groups involving workshops and site visits were conducted to validate the collected data. The confirmed themes are also compared against existing literature to check whether to contribute to the knowledge.

At the descriptive stage, two value forms are identified as the interventions for failed exchanged value, namely *value complement* and *value mitigate*. The definitions of the two value forms are described in detail. The value opportunities are further investigated for failed value transformation in each case. An AM critical factor framework is developed as the guidance for sustainable AM business model development. Furthermore, a working definition of sustainable business model is proposed based on interpreting the meaning of themes and descriptions (see Chapter 6).

5.1 Case Study D

5.1.1 Introduction to Company D

Company D is a 3D-printing company concentrating on the development of the high precision FDM printers and the online printing service platform. Company D specializes in FDM printers with high precision, high stability, improved safety, excellent print and surface quality. The company develops a series of printers for industrial applications and a printing service platform with design-to-manufacturing strategy, prototyping, and processing service. The company targets customers in the industrial, arts, education and medical sectors.

The reason for choosing this company is that it is quite innovative and technology-oriented with the innovation of a series of FDM printers and development of a printing service platform to cater to the target customers and apply to different industrial sectors. The company can analyze and repair customers' 3D files, print 3D models and prototypes with a wide range of materials along with tutorials, articles and educational materials. However, this company is still quite small and has limited awareness and knowledge of sustainability concepts and eagers to transform business model towards sustainability. In this case study, in-depth interviews were conducted with the CEO, CTO, COO, Sales Manager and Project engineer. The interviews were then transcribed, and observations were made combining with the secondary data from documentary analysis.

5.1.2 Business Model of Company D

The business model for Company D is to provide a series of high-precision printers and a printing service platform incorporating original design, manufacturing, and processing service to the customers. Users can order services of having the product printed and delivered through the online platform at a low cost without owning a 3D printer. The Sales Manager said: *"Our customers are mainly the industrial companies."* The customer value propositions of Company D lie in two perspectives. The first value proposition is a series of FDM printers equipped with ball screws and linear guide, with a minimum nozzle diameter of 0.12mm and highest accuracy of 0.02mm. The company has successfully developed and launched three types of high precision printers with different printing sizes, printing materials, and printing speed to cater to customers with multi-professional applications.

The second value proposition is an online customized printing service platform which provides design-to-manufacturing strategy, original design, prototyping, and processing through the process of first understanding customer requirement, creating the model (users can customize design), selecting materials, manufacturing product, managing product lifecycle, and then shipping to customers. The online platform is responsible for R&D, design, customization, material selection, manufacture, lifecycle management, delivery concerning the products. The company develops smart price calculation system through optimization of the algorithms to make accurate pricing for the customer. As commented by the CEO:

"*We have rich experiences for design modelling, slicing data and printing with modularized service […] we focus on selling printers with additional services such as industrial design, 3D model creation, mold development and other printing services."*

The company's value creation is that the company has substantial technical advantages and research abilities to develop the high precision printers that can replace the costly DLP machine and are more precise than other FDM machines in the current market in China. One of the core competencies is that the printer can print a wide range of materials including ABS, TPU and TPE. Notably, the printer has the function of continuously printing the object even without power to ensure printing safety and completion. The online printing service platform also generates a significant amount of value that helps initially create an object from scratch and ship to customer ultimately. Value is also created through an excellent partnership with the materials and parts suppliers to ensure the materials and machine parts are capable of meeting the needs.

The company also offers the educational materials for employees to understand different AM technologies and to teach customers operating and adjusting the printers. The COO said:

"*We are taking cautious steps in terms of working with our customers and seeing how they use the printers and educate their employees to apply our technology*."

In terms of value capture, the company makes profits by the nonrecurring charge of the 3D printers and various pricing models of the original design manufacturing service on the service platform. The value delivered to customers is mostly through online service platform, exhibitions promotion, resellers and distributors. The Sales Manager said:

"*Particularly in the education market, if we have a powerful distribution channel that can help us build up a reliable connection with the local government and education bureau, we would be very easy to get orders from the schools.*"

5.1.3 Value Systems and PSS Solutions in Company D

The business model of Company D was analyzed by identifying the value systems. In terms of PSS solution, the relationship between Company B and value proposition for customer indicates the type of PSS model. Mainly, the company sells a series of FDM printers as a product-service solution. The company adopts the product-oriented PSS solution as the value is created by the owner of the printer with the after-sales service such as installation, technical support, customized training sessions, email and phone support. Furthermore, the company has developed the online printing service platform to help customers with efficient and low-cost approaches to complete the original design, product development, print validation, model manufacturing, lifecycle management, and delivery. In light of this, the company adopts the result-oriented PSS model to some extent as customers only pay for printing service and do not need to own the machine or materials. The platform can automatically calculate the price for users and make smooth transactions. The value is created via selling a result of design, printing and delivery service, while the machine and materials remain the property of the company, thereby reducing the need for customer ownership.

The author further identified the value systems along with the economic, environmental and social value for Company D based on the interview, observations, company reports, and other documentation. The codes of sustainable value emerged and were grouped into the categories with the combination of the business model attributes, shown in Table 5.1.

Table 5.1: Value system analysis for Company D

Valve System	Main Findings
Value Proposition	Series of FDM printers with high precision; after-sales service including technical support, customized training sessions, email and phone support, installation; online printing platform with the original design, manufacturing, product lifecycle management, and distribution service
Value Creation	Robust technology focus on the FDM precision improvement; capabilities of developing series of printers with different speed, size and materials; core competencies of the original design, design customization, lifecycle management, and printing customization
Value Capture	Different price levels of printers cater to different customers; charging online for printing service, design customization, manufacturing, and delivery
Value Delivery	Selling through the online platform, resellers and distributors; delivery through distributors
Social Value	Printers can encourage student creativity, support immersive learning and maker education in schools; close engagement with customers for R&D and original design;

	maintain a good relationship with resellers and suppliers; use less ABS for health safety; rapid prototyping for idea verification
Environmental Value	Improved material efficiency; reduced environmental impacts; generate less material wastes; less material consumption
Economic Value	Online printing service platform for original design, printing process, and lifecycle management; selling series of high precision printers; no moulds, casting, tooling necessary; shorten manufacturing process and supply chain; smart pricing system with secure transactions

5.1.4 Failed Value Exchanges in Company D

In this section, the failed value exchanges with multi-stakeholders in Company D were identified and analyzed based on the qualitative data. The author intended to understand better the failed exchanged value in the AM service platform. The codes of failed value exchanges emerged and were grouped into 63 examples in Table 5.2.

Table 5.2: Failed value exchange analysis in Company D

Failed Value Exchanges	**Examples/Explanations**
Value Missed	• High initial investment in printer manufacturing • Failed to capture value from the education market • High precision printers failed to meet the school requirement and education purpose • Best time missed for promoting printers to the domestic education market and schools • Costs of manufacturing printer are too high

	• Fierce competition with other cheaper FDM machines • Implement sustainability efforts maybe pose negative impact on making profits and cause economic downside • Highly competitive market for desktop FDM printers in China • Manager's reduced abilities to identify failed value
Value Absence	•Limited capability of providing proper Maintenance service due to the lack of service employees •Failed to produce large-scale printer for customer •Incapable of printing large-size objects using FDM printer • Not consider printer leasing, sharing or subscription • Failed to make cost-effective printers •Lack of a wide range of material selection •Challenges of keeping product lower cost and higher quality •Function limitation of FDM printers •Lack of different service levels for customer requirements •Lack of AM and subtractive manufacturing integration solution •Challenge of achieving mass customization •Lack of high value-added printed products for general customer consumption •Failed to meet education market demands due to high precision is not needed

	•Failed to meet medical market due to the needs of the high-speed printer with high strength materials rather than high precision one •Customers are not satisfied with the printer screen size, printing resolution and printer gate • Lack of promotion and branding abilities • Cost of printer maintenance too high • Lack of resilience, flexibility and responsiveness for the printing service platform • Failed to penetrate the foreign market due to the lack of resellers and distributors in foreign countries • Lack of social networking and storytelling skills for founding team •Using glue for printing may cause health problem •Lack of support parts reuse and recycle •No recycle and reuse filaments •Lack of the eye-washing facility for working condition •Lack of protective kits for working condition •Need a strategic framework for decision making, idea generation and implementation. • Unclear about customer needs (potential needs, hidden needs)
Value Destroyed	• Limited recycling and reusing printed materials • Waste streams in the printing process (materials, scraps, printing support, etc.) • ABS materials generate uncomfortable smell and may cause health issue • Unpleasant smell from surface spray painting cause environment pollution

	• Design of the three-axle floor and backplane of the printer is not economical and not cost-effective • Hard to balance production and environment • Negative outcome during the printing process include noise, supporting material wastes, used parts are thrown away and no recycling • Challenge of managing customer expectation if the supply is constrained •Machine crash down sometimes •Glue is harmful to the customer and not suitable for the environment •Limited strength, rigidity and heat resistance for printed parts which are not conducive to long-term preservation •Not care about sustainability due to the low the volume of material wastes and energy loss •Lack of design for sustainability •Excessive energy consumption •Bad quality of recycled and reused materials •Defective filament quality with small porous and dust inside
Value Surplus	• Too many FDM printer companies that cause vicious competition • Overproduction of printers and market becomes mature • Printers idle in schools only for display • The base frame of the printer does not need good materials which cause wasted materials
Value Unsupported	• Lack of complete and well-developed agent system support for providing leasing service • Lack of qualified human resources for design,

	supply chain, research, and management in the AM industry • Lack of experienced salespeople who have the market resources and distribution channels in the AM industry • Need government relationship for marketing and sales • Lack of AM education system in the AM industry • Lack of the conventional AM industry standards • Lack of an open language for 3D printer operation

The author identified the above-failed value in detail following the same coding and categorization process at the exploratory stage. The failed exchanged value mainly with the customers, suppliers, environment, and society indicated the potentials of uncovering value opportunities and creating sustainable value for Company D. Failed value identification aims to transform the failed value into value opportunities in Company D. Value absence involves lack of PSS models, comprehensive materials selection, mass customization, printing machine that can produce large scale objects. Value destroyed relates to lack of recycling, reuse, design for sustainability, safety and health issues corresponding to the findings at the exploratory stage. The failed value and captured value helped formulate the categories to add and shape the themes to form the confirmed themes which will be discussed in Section 5.1.6. The negative root causes identified from the online printing platform and machine development in Company D are presented in Table 5.3. It shows the challenges of a printing service platform that fundamentally impede the comprehensive implementation of AM in different industries and sectors.

5.1.5 Challenges of Printing Service Platform

The author identified and summarized the negative root causes in the AM printing service platform. The root causes help identify the challenges of the printing service platform and understand the barriers for wide AM adoption from the printing service perspective. The root causes were identified based on the interview, observations, and documentary analysis along with the academic literature in the printing process in Table 5.3.

Table 5.3: Root cause analysis in the printing service platform

Key Challenge	Root Cause Analysis in Printing Service Platform
Printing service speed	Low slicing speed
	Low printing speed due to the FDM machine limitation★
	The whole process of online printing service is quite slow
Material quality	Materials toxicity for ABS★
	Low fault tolerance
	Low-quality consistency
	Limited material available in online printing★
	Difficulty of predicting the microstructures and fatigue properties of materials during the printing process
	Hard to guarantee material properties for a given process
	Lack of online control of material composition and phase transformation, and the repair of defects such as pinholes/porosity, micro-cracks, and segregation
Printing software	Slicing failure of broken object face or hole
	Online printing software is not open source and strictly bounded with machine

Service capability	Limited printing service capability for mass production
	Challenge of achieving mass customization through online printing
	Deficits in designers and engineers skilled in AM to provide service★
Printing quality	Printed parts are less reliable than injection molding
	Low machine reliability for printing service
	Lack of repeatability and consistency of the manufactured parts
Service quality	Poor service effectiveness and efficiency
	Printing service is fragmented and unevenly distributed
	Inconvenience of changing wire during the printing process
	Lack of effective use of online resources
Cloud manufacturing service	Lack of facility for cloud manufacturing enabling sharing of manufacturing resources online
	No readily applicable systems can be used for cloud-based AM
	Lack of cyber-facturing (cyber-enabled manufacturing) that manufacture products at geographically dispersed locations via communication and control online★
Printing sustainability	Lack of recycling and reuse support and method★
	Lack of remanufacturing guidance and methods★
	Uncomfortable smell produced when printing ABS★

Printing process	Lack of fundamental modelling, analysis, and simulation in the online printing process
	Lack of system to model the temperature, stress, and composition history
	Lack of fast in situ measurements of temperature, cooling rate, and residual stress in sensing of AM processes
	Lack of integrating AM process with other manufacturing technologies in design and production (machining, injecting molding, casting) ★
	Lack of in-process monitoring of geometric dimensions and the surface quality of finished layers
	Lack of understanding of how process parameters affect the material properties and part performance
	Hard to coordinate material flow control with machine motion control in the printing processing within each layer and between layers
	Existing printing systems are still predominantly based on rapid prototyping machine architectures
Printing standardization	Lack of certification of equipment, materials, and personnel★
	Lack of open and unified standards for printing development★
	Lack of unified printing principles, rules, guidelines and regulations★
	Lack of development and standardization of new materials★
	Challenge of the fabrication of large-scale parts to produce parts of nearly unbounded size

The root causes were classified into 41 examples of key challenges for the printing process and service platform. The root causes reflected the challenges of printing service and the barriers of wide AM adoption in different industries.

Each root cause was analyzed and classified into 10 categories including *printing speed, material quality, printing software, service capability, printing quality, service quality, cloud manufacturing service, printing sustainability, printing process, and printing standardization.*

The identification of the failed exchanged value and root causes in Company D would help uncover value opportunities for the company, particularly for the environment, and society. Therefore, the critical factors that help develop a sustainable business model are identified in the following section.

5.1.6 Critical Factors Identified in Company D

The critical factors were identified through thematic analysis to determine the high-level themes step by step. The author introduced the initial themes at the exploratory stage, respectively *PSS for AM, qualified AM professionals, IP management, mass customization, sustainability, stakeholder management, system thinking, and technology innovation*. Based on that, the author has gone through all the codes and concluded names based on the initial themes. The author rejected, shaped and confirmed the critical factors that might be needed for the transition towards a sustainable business model for Company D. Likewise, the simplified thematic analysis findings are presented in Table 5.4.

Table 5.4: Simplified thematic analysis findings for Company D

Initial Quotes (Clustering)	Similar Codes	First Order Theme	Second Order Theme
"Due to the technical team and R&D problem, we fail to make a low-price machine to make profits."	Failed to make a cost-effective machine; technology immature	Machine problem	**Technology innovation**

"We want to penetrate the foreign market; however, most of them have preconceived notions of the machine is not as good quality."	The preconceived notion of low-quality product in China	Technology immature	
"Screen size, resolution and printer gate are complained by the customers."	Customer unsatisfaction; the product needs improvement	Machine problem	
"Educational opportunities missed is due to the timing and fail to fulfil the customers' needs."	Failed to capture the education market; timing issue	Education market uncaptured	**Multi-stakeholder engagement**
"Orthopedics and medical protection tools do not need high precision printing, and they need high speed and strength printer."	Failed to capture medical market due to less demand for high precision printers	Medical market uncaptured	
"The education, vocational and schools are not necessary to have such high precision printers […] therefore, it is the value missed for the education industry."	Failed to meet the education market need; mismatch for customer need	Education market uncaptured	

"In China, we need the government network and support to promote product and service in different cities and industrial sectors."	Lack of transparent market environment; lack of government relations and social networks	Government relationship	
"After-sales service and maintenance need significant work commitment […] thus, you need a powerful team. However, we cannot do that."	Lack of maintenance service people; lack of capability of providing comprehensive service	Maintenance service	**PSS for AM**
"Customer needs are not satisfied because of the maintenance issue."	Insufficient customer service; lack of maintenance team	After-sales service	
"We do not have the well-developed agent system for after-sales […] this is a big problem."	Lack of maintenance service agent support	Service support	
"For working condition, we have no eye-washing facility [...] sometimes we use the glue for printing, it may cause the problem."	Lack of cleaning facility; printing glue causes pollution	Pollution generation	**Printing for sustainability**
"We do not have shielding shoes and protective footwear."	Lack of protective kits for printing	Safety issue	

"When we conduct ABS materials adjustment setting, we would have the bad smell."	Materials pollution; health issue	Environmental pollution	
"The surface spray painting has some unpleasant smell when manufacturing the outer product shell."	Health issue; unpleasant smell	Social wellbeing	
"Our glue may be harmful to people. However, if you do not use the glue is not good for production […] the glue is not good for people and the environment but is good for production."	Glue is not suitable for the environment; hard to balance the environment and production	Environmental pollution	
"Negative outcome such as noise, supporting materials wastes, used parts throw away, no recycling and no reuse for the environment."	Noise pollution and materials wastes; no recycling and reuse	Environmental problems	
"The whole 3D printing industry is very competitive, which causes millions of 3D printers wastes."	Highly competitive machine market; overproduction cause wastes	Market mature	**System thinking**
"We should lower the costs instead of	High costs; failed to make breakeven	Failed to control cost	

making it expensive and failing to payback and breakeven."			
"The suppliers are not satisfied due to the low selling volume […] we need to reduce the costs."	High costs and low sales volume	Failed to control cost	
"For human resources, we need to improve our employee capability for sales, design, supply chain, and marketing."	Lack of qualified human resources; lack of skilled talents	Human resource	**Qualified AM professionals**
"Need experienced salespeople having resources and channels. Particularly, have experience in education, furniture and fashion industries."	Lack of sales team	Human resource	

The author confirmed the six high-level themes as the critical factors for sustainable value creation in Company D. The critical factors include *printing for sustainability, PSS for AM, technology innovation, multi-stakeholder engagement, qualified AM professionals and system thinking.* The author gained a more in-depth understanding of AM business models and failed exchanged value with multi-stakeholders where the initial themes were shaped and confirmed.

Notably, the data emphasized the significant role that the qualified AM professionals with system thinking played in the technology innovation and multi-stakeholder engagement in Company D. The author pointed that the use-oriented PSS model has not been implemented yet; for instance, machine leasing and subscription. Now the company only provides after-sales service in which the company needs to strengthen the maintenance service team for better fulfilment of customer demands. Furthermore, the data suggested that the pollutions generated during the printing process and the unpleasant smell produced using ABS materials posed a negative impact on human health and the environment. Thereby, the company needs to embed the sustainability concepts into machine development and printing service to gain environmental and social benefits.

5.1.7 Value Opportunities Identified in Company D

Four typical failed value exchanges were selected and analyzed, including *customer failed value*, *lack of sustainability, technology immature, and human resource scarce*. By analyzing the identified failed value exchanges, the similar value opportunities were clustered into groups under the categories of each failed value exchanges. 16 examples of value opportunities were provided, shown in Table 5.5.

Table 5.5: Selected examples of value opportunities in Company D

Failed Value Exchange	Examples of Failed Value	Identified Value Opportunities
Customer failed value	Failed to capture value from the education market in China	Develop large-size and high-speed printer for education purpose with lower price; strength the maintenance service team
	Lack of different service levels for customers	Consider implementing the subscription or leasing service for printer
		Deliver functionality rather than ownership that

		customers are willing to buy service
		Develop multi-level service packages to cater to different types of customers
		Improve the service efficiency of the online printing process
Lack of sustainability	Waste streams in the printing process (materials, scraps, printing support)	Primarily use biodegradable PLA to print
		Reuse of broken parts and failed products
		Develop environmentally friendly materials for printing
	ABS materials generate uncomfortable smell and may cause health issue	Provide mask or protective kits for operating ABS for printing
	Glue is harmful to the customer and not suitable for the environment	Find out a substitution of glue that is environmentally friendly for printing
Technology immature	Service platform is not user friendly	Develop a printing service platform with high efficiency, high resilience, low cost, and high flexibility
	Recycling materials is not well received	Develop recycling technology to separate recycled mixed materials without compromising quality and characteristics
	FDM printer is not good enough for customer printing big objects	Innovate the printer and materials to print large-size product without increasing the printing time and costs

Human resource scarce	Lack of qualified human resources	Provide a training program to customers and employees such as online teaching system
		Collaborate with schools to provide AM education programs
		Develop educational materials including PPT, textbook, curriculum, evaluation system, videos

5.2 Case Study E

5.2.1 Introduction to Company E

Company E is an emerging AM technology company focused on developing a range of AM education products for enabling STEM (Science, Technology, Engineering, Math) learning objectives. The company was founded in 2015 and dedicates to AM education for labs and classrooms to empower student innovation, research and career development. The company develops complete education packages including affordable 3D printers, resource materials, curriculum, textbook, certification and training programs. The company aims to educate students with hands-on training to comprehensively understand all aspects of AM and to prepare students with STEM skills and theoretical knowledge for today's fastest-growing environment and careers.

The reason for choosing this company is that the AM education sector is emerging and ever-growing with increasing players tapping into this market. AM can benefit students' learning, particularly in STEM subjects, and has become more accessible and affordable as a classroom technology. In this case study, the qualitative data were collected from the semi-structured interviews with the CEO, CTO, COO, Sales Manager, HR, and Business Development Director. Observations and documentary analysis were conducted to collect data.

5.2.2 Business Model of Company E

The business model for Company E is to provide integrated solutions for AM education to customers in China. The customer value propositions of Company E lie in three perspectives. The first value proposition is the course system combined with theories and practice, including AM general class, teacher training, post-processing study class, design modelling training and certification. The company collaborates with universities to offer graduate-level courses focused on AM technologies and management. The CEO said: *"We published several books and articles about the 3D printing development."*

The second value proposition is the teaching resources for AM education such as textbook, lesson plans, online videos, webinars, design model repositories, case studies and study projects. As commented by the CEO:

"*I feel like mastering 3D printers would be the core in the education sector, and we strive to make the printer affordable and materials accessible […] who knows, the printer would become a widely used educational tool as the electronic calculator*."

The third value proposition is printers and materials. The affordable FDM printer is designed from the ground up for the classroom. The printer works with non-toxic, biodegradable materials and is safe to use in a closed environment. The materials are mainly thermoplastic filament (PLA, TPU, PC) developed for use in classrooms and schools with excellent surface finish with no odor. The company does not research and develop materials itself, while partner with suppliers to provide the selection of materials.

The value created for company E is based on education resources and teaching development capabilities. The AM education solutions integrate the hardware, curriculum, and support package for value creation. One of the core competencies is the capabilities of developing affordable, ease-of-use 3D printer for teaching STEM in schools. The company intends to design the printer that students can easily engage with, understand and use. Furthermore, the technical resources are integrated to establish the education center for promoting AM technology, cultivating STEM skills, knowledge exchange and sharing. The COO said:

"*We aim for working with universities and the government to set up ten printing innovation and education centers.*"

The value is captured through multi-revenue models. Notably, the company charges for education programs with different course schedules. It promotes different all-in-one bundles to schools where the bundles consist of printers, materials, training with teachers, and a full repair and the maintenance cycle.

5.2.3 Value Systems and PSS Solutions in Company E

The business model models were analyzed to provide a comprehensive description of the current value systems in Company E. The company still adopted the typical product-oriented PSS model as schools owned the printers and materials. A full repair and maintenance cycle were provided as a product-service solution. The author also analyzed the economic, environmental and social value from the education perspective. The information in this table was mainly generalized from interview data. Likewise, the value systems identified along with the emerged sustainable value were grouped into the categories, shown in Table 5.6.

Table 5.6: Value system analysis for Company E

Valve System	Main Findings
Value Proposition	Course system for AM training; curriculum materials; online teaching resources; AM post-graduate programs; 3D printer all-in-one bundles including printers, materials and technical support
Value Creation	Education resources; teaching resource development; R&D abilities; curriculum design capabilities

Value Capture	Multi-revenue models for courses and teaching resources; AM bundles as sales packages for classrooms
Value Delivery	Selling through the online store, resellers and distributors; partnership with distributors in China; offline training classes
Social Value	Maker education; improve innovation capabilities and design thinking; offer a hands-on experience; see the physical realization of students' work; support immersive learning in schools; improved safety; STEM skill cultivation; printer is portable and safe to use; no annoying tweaks and adjustment
Environmental Value	Reduced environmental impacts; use biodegradable materials; generate less material wastes; non-toxic materials; no sizeable hot moving parts to be careful of
Economic Value	AM bundles including printer solution, materials, training, and support service; integrated AM education solutions with personnel training, teaching materials, certification, and post-graduate programs; offer professional service to solve customer problems

5.2.4 Failed Value Exchanges in Company E

In this section, the failed value exchanges with different stakeholders in Company E were identified and analyzed. The author intended to gain a more comprehensive understanding of the failed exchanged value in AM education. The identification of failed value would help uncover value opportunities. The codes of failed value exchanges emerged and were grouped into 50 examples of bullet points in Table 5.7 as follows.

Table 5.7: Failed value exchange analysis in Company E

Failed Value Exchanges	**Examples/Explanations**

Value Missed	•3D printer bundles are not well received due to high prices •High investment for the development of printers and educational materials •Few predictions about potential customer needs • AM graduate-level classes are not well received in China •The tuition fees for graduate-level programs are too expensive
Value Absence	•Printer cannot produce large scale objects • Not consider printer leasing, sharing or subscription •Function limitation of the printer •Lack of printing software for workflow management • Lack of software service for 3D printable designs management • Lack of user-friendly software for model design • Lack of printer connection from remote locations • Insufficient teaching personnel • Lack of qualified professionals for teacher training • Printed objects sometimes have breakage, the deformed and weak supporting structure • Lack of simulation function for the printer to optimize and validate 3D models • Lack of quick and efficient response for customer inquiries • Lack of 3D model design service • Lack of skilled labor for course development, printer R&D, sales, management

	•Lack of design for sustainability • Lack of recyclable materials for education sector •Lack of printer reuse and recycle •No recycle and reuse filaments •Lack of teaching methods for printed objects recycling •Difficulty of integrating sustainability considerations into education •Difficulty of educating students about recycling 3D printed materials • Insufficient capacity of service workers •Customers' insufficient use of printed old objects • Lack of systematic AM education programs in schools and universities •Open-source software is unstable and unreliable
Value Destroyed	• Limited recycling and reusing printed materials • Waste streams in the printing process (materials, scraps, printing support, etc.) •Machine crash down sometimes •Limited strength and rigidity for printed parts that is not conducive to long-term preservation •Not care about sustainability due to the low volume of material wastes and energy loss •Defective filament quality with small porous and dust inside •Lack of support and method for printed objects recycling
Value Surplus	• Too many printer companies to do education business that results in vicious competition • Overproduction of printers and market becomes mature

	• Printers idle in schools only for display and remain unused
Value Unsupported	• Lack of qualified human resources in AM education sector • Lack of experienced salespeople who have the market resources and distribution channels • Need government relationship for business development in schools • Lack of AM education system in the AM industry • Lack of the innovation education system • Lack of formally teaching AM in the engineering curriculum • Lack of financial support from external parties for purchasing high-end equipment for education • Lack of financial aid and funding for SMEs and start-ups in AM • Lack of an open language for 3D printer operation • Lack of open standards for 3D printer

Some frequently mentioned from the interviews about the failed value was unclear customer needs, lack of qualified professionals, limited recycling and reusing printed materials, lack of user-friendly software for model design and low efficient workflow management. As the HR commented:

"*The most fundamental challenge is that there are very few qualified talents in the current AM market*." Other failed value was highlighted such as poor capabilities of service workers, lack of sustainability awareness, lack of 3D model design service for schools, no printer leasing and subscription service and printers idle and remain unused. As the CEO emphasized:

"*In school, teachers are not capable of teaching 3D printing, and school bought several machines and just left them unused*."

5.2.5 Challenges of AM Education

At the descriptive stage, the author intended to gain deep insights into the AM business models, particularly in the AM education sector. The negative root causes showed the challenges of AM education and notably, the failed value exchanges overlapped with the negative root causes to some extent. The codes relating to root causes in Company E emerged and were categorized into six types, shown in Table 5.8.

Table 5.8: Root cause analysis in AM education

Key Challenge	Root Cause Analysis in AM Education
Education materials	Lack of resources for developing AM textbook and curriculum★
	Limited quality of teaching textbook and lesson plans
	Lack of teaching standard and education quality evaluation
	AM education and training materials are still very limited in schools★
	Challenge of incorporating AM into teachers' curriculum
	Lack of AM courses for the training of engineering students in 2-year community colleges
	Challenge of incorporating AM technologies into the existing curriculum while meeting the Accreditation Board for Engineering and Technology (ABET) requirements in colleges and universities
Qualified educator	Lack of qualified teachers for AM education★
	Lack of sufficiently trained personnel to deliver quality AM products and teaching materials★

	Some teachers have trouble with clear and concise communication with students
	Lack of knowledge of AM technologies and processes★
	Lack of general awareness of AM for K-12 schools
	AM educators lack of teaching qualification★
Education equipment	Lack of machine to meet the teaching requirement
	High-level educational tools are missing in community colleges, particularly for AM
	Industrial printing equipment (SLM, EBM, etc.) may be financially out of reach for many community colleges
	Lack of financial support and funding for high-end AM equipment in community college
	Lack of integrating AM process with other manufacturing technologies in teaching and demonstration
	Challenge of fabrication of large-scale parts for a printing demonstration
Sustainability education	Difficulty of integrating sustainability considerations into education
	Difficulty of educating students about recycling 3D printed materials
	Challenges of educating recycling plastics and other materials
	Material wastes generation during printing practice and demonstration
Design for education	Need further development of AM design methodology for teaching
	Lack of readily applicable and proved 3D models for AM education and training★

	Students are scared of failure which limits their experimental potential
Education service	Lack of online education resource management
	Lack of regulation of fixed teaching time in schools
	Lack of integrated software solutions for model design, printing management, etc.★

The data was analyzed, and the negative root causes were categorized into 29 groups which reflected the challenges of AM education and the barriers of wide AM adoption in the education perspective. Some of the root causes are generic, others are specific and similar root causes were put together. In essence, the challenges were classified into six categories such as *educational materials, qualified educator, education equipment, sustainability education, design for education, and education service.*

5.2.6 Critical Factors Identified in Company E

The author conducted the thematic analysis to determine the critical factors needed for business model development towards sustainability in the AM education company. Based on the initial themes derived from the exploratory stage, the author further analyzed the data and shaped the themes step by step, shown in Table 5.9.

Table 5.9: Simplified thematic analysis findings for Company E

Initial Quotes (Clustering)	Similar Codes	First Order Theme	Second Order Theme
"I want to recruit more employees, but it is tough to have that human resources."	Qualified employee scarce	Human resource	**Qualified AM professionals**

"I want to point out that the difficulties and challenges for companies are to recruit qualified and skillful people."	Difficulties of recruiting qualified people	Human resource	
"In school, teachers are not capable of teaching 3D printing, and school bought several machines and just left them unused."	Lack of teaching capabilities; over idle printers	Teacher qualification	
"Most funding only go to the famous universities and big-name researchers rather not pay attention to start-ups and SMEs."	Lack of support and funding for SMEs and Start-ups	External financial support	**Multi-stakeholder engagement**
"For education, some company do not know what the schools want and what the customers want to learn."	Unclear about customer needs	Customer engagement	
"Schools do not know what printer to buy; students do not know what to do with the machine, and how to use digital software."	Lack of understanding of AM	Customer engagement	

"We aim to work with universities and government to build the education service platforms, including innovation maker centers for exhibition, demonstration, training, printing hub in different cities."	Government relationship for business development	Partnership management	
"However, domestic companies have no software, and the machine uses open-source software […] once the software stops, the hardware is useless."	Open-source software unstable; lack of integrated software solutions	Software problem	**Technology innovation**
“During the printing process, how to better use the materials and improve the printing process for education are quite challenging.”	Challenges of printing efficiency and material optimisation	Printing problem	
“There is a lack of software that can optimize the models and test the model if it can be printed.”	Lack of software solutions with optimisation and testing	Software problem	
“But in reality, the printed objects still have breakage or deformed.”	Printing deficient	Printing problem	

"If every single printer company invent its language, it will be challenging for the customer to understand and print. The printer needs to be universal."	Lack of AM industry standards; lack of an open language for printer operation	Standards for printing	
"Most people think that the challenges lie in the hardware issues […] however, there are many problems in 3D printing software perspectives."	Lack of integrated software for education	Software problem	
"No, we do not provide leasing service for university."	No leasing service	Use-oriented PSS	**PSS for AM**
"However, when every school have the printers. They do not quite know what to print and how to print […] there are not many applications in the market."	Applications limited; service insufficient	Application and service scarce	
"3D printing technologies are multi-disciplinary, and so far, no universities offer the 3D printing major and systematic training program."	Lack of education program in universities; lack of education system support	Education system and service	

"We do not want the printed objects and printing process are detrimental to the environment and generate materials wastes."	Environmental pollution; no recycle and reuse	Environment protection	**Education for sustainability**
"We may collect the wastes of materials or pieces of the machine that need to be replaced."	Material wastes and machine replacement	Recycle and reuse	
"No, we do not do the recycling and reuse for materials."	Lack of material recycling for education	Recycle and reuse	
"It is the awareness of sustainability. Not many students understand sustainability."	No sustainability awareness	Sustainability education	
"We need to provide a complete set of solutions including curriculum, teacher, printer, software and community."	Integrated education service	AM education ecosystem	**System thinking**
"That means to the development of an ecosystem."	All-in-one education solutions	AM education ecosystem	
"We need to improve the fragmented process, including software, hardware,	All-in-one education solutions	AM education ecosystem	

materials to be connected to provide all in one solution for 3D printing education."			

Six high-level themes were identified and shaped as the critical factors for the development of the sustainable business model in Company E. The themes were then confirmed including *education for sustainability, PSS for AM, technology innovation, multi-stakeholder engagement, qualified AM professionals and system thinking.* In light of this, the data shows that one of the most significant problems for AM education sector is the lack of qualified AM educators. In terms of technology innovation, the user-friendly and integrated software is quite demanding with functions of model design, printing, optimization, simulation, workflow management, and post-processing. Furthermore, material wastes are generated when students use the printers to print and demonstrate. Therefore, to better recycle and reuse the materials remains to be solved for sustainability.

The data also suggests that system thinking plays a significant role of AM education ecosystem development involving setting up not only the maker innovation centers for exhibition, demonstration, training, printing hub, but also the connections with software, hardware, materials as well as teacher, school and community. In light of this, Company E needs to embed the system thinking and sustainability concepts into the development of AM education ecosystem for sustainable value creation.

5.2.7 Value Opportunities Identified in Company E

The author selected the examples of the failed exchanged value and identified the value opportunities for Company E. The typical failed value exchanges were analyzed including *customer failed value, lack of sustainability education, technology immature, qualified educator scarce*. The value opportunities were clustered into groups under the categories of each failed value exchanges. 16 examples of value opportunities were provided, shown in Table 5.10.

Table 5.10: Selected examples of value opportunities in Company E

Failed Value Exchange	Examples of Failed Value	Identified Value Opportunities
Customer failed value	Lack of well-developed machine for education	Develop high-speed, ease-of-use and affordable printers for education purpose
	Schools want to have the printing experience rather than owning a printer	Consider implementing the subscription and leasing service for schools
	Lack of software solutions for students to use	Develop the user-friendly software with different functions for education purpose
	Lack of AM professionals	Collaborate with universities to develop undergraduate-level class in AM major
		Establish AM education center at schools with skillful teachers and equipment for demonstration
Lack of sustainability education	Lack of sustainability education environment	Develop sustainability-oriented class and provide training to the employee for sustainability education
		Integrate sustainability considerations into educational materials and improve knowledge of AM processes for students
	Material wastes generation during printing practice and demonstration	Using environmentally friendly materials for printing
		Reuse and recycle the broken parts and failed products

Technology immature	Incapable of printing large-size objects using FDM printer	Develop the printer and materials to print large size object for education and demonstration
	Lack of software solutions with optimization and testing	Develop the all-in-one software with functions of model design, printing, optimization, testing, management and post-processing
	Parts not well printed	Develop high-quality printer without flaw and deformation in printed parts
Qualified educator scarce	Lack of qualified human resources	Provide training to improve teaching capabilities and skills of the employees
	Lack of teaching capabilities	Develop the teaching standards and certification for AM teacher qualification
		Improve communication with students during teaching and service process to clearly understand their needs
	Lack of AM education system support	Collaborate with schools to provide AM education programs

5.3 Case Study F

5.3.1 Introduction to Company F

Company F is an independent consulting service company focused on providing technical and strategic consulting in AM and rapid product development. The company specializes in customized AM consulting and strategy implementation. It builds a strong strategic relationship with many of the leading AM companies. The consulting and support team work closely with the customers in their business to understand their technical and operational needs; thus, the team provide custom programs and recommendations of the machine, system, material, and design service to improve customers' business.

The reason for choosing this firm is that AM consulting service is a new emerging paradigm of AM business model. The demand of consulting service is increasing owing to the fact that companies are not well familiar with AM technologies and lack the skills to adopt AM alone (Bugdahn et al., 2018) Company F is a consulting firm providing the services of on-site meetings with client companies, researching new processes, delivering industry reports, technology articles and other documents for customers. In this case study, in-depth interviews were conducted with the consultants. The interviews were then transcribed, and observations were made combining with the secondary data from documentary analysis.

5.3.2 Business Model of Company F

The business model of Company F is to provide customized AM consulting service with the implementation strategy for target customers. The main clients are manufacturing organizations from a wide range of industries. The customer value propositions of Company E mainly lie in three perspectives. The first value proposition is AM consulting with custom programs and recommendations to help customers improve work efficiency and business profitability. Mainly, the consulting projects are conducted involving on-site visits and meetings with client companies, model design service, new technologies research, report generation with the illustration of all systems and costs, equipment and process assessment. One of the interviewees said:

"We know how to pick which printer is good for our customer and then go to the design phase […] we help our client design and iterate the design, and then we deliver results."

The second value proposition is a comprehensive review and analysis of product development and printing processes with a variety of industry reports, technology articles, blog, and other publications. One of the interviewees commented:

"*We help create a strategic roadmap to make sure that it involves your implementation and operation*."

The third value proposition is the educational materials and training programs for clients to understand different AM processes and know-how to operate and adjust the printers. One of the consultants emphasized:

"*We provide the education and training service, and then we give our report […] we have to make sure the printer works and implement well*."

The company has strong technical and research abilities to provide the customer with strategic advice on AM technologies and product development for value creation. The company also has the abilities to comprehensively understand operational and technical challenges and apply the right engineering solutions to solve the problems. Value is also created through a good partnership with the AM companies to ensure the effective implementation and integration of AM technologies into the existing manufacturing process to meet the clients' needs.

5.3.3 Value Systems and PSS Solutions in Company F

The company adopts the result-oriented PSS solution by providing a simple consulting service. Notably, customers only pay for service or publication and do not need to own any hardware or software. The value is created via selling a result of consulting, written and oral reports, thereby reducing the need for customer ownership. The author identified the value systems along with the economic, environmental and social value for Company F. The codes emerged and were grouped into the categories as the main findings in Table 5.11.

Table 5.11: Value system analysis for Company F

Valve System	**Main Findings**
Value Proposition	AM consulting with custom programs and recommendations; model design service; industry reports, technology articles, blog, and other publications; educational materials and training programs; implementation plan and strategic roadmap
Value Creation	Technical and research abilities; good partnership with the AM companies; problem-solving abilities to apply the right engineering solutions
Value Capture	Different pricing models of service for consulting projects; charging for consulting reports and technology articles online
Value Delivery	Selling reports through the online website; work with customers to deliver consulting service
Social Value	Provide custom solutions built for organization and society; help make strategic decisions that can have a long-term impact; improve customer relationship; increased job opportunities; close stakeholder engagement
Environmental Value	Help clients reduce energy and material consumptions; help clients improve material efficiency; help clients integrate AM into a traditional manufacturing system to reduce environmental impacts; help reduced wastes during the manufacturing process
Economic Value	Increased revenue from consulting service improve the manufacturing efficiency; provide professional service to solve client problems; reduced costs and achieved business profitability for clients

5.3.4 Failed Value Exchanges in Company F

The author identified the failed exchanged value in the course of working with the stakeholders in clients' business. The author aims to gain a deep understanding of the failed exchanged value in AM consulting. Over a hundred of codes from the interviews and workshops emerged and were grouped into 23 examples in Table 5.12 as follows.

Table 5.12: Failed value exchange analysis in Company F

Failed Value Exchanges	**Examples/Explanations**
Value Missed	• The emerging-firm threat with fierce competition coming from new consulting firms and larger competitors • Worries about the changing ways of clients buying service • Increasing pressure of lower prices from cheaper alternatives • Consultants face unrelenting pressure to acquire new skills and keep up with the technology change • Challenge of building a compelling consulting brand and a strong reputation in the AM sector • Challenges of the adaption to the rising 3D printing market pressure
Value Absence	• Limited-service capabilities due to a small service team • Lack of skilled labor for model design and new technology research • Lack of abilities to innovate recycling technology • Lack of abilities to help clients develop materials recycling system • Need to use time and resources more effectively

	•Challenge of continually generating new ideas •Lack of a structured and strategic framework •Lack of AM consulting service in China market •New consultants struggling to master 3D fully printing technologies
Value Destroyed	•Not care about sustainability due to the low volume of material wastes and energy loss • Customers' pollution and waste generation •High consulting service fees
Value Surplus	No data
Value Unsupported	• Lack of qualified professionals for AM consulting •Need government relationship for business development to secure new clients • Lack of AM education system in the AM Industry • Expensive to hire new talents • Challenge of finding the talents in AM

Through the interviews with several consultants in Company F, the most frequently mentioned failed value was the challenges of finding qualified talents. The second frequently mentioned failed value was dealing with a competitive marketplace. Some other frequently ones included developing new business internationally and generating new ideas. No data were collected about value surplus in Company F. The reason for this might be that there was no redundant value that was larger than the requirement. Other critical failed value was highlighted, such as lack of sustainability awareness, lack of abilities to help clients develop materials recycling system and lack of support and method for printed objects recycling.

5.3.5 Challenges of AM Consulting Service

Besides the failed value exchanges, the author further identified the root causes of the customer perspective in AM consulting service. The author intended to gain a more comprehensive understanding of AM consulting business model and the customers' failed value. Notably, the root causes of customers' problems were perceived as practical evidence to confirm the themes for sustainable business model development. The root causes were categorized into four types, shown in Table 5.13.

Table 5.13: Root cause analysis in AM consulting

Key Challenge	Root Cause Analysis in AM Consulting
Qualified consultant	Lack of qualified AM professionals for AM consulting
	Lack of professional consulting service in the AM industry
	Challenge of innovation and generating new ideas for AM consultants
Consulting service	Inefficient and ineffective use of data for consulting
	Challenges of understanding clients evolving requirements★
	Need to use time and resources more effectively★
	Lack of user-friendly software solutions for model design, printing management, etc.★
	Lack of structured and strategic framework for AM★
External environment	Continuously changing the set of competitors in service bureaus★
	AM market changes and investment environment uncertain issues cause risks★
Sustainability consulting	Lack of embedding sustainability considerations into consulting service
	Clients don't consider sustainability

	Lack of hard data on the comparison between AM products and traditionally manufactured products in terms of energy use, supply chain, material consumption, CO_2 emission

The data was analyzed, and similar root causes were classified to form 13 examples under four failed value categories including qualified consultant, consulting service, external environment, and sustainability consulting.

5.3.6 Critical Factors Identified in Company F

The author followed the thematic analysis process to extract the meaningful quotes and analyzed the themes for the AM consulting firm. The attractive and similar codes were clustered into generic groups. The themes were identified to generate high-level themes that are critical to develop a sustainable business model, shown in Table 5.14.

Table 5.14: Simplified thematic analysis findings for Company F

Initial Quotes (Clustering)	Similar Codes	First Order Theme	Second Order Theme
"There are very few 3D printing consulting firms out there […] other big consulting firms like BCG and Mckinsey, and they do not have that business model like us."	Lack of AM consulting service	Consulting service	**PSS for AM**
"There is no 3D consulting firm in the UK and China."	Lack of AM consulting firm	Consulting service	

"Most 3D printing firms provide the machine, and very few offer after-sales services. I think it is a big gap."	Lack of after-sales service; machine sales oriented	After-sales service	
"We help them design and system selection."	Provide in-house design services; have the know-how for AM transformation	Design service	
"Not like other consulting firms, we help our clients with the printer operation and evaluate the performance".	Work with the client; help with operation and evaluation	Integration and evaluation	
"We do education and training, and then we give our report."	Training report; system selection training	Education services	
"They do not think about sustainability so far. Our client is not keen on recycling and reuse either."	Not consider recycling	Recycle and reuse	**Consulting for sustainability**
"The sustainability issue has not been addressed […] sustainability is coming, but I would say it is lacking."	Lack of sustainability consideration	Lack of sustainability	

"We are always looking for the best talents to join our team, and we know it would be costly to hire them."	Expensive to hire new talents	Human resource	**Qualified AM professionals**
"It is hard to find people with 3D printing qualification."	Lack of qualified people with the qualification	Human resource	
"What we need is a framework that can sit on top of the basic one. Now the framework is just task-based. We want a framework is much more theoretical and strategic."	Need a more theoretical and strategic framework	Strategic framework	**System thinking**
"We have a basic framework which applies different industries […] however, we want to develop one that only caters to 3D printing."	AM roadmap; framework development	Strategic roadmap	
"Processing and polishing are very significant problems."	Lack of knowledge of polishing	Post-process problem	**Technology innovation**
"It is the metal equipment, the surface finish [...] they do not know how to polish it.	Surface polishing problems	Post-process problem	

Also, the biggest issue is the polish."			
"We partner with other service bureaus like Wohlers Associates."	Partner with the AM experts	Partnership	**Multi-stakeholder engagement**
"We have many connections in the 3D printing industry […] we partner with different companies for materials data, printer selection, software."	Partnership with AM companies and service bureaus	Partnership and collaboration	

The author determined six themes as critical factors including *multi-stakeholder engagement, technology innovation, system thinking, qualified AM professionals and consulting for sustainability*. In essence, the critical factors guided sustainable value creation in Company F.

5.3.7 Value Opportunities Identified in Company F

Similar to Case D and E, the author followed the coding and categorization process to analyze the *customer failed value, insufficient consulting service, and human resource scarce* as the selected failed exchanged value within Company F. By looking at what value exchanges failed across the multiple stakeholders, the company was able to see many value opportunities. In this case, the author identified the value opportunities and provided advice to realize them. 10 examples of value opportunities were presented in Table 5.15.

Table 5.15: Selected examples of value opportunities in Company F

Failed Value Exchange	Examples of Failed Value	Identified Value Opportunities
Customer failed value	Customers do not understand how to embed	Provide a sustainability-oriented strategy and solution

	sustainability into a business model	Provide training class to the customers about sustainability principles and methods
		Provide solutions for wastes reduction and material recycling
Insufficient consulting service	Lack of using data and resource effectively	Use information management system to improve accuracy and efficiency
	Lack of strategic planning for customer	Develop a specific AM roadmap for the client's strategic planning and business model transformation
	Challenge of continually generating new ideas	Hire new talents for idea generation
		Work with partners to learn new perspectives and technologies
Human resource scarce	Lack of research and development	Recruit employees from large manufacturing firms with extensive experiences in research and design
	Difficulty of using AM technologies and acquiring new skills	Provide training programs to staff
		Encourage employees to keep up with the technology trend and improve problem-solving and innovation capabilities

5.4 Findings of the Focus Groups

This section introduces the findings of focus groups. The focus groups were conducted at the descriptive stage in the forms of workshops, group presentations, discussions, and brainstorming on the AM business models, challenges of AM adoption, and AM sustainability. The author designed the focus group process and acted as a participant and an observer to facilitate the data collection process. Two workshops were conducted with 18 participants in total in Company G and Company H to discuss the interview questions in a structured way. Specifically, the focus groups included the investigation and validation of the critical factors for AM business model development, failed value exchanges identified, negative root causes and sustainability solutions.

Each group was given several questions to discuss in English; the answers were then debated among the group of 7-10 people, who were from different levels and departments of the company. After discussing for between 15-20 mins, a shared view was expressed to the facilitator/questioner (the author). All interactions were recorded in writing by the practitioners and then copied/photographed by the author. The purposes of the focus groups were to develop knowledge and obtain insights from practitioners with diverse perspectives to address the research questions. The discussions between the practitioners were highly relevant to the research and provided valuable insights on AM business models and sustainable value creation and capture.

Company G is a China-based AM service company which operates in two segments: AM e-commerce platform and education service. AM e-commerce platform offers an industry information exchange opportunity; education platform strives to develop the AM educational materials such as textbook, industry report, research articles. Company H is also an AM service company that provides an open application service platform with exhibition planning, rapid prototyping and printing processing service. Users can order service through an online platform to have 3D model printed and delivered at a low cost without owning a printer. In the workshops, the participants discussed the AM implementation process and business models.

The empirical findings from the focus groups revealed that the new structuring of value was helpful for AM practitioners to understand business models and sustainability aspects better. Data showed that in the AM companies, failed value exchanges existed extensively. The significant failed value and challenges of AM adoption were identified from the focus groups, which corresponded to the findings from the case studies. The high-level themes for sustainable AM business model that identified from case studies were validated and refined. Value opportunities for sustainable business model development were also identified through group discussions.

Particularly, the findings of focus groups confirmed the difficulties of recruiting qualified AM professionals with R&D, service and management experiences. It is necessary to develop teaching programs and educational materials to support the human resource cultivation system within the companies. Qualified AM professionals were regarded as a key condition and the one that the AM companies most needed. The lack of AM talents was emphasized as a failed value and a barrier for developing a sustainable business model. One of the interviewees in Company H indicated:

“3D printing application market is not well-developed, and the lack of 3D printing talents hinder the further development of the 3D printing industry in China.”

The general manager of Company G emphasized the challenges of finding skillful employees:

“Developing AM technologies and sustainable business models require capable employees with comprehensive knowledge of materials science, software, design, manufacturing, supply chain, service, and business management. However, in China, there is a lack of such talents, and it is hard to train a person with these skills and knowledge.”

The findings also showed that the PSS model was not paid much attention by the AM companies so far. The results revealed that most of AM companies have limited knowledge of PSS and provided insufficient services to the customers and other stakeholders. The traditional, material-intensive ways of manufacturing and production modes were still dominant. They need to be replaced by the provision of dematerialized services such as use- and result-oriented PSS models in AM companies. Service platform was mentioned frequently, and the participants confirmed that there was a lack of PSS models in the current business models which aligned with the critical factors of PSS for AM. The CMO of Company G emphasized:

"*3D printing is not a strong alternative technology, and most of the Chinese users have no awareness of what significant changes that 3D printing will bring to them now and in the future […] also, there is a lack of a public service platform in the AM industry."*

The CEO of Company H stated: "*the service providers are relatively absent in the current 3D printing market. Many of the incumbent companies fail to make profits and still follow the old path of solely producing and selling equipment with limited after-sales services*."

Data for the benefits of PSS solutions for AM indicated that retaining the ownership of AM machines/accessories enabled AM companies to generate some unplanned environmental benefits, such as improved efficiency, better resource utilization, better fulfilment of customer demands. Customer acceptance of service provision needs further investigation as some customers still want to stick with traditional business models rather than pay for services and lose ownership. However, some customers want 3D printed products rather than the machine to reduce initial costs. This implied that PSS solutions for AM have the potential to create more benefits that have not been found yet. Thus, AM companies need to use PSS models and navigate service data more efficiently and effectively.

To this respect, it is evident that sustainability is a critical condition that AM companies need to implement into their business models. Notably, companies need to create value for the environment and society, not just for monetary profits. However, environmental and social motivations for AM business models were less mentioned. They did not trigger much discussion in the workshops, which implied that for these companies, AM business models were mainly driven by the economic benefits. However, the companies viewed the sustainability considerations as significant potential value opportunities that would generate environmental and social benefits. They investigated the sustainability solutions from the service and printing perspectives.

The findings indicated that sustainability solutions such as using environmental-friendly materials, recycling and reusing, improving social well-being and safety could create sustainable value and at the same time, achieve the companies' business purposes. However, sustainable value creation and capture were surprisingly overlooked in AM companies. It was noted that AM companies were not primarily interested in environmental and social benefits instead of putting economic profits as the priority. Integrating sustainability concepts into AM business models was difficult as most managers were confronted with challenges of understanding business models and sustainability concepts. There is a lack of knowledge in the AM industry on how to embed sustainability into the business model development process.

Technology innovation was considered as one of the most urgent issues faced by AM companies. It was also most frequently mentioned as an important condition. The AM technologies need to be improved mainly from the perspectives of material quality, design methodology, printing speed, modelling, control, processes, polishing, characterization and certification which also agreed with the Huang et al. (2015) research in AM technology components and system integration. Additionally, to create sustainable value, AM business models need to consider all stakeholders, particularly the environment and society and to harmonize multi-stakeholder' interests. Also, it is beneficial for AM companies to find new partners and develop collaborative partnerships.

What is more, the findings indicated that the managers confronted challenges in the AM processes without the capability to understand and manage dynamic systems in a structured and holistic manner. The AM managers failed to embed the sustainability concepts into the AM business modelling process. Thus, system thinking as a critical condition could help understand the complex and interconnected AM systems of business. System thinking enables the managers to take the whole perspective to investigate the interrelationships among different parts of a system. It also helps people broaden the system boundary and identify improvements systematically to achieve sustainability.

The findings from the focus group showed that, for these AM companies, the critical factors were confirmed, and the corresponding value opportunities were validated. The results from focus groups have three implications. First, the failed value exchanges existed extensively in the AM business models. PSS solutions have the potential to reduce failed value and create more value. Second, the critical factors were validated which helped companies develop business models in a way that enable the sustainable value to be realized. Third, the empirical insights from the workshops were used to re-visit the data from the cases at the explorative and descriptive stages, and then both the case studies and the insights from industrial practitioners informed the conclusions. The focus groups offered the independent perspectives in which the whole process is unbiased. The focus groups contributed to cross-case synthesis in Chapter 6.

5.5 Chapter Summary

In this chapter, three case studies and two focus groups were deeply analyzed to show how AM companies created and captured value through different business models, what the failed exchanged value existed in business models, what the key challenges hindered comprehensive AM implementation, what the critical factors can guide sustainable business model development and how can realize the value opportunities. The findings from both the exploratory and descriptive stages have addressed the sub-research questions: 1. What are the current business models within AM companies? 2.What are the failed value exchanges among multi-stakeholders? 3.What are the key challenges that prevent the adoption of AM? 4. What are the critical factors that help AM companies develop sustainable business models?

Chapter 6 Cross-case Synthesis

At the exploratory and descriptive stages, six cases and two focus groups were comprehensively analyzed and discussed in detail — the selected cases were involved in a range of AM sectors and all were seeking to understand the AM business models better. The empirical findings indicate six typical business models, namely the design of 3D models, the offering of printing materials, the manufacture of 3D printers and accessories, the development of AM software, the integrated platform of printing service, and the AM-related service (scanning, media, consulting, education). Then the cases were analyzed in the sequence of: the value systems and PSS solutions, failed value exchanges among multi-stakeholders, key challenges of AM adoption, critical factors for sustainable business model development and value opportunities. Therefore, the sub-research questions 2-5 have been answered in Chapter 4 and 5.

Chapter 6 presents a cross-case analysis, synthesizing the emerging patterns and discussing the findings to develop the core contributions and address the sub-research question: *how AM companies can identify opportunities for sustainable value creation and capture*? In this chapter, the author proposes a series of frameworks which are grounded in the theoretical assumptions and empirical findings. The author conducted the rounds of thematic coding, document analysis and observations to understand the reasoning behind the categorizations and themes. The comparisons of similarities and differences are conducted here to achieve precision and consistency for the cross-case synthesis. In the following sections, the author will use one or more insights from the findings to re-visit the whole data, and hence offer insights to the whole problem. Each insight is complete and presented separately here.

In Section 6.1, the author presents an analysis through the lens of failed value exchange and adds two new forms of value transformation. In Section 6.2, an AM critical factor framework is developed to understand the complex interplay of critical factors identified from the case studies. In Section 6.3, the author develops the visualized flow charts to perceive the process of failed value exchanges and illustrates the dynamic stakeholder relationships. In Section

6.4, an AM ecosystem map is developed to understand the business relationships. In Section 6.5, an AM value chain model is proposed to understand value flow and value exchange throughout the product life cycle. In Section 6.6, the author develops the significant sustainability solutions to help AM business models turn value opportunities into sustainable value. In Section 6.7, the author develops an AM business model transformation framework to guidance AM practitioners to develop sustainable business model. In Section 6.8, AM value transformation process is generated to illustrate the dynamic process of value transformation towards sustainability. Notably, in Section 6.9, a framework for this research is developed based on the theoretical and practical findings.

6.1 Defining Two New Value Forms for Transforming Failed Value Exchange

In this study, the author developed a new failed value form, *value unsupported*, showing that the company fails to capture customer value due to the lack of external support such as policy, environment, and regulation. For instance, the emergence of open-source AM services has generated several challenges and risks to the IP, patents and design protections. In Company A, the designers confront with the IP infringement by the competitors. However, the regulation and policy for IP protection and IP trade environment in the AM industry have not well developed. It is a typical example of value unsupported from the data of a failed value exchange that did not fit the current four types and could not be categorized under the current thinking of failed value exchange. In the data, there is a large set of data and many such examples that were thematically collected with the common characteristics that represent forms of failed value where the failure is due to complement or mitigate for value transformation. However, the mechanisms of transforming the failed value and making value success have not been discussed in the literature.

Furthermore, the author identified value opportunities for each case through the lens of failed value exchange. The uncovered value opportunities help gain an in-depth understanding of how failed value could be reduced and transformed into a success. However, the development of solutions and actions to mitigate and complement the failed value have not been explored. Very few researchers investigate new value opportunities by identifying failed value exchanges or by exploring value across the value network instead of firm-centric value creation (Rana et al., 2013; Yang et al., 2016; Bocken et al., 2014). In light of this, the author proposed two new forms of value transformation from the data, respectively, *value complement* and *value mitigate* as a novel perspective on failed value exchange. Notably, *value complement/mitigate* is defined as the specific development of solution modes and types of action taken to resolve the failed value and realize the value opportunities. The two value forms are valuable additions to value transformation that bring the novel perspectives of overcoming failed value. Mainly, *value complement* is to complement absent, missed and unsupported value; *value mitigate* is to mitigate destroyed, surplus and unsupported value in a dynamic way rather than a static process. The author, therefore, provides the working definitions of two new value forms in Figure 6.1.

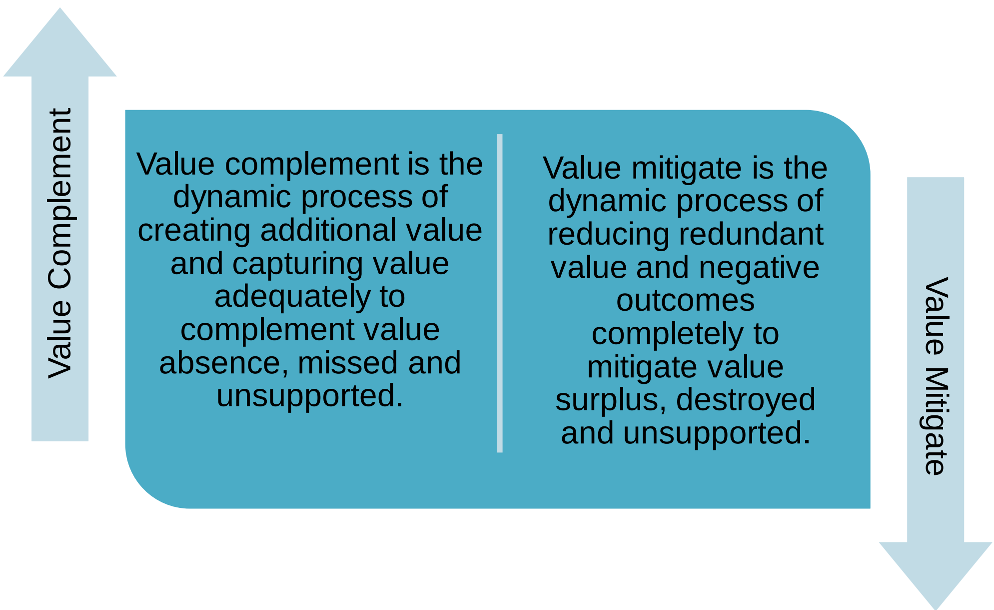

Figure 6.1: Working definitions of value complement and value mitigate (Author generated)

Then *value complement/mitigate* were put into practice as a specific search for actions that would create solutions to reduce the value failures (realize the value opportunities). For instance, in Company A, the typical value missed is that the products do not cater to general customers' demands. The value complement is the action of expanding the product line to encompass more 3D-printing products to fulfil different customer demands and reduce prices to enable more people to use AM for their daily lives. Furthermore, the interviewees identified that there is no recycling and reuse for printed materials and scraps in Company C as a notable failed value (value missed). The value mitigation here is the solution of developing recycling and reuse technologies for mixed and multi-color materials and improving the recycled material quality for regular use. There are many such examples that were thematically collected in the case studies and determined their common characteristic, which is that they represent forms of value transformation where the failed value is complemented and mitigated to realize the value opportunities. The novel aspects of the two value forms are the development of the concept of value transformation, which has not been found in the literature.

6.2 AM Critical Factors for Sustainable Business Model Development

At the exploratory stage, the initial themes were developed through inductive thematic coding. The titles of the themes emerged through the sequence of clustered quotes, grouped codes, first-order themes, and second-order themes. These higher-order codes and concluding names were used to draw out the critical factors that underpin the development of a sustainable AM business model. Such critical factors are those parts of the data that the interviewees identified as essential components of the problems, which can also refer to as the essential components of the solutions by using a positive framing (X is a problem when absent; X is a solution when present; X becomes a critical factor). The initial themes generated included *PSS for AM, qualified AM professionals, IP management, mass customization, sustainability, stakeholder management, system thinking, and technology innovation.*

At the descriptive stage, the author implemented the same inductive thematic coding strategy. These initial themes were used as the starting points for data collection and analysis. New data were then collected to shape, reject and confirm the themes. The author intended to provide an accurate description of the themes proposed. Based on the significance of each theme and generalization of findings, the author identified six high-level themes as the critical factors that help AM companies develop sustainable business models. The confirmed critical factors include *qualified AM professionals, PSS for AM, AM technology innovation, AM sustainability, multi-stakeholder engagement, and system thinking.*

Figure 6.2: AM critical factor framework (Author generated)

Each identified theme was compared against existing literature. For instance, in terms of multi-stakeholder engagement, the author found that in Company E the managers do not know what the schools want and what the students want to learn which result in not delivering the desired service/products. The managers were unclear about the customer needs and failed to engage with the customers and partners well and not developed collaborative partnerships, which matched the mentions multi-stakeholder as a general concept of shared value creation, with no literature focusing on AM business models. This confirms and adds empirical evidence to arguments from the literature. In light of this, the author proposed the AM critical factor framework to form the systematic theme connections in detail (see Figure 6.2). Notably, the identified value opportunities in the case studies were integrated into the framework as the tactics for sustainable AM business model development. The AM critical factor framework aims to address the sub-research question: *what critical factors can help AM companies develop sustainable business models*?

The framework shows the critical factors along with the solutions to develop AM sustainable business models indicated in each block. The author further validated the framework and reflected back into the evidence from the case studies. The findings show that most of the AM companies, particularly the machine and material-oriented ones, are not driven by the environmental and social goals and may even not recognize the coincidental sustainability benefits that PSS models can bring. For instance, Companies B, C and D considered the AM critical factor framework helpful by which the factors *PSS for AM* and *AM sustainability* can guide them to develop PSS models to deliver functionality and use service data more efficiently and improve resource efficiency. This also indicates that AM companies are interested in environmental and social value only when combined with economic profits. This confirms the wider findings that PSS solutions are beneficial for AM companies, especially, the AM machine and materials ones, to create sustainable value.

However, those companies are mainly motivated to consider environmental and social value when these directly generate economic value. This also adds empirical evidence and detail to similar arguments from the literature (such as Yang, 2015). For instance, Company A has established an Innovation Design Center to train and educate AM designers. Even though the company has developed a better training program to educate new employees and make them become qualified designers faster, it is still time-consuming and expensive. This is the same as Company F, where the company indicated that there is a lack of skilled AM professionals for new technology research and consulting. It is challenging to acquire qualified AM designers and engineers with limited-service capabilities. Particularly, the CEO of Company A said:

“One of our important development issues is the human resource. There are

not enough and sufficient people in the market that can directly work for us."

One of the consultants in Company F commented:
"There is no structured and completed 3D design education system in the AM industry to provide qualified 3D printing professionals for us."

Therefore, both Company A and F supported that the factor '*qualified AM professionals'* is quite essential, and the teaching materials and training programs are needed to educate more AM talents for companies. The critical factors for AM have not been discussed in the literature and this understanding can contribute to the concept of AM business models. Therefore, the AM critical factor framework can be used as the guidance to help AM companies transform business model from business-as-usual to a sustainable business model.

6.3 Illustration of Failed Value Exchanges

To help practitioners to better understand failed value exchanges, the author developed the visualized flow charts (Figures 6.3 to 6.8) to illustrate the process of failed value exchanges. This confirms and adds empirical evidence and detail to similar arguments from the literature (Yang et al., 2016). The author incorporated the definitions of each failed value form into the visualized value flows. The definitions of each value flow are based on Types of failed value (Fernando, 2016). *Value complement* and *value mitigate* are integrated into each visualized flow as the solutions to illustrate the dynamic process of reducing failed value to realize value opportunities. The dynamic stakeholder relationships of failed value exchange between the focal firm and customer (You = Customer, I = Focal Firm) are shown as follows:

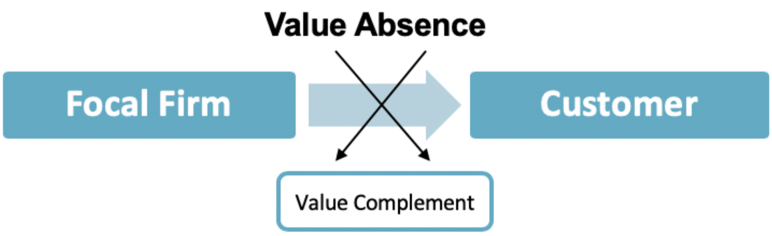

Figure 6.3: Visualized flow chart for value absence
"*You want, but I do not give.*"

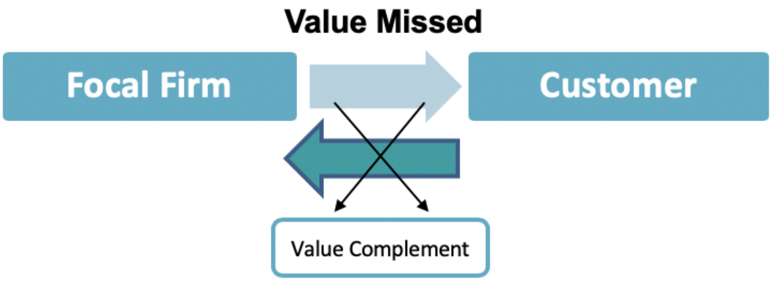

Figure 6.4: Visualized flow chart for value missed

"*I give but do not get a return.*"

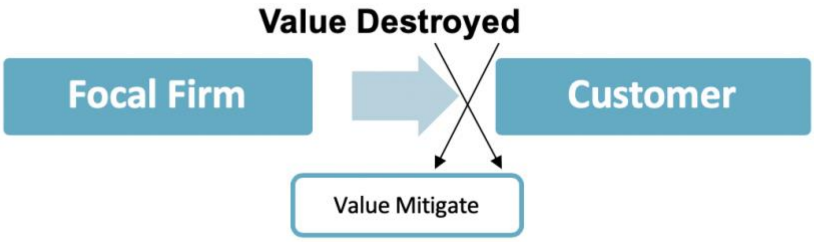

Figure 6.5: Visualized flow chart for value destroyed

"*I give, but you do not want.*"

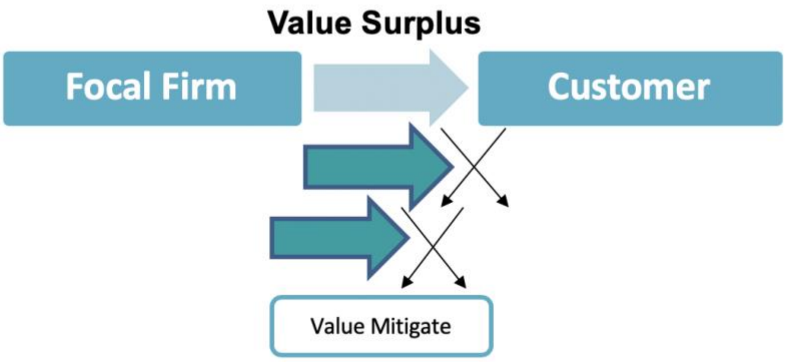

Figure 6.6: Visualized flow chart for value surplus

"*I give or have too much.*"

But the data regularly refers to other stakeholders and this representation of value flow as being only between customer and company was obviously not representing the full situation. In particular, value missed, value absence, value destroyed, and value surplus indicate a two-side relationship between focal firm and customer, while value unsupported brings in the three-side relationships among the firm, the customer and external stakeholders, as shown in Figures 6.7-6.8. The author identified several different and significant stakeholders in the data, such as partners, employees, customers, suppliers, society, environment, and many others.

The first type of value unsupported is identified from the analysis of the empirical data at both exploratory and descriptive stages, showing that due to lack of support from external stakeholders, the focal firm fails to create and capture value for the customer (see Figure 6.7). However, the second type of value unsupported is proposed as a novel perspective in Figure 6.8. This second type, while being logically inferred, has not been verified by the author in this research due to a lack of empirical data in the case studies. It is evident that in this situation the focal firm fails to create and capture value for their customer due to the negative outcomes provided by external stakeholders that undermine value. In such a situation, value mitigate needs to be used as the solution to reduce value unsupported and realize value opportunities.

This discussion indicates that the current four failed value forms may not be the most suitable categorization to illustrate the relationships among customer, company and other stakeholders. Therefore, two types of value unsupported are proposed to imply dynamic stakeholder relationships. It should be noted that type two 'value unsupported' is not derived from the empirical data from this study but is logically inferred by the case study findings. Future work is needed to validate the second type of value unsupported with the definition of "*you give, but I do not want*." (You = External Stakeholder, I = Focal Firm)

Figure 6.7: 1) Visualized flow chart for value unsupported
"*I want, but you do not give.*"

Figure 6.8: 2) Visualized flow chart for value unsupported
"*You give, but I do not want.*"

The visualized value flows were used in the case studies to illustrate the failed value exchanges during the interviews, workshops, and discussions. For instance, one of the interviewees in Company A commented:

"I feel that the visualized display of failed value exchanges helps me better understand the meaning of different failed value forms and clarify the meaning of how value is exchanged between customers and us."

The CEO of Company E also said:
"It is very helpful …. and I think it would be good to incorporate into our 3D printing educational materials…"

But still some managers encountered difficulties of understanding the stakeholder relationships and failed value exchanges. It was sometimes difficult for them to accurately separate the forms of failed value due to some overlapping.

For instance, one of the interviewees in Company C said:
"I feel that the various failed value forms are a bit complicated and hard to distinguish. Even the flow charts are clear, but to understand the mechanisms of how the value exchanges, where the value go to, and what value are missing lack transparency and not easy for me to understand."

The Product Manager of Company B commented:
"I think that the flow charts and the concept of failed value exchange are very interesting, I can understand the stakeholder's relationships, however, the flow charts do not tell me how to solve the failed value problems."

The CEO of Company D mentioned:

“I am confused by failed value exchanges, and different forms of failed value, and it’s hard for me to apply them into the real business.”

It should be noted that there is little empirical data collected for value destroyed and no data for value surplus in Case F as the AM consulting service provider. The author’s use of visualized illustration of failed value exchanges has not been proposed and addressed in the literature. The data showed that when the author conducted interviews and explained to the interviewees about terminologies of the concept of multiple forms of value and failed value exchanges from a multi-stakeholder perspective, higher-level managers were more likely to understand and provide positive feedback than their employees. However, the flow charts failed to explain the ways of resolving failures in the stakeholder’s relationships. In all, the flow charts were helpful for demonstration and explanation in workshops and interviews. The cases found the failed value exchanges useful, which helped them understand the business models better.

6.4 Understanding the AM Ecosystem

In the literature, Liu and Rong (2015) illustrate two types of business ecosystem within the AM sector in terms of market opportunities: a product-based ecosystem and a platform-based ecosystem. There is an increasing number of stakeholders involving in the AM ecosystem to foster the value creation and facilitate experimentation within the business models. Through the case studies, the author gained a comprehensive understanding of the AM processes, resources, players and critical factors in the AM industry that enable a business ecosystem structure. The research respectively explored cases in the design, material, machine, online platform, education, and consulting sectors that helped gain insights into every aspect of AM within the ecosystem. The empirical findings indicate that AM is still an emerging technology and the market demands remain uncertain but promising.

Notably, the data shows that there are mainly two market segmentations identified in the AM industry that are namely, industrial application and personal/home use. The key resources were identified through the analysis of different AM business models, including the 3D model designer, software developer, material engineer, service bureau, system & mechanical engineer, and AM educator. In essence, AM follows a digital manufacturing process with several key processes in place to make things happen compared to traditional manufacturing. Based on the cross-case analysis, the key processes involve design marketplace, material supply, scanning service, machine manufacture, local/in-house printing, and online printing platform. The literature identifies that challenges of AM lie in design capability, material development, software solution, machine quality, standardization/certification and polishing/finishing that remained to be improved.

In light of this, some AM players have identified the need to play a significant role in promoting the wider AM ecosystem. For example, AM companies support and promote user innovator and maker communities as they are key players for the personal/home application due to increased participation of users in the production process. This increased user participation and innovation enable the boundary of consumption and production activities to become overlaps as user become “prosumer”.

For traditional applications of AM technologies in a wide range of industrial sectors such as automotive, aerospace, architecture, consumer goods, biomedical areas, etc., there is an increasing need for information exchange, publicity, and consulting service from the AM companies. The data showed that AM companies were likely to seek external technical support and market promotion through third-party organizations. Thus, the independent AM media platform and AM consulting company become critical components within the AM ecosystem. In this respect, it is noted that the AM ecosystem map consists of three integrated parts with the emphasis of key resources, key processes and key players. As such, the AM ecosystem map is thereby proposed in Figure 6.9 that presents a complete view of the ecosystem.

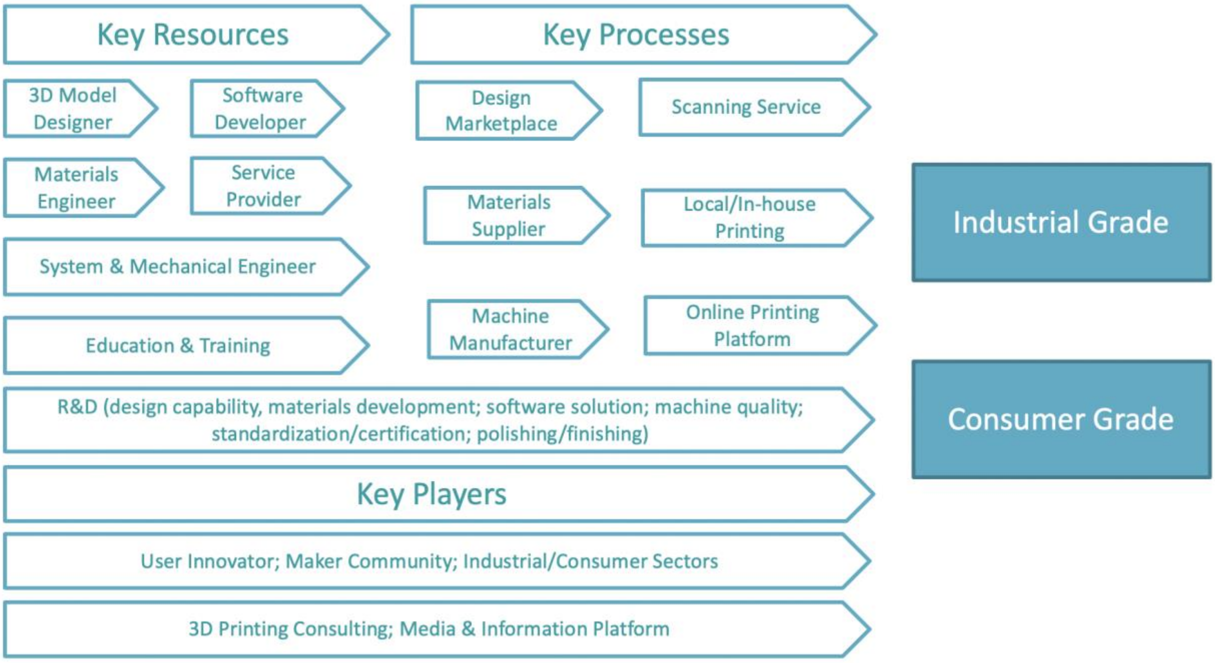

Figure 6.9: AM ecosystem map (from this study's empirical data)

The AM ecosystem map was used as guidance in the workshops and discussions for AM practitioners to understand the AM industry better. The map provides a clear picture of key resources, process, players and market segmentations that help managers position their business and identify business models. For instance, one of the interviewees in Company F emphasized:

"As a consultant, the map is helpful for us to have a clear view of the AM resources and processes, and it would be good to incorporate the map into our framework and provide strategic consulting for our customers."

The CEO of Company A emphasized the importance of 3D data as the key resource and commented:

"The ecosystem of 3D printing is like the triangle model. At the top of the model is the consumer market; the second level is the 3D printing industry. The bottom is the cornerstone, including software, materials, processing, and machine. The upper level is the service provider that creates a platform to bring all the products and service onto it […] the data is the bottleneck to connect the market and the foundation..."

Figure 6.10 shows that data plays a significant role in connecting the upper triangle model (industry and consumer market, 3D printing industry) and lower triangle model (service platform, materials, machine, software, and processing providers) in the ecosystem. The data act as the vessels to provide the "nutriments" as a symbolic metaphor to the upper and lower triangle models and connect them. The data feeds all other parts of digital manufacturing, connecting manufacturing industry and consumer market, AM industry, AM service platform, AM software, AM materials, and AM manufacturer. The "nutrients" is defined as the contents and the value of data which could benefit ("feed") every aspect of the AM ecosystem.

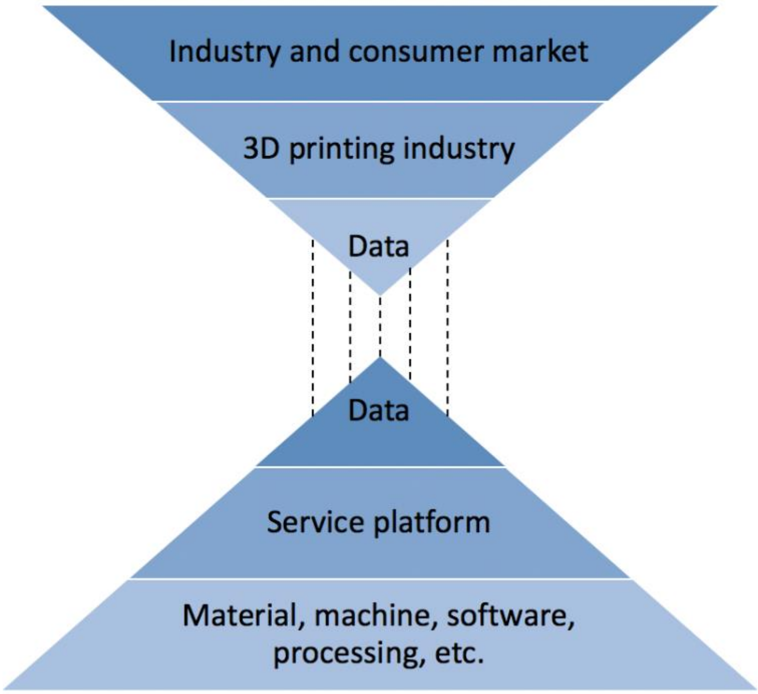

Figure 6.10: Data in the AM ecosystem (Author generated)

The AM ecosystem map inspired Company A to develop a new business model to provide value to the business partners and customers continually. The research findings showed that the AM ecosystem map helped practitioners to better understand the business relationships and provided a better view of the industry. The development of an ecosystem map contributes to the research of the AM business models. The data triangle (Figure 6.10) could be integrated into the ecosystem map for practical application in future work.

6.5 Understanding the AM Value Chain

The case studies presented a structured analysis of the AM business models with the emphasis of the value systems across six AM sectors. Each case revealed the value flow from the upstream to downstream with the detailed description of what value is available, how value is extracted, captured, and delivered. The value chain model is therefore developed across the product life cycle in the sequence of how the AM value is initiated, created, delivered and ultimately realized close-loop. The AM value chain goes through three phases of the product life cycle in the order of beginning of life (BOL), middle of life (MOL) to end of life (EOL) (Jun et al., 2007). Notably, from the AM perspective, BOL is when the 3D model is designed, the product is prototyped or directly manufactured; MOL is when printed product is distributed, used or maintained; EOL is when used product and support part are disposed of, recycled, reused, or repaired. The AM value chain model is proposed, shown in Figure 6.11.

Following the product life cycle, the value chain model starts from the stage of design requirement & product design, then flows through the stage of process selection, planning & material processing to the stage of production activities of prototyping & direct manufacturing, which are all placed in the BOL. In light of this, essential resources and processes identified from the AM ecosystem map (Figure 6.10) are adopted to present the value flow and value exchange in detail. It is evident that at the BOL phase, the designers create 3D models, the material suppliers provide materials, machine manufacturers offer 3D printers, service bureaus provide software solutions and scanning service to create and capture value. It should be noted that at the MOL, the product can be printed through different methods such as online platform, in-house printing facility, local printing shop or just fabrication at home. The printed product is distributed by express delivery or pick-up at the local printing shop to be used by the consumer. Notably, for the home user and user innovator, they get involved in the production activities and become the prosumer.

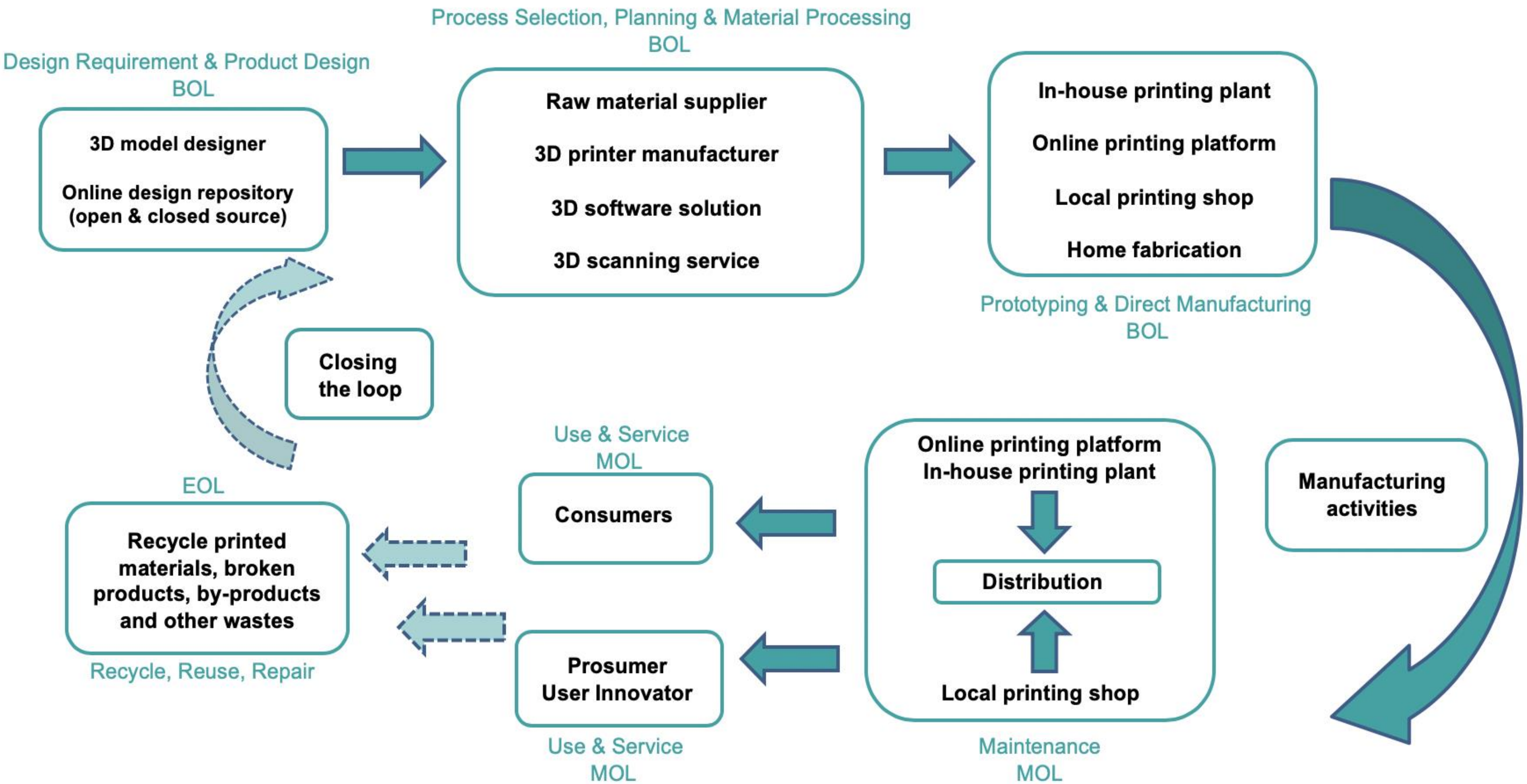

Figure 6.11: AM value chain model (from this study's empirical data)

Furthermore, the empirical data showed that the AM companies seldom recycled or reused printed product/wasted materials. It is noted that there is a lack of well-developed recycling technology and method to separate mixed materials without compromising material quality and characteristics. In this respect, at the EOL, the dashed arrows are used to illustrate the situation at this stage, where recycle, reuse and repair are not well executed in the companies; thus, not all value finally returns to the BOL and closes the loop. The AM value chain model consists of six stages of value flowing through three phases of the product life cycle. The framework was used and validated in the workshops and discussions. One of the senior managers of Company G indicated:

"I never consider the value flow of our business through the life cycle, and I feel the framework is quite inspiring that would help us understand more about the whole business process."

Data from the workshops showed that the value flow at the EOL encountered difficulties to close the loop. The Director of Company C emphasized:

"The resin cannot be recyclable. We can all throw them away. Some metal can be recycled, but for resin, I do not think so."

That is quite a challenging issue for achieving close-loop in the AM material companies. Particularly the printed materials and scraps cannot be recycled and reused at the moment. The photopolymer resin can generate uncomfortable smell and may cause health issue for people who operate the printer and handle the materials. Therefore, the data demonstrated the facts that at the EOL, most of the 3D materials could not be recycled and reused where the value failed to return to the BOL to close the loop. The Sales Manager of Company B mentioned:

"The value chain is quite clear for mapping out the value flow…as an SLA printer manufacturer, we do not recycle and reuse printed resin. I think to close the loop, we need to embed sustainability into our current production systems."

The data showed that in Company B, the manager mentioned that too much resin spill out would damage the machine and cause a problem for the tank; thus, recycling and reusing the printed resin and wastes can reduce negative environmental impacts and close the loop. In light of this, the sustainability considerations need to embed into the business modelling process to create and capture sustainable value. The research findings showed that the AM value chain model was helpful for understanding value flow and value exchange throughout the product life cycle. The companies gave positive feedback on the framework and thought it could help generate some creative ideas and feedback. The AM value chain is new and has not been found in the literature. The AM value chain model contributes to the concept of sustainability and AM lifecycle that can be used as a guidance in more AM cases.

6.6 Sustainability Solutions for AM Business Model

The case studies indicate that identifying failed value exchanges help in revealing value opportunities. The value opportunity related codes emerged and were categorized in each case. The value opportunities were then selected and classified into several types. The selected types of the value opportunities derived from the relevant failed value such as customer failed value, technology immature, lack of sustainability and human resource scarcity. Based on the cross-case analysis of the identified value opportunities, the author proposes the set of most significant sustainability solutions for a range of AM sectors including design, machine, material, printing process, service, and education to help AM business models turn value opportunities into sustainable value. The author generated a total of 95 examples of value opportunities in the six companies (see Sections 4.1.7, 4.2.7, 4.3.7, 5.1.7, 5.2.7, 5.3.7). In light of this, the author integrated the value opportunities and classified the solutions into six categories namely, design for sustainability, material for sustainability, machine for sustainability, printing for sustainability, service for sustainability and education for sustainability.

For instance, in Company A, the author analyzed each significant failed value exchange and generated 23 examples of value opportunities (See Table 4.5).

From the 23 identified value opportunities, the author identified 11 key tactics of design for sustainability, shown in Table 6.1. Some of the value opportunities were deleted or merged into other tactics according to significance and frequency. The author then synthesized the identified value opportunities in all the cases and developed the key tactics consecutively for the AM material, machine, printing platform, education and service for sustainability. It should be noted that some of the sustainable solutions overlapped and some might be not feasible for certain companies. Based on this, 55 types of key sustainability solutions were proposed and defined, which is proposed as a comprehensive set of actions that can help AM companies develop business models to create and capture sustainable value. Some of the solutions are new and have not been covered in the literature.

Table 6.1: Summary of key sustainability solutions for the AM business model (Author generated)

Sustainability Solutions	Key Recommendations/Tactics
Design for sustainability	1. Develop design capabilities, guidance and principles; 2. Incorporate sustainability concepts into product design; 3. Integrate design thinking into the design process; 4. Improve design knowledge of AM characteristics and limitations; 5. Strengthen the communication between designer and manufacturer; 6. Expand the data pool to have more design models that can be printed with no flaws and defects; 7. Leverage the advantages of AM for direct manufacturing; 8. Improve IP management and protection of 3D model; 9. Develop AM design education system; 10. Build up the data management system;

	11.Improve the efficiency of data utilization through data management and configuration.
Material for sustainability	12.Maximize material and energy efficiency; 13.Provide a training program to improve the awareness of wasted and printed materials recycling and reuse; 14.Develop environmentally friendly materials for printing; 15.Provide mask or protective kits for operating harmful materials; 16.Provide solutions for wastes reduction and material recycling; 17.Develop recycling and reuse technologies for mixed materials and multi-color materials; 18.Develop recycling technologies to separate recycled mixed materials without compromising quality and properties; 19.Develop guidance and standards for recycling; 20.Standardize materials data; 21.Implement sustainable PSS such as user-oriented and result-oriented models.
Machine for sustainability	22.Deliver functionality rather than ownership; 23.Provide machine sharing, subscription, and leasing service; 24.Accelerate the development of AM standards and specifications that consistent with stakeholder needs; 25.Develop advanced printer that can print multi-color materials with good quality; 26.Develop printer with the compatibility of different materials; 27.Reuse broken 3D printers and failed products. 28.Develop high-quality printer without flaw and deformation in printed parts.

Printing for sustainability	29.Improve the efficiency of the online printing process; 30.Provide a sustainability-oriented strategy and solution for printing; 31.Develop scale-up solutions for printing; 32.Explore the open-source approach and establish local and replicable production network; 33.Develop printing standards and requirements; 34.Develop printing service platform with high efficiency, low cost, and high flexibility; 35.Innovate the printing process to print high quality products without increasing the printing time 36.Use biodegradable PLA and other environmentally-friendly materials for printing.
Service for sustainability	37.Implement the subscription service for the customer; 38.Strength the maintenance service team; 39.Develop the printer and materials to print large size objects for demonstration; 40.Develop the user-friendly software with different functions for printing service; 41.Use service data efficiently and effectively; 42.Clearer about customer needs (real needs, potential needs, hidden needs and future needs) to provide high-quality service; 44.Develop all-in-one software solutions 45.Develop functions of model design, printing optimization, testing, management and post-processing.
Education for sustainability	45.Develop large-size and high-speed printer for education purpose with lower price; 46.Develop ease-of-use and affordable printer for the education market; 47.Develop the subscription and leasing service for

	school; 48.Provide training classes to customers about sustainability principles and methods; 49.Improve the knowledge of sustainability concepts; 50.Develop the teaching standards and certification for AM teacher qualification; 51.Provide training to the employee about the teaching method for sustainability education; 52.Collaborate with universities to develop an undergraduate-level class in AM major; 53.Establish AM education center at schools with skillful teachers and equipment for demonstration; 54.Provide training to improve teaching capabilities and skills of the employees; 55.Improve communication with students during teaching and service process to clearly understand their needs.

The 55 types were analyzed further by presenting to AM companies and seeking reactions. The author applied the summary of AM sustainability solutions into the interviews and workshops to validate the key tactics. Notably, the CTO of Company C said:

"We try to develop the polymers that can be recycled and reused as sustainability solutions; however, these recycled polymers are typically not mechanically strong. Actually, they are quite weak mechanically […]

The Director of Company C also commented:
"We will not put the recycled materials into our new materials production process which would negatively affect the overall materials properties."

The solutions of 'material for sustainability' indicate developing recycling and reuse technologies for wasted and printed materials. However, it is still quite challenging to recycle and reuse most of the AM materials, particularly for the multi-materials products and mixed materials with different colors. The interviewees indicated that the recycling technologies were immature and recycled materials properties were not good enough. More importantly, the material manufacturers were lack of knowledge and awareness of material sustainability concepts. The research findings showed that there were very few AM companies taking action in material recycling and reuse, and only a minimal number of printed materials was dealt with the recycling process and sent back to the inputs of the new materials.

The CTO of Company C also emphasized:
"Material recycling is pretty difficult. There is a machine which can melt the plastics to make the filament. However, the recycled filament is not good quality with small porosity and dust inside, which negatively affect the nozzle."

One of the sustainability solutions for materials is to develop environmentally friendly materials for printing. However, Company D only considered PLA for recycling as its characteristic is biodegradable but not for ABS, TPU and PC, which are not recyclable. More importantly, it should be noted that the recycled materials have fragile mechanical properties and low strength that are not ideal for re-printing and result in a negative impact on the overall material properties. The Sales Manager of Company D emphasized:

“The materials recycling is not being paid much attention by senior managers in our company, and we still set making profits as the priority.”

The CTO of Company D also mentioned:
"Comparing with traditional manufacturing, the generated wastes are million times more than that of 3D printing. We do not need to care about the wastes in 3D printing, because it is just too little and have very minimal impact on the environment."

The data showed that the summary of sustainability solutions for AM business models was inspiring and helpful. However, sustainability considerations have not been embedded into their current production systems and business models.

As the interviewees indicated, AM material companies still set making profits as the priority without paying much attention to the environmental and social value. Furthermore, as the 3D printer manufacturer, Company B sells the 3D printers with limited additional service. One of the solutions of 'machine for sustainability' is to provide machine sharing, subscription and leasing services. Delivering functionality rather than selling ownership of a product to fulfil customers' needs would bring resource efficiency and environmental benefits (Schaltegger et al., 2011). However, Company B is not likely to change its business model to deliver functionality rather than ownership. The company is aware of the environmental and social benefits that the PSS models would bring to the business through machine subscription that entirely replaced by services, but the company would only consider it when it combined with economic value. This confirms the findings from the case studies that AM companies intend to consider environmental and social value when they can make financial profits.

The Sales Manager of Company B emphasized:
"We do not consider the leasing and subscription business models. We now just sell the machine."

It should be noted that for Company B and many other AM machine manufacturers, they stick to the product-oriented PSS model to manufacture the machine, sell the machine directly, and provide the after-sale service traditionally. They never consider leasing or subscribing the printers for the customer. Particularly, leasing a 3D printer would bring benefits such as no down payment, low monthly payments, and no need to compromise for the customer. It is expected that more AM companies would sell the availability of the printers without customer ownership through the PSS models due to the fact that industrial printers are quite expensive and not widely adopted by industrial customers. The solutions of 'service for sustainability' showed the benefits of minimizing negative environmental impacts while in the meantime maximizing economic value and social well-being. It is also very beneficial to establish a replicable production network and develop scale-up manufacturing solutions to achieve mass customization as the solutions of 'printing for sustainability' to create and capture sustainable value.

In sum, based on the 95 examples of identified value opportunities, the author analyzed and integrated the value opportunities into a key sustainability solutions list, which could be helpful for AM companies to improve competitiveness and sustainability. While the implementation effectiveness of the sustainability solutions to turn value opportunities into a sustainable value is not discussed in the scope of this research but could be further investigated. The 55 significant sources of sustainability solutions could be used to help AM companies develop new business models and technologies. It should be noted that these sustainability solutions could also reflect the situation of other manufacturing companies. However, due to the limitations of the data, the summary list might not be complete. Table 6.1 could be extended to embrace more AM sectors and develop more tactics in future work. The summary of sustainability solutions contributes to the concepts of sustainability and sustainable business model in the context of AM.

6.7 AM Business Model Transformation

This research has investigated various AM business models across a range of AM sectors. From the action perspective, the author therefore developed the AM business model transformation framework, shown in Figure 6.12. The framework comprehensively combined significant parameters developed from the case studies including sustainability solutions (See Table 6.1), together with failed value exchange analysis, critical factors (*multi-stakeholder engagement, system thinking, AM sustainability, qualified AM professionals, PSS for AM*) and technology innovation highlighted as the cornerstone. The framework demonstrates the process of AM business model transformation towards sustainability and is intended to be used by AM practitioners for business strategy development, business model transformation and technology direction.

All six cases showed the significance of sustainability in the AM business models and emphasized that the sustainability solutions need to embed into the business model development process. The author investigated the value transformation mechanism and looked into the value captured and failed value exchanges of AM business models. Yang et al. (2016) present that reducing any kinds of failed value would create sustainable value opportunities. In light of this, the failed value exchanges need to be reduced and turned into value opportunities. At the exploratory stage, *value unsupported* was proposed as a new value form in the failed value exchange category. At the descriptive stage, *value complement* and *value mitigate* were proposed as solutions for transforming failed value. Therefore, *value unsupported* was incorporated into the framework and *value mitigate/complement* was implemented as the solutions to reduce failed value. The failed value exchanges were employed in the framework to help identify value opportunities.

Furthermore, the identified AM critical factors play a significant role in sustainable value creation and capture (see Figure 6.2). Following the transformation process, the critical factors were adopted into the framework to help develop sustainable AM business model. Technology innovation, as one of the critical factors, lays the foundation for the business model transformation. Notably, the key challenges of AM technologies identified in the perspectives of design capability, material development, software solutions, processes, machine quality, standardization/certification and polishing need to be solved and improved. Therefore, the framework was proposed to guidance AM practitioners to develop sustainable AM business model shown in Figure 6.12. The underlying logic of the framework is to show the dynamic process of business model transformation towards sustainability from the action perspective. The author used the framework in the interviews and discussions to inspire AM practitioners to think about current business models and identify opportunities for sustainable business model transformation.

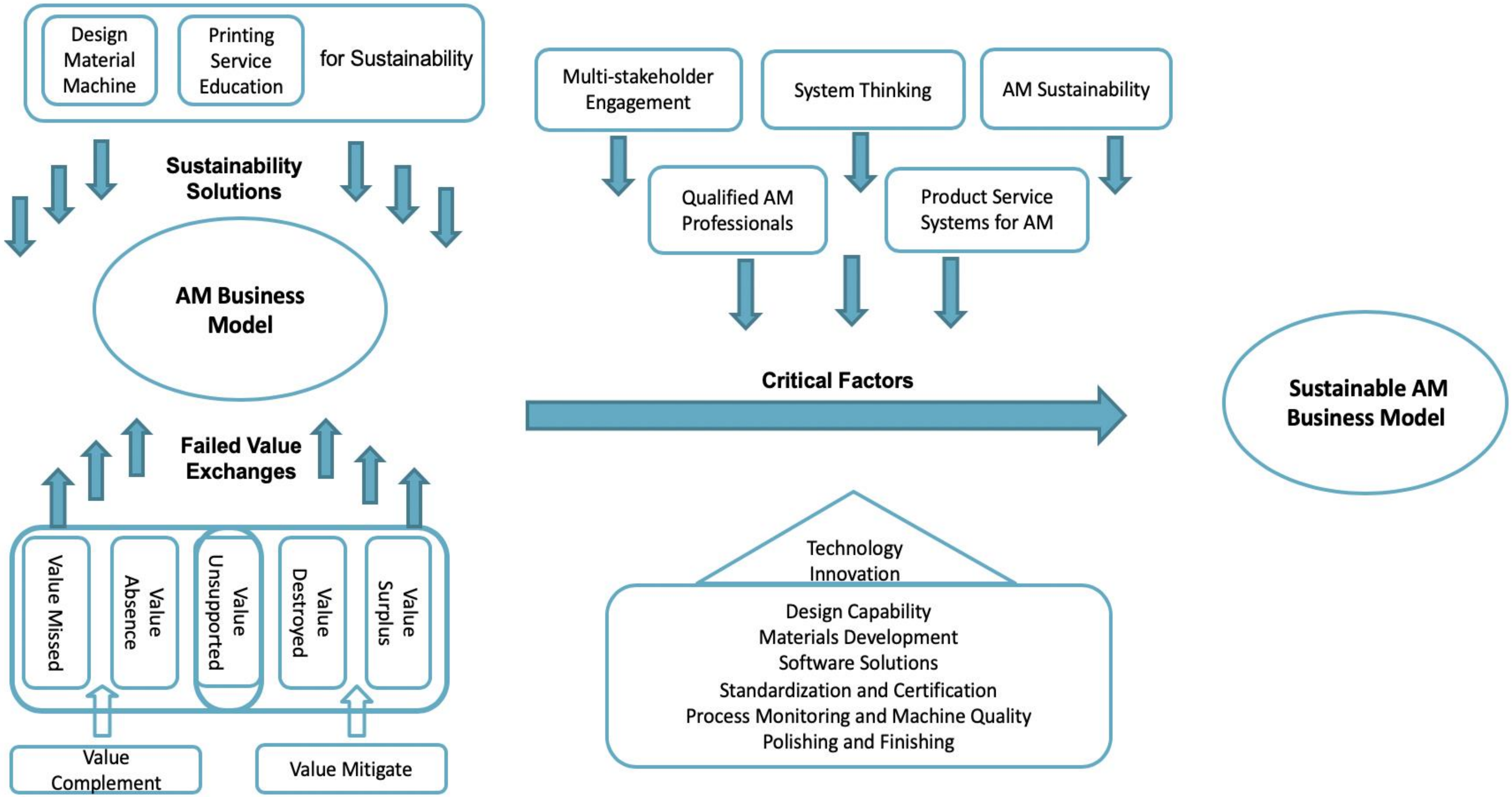

Figure 6.12: AM business model transformation framework (Author generated)

In Company B, the framework was used in the workshops and interviews. The material unsafety and quality issues were considered important conditions for a successful transformation into a sustainable business model. For instance, the customer is more likely to produce multi-color products using mixed materials with high quality. Thus, a reliable and advanced multi-color 3D printer needs to be developed. The Product Manager of Company B indicated:

"We want to develop a sustainable business model, but the technology is one of the biggest challenges. The framework is quite informative, and we would consider critical factors and sustainability solutions."

In Company C, the framework inspired managers to investigate the current business model and identify some failed value. For instance, a lack of human resource was regarded as a significant challenge. The current employees have limited design capabilities and poor knowledge of using 3D software. Also, customers are more likely to have unique and personalized AM materials; therefore, providing material customization service would be much valuable and achieving mass customization would be the future of material development.

The CTO of Company C presented:
"The framework gives me an insightful perspective of how to transform our current business model towards sustainability. I feel, personally, that the framework contains a lot of information that can be used for strategic planning."

Furthermore, the multi-stakeholder engagement was generated as a critical factor for sustainable business model development. The framework helped Company D understand the significance of effective multi-stakeholder management with the customer, distributor, reseller, supplier, and government. The data also showed that system thinking enabled AM practitioners to effectively manage the product development process to create printing accessories from scratch and achieve the balance of aesthetics, function and reliability.

The CEO of Company D mentioned:
"It is very important for us to develop a sustainable business model; but I am confused by failed value exchanges, and different forms of value, and sometimes it is not very easy to understand in relation to real business."

Based on the framework, the Sales Manager of Company D identified that effective customer management and user experience contributed to the business performance that enabled the company to maintain healthy relationships with stakeholders and strengthen the customer stickiness. The Sales Manager emphasized the importance of multi-stakeholder engagement:

"We use the framework for idea generation and discussion, we found that it is important to understand our customers' needs and give them the best of what we can provide […] look! we make our machine as simple to use as possible for customers."

In all, the empirical data indicated that several managers in different companies thought the framework were useful, but the employees thought that more details need to be added in the framework. The novel aspects of the framework are the synthesis of sustainability solutions, failed value exchanges and critical factors. The business model transformation for AM has not been addressed yet in the literature and the framework contributes to AM business model research. The framework will be used in other AM companies to help create and capture sustainable value in future work.

6.8 AM Value Transformation Process

The research findings showed that the failed value exchanges and negative root causes existed in all six cases. The value systems were articulated in each case with the analysis of *value proposition, value creation, value capture and value delivery* (Richardson, 2008). The economic, environmental and social value were also analyzed and considered as value captured in the case studies. Some types of sustainable value were emerged and identified in the current AM business models. Furthermore, *value complement* and *value mitigate* were proposed as the solutions to reduce failed value. Based on that, the author, therefore, illustrated the dynamic process of value transformation towards sustainability in Figure 6.13. This may help AM practitioners understand the process of continually increasing value captured and correspondingly reducing failed value; ultimately, failed value become minimal and value is completed captured, then fully realize sustainable value.

The AM value transformation process presents the dynamic change of the "*volume*" of value captured and failed value (*VM, VA, VU, VD, VS*) within the block that value captured gradually increases and five forms of failed value accordingly decrease in each block step by step. The *value complement* and *value mitigate* take action to reduce failed value until realizing sustainable value completely which are incorporated into the transformation process. The AM value transformation illustrates the dynamic process of value captured evolving step by step, which improves the value captured, and overcome the failed value, ultimately, value is fully captured, and failed value becomes minimal, then to create and capture sustainable value.

When the author presented the AM value transformation process to the companies, some of the interviewees rejected it, as saying:

"*The sustainability issue has not been addressed in the company […] I would say the 3D printing sustainability is coming but is lacking now, the value transformation process is not our focus*." The CEO of Company E also commented:

"The AM value transformation is quite academic and encompasses several terminologies that are not easy to understand, but the logic is quite simple and easy to catch up."

The CTO of Company E indicated that 3D software service played an essential role in AM education. However, there was a lack of good software that enables the company to improve value captured according to the value transformation process. As the CTO articulated:

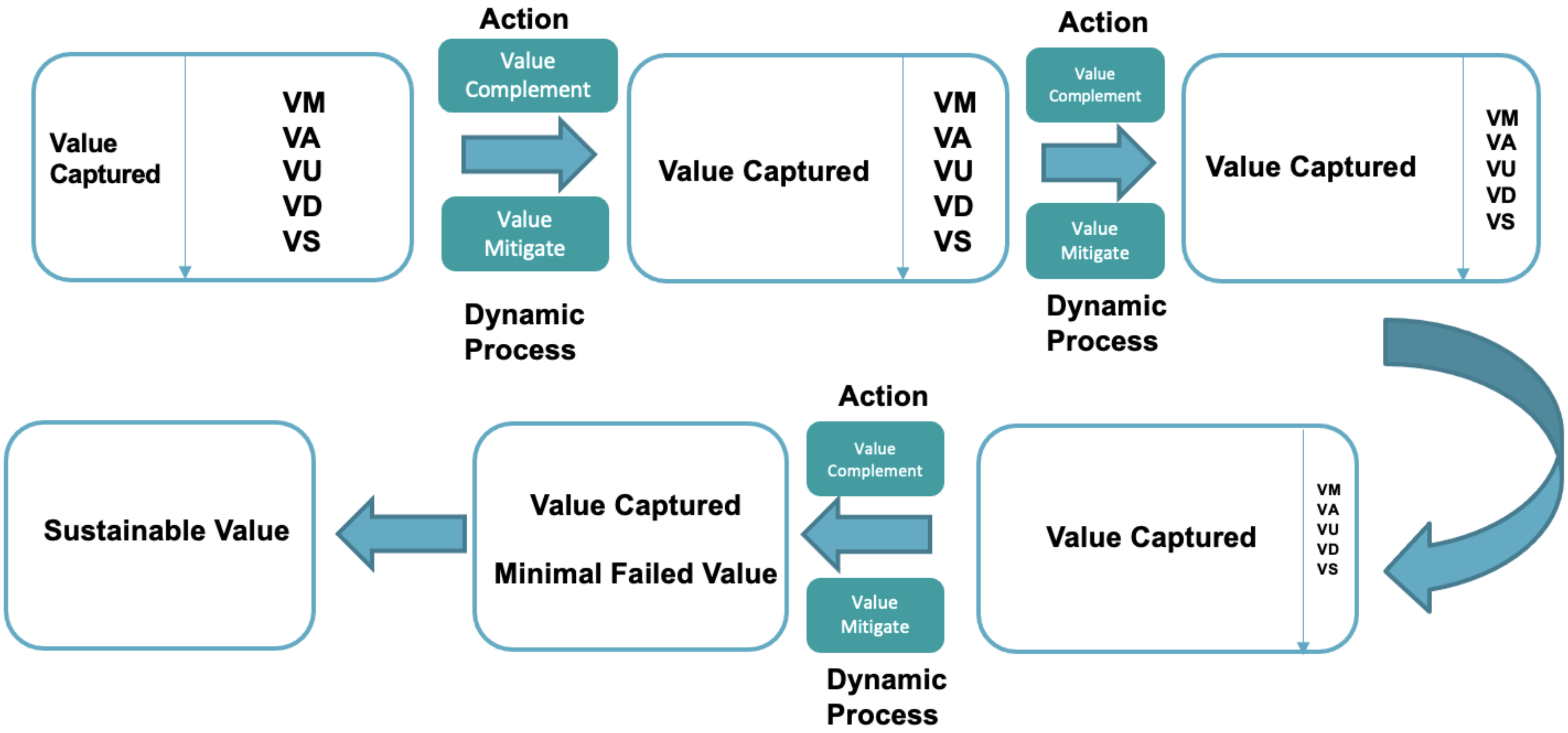

Figure 6.13: AM value transformation process (Author generated)

“We have no capabilities of developing the integrated and user-friendly software with multi-functions encompassing model design, printing operation, workflow and resource management.”

The COO of Company E also indicated:
"The value transformation process is quite beneficial, we aim to increase the sustainable value, but there is a problem that we have no software, and our machines use open-source software. Once the software stops, the hardware is useless."

Furthermore, insufficient qualified AM educators became prominent and the teaching staff lacked educational qualifications. Apart from that, sustainability education was identified as a significant failed value due to the difficulty of integrating sustainability considerations into education and the lack of teaching methods for printed objects recycling. Notably, the CEO of Company D emphasized:

“We recognize the value transformation process and failed value problems. Due to the limited printing service capabilities, we could not achieve mass production and customization, and I think it is the failed value, and we need to overcome it […] I believe it will be realized in the future.”

The transformation process from value captured to sustainable value step by step inspired the companies to look into the current business models and figure out what could be done to improve sustainable value. For instance, the idea of cloud-based AM manufacturing was brought up by the CTO of Company D, and he presented:

“*It would be effective if we could build up facilities to allow all the manufacturers to make products in different locations using their printers and sharing the resources seamlessly through communication […] if happens, we would be very close to mass customization*.”

In sum, the AM value transformation process was validated in the cross-case synthesis and the companies gave some positive feedback on the process. The value transformation process inspired some companies to improve value captured and reduce failed value. It should be noted that the mechanism of the value transformation process has similarity with business model transformation with the aims of creating and capturing sustainable value, which contribute to the concept of sustainable value creation.

6.9 Building the Framework

The research findings indicated that the conceptual framework (see Figure 2.7) using AM business model as the unit of analysis, was helpful for AM companies trying to develop sustainable business models. This was shown by how the critical factors, sustainability solutions, value chain model, business model transformation and value transformation has helped AM companies to identify opportunities to create and capture sustainable value. Based on the cross-case synthesis and empirical findings, a more comprehensive framework was therefore proposed on top of the conceptual framework to address research questions shown in Figure 6.14. In essence, the framework is to help companies understand the key points in three categories, and the new concepts/original contributions made by this framework are:

1: AM technology

- A better understanding of the AM technologies and AM sustainability through a systematic review of the literature (Section: 2.2 and 2.3);
- Identification of the key challenges of AM adoption from the case studies (Table: 4.3, 4.8, 4.13, 5.3, 5.8, 5.13);
- Key challenges in the perspectives of design capability, material development, software solutions, processes, machine quality, polishing and standardization/certification needed to be improved through technological innovation.

2: AM business model

- Investigation of value systems and PSS solutions to understand the current AM business models (Section: 4.1.2, 4.1.3, 4.2.2, 4.2.3, 4.3.2, 4.3.3, 5.1.2, 5.1.3, 5.2.2, 5.2.3, 5.3.2, 5.3.3);
- Value unsupported as a new failed value exchange (Section 4.4);
- Value complement and value mitigate as the solutions to reduce the failed value (Section 6.1);
- The failed value exchanges and the failed value flow charts are helpful to gain deep insights into the AM business models and the relationships among customer, focal firm and external stakeholders (Table: 4.2, 4.7, 4.12, 5.2, 5.7, 5.12 and Figures: 6.3 – 6.8);
- The AM ecosystem map is helpful to understand the whole industry for AM practitioners (Figure 6.9);
- The AM value chain model is helpful to understand how the AM process is initiated, what value is available, how value is created, extracted, captured, and delivered, ultimately to realize close-loop through the product life cycle (Figure 6.11).

3: Sustainable AM business model

- The AM critical factor framework is helpful as the guidance to develop sustainable AM business model (Figure 6.2);
- The 55 key sustainability solutions are helpful for AM companies to realize the value opportunities (Table 6.1);
- The AM business model transformation framework is to help AM companies transform the current business models into sustainable business models (Figure 6.12);
- AM value transformation process is useful to understand different dimensions of AM value and overcome the failed value to create and capture sustainable value (Figure 6.13).

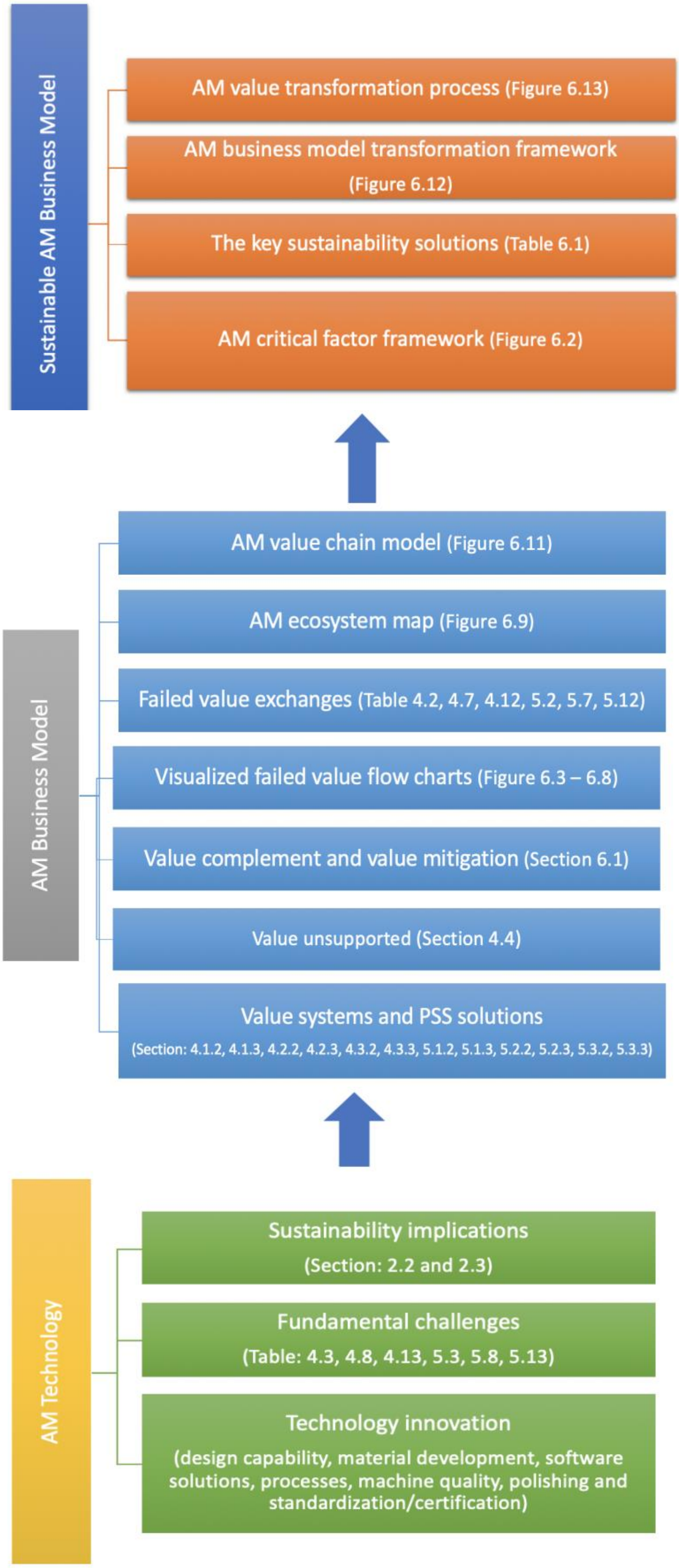

Figure 6.14: Framework for sustainable business model development

This over-arching framework was developed based on the findings from rich empirical data and analyzed through the case studies and focus groups. It systematically shows the logic of how the author addressed the research questions step by step through the investigation of AM sustainability issues, value systems, PSS solutions, failed value exchanges, challenges of AM adoption, critical factors and value opportunities comprehensively. This approach is proposed for the first time by this research and has not been covered in the literature yet. The framework contributes to the new perspective of a sustainable business model.

As discussed in Chapter 2, several studies investigated the development of a sustainable business model; for instance, Despeisse et al. (2017) present the need for developing a framework to guide business model innovation in a well informed and sustainable manner; Yang et al. (2014) propose the uncaptured value concept and point out that value uncaptured exists in almost all companies; Bocken et al. (2013) develop negative forms of value to deliver sustainability; Rana et al. 2013; Yang et al. 2013; Bocken et al. (2014) contribute to understanding sustainable value creation. However, none of the studies has combined the concepts of various forms of value, failed value exchange, sustainability, and business model to study AM technologies; and none has used the analysis processes derived from the framework to investigate sustainable value creation and capture in the AM business models.

Furthermore, in the AM cases, industrial practices appeared to be ahead of academia in exploring the different ways of using AM technologies and developing business models for AM applications. The data showed that most existing AM business models focused on creating, delivering and capturing economic value, with limited attention to the environment and social value. For instance, environmental benefits were not regarded as driving forces for providing PSS solutions although they recognized the benefits. The companies still set economic profits as a priority. It should be noted that the senior managers considered that there would be more potential environmental benefits that have not been found yet.

Based on the cross-case synthesis and new empirical findings, the author proposed a working definition of '*a sustainable business modelling process'*. It is a new theoretical perspective to improve our understanding of sustainable AM business model transformation process.

"*A sustainable business modelling process helps reduce negative outcomes and create additional value towards sustainability through identifying failed value exchanges with a range of stakeholders, particularly the environment and society, and then dynamically complementing and mitigating failed value to realize sustainable value*."

This definition provides a new perspective for explaining sustainable business modelling process. It emphasizes failed value exchanges and multiple stakeholders, where the value is not restricted to economic benefits but includes social and environmental value. Notably, it highlights the significance of value mitigate and value complement by complementing and mitigating failed value to create sustainable value, which helps better understand the value exchanges mechanism. The new perspective to improve understanding of sustainable AM business model transformation process is revealed. The current views of the sustainable business modelling process literature are confirmed (Bocken, N.M.P et al., 2013 and N.M.P. Bocken et al., 2015) by adopting multiple stakeholder views of value, particularly the environment and society. The definition of a sustainable business modelling process is first proposed, which has not been found in the current literature.

6.10 Chapter Summary

This chapter presents the cross-case synthesis and new findings of the six case studies and two focus groups. The new value forms for value transformation were defined, and the AM critical framework was developed. The processes of failed exchanged value and dynamic stakeholder relationships were illustrated through the flow charts. The author then developed the AM ecosystem map, AM value chain model, AM business model transformation framework and presented the AM value transformation process. The key sustainability solutions for AM were summarized for sustainable business model development.

Mainly, the overall framework was developed for this research to present the mechanisms of developing business model towards sustainability. In practice, the framework could be used to help the company effectively understand AM technologies, analyze the failed exchanged value and develop a sustainable business model in a structured and sustainable manner. The findings, therefore, highlight the critical processes and resources of business models in helping AM companies to realize value opportunities and establish competitive advantages.

Furthermore, a working definition of ‘a sustainable business model’ was proposed, which emphasizes the dynamic intervention process for reducing the failed value and realizing value opportunities.

Chapter 7 Discussion

7.1 Discussion on Failed Value Exchanges in AM Companies

In this study, the author adopted the concept of failed value exchange from literature. The author proposes one new form of failed value exchange, *value unsupported,* and two new forms of value transformation, namely*, value complement* and *value mitigate,* one of which is a new form of failed value exchange and two of which are solution pathways for transforming the failed value exchange into the successful value exchange. The *value unsupported* can assist AM companies in understanding the negative aspects of their business models. The novelty of the value unsupported is that it supplements the established failed value exchange perspective (Rana et al., 2013; Yang et al., 2016; Bocken et al., 2014) with the significant identification of the three-side relationships among the focal firm, customer and other stakeholders. It distinguishes value absence with '*the value required but is not created by other stakeholders for the focal firm'* instead of '*the value required but is not created for the customer.'* In light of this, based on Fernando (2016), *value unsupported* is given a working definition of '*I want, but you do not give'* that "I" refer to the focal firm, and "you" refer to other stakeholders instead of the customer (see Section 4.4).

All six companies found the value unsupported useful and it effectively helped them identify value opportunities. For instance, there is a lack of IP protection mainly in Company A. One of the reasons is that the government could not provide the regulations, not effectively execute the policy, and the IP protection environment has not been fully established in the AM industry, which is a suitable example of the value unsupported.

Furthermore, the novelty of the *value complement/mitigate* is that the two value transformation forms are dynamic rather than static. They are considered as interventions, solutions and actions to transform value absence, missed, unsupported, value destroyed and surplus in a dynamic process (see Section 6.1). The strength of the new value forms is that they are developed from the rich empirical data rather than a conceptual idea derived and placed into the literature. However, the weakness is that the data are mainly from AM cases and needs to be validated in other manufacturing companies. The identification of failed value exchanges in AM companies has been shown to help companies understand the negative aspects of their business models. *Value unsupported*, *value complement/mitigate* have improved the general understanding of failed exchanged value for the practitioners of AM business models.

It is the first time to use the failed value concept to analyze and tackle AM business models. The author has generated six tables of failed value with a total of 283 examples/explanations in the perspectives of design, machine, materials, printing process, education, and consulting service. The studies analyzed the VM, VS, VA, VU, VD in each case in a structured and comprehensive way.

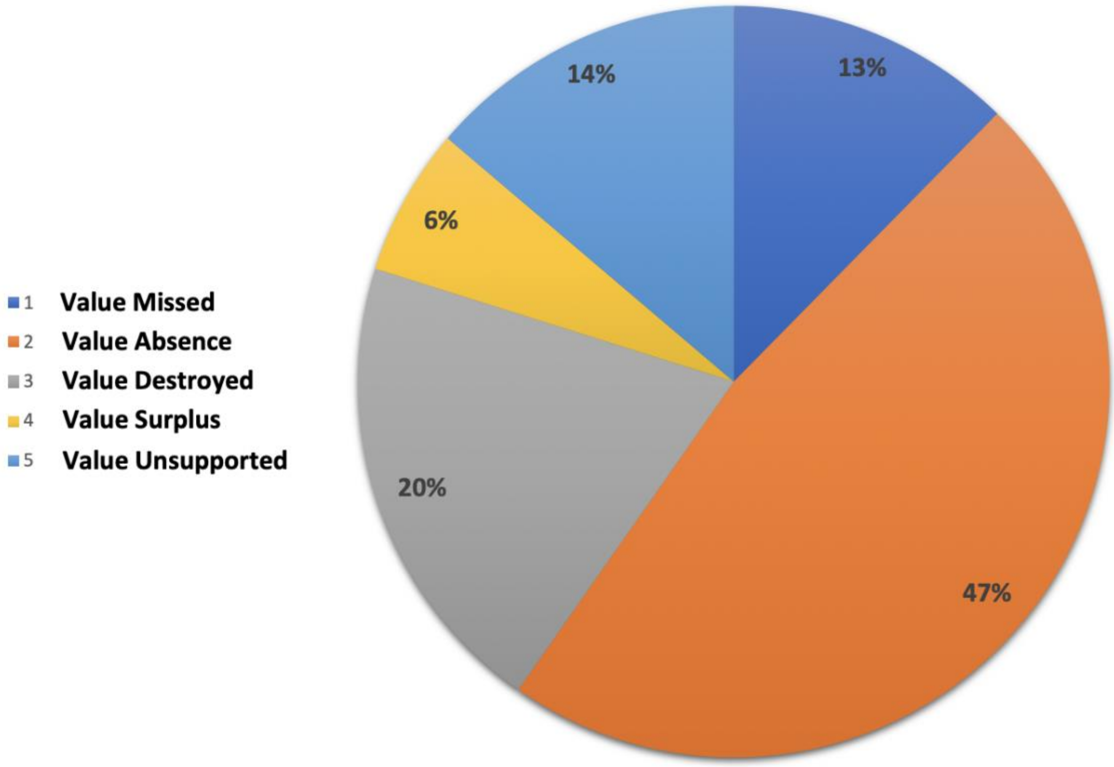

Figure 7.1: Data distribution of failed value exchanges in six case studies

Figure 7.1 shows the frequency with which five failed value forms were identified in the case studies. It should be noted that the figures were calculated from the number of times that each failed value was mentioned and identified. Respectively, the total number of the examples of VM, VS, VA, VD, and VU are 35, 134, 57, 18, and 39 across the cases. It should also be noted that the identification of failed value was sometimes difficult especially some failed value was invisible. For example, it can be learned from Figure 7.1 that the value surplus was the least mentioned from the case studies with only 6%, which means value surplus was quite hidden in AM companies. The second least mentioned failed value is value missed with 13%, which indicates it is sometimes invisible. While the most frequently mentioned and identified is value absence with 47%. This confirms the findings from all the case studies that the current AM business models failed to create and capture sustainable value which needs to redevelop and transform to sustainable business models.

Furthermore, it should be noted that sometimes it was difficult to clearly separate the five forms of failed value, such as value missed and value absence due to the overlaps. Also, different kinds of failed value are of varying significance for different business models. For instance, human resource scarcity was regarded as a common failed value for most AM companies, while the data management problem was more important for AM design companies. Likewise, lack of PSS models was a primary failed value in AM machine and material companies but was less important for service companies such as AM printing platform and consulting due to customers only paying for the service. They do not need to own any hardware or software. Based on Figure 7.1, little data was identified in value surplus which reflects the fact that not many AM companies have considered the redundant value, particularly in Company F. This issue is worth further practical investigation.

Figure 7.2 illustrates the percentage of sources of failed value exchanges identified in the six companies respectively. It shows that most of the failed value were identified in Case D, which implied the AM platform service company encountered more problems than other companies and/or that they were more observant of failures in value exchange. AM design and machine also have the significant failed value that they need to overcome. Many interviewees had positive feedback on the identification of failed value. For instance, the CEO of

Company B commented that '*printers idle in some research institutes*' and *'too much resin in the tank*' as the examples of value surplus were very helpful. It should also be noted that all six companies found the concept of failed value exchange useful and it inspired them to identify value opportunities. Notably, there are 55 key sustainability solutions and 95 value opportunities identified in all case studies, even though some overlapped, and some might not be feasible. The total of 283 examples of failed value exchanges were generated from the real industrial samples. They are new and have not been covered in literature and they can be used as the guidance to identify the value opportunities and develop tactics to realize them.

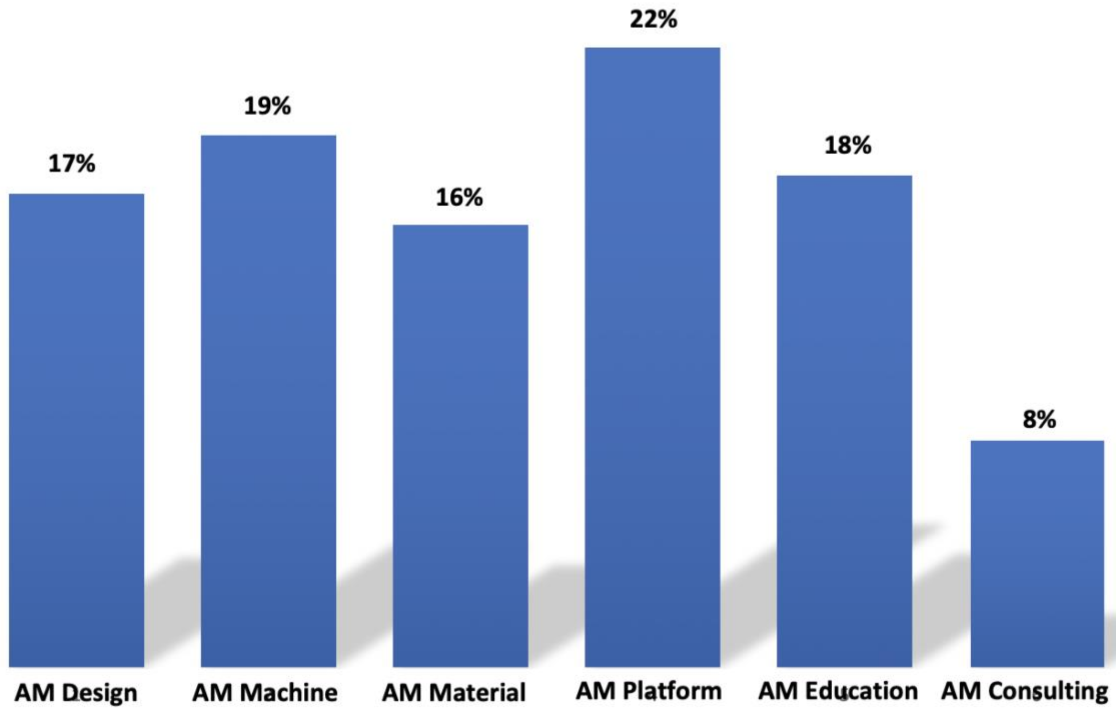

Figure 7.2: Percentage of failed value exchanges identified in each AM case

Furthermore, the visualized flow charts were developed to demonstrate the process of failed value exchanges and the dynamic stakeholder relationships among customer, focal firm and external stakeholders in a different level (See Figure 6.3-6.8). The flow charts were shown to have some utility in guiding AM companies to identify failed value exchanges in their business models. In essence, the identified failed value exchanges laid the foundation for the generation of the critical factors and helped the AM practitioners understand their business models better. While, due to time and data limitations, the analysis and explanations of AM failed exchanged value would only be the start of a path in creating the failed value tables. The tables could be used as examples to help companies create more comprehensive lists. The value flows contribute to the concepts of failed value exchange and multi-stakeholders.

7.2 Discussion of Key Challenges of AM Adoption

To address the sub research question: *what are the key challenges that prevent AM adoption*, the author comprehensively analyzed the negative root causes existing in the AM companies. Identification of challenges of AM adoption aims to better understand the AM technologies and investigate how the AM technologies can be more widely adopted. Different from the failed value exchanges among multiple stakeholders, root causes are mainly those problems that embed into the AM technologies and printing processes. It should be noted the identified root causes and failed value have some overlaps.

The limitations of AM technologies have been discussed in the existing literature from the perspectives of material, machine and printing process (Huang et al., 2013; Petrovic et al., 2011; Berman, 2012; Huang et al., 2015; Bourell D L et al., 2009). While this study not only identified the challenges of AM adoption in the areas of material, machine, and printing process, but also comprehensively explored challenges in the design, service, education and consulting AM sectors. In light of this, the AM critical factors that were identified from the case studies indicated that technology innovation lay the foundation for AM business model transformation. The novelty of the identified challenges is that they were generated from both literature and empirical data and encompassed the broader concerns of business, management, and operational contexts. The root causes analysis was conducted to identify the relevant codes in each case. Similar ones were then classified to form 200 examples of root causes. Furthermore, the 200 types of root causes were classified into 43 categories, which helped better understand the challenges of AM adoption.

Table 7.1: 43 categories of identified key challenges

AM Design	AM Machine	AM Material	AM Platform	AM Education	AM Consulting
Design guidance	Printer speed	Material properties	Printing service speed	Education materials	Qualified consultant
Design quality	Printer development	Material recycling and reuse	Material quality	Qualified educator	Consulting service
Design factors	Printing quality	Material quality	Printing software	Education equipment	External environment
Design methods	Printer cost	Material standard	Service capability	Sustainability education	Sustainability consulting
Design rules	Printing sustainability	Material costs	Printing quality	Design for education	
Design sustainability		Material selection	Service quality	Education service	
Design tools		Material development	Cloud manufacturing service		
Design software			Printing process		
Design IP			Printing standardization		
Design certification			Printing sustainability		

Design standards					
Literature Extended/Confirmed/Contradicted					
36 root causes in AM design were developed and grouped into 11 categories. The challenges of design standards, certification, IP, software, tools, rules confirm the implementation and challenges of AM process (Nannan Guo and Ming C. Leu, 2013; Gao et al., 2015). For instance, the findings confirm the shortage of designers and	35 root causes in the AM machine were generated and grouped into 5 categories. The challenges of printing speed and printing quality confirm the literature in Nannan Guo and Ming C. Leu, 2013); Gao et al., 2015; Martinsuo and Luomaranta, 2018). Particularly, it provides new perspectives on essential technology	47 root causes in AM material were generated and grouped into 7 categories. The challenges of material properties, qualities, material development and standard confirm and extend the literature about AM materials characteristics and principles (Nannan Guo and Ming C. Leu, 2013; Gao et al., 2015); Huang et al.,	41 root causes in AM printing service were generated and grouped into 10 categories. The challenges of printing speed, printing quality, printing process, standardization confirm and extend the literature about strengths and limitations of AM (Nannan Guo and Ming C. Leu, 2013; Huang et al., 2015;	29 root causes in AM education were developed and grouped into 6 categories. The challenges of education materials, qualified teachers, and education equipment were mainly derived from interviews and workshops which contribute to social impacts of AM (Matos et al.,	13 root causes in AM consulting were developed and grouped into 4 categories. The challenges of lack of qualified consultant and consulting service were derived from interviews and workshops which have not been identified in the existing literature (Huang et al., 2013; Martinsuo

engineers skilled in designing 3D models and the legal issues of who should be responsible when the component design goes wrong.	elements and system integration (Huang et al., 2015).	2015 and Berman, 2012). Notably, it provides new perspectives to the principles of AM processes. The findings also confirm the limitations of materials standardization, process productivity, and dimension accuracy.	Martinsuo and Luomaranta, 2018; Gibson et al., 2010). Notably, the printing speed process slower than conventional manufacturing, process qualification, certification, and low precision needs improvement.	2019; Chen et al., 2015; Huang et al., 2013).	and Luomaranta, 2018).
The challenges of design methods, design factors, quality, and guidance and sustainability extend the literature about AM	The sustainability challenges confirm and extend AM sustainability literature (Ford and Despeisse, 2016; Baumers et al.,	The challenges of material recycling and reuse, selection, and standard confirm the strengths and limitations of AM	The challenges of printing sustainability extend the AM sustainability literature (Ford and Despeisse, 2016; Tao	The challenges of sustainability education and design for education extend the literature about	The external environment regarding the uncertain AM market extends the literature about AM

strengths (Huang et al., 2015 and Ford and Despeisse, 2016; Martinsuo and Luomaranta, 2018). For instance, the findings confirm the existing literature about lack of design guidance, guidelines, lack of sustainability considerations into AM design, etc.	2011 and Tao et al., 2018). Mainly, there is a lack of sustainability metrics, unawareness of sustainability concepts, and recycling limitations for broken and used printers.	technologies and AM sustainability (Ford and Despeisse, 2016; Tao et al., 2018; Chen et al., 2015; Y. Long et al., 2017). Notably, it confirms that support structure materials cannot be recycled, though metal powders can be mostly recycled during melting processes.	et al., 2018; Chen et al., 2015; Y. Long et al., 2017). Notably, it confirms that there is a lack of recycling and reuse methods and remanufacturing guidance. Furthermore, the printing glue is harmful to the customer and not suitable for the environment, which is not discussed in the current literature,	AM sustainability in the education sector. In the AM industry, there is a lack of education equipment, qualified teachers and 3D model service which has not been developed in the literature (Matos et al., 2019; Chen et al., 2015; Huang et al., 2013).	industry and development (Huang et al., 2015; Shahrubudin et al., 2019; and Holzmann et al., 2019; Ford and Despeisse, 2016).
	The challenges of printer development and cost confirm AM	The challenges of material costs confirm the literature about the	The challenges of printing software, service capability,		The lack of sustainability considerations in

	cost and AM business (Baumers et al., 2016; Berman, 2012. For instance, limitations relating to high cost, low printing quality need to be overcome; full industry acceptance and adoption are not achieved.	AM costs (Baumers et al., 2016). Notably, high material costs remain a significant barrier to widely adopt AM technologies.	service quality and cloud manufacturing were mainly developed from interviews and workshops which extend the literature of Huang et al. (2015).		consulting service, particularly lack of hard data in energy use, material consumption provides new perspectives on AM service and AM sustainability (Mojtaba and Fabio, 2016; Despeisse et al., 2017).

Table 7.1 summarizes the 43 key challenges in design, machine, material, printing platform, education, and consulting service respectively. The author identified the key challenges from the perspectives of design capability, material development, printing process, software solutions, machine quality, standardization/certification and polishing that need to be solved and improved. These challenges explain why AM technologies are not widely adopted and indicate that some of the challenges need to be overcome to develop sustainable business models. For instance, the AM machine and AM printing platform companies both have the challenges in the category of *printing sustainability*, e.g., '*waste streams in the printing process (materials, scraps, printing support, etc*.)' and '*lack of materials recycle and reuse*'.

AM material and AM printing platform also have some common challenges in terms of *material quality*, e.g., '*limited recyclability of materials due to quality loss*' and '*hard to guarantee recycled material properties for a given process'.* Table 7.1 is developed from not only the literature, but also combines with the empirical data of case studies and cross-case synthesis. Some of the root causes have not been addressed in the literature before. Also, no current research offers the categorizations into these AM sectors which provide significant implications for future AM development.

Figure 7.3 illustrates the percentage of key challenges in all six companies. It shows that 62% of challenges are identified in the AM design (17%), AM material (23%), and AM printing (21%). This confirms the findings from the literature (such as Huang et al., 2015) that design methodology, materials development, and modelling, sensing, control, & process need to be addressed. This indicates that '*technology innovation*', as the AM critical factor, lays the foundation for business model transformation, which also conforms with the AM business model transformation framework (See Figure 6.12).

The author evaluated and compared the findings with the literature. It should be noted that some of the key challenges identified correspond to the challenges of adopting AM in SMEs (Martinsuo and Luomaranta, 2018). The challenges identified in this research extend the scope and requirements in related to technology, strategy, supply chain, operational, organizational and external clusters (Martinsuo and Luomaranta, 2018). For instance, regarding the technology-related challenges, the author analyzed the technical challenges from the perspectives of machine, materials, design, and processing issues. Martinsuo and Luomaranta (2018) only investigate machine, material and provide very simple and common challenges. Furthermore, regarding the strategy, supply-chain, operational, organizational and external marketing-related challenges, Martinsuo and Luomaranta develop only 26 types of AM adoption challenges. While this research provides around 200 examples/explanations in the perspectives of AM design, AM machine, AM materials, AM printing process, education, and AM consulting service, which includes the abovementioned strategy, supply chain, operational and organizational related challenges.

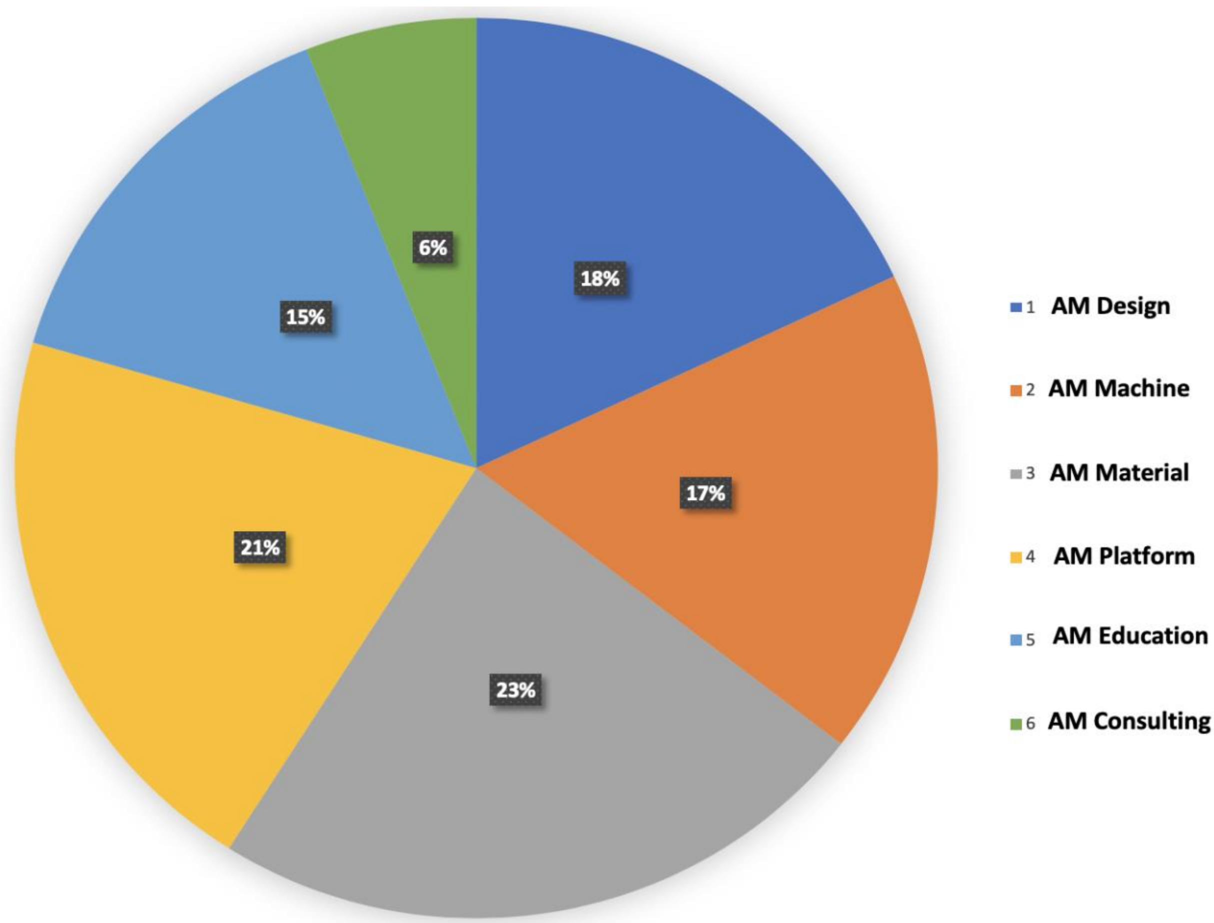

Figure 7.3: Percentage of key challenges in different AM cases

7.3 Discussion of AM Critical Factors and Value Opportunities

One of the research aims is to help AM companies identify opportunities for sustainable business model development. The author used inductive coding methods to analyze and code the interviews, workshop transcripts, supporting documents, and observation notes through the exploratory and descriptive stages. Each confirmed theme was compared against existing literature and the high-level themes were established as the critical factors to help AM companies create and capture sustainable value. The author emphasized that the concluding names given to the themes needed to reflect what was being observed accurately and all themes needed to be accurate, distinct and relevant.

For instance, the initial theme '*stakeholder management*' developed from the exploratory stage was a suitable theme but could not be distinguished from the theme '*multi-stakeholder engagement'*. Therefore, the author combined the similar themes that had commonality. According to the significance and relevance levels of the themes, the two initial themes '*IP management' and 'mass customization'* developed from the exploratory stage were shaped and grouped into the themes *'technology innovation'* and *'multi-stakeholder engagement'* respectively. Thus, the confirmed six themes at the descriptive stage presented a clear separation between each other, and all matched the criteria of being accurate, distinct, and relevant. These critical factors are considered as essential elements for AM companies to develop sustainable AM business models. The critical factors provide fresh insights that help practitioners to identify value opportunities and increase the 'overall size of the value captured pie'. These have not been found in any of the business model literature and is claimed as one of the contributions.

Furthermore, very few researchers have investigated the new value opportunities in the AM business models. The strength of the value opportunities identified is that they are generated from rich empirical data rather than literature and, more importantly, the value improvement opportunities helped the AM companies better understand the underlying logic of how failed value exchanges could be turned into value opportunities and how the opportunities could be realized. The author also integrated the selected value opportunities examples into the sustainability solutions to serve as tactics for sustainable value creation. Its weakness is that sustainability solutions need to be further validated in more AM companies. Also, the summary of the key sustainability solutions needs to encompass more tactics in different AM sectors in a broader context. The effectiveness of implementation and execution of the sustainability solutions is not included in the scope of this study but will be investigated in the future.

7.4 Discussion of Sustainable AM Business Model Development

In Chapter 6, the author empirically generated the AM value chain model, the AM business model transformation framework respectively, and also illustrated the AM value transformation process for sustainable value creation. The author intended to develop a profound understanding of the AM business models, the underlying logic of how the AM technologies can be best used to create value, how the value chain flows through the product life cycle, and how the value transforms, fails and evolves to become sustainable value. The novelty herein is that there are no studies in the literature concerning the underlying logic for sustainable business model development in the context of AM. These findings improve our understanding of sustainable business model development in the AM companies.

Notably, the AM value chain model is first being proposed to improve understanding of the value systems and the value flow throughout the product life cycle. Furthermore, the AM business model transformation framework and the AM value transformation process provide deep insights into how AM firms could develop business models from AM technologies in different ways. The proposed AM business model transformation framework can be used to guide AM companies seeking to create and capture sustainable value. This is a new approach not found in the literature.

7.5 Limitations of the Research

The research developed subjective descriptions of AM business models, explored the sustainable value in the context of AM, and investigated the new possible ways of using AM technologies to create value. The exploratory nature of this research justified the chosen inductive research approach as being more suitable than other philosophical paradigms. Constructivism was chosen as the methodological choice as a basic set of beliefs.

The research collected AM practitioners' opinions and experiences about the current AM business models and the failed value exchanges to build new knowledge from empirical evidence. The research addressed the complex, real-world problems identified by the AM companies. It involved exploration and analysis of individuals' opinions and highly interactive engagement with AM practitioners. The research showed that the existing theories do not adequately capture the complexity of the research problem, and quantitative measures did not fit the problem. Therefore, the qualitative method has been chosen as the method to address the research question. The main research focus is to understand a practical problem and develop an in-depth description of multiple cases. The lack of viable theory and empirical evidence justified case study as a suitable qualitative approach. The lack of quantitative data, and the subjectivity of those interviewed present challenges of replicability and reliability to this research. Further quantitative studies are required to verify the actual implications for AM sustainability from the environmental and social perspectives along with the effectiveness of sustainable AM business models.

Furthermore, the author has attempted to cover all the existing AM business models from different sectors. Potentially, one of the limitations is that the author selected six typical AM sectors, and most of the company case studies are SMEs and start-ups. Also, most of the case companies are at an early stage of transformation into sustainable business models. The research did not cover other types of companies in other AM sectors. All of these might limit generalization and applicability of the findings. Further research is needed to overcome the limitations by increasing the sample size and considering large multi-nationals in the AM industry.

Particularly, the main limitation of this research could be the challenge of replicating the studies and findings for other researchers and wider population (compared to a quantitative approach). The small number of case studies would raise the issue of generalization that could cause bias. Case study may also cause ethical issues, particularly of confidentiality. Besides, the author’s own subjective opinion and feeling may impact on the process and result of case study. Thus, the author has used multiple sources of evidence, triangulating different sources of data to ensure the consistency, the transparency and the rigor of the research so that anyone who analyses the same case studies would draw the same results.

Chapter 8 Conclusions

8.1 Overview of the Research

This chapter presents the research conclusions, including the research overview, the key contributions to theory and practice, and the opportunities for future work. The research aimed to make both theoretical and practical contributions to the concepts of business model, sustainable business model, and sustainability in the context of AM technologies. This research explored how sustainability concepts could be embedded in the AM business models to create and capture sustainable value. The primary research outcomes are a better understanding of the AM business models and the novel ways of creating sustainable value outcomes. It also contributes insights into the sustainable ways of using AM technologies through building on and connecting existing theories. The principal contributions to knowledge and practice are summarized respectively in Section 8.2 and Section 8.3, all of which have not yet been systematically covered in the literature. All the vital contributions improve the understanding of the research question:

How can AM companies develop business models to create and capture sustainable value?

This author answered the research question: AM companies can better develop sustainable business models by embedding the sustainability concepts into the value captured systems, by identifying the failed exchanged value among multi-stakeholders, by analyzing the key challenges of AM adoption, by using the critical factors as the guidance, by identifying the value opportunities, and by implementing the sustainability solutions based on the technology innovation. Table 8.1 presents an overview of the study as follows:

Table 8.1: Overview of the research (Author generated)

Research Aims

Better understand the AM sustainability	Better understand the AM business models	Help AM companies identify opportunities for sustainable value creation and capture

Main Research Question: How can AM companies develop business models to create and capture sustainable value?

Sub RQ1: What are the sustainability implications of AM?	Sub RQ2: What are the current business models within AM companies?	Sub RQ3: What are the failed value exchanges among multi-stakeholders?	Sub RQ4: What are the fundamental challenges that prevent adoption of AM?	Sub RQ5: What are the critical factors that help AM companies develop sustainable business models?	Sub RQ6: How can AM companies identify opportunities for sustainable value creation and capture?

Philosophical Paradigm: constructivism

Research Approach: qualitative method/inductive/theory building

Qualitative Methods: literature review, case studies, focus groups

Data Collection

Case studies: 34 interviews; 25 participants	Two focus groups: 18 participants	Observation and fieldwork	Documentation: newspaper articles, annual reports; technology reports; consultancy articles; government documents; websites

Data Analysis: within-case analysis and cross-case analysis

8.2 Theoretical Contributions and Academic Implications

The literature showed a lack of research on AM business models that draw on sustainability concepts. The AM literature suggested the need for more empirical studies on AM business model to improve sustainable value creation (Costabile, 2017; Mojtaba and Fabio, 2016). This study fills this research gap and contributes to the existing knowledge. The author has indicated that many AM business model studies highly focus on the economic analysis or cost modelling without drawing on the concepts of sustainability. In each case study, the author has analyzed the value systems through multiple lenses, including the economic, environmental and social value in different business models, the failed value exchanges among multi-stakeholders, the key challenges of AM adoption, the critical factors for sustainable business model development and the value improvement opportunities, all of which have not been previously discussed in the existing literature.

Based on the empirically generated results, the author, therefore, developed the framework to address the research questions. The answer was visualized in the framework shown in Figure 6.14. In all, ten theoretical contributions are offered:

1. This research proposed a new failed value form – value unsupported (see Section 4.4), and a new concept of value transformation in two forms -- *value complement* and *value mitigate* (See Section 6.1). *Value unsupported* distinguishes the relationships among the firm, customer and other stakeholders in a different level and stakeholder dynamic mechanism. *Value complement* and *value mitigate* are identified as the actions and the solutions to reduce failed value and create sustainable value. The new value forms contribute to the concepts of failed value exchange and value transformation.

2. The research identified 283 significant examples/explanations of failed value exchanges in different AM sectors, which help better understand the AM business models. The failed value exchange analysis in each

case contributes to the concept of failed value exchange (See Table: 4.2, 4.7. 4.12, 5.2, 5.7, 5.12).

3. The research conducted the root cause analysis in each case and identified 200 examples of key challenges that prevent the adoption of AM (See Table: 4.3, 4.8, 4.13, 5.3, 5.8, 5.13). The key challenges contribute to the research on AM technologies.

4. The research identified six high-level themes as the critical factors including *qualified AM professionals, PSS for AM, AM technology innovation, AM sustainability, multi-stakeholder engagement,* and *system thinking*, which help AM companies develop sustainable business models (See Figure 6.2). This has been empirically demonstrated in the AM business models. The critical factors contribute to the literature about sustainable AM business model.

5. The research proposed the AM ecosystem map that would help understand the business relationships and provide a better view of the AM industry (See Figure 6.9). The AM ecosystem map contributes to the literature about the AM business model.

6. The research developed the AM value chain model to demonstrate the value flow and value exchange throughout the product life cycle which is helpful for understanding AM business models (See Figure 6.11). The illustration of AM value chain contributes to the research of AM business model.

7. The research has identified 55 significant sources of sustainability solutions based on the examples of value opportunities identified, which are helpful for AM companies to develop sustainable business models (See Table 6.1). The key sustainability solutions contribute to the concepts of sustainability and sustainable business model in the context of AM.

8. The research proposed the AM business model transformation framework to help AM company develop a sustainable business model (See Figure 6.12). This framework provides the methods to facilitate the current business model to achieve the transformation towards sustainability from a holistic perspective. The framework contributes to the literature on the AM business model.

9. The research developed the AM value transformation process with the illustration of the logic of increasing the "overall size of the value captured pie", which is to improve the value captured, to overcome the failed value, and to achieve sustainable value ultimately (Figure 6.13). The value transformation process contributes to the concept of sustainable value creation.

10. The research contributes to the concept of the sustainable business model by proposing a working definition (See Section 6.9). It involves the identification of failed value exchange and integrates the value complement/mitigate as the solutions into the dynamic process of reducing failed value and creating sustainable value.

8.3 Practical Contributions and Industrial Implications

Based on the research findings, ten practical contributions and industrial implications are summarized as follows.

1. The new failed value form has the potential to inspire AM practitioners to consider the value unsupported with wider stakeholders. For example, practitioners can identify what value is required, but is not provided by other stakeholders for their own companies (e.g. regulations, education systems, policy).

2. The 283 significant sources of failed value exchanges identified in this research can guide AM practitioners to identify failed value exchanges among multi-stakeholders in their companies. The key sources of failed

value might vary at a different time for different AM companies.

3. The visualized failed value exchange flows provide a structured approach for AM practitioners to better understand the relationships among customer, focal firm and external stakeholders; help identify detailed sources of failed value based on the 283 examples for their own companies.

4. The total 200 examples of key challenges of AM adoption in 43 categories can direct AM companies to develop technologies and strategies to overcome these challenges in terms of design, material, machine, printing platform, education, and consulting service. The findings indicated that technology issues bring the most significant challenges which imply that practitioners should develop technology preferentially.

5. The proposed AM critical factor framework can help AM practitioners conduct strategic planning and transform business models toward sustainability. It implies that the critical factors can stimulate dialogue between academics and practitioners on the subject of AM business model.

6. The proposed AM value chain model can help AM practitioners understand how the AM processes are initiated, how value is extracted, exchanged, captured, and delivered, ultimately realize the close-loop throughout the product life cycle.

7. The proposed 55 significant sources of sustainability solutions can guide AM practitioners to embed sustainability considerations into business models and identify opportunities for sustainable value creation. This implies that the sustainability solutions, together with the identified value opportunities in each case can be further applied to the AM business models in their own companies.

8. The proposed AM business transformation framework can help AM

practitioners understand current value captured systems and develop sustainable AM business models in a structured and sustainable manner. It implies that the framework can encourage new strategy development to trigger communication and collaboration.

9. Understanding the AM value transformation process can help AM practitioners investigate multiple forms of value in their own companies for sustainable value creation.

10. The proposed frameworks can be further used for educational and consulting purposes. Mainly, this implies that they can be further transformed into teaching materials and business tools for college education and management consulting.

8.4 Future Research

The research findings indicated the opportunities for future work which would benefit both theory and practice:

- The new value forms, in particular, the value unsupported could be further explored and validated in certain manufacturing companies.
- The identified failed value tables could be used as examples to help discover more failed value exchanges in the AM business models, which would make a significant impact on AM industry.
- Further research on how to solve the key challenges, achieve mass customization and adoption of AM would have significant practical benefits.
- The sustainability solutions could be extended in a broader context. The effectiveness of implementation and execution of the sustainability solutions could be investigated in the future.

8.5 Final Words

AM technologies are still in their infancy and need further improvement. So, it is no surprise that the research on AM business model towards sustainability is also at the nascent stage. This early study has shown that AM is not as sustainable as many have suggested as it generates more energy consumption than that of casting and injection molding. This research has observed a growing number of AM companies have started paying attention to the environmental and societal impacts instead of only focusing on economic profits. Simultaneously, academics are getting more interested in AM technology and related business models and sustainability issues. The author has shown that the research questions have been addressed. The theoretical and practical contributions of the research are illustrated and reinforced. The author hopes that there will be more AM companies that emphasize the significance of sustainability and integrate sustainability solutions into business models to create more sustainable value while making the technologies more advanced and better.

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Appendix A. Interview Questionnaire Sample

The appendix presents the semi-structured interview questions that were asked to each company. The questionnaires were adapted according to each type of AM company.

Interview Questions (Semi-structured):

Part 1	**General questions**
1. What products/services do you offer in your company? 2. How many different 3D printing processes do you use, or do you only concentrate on one? 3. What is your plan for using other 3D printing processes? 4. What specific 3D printing changes will take place in the future? (please tell me when you think this might happen?) 5. What's your strategy for implementing 3D printing to make profits? 6. What's your milestone/business planning of developing 3D printing products/services? 7. When do you expect that 3D printing can be widely used like CNC or any conventional manufacturing?	
Part 2	**Products/services**
8. How do you make your technology available to your customers? (do you offer sharing service, lease, rent, sell with a service package, etc.) 9. Do you manufacture products and sell (direct, retail or online)? 10. How will this relationship change with your customers in the future? 11. What would be the new products made by 3D printing in your company? 12. What level of complicated structure can be designed and made by the 3D printer, for instance, circuit, sensors, or shoes?	
Part 3	**Customer problems**

13. What difficulties do your customers have in integrating 3D printing into their existing production and process systems? 14. What difficulties do your customers have in using 3D printing related products/services? 15. What are the barriers for applying 3D printing into future production and process systems plan in your customer companies? 16. Why do some customers hold an optimistic or pessimistic attitude towards using 3D printing? For potential users, especially for pessimistic ones, why are they worried about the current 3D printing? 17. What would be the effects on product design using 3D printing?	
Part 4	**Provider problems**
18. What are the difficulties of offering 3D printing to your customer? 19. What are the barriers for you to reduce wastes and entirely use resources in printing processes? 20. What are the challenges for you to provide recycling, reuse, remanufacturing?	
Part 5	**Future development**
21. In the future, how might you change the way that you make 3D printing available to your customers; for instance, if you sell it now, will you be renting or leasing it in the future? 22. Do you think you will keep your technology in your factory than just sell the output? 23. Will you provide recycling, reuse or remanufacturing in the future? 24. How do you develop and maintain a 3D printing platform or community online/offline in the future? 25. How do your employees improve their understanding of 3D printing principles; for instance, what kinds of training program do you offer? 26. What would be your biggest challenges in the future in terms of 3D printing development?	
Part 6	**Wide open**

27. How important do you think sustainability is? Is there beneficial or difficult for the industry?

28. How important do you think that 3D printing companies make their products/services available in different ways to their customers?

29. How would 3D printing affect your way of making product/service available to your customers and which have been proved to be successful?

30. What would be the critical abilities that you need to provide excellent product/service to your customer?

31. What would be the key capabilities that you need to innovate and produce excellent product/service?

32. Does 3D printing have the potential to change the way business model innovation is done?

33. Do you think 3D printing has abilities change the way value create, capture and deliver are done?

34. By using the 3D printer, do you think it is good or bad for the environment and society?

35. If the 3D printer can print mixed multi-materials, do you think it hard to disassemble for recycling/reuse?

36.Whether sustainability efforts have a positive or negative impact on the firm's financial performance?

Appendix B

List of Acronyms

Acronym	Expansion
AM	Additive Manufacturing
ABS	Acrylonitrile Butadiene Styrene
ASTM	American Society for Testing and Materials
BMI	Business Model Innovation
BOL	Beginning of Life
CNC	Computer Numerical Control
DLP	Digital Light Processing
DLMS	Direct Metal Laser Sintering
EBM	Electron Beam Manufacturing
EOF	End of Life
FDM	Fused Deposition Modeling
LENS	Laser Engineered Net Shaping
LOM	Laminated Object Manufacturing
LMD	Laser Metal Deposition
MJM	Multi-jet Modeling
MOL	Middle of Life
PC	Polycarbonate
PLA	Polylactic Acid
PSS	Product-service System
SBM	Sustainable Business Model
SHS	Selective Heat Sintering
SLA	Stereolithography
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
TBL	Triple Bottom Line
TPE	Thermoplastic Elastomer
TPU	Thermoplastic Polyurethanes
UAM	Ultrasonic Additive Manufacturing
3DP	Three-Dimensional Printing