Production Planning & Control
The Management of Operations

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/tppc20

Is 3D Printing a myth and hype to achieve sustainability? Evidence from Chinese manufacturing firms

Jia Jia Lim, Jing Dai, Carman K. M. Lee & Hing Kai Chan

To cite this article: Jia Jia Lim, Jing Dai, Carman K. M. Lee & Hing Kai Chan (26 Mar 2024): Is 3D Printing a myth and hype to achieve sustainability? Evidence from Chinese manufacturing firms, Production Planning & Control, DOI: 10.1080/09537287.2024.2321288

To link to this article: https://doi.org/10.1080/09537287.2024.2321288

Published online: 26 Mar 2024.

PRODUCTION PLANNING & CONTROL
https://doi.org/10.1080/09537287.2024.2321288

Is 3D Printing a myth and hype to achieve sustainability? Evidence from Chinese manufacturing firms

Jia Jia Lim[a], Jing Dai[b], Carman K. M. Lee[c] and Hing Kai Chan[b,d]

[a]International Business School, Zhejiang University, Zhejiang, PR China; [b]Nottingham University Business School China, University of Nottingham Ningbo China, Ningbo, China; [c]Department of Industrial & Systems Engineering, Hong Kong Polytechnic University, Hong Kong, PR China; [d]Nottingham Ningbo China Beacons of Excellence Research and Innovation Institute, University of Nottingham Ningbo China, Ningbo, China

ABSTRACT

The immense sustainability challenges facing by organization today have warranted research effort towards exploring industry 4.0 technology such as 3D Printing for new business model innovation. But how firms could leverage 3D Printing achieve sustainability needs more empirical studies, in particular, there are disconnect between industry 4.0-enabling technology and circular economy for sustainability. We seek to contribute to the current literature by weaving the interconnectedness of abovementioned topics. Through 16 semi-structured interviews with Chinese manufacturing sector who has adopted, our result confirmed the role of 3D Printing contributes to sustainability. The result of our investigation shows that 3D Printing firms who successfully reap the benefit to realize circular economy principle will achieve economic benefit; firms realized all dimensions of sustainability when 3D Printing at product and product offerings base on circular economy principle are met in production process, evidenced by spare part and automobile industry. Our study concludes with theoretical and managerial implications.

ARTICLE HISTORY
Received 4 January 2019
Accepted 16 February 2024

KEYWORDS
Industry 4.0; 3D printing; circular economy principle; sustainability; manufacturing

1. Introduction

United Nation Climate Change Conference (COP 26) has put forwarded to reduce the worst impacts of climate change-the cut of carbon dioxide (CO_2) emissions. Anthropogenic-induced environmental degradation is a global concern, where a quarter of global greenhouse gas emissions come directly from industrial sources (EPA 2022). In the past decades, governments, academics and the industry have investigated the problem of resource consumption from the manufacturing industry. The resources consumption in traditional one-way process of 'take, make, dispose' manufacturing method are disposed of in landfills, wastage or incinerators while the product's value is not being fully exploited (Geng and Doberstein 2008). Instead of producing in a linear system, circular economy is an alternate way which calls for better use of resources via a circular system could promote economic growth, environmental stewardship and social benefits (Kazancoglu et al. 2021). For example, Dell's launched 'moonshot goal' of circular economy principle into the business by ensuring packaging made up with 100-percent recycled or renewable materials, while Cisco incorporate circular design in all new products.

Despite the offering of circular economy principle that promise for longevity of products, materials and components at their highest value and utility that could unlock sustainability potential (Gebler, Uiterkamp, and Visser 2015). Enterprises are showing reluctant attitude or struggling experiences when implementing circular approach. Circular economy is a multifaceted societal concept with the aim of rebuilding and reframing the economy of sustainable growth, which extends beyond the material resources that require reconfiguration of business model (Valenzuela and Böhm 2017). The emergence of industry 4.0, with one of the pillar that aim to integrate cyber-physical connectivity to boost smart manufacturing, suggesting 3D printing as a green technology (Peng et al. 2018; Xiong et al. 2022) with digital-to-physical transfer capabilities along the supply chain enabling materials efficiency, reducing life cycle impacts and enabling greater engineering functionality in the supply chain (Fatorachian and Kazemi 2020; Shukla, Todorov, and Kapletia 2018).

In current literatures, there are disconnect between industry 4.0-enabling technology and circular economy (Nascimento et al. 2019). Most of the literatures focused on industry 4.0 technology, circular economy and sustainability independently or nexus of abovementioned topics. On particular topic of 3D Printing technology in industry 4.0 context, most of the academic debates surround 3D Printing features and applications (Chan et al. 2018) in industry, intention to adopt new technology to supply chain (Schniederjans 2017), integration with suppliers/customers through 3D Printing (Delic, Eyers, and Mikulic 2019), little empirical evidence has been provided of its impact on firm performance (Lam et al. 2019), notwithstanding the sustainability impact. While circular economy base model has been explicitly linked with sustainability development on multiple occasions, but specifically to economic and environmental

CONTACT Hing Kai Chan hingkai.chan@nottingham.edu.cn

dimensions that work in line with socio economic and environmental system for the benefit of current and future generation (Bruntland 1987) the social dimension of sustainability is lack (Tang 2018).

Thus, in line with the advocate of United Nations of 2030 Agenda for Sustainable Development (United Nation 2015) that suggested the interplay of industry 4.0 technology, circular economy, sustainability and Ellen MacArthur emphasizing the role of digital technologies in fostering circular economy principle, our study seeks to understand whether and how 3D Printing contribute to sustainability. In addition, we responded to the call from Agrawal, Atasu, and Van Wassenhove (2019) for more research on circular economy in sustainability. Given the probable significance of sustainability for organization long term survival, our study addresses the research gaps with central research question drawing on socio-technical perspective, we asked: How the nexus of 3D Printing and circular economy unlock sustainability (economic, environment and social) potential?

To answer this question, we studied manufacturing sector in China. We focused in China context for several reasons. First, China is the world largest emitter of air pollutants (Lin et al. 2014). It is emergence to look for a new means to mitigate the environmental pollution. Second, China government response to industry 4.0 with Made in China 2025 to transform mass production economy to high tech economy (Chekurov et al. 2018), substantial investments has made in renewable technologies to transform from high carbon economy to zero carbon economy. It is rather critical for the local companies to adopt new technology to innovate alongside with the government policies. Also, the pace of development or maturity of 3D Printing is heterogeneous across nation and industry (Zangiacomi et al. 2020). Some manufacturing firms that already been utilizing the technology for several years and are developing the next generation of applications, while some slower companies do not possess the ability to go digital. Our paper draws on multidisciplinary literature and intends to make several contributions by examining the complex links among circular economy, 3D Printing, sustainability. In particular, we developed a circular base 3D Printing framework based on current literatures. This study also answered the call from Agrawal, Atasu, and Van Wassenhove (2019) and Sodhi and Tang (2021) to explore the role of circular economy and new technology for sustainability. Furthermore, our study embraces all three dimensions of sustainability (economic, environmental and social) in exploring the value of circular 3D Printing. Besides contribution to the scholarship, the proposed circular base 3D Printing for sustainability to the practice is manifolds. First, this article provides a roadmap help managers to identify technology trends under this new paradigm. Second, by drawing on 16 3D Printing relates companies in different industry, this study demonstrate business case of potential of circular base 3D Printing in different industry. Third, we also provide guidance on opportunities to improve technology for sustainability development in response to the country level policy. The policy implications linking 3D Printing, circular economy and sustainability are manifold. The policy makers could establish technology roadmap to reveal the complexity of challenges for the 3D Printing industry.

The remaining of the article is organized as follows. Section 2 reviews related studies. Section 3 presents the research method employed in this study, including the data collection and analysis procedures. Section 4 summarizes and discusses the results from the qualitative interviews, and Section 5 concludes this article.

2. Literature review

2.1. Industry 4.0 technology, circular economy

The existing research on 3D Printing has primarily focused on the technological aspect, its application to the industry (Lam et al. 2019; Despeisse et al. 2017) and intention to adopt new technology to supply chain (Schniederjans 2017). 3D printing, also known as additive manufacturing, is an industry 4.0 technology where a digital computer-aided design model is used to build a 3D object by joining materials layer by layer. 3D Printing provides huge potential for product and process innovation (Baumers and Holweg 2019). It is made up of software, printer, digital design and material, which is rather straightforward as interrelated of design and materials for product. The main proposition of this technology is the input of powder-like materials that pass through the printer's extruder with digital interactive design *is equal to the final product* allows the quantification of material flow throughout the supply chain. Throughout the development of technology, 3D Printing possess direct manufacturing in various contexts including repairing existing products, recycled and reclaimed materials as input, and manufacturing end-use components and products (Atzeni and Salmi 2012; Thomas-Seale et al. 2018). 3D Printing is postulated as cleaner production technology that enabling circular economy business model, the key circular economy principle (product-life extension, redistribution/reuse, remanufacturing and recycling) set in to replace linear manufacturing with closed system (McDonough et al. 2003; Geng and Doberstein 2008). To elaborate, the additive nature of 3D Printing produce using less material enable a closed-loop circulation process (Despeisse et al. 2017). On the other hand, 3D Printing offer flexibility in adapting design to various product change requirements (Friesike et al. 2019) and recycling material selection enhance the product life. It also break the geography by producing anywhere potentially disrupt structure and operations (Hannibal and Knight 2018). However, Geng and Doberstein (2008)'s study proposed the full adoption of circular economy principles within organizations and supply chains is challenging due to insufficient information on the life cycle of products. Kamble and Gunasekaran (2021)'s research put forward that industry 4.0 technologies support efficient circular economy environment. However, the pace of development or maturity of technology is heterogeneous across and within the industry (Bag, Gupta, and Kumar 2021)have diminished the goal of circular economy principles. On the other hand, most existing approaches to design for a circular economy at product and/or component level, where the implementation of circular economy principle is a product-process approach (Ripanti and Tjahjono 2019; MacArthur 2013).

Turning into circular economy principle, it mainly represented by the mean of the key four loops from the perspective from the product side (MacArthur 2013), namely, (i) product-life extension, (ii) redistribution/reuse, (iii) remanufacturing; (iv) recycling. Product life cycle extension refers to '*Products are designed to be durable and to have a long lifetime, thus reducing consumption. Such products are by definition high quality, so businesses often need to change their business model in order to offset the increase product cost, for example by leasing instead of selling products or generating revenue by selling additional services*'. Despeisse et al. (2017)'s study on redesign of product and components with the design freedom offered by 3D Printing. The design of lightweight components with selective material selection at the forefront design stage will subsequently reduce the manufacturing process and supply chain complexity. Meanwhile, rapid prototyping and small batch customization provides product and process flexibility that reduce production and waste consumption comparing with traditional open mould production (Zhang et al. 2021). The industry such as spare part industry reaps benefits from this offering (Chekurov et al. 2018). With the introduction of 3D Printing in the supply chain for spare parts, it is possible for the ship operator to immediately replace a malfunctioning part with a 3D-printed spare part during transportation. This on demand production that association with 3D Printing provides short lead time, less challenging for minimum order quantities, and less environmental impact associated with transportation, logistics, inventory holding and ending production runs on idle (Kunovjanek, Knofius, and Reiner 2020).

Redistribution in circular economy principle refers to '*The most sustainable product is often one we already own. Reusing a product preserves all of the added-value within* that *product.*' Price, quality and process handling complexity are the challenges in material recovery for redistribution and reused (Tian et al. 2017). It is less like materials can be retrieved at similar level of performance compare to virgin materials and applied at the similar application. In management context, redistribution also indicating economic activities redistribution and geographical redistribution. The value-adding activities of 3D Printing transferred from manufacturer to consumer (Halassi, Semeijn, and Kiratli 2019) as its involvement of consumer at the product development stage result in consumer-oriented print-on-demand services. Moreover, the significant growth in the sales of personal desktop printers between 2007 and 2014 signifies the development of decentralized supply chain. A decentralized supply chain allows manufacturers or individual to complete the manufacturing at any location. The incentive generates from the economic activities are redistribute base on functional to the activities, but not the possession over the products, design or intellect property. Janssen et al. (2014) commented that 3D Printing is a strong enabler of digitalization will notably influence the production and distribution of the supply chain. Also, 3D Printing is a design content-oriented ecosystem, where individual designer is in a predominance status in the value chain. Compare to traditional manufacturing where production of a product that possess complex network, the economic incentives are redistributed according to value-added activities instead of possessing of production plant. The high flexibility of 3D Printing allows production activities to take place at any locations (Hannibal and Knight 2018). Manufacturers thus do not need to seek low-wage labour countries to complete some of the manufacturing process; hence, manufacturing firms could be located near inventory and distribution centres (Yoo, Ko, and Chun 2016). 3D Printing helps organizations achieve a geography redistribution or global localization strategy under the digital supply chain era.

In remanufacturing, which *is defined as series of manufacturing steps acting on an end-of- life part or product in order to return it to like-new or better performance, with warranty to match*. 3D Printing techniques that based on automated welding or directly energy deposition is ideal to replace missing, broken or worn part of metal parts (Kerin and Pham 2019). In 3D Printing, metal is regarding as a form of material source to originate the printing process, the other materials used in the printing process include polymers, ceramics and so on (Jayakrishna et al. 2017). In another words, 3D Printing is offering a new level of automation. Before the introduction of 3D Printing, the remanufacturing process was completed with manually repaired by welding and grinding. With 3D Printing, the concept of open manufacturing that fundamentally understands the physics and process of parameters for a high accuracy in predicting the final products.

For the last loop, recycling refers to '*used materials are treated so as to make them suitable for reuse*'. Recycling happens when the excess and unwanted material primarily into new feedstock or finding new methods for the material to degenerate or compost into harmless, or material consumption is well predictable at the product design stage to eliminate the largest extent of material waste (Su et al. 2013; Gao et al. 2017). This recycling loop in 3D Printing context is mainly about material selection for material-printer fit, material consumption, material saving for economic and environment performance. However, the balance between economic and environment are controversial in recycling 3D Printing context (Faludi et al. 2015), for instance, metal material is inevitably expensive while the energy emission during printing process is not quantifiable.

To the best of our knowledge, there are scant literatures that provide understanding of the characteristics of the 3D Printing that resulting products-process that align with circular economy principles. Our study complements the literature by focus on how the characteristic and offerings of technology itself that impacts manufacturing in consideration of circular economy principle, and how circular base 3D Printing contribute to all triple bottom line performances, instead of focusing on single sustainability outlook. In Table 1, we summarized and proposed 3D Printing at product and product offerings base on circular economy principle.

2.2. 3D Printing and sustainability

3D Printing is a promising industry 4.0 technology to unleash sustainability (Ghobadian et al. 2020; Bai et al. 2020).

Table 1. Proposed framework: 3D Printing at product and product offerings base on circular economy principle.

	Product life extension	Redistribution	Remanufacturing	Recycling
3D Printing offering at product level	Redesign for product durability (Greenhalgh 2016; Vazquez-Martinez et al. 2018)	Material redistribution, increase in selection of materials (Bourell et al. 2017)	Certain timing and quantity of returns, Balance returns with demands, Assembly of returned products, High certainty in materials recovered from returned items, Complication of material matching restrictions, Stochastic routings for materials for remanufacturing operations (Tian et al. 2017; Guo, Choi, and Chung 2021; Bernon, Tjahjono, and Ripanti 2018)	Material saving (Faludi et al. 2015; Joshi and Sheikh 2015)
	Make to order model for product repair and remanufacturing/tool less manufacturing (Kerin and Pham 2019; Hedenstierna et al. 2019)	Economic activities redistribute (Kapletia et al. 2019)	Rapid design modification (Despeisse et al. 2017)	Low cost entry level material extrusion printer (Sanchez et al. 2020)
	Direct in-site repair of worn damaged and broken product parts (Despeisse et al. 2017)	Geography redistribution (Kapletia et al. 2019; Rehnberg and Ponte 2018; Birtchnell and Urry 2016)		Recycling 3d printed waste and part (Tian et al. 2017)
	Rapid prototyping and research development of product design Despeisse et al. 2017)			Biodegradable 3D Printing filaments (Sfetsas, Patsatzis, and Chioti 2021; Faludi et al. 2019)
	Design for thermal stresses (Thomas-Seale et al. 2018)			
	Customer involvement (Halassi, Semeijn, and Kiratli 2019)			
	Remixing for product design (Friesike et al. 2019)			
3D Printing offering at process level	Monitor and control product life cycle (Gebler, Uiterkamp, and Visser 2015; Kreiger et al. 2014; Cerdas et al. 2017)	Incentive redistribution lead labour structure change	Monitoring and allocation of resources; decision making for MoL for end of life processing (Bernon, Tjahjono, and Ripanti 2018)	Complexity recycling handling process (Tian et al. 2017)
	Process simulation/ thermomechanical simulations (Thomas-Seale et al. 2018)	Material savings by reduction of subtractive manufacturing processes (Schniederjans 2017)	Requirement for a reverse logistics network (Bernon, Tjahjono, and Ripanti 2018)	Lower energy consumption (Faludi et al. 2019; Ford and Despeisse 2016)
		Reduced need for tools and moulding (Petrovic et al. 2011; Huang et al. 2021)		

The triple bottom line framework of Elkington (1997) that considers economic, environment and social aspects are widely adopted to assess sustainability performance. The extant literature on 3D Printing and sustainability are mainly remained at the conceptual and mathematical simulation, with scant literatures empirically assess the potential of the emerging technology on sustainability (Lam et al. 2019). For instance, Ghobadian et al. (2020) conceptually demonstrate how 3D Printing is a breakthrough sustainable innovation through eliminating wastage in the manufacturing process. Bai et al. (2020) introduced industry 4.0 technology sustainability performance and application measurement framework base on triple bottom lines attributes.

On the other hand, the current literatures incorporate single dimension or combination of two dimensions of triple bottom lines in the discussion of 3D Printing contribution to sustainability. Environment sustainability is the dominant in the literatures of 3D Printing and sustainability nexus. The discussion surrounds 3D printer components selection and material selection to decrease ecological footprint (Faludi et al. 2015), and enhance energy, resource consumption and product life cycle (Sanchez et al. 2020; Kreiger et al. 2014). While social sustainability has gained substantial attention, several studies narrowed the focus lens by exploring the impact of 3D Printing adoption and implementation on societal. For instance, Beltagui, Kunz, and Gold (2020) focused on how socially oriented firm benefitted from 3D printing to overcome resource constraint, 3D Printing automation enhance efficiency by replacing manual work (Gebler, Uiterkamp, and Visser 2015). Corsini, Aranda-Jan, and Moultrie (2020) examine 3D Printing responses to humanitarian need changes; Hohn and Durach (2021) studied the emergence of 3D Printing impact social sustainability in the apparel industry. While notable number of literatures focused on the merits of how 3D Printing contribute positively to the sustainability, one should not neglect the associated risks of adopting new technology (Liu, Zhu, and Seuring 2020). Therefore, our study aspires to study the impact of 3D Printing by embracing all three dimensions of sustainability (economic, environmental and social) in term of opportunities and challenges to manufacturing firms.

2.3. 3D Printing, circular economy and sustainability

Despite a wealth of research on 3D Printing, circular economy and sustainability, gaps remain with respect to how firms successfully navigate technology advancement for sustainability development through circular economy-oriented business model innovation. Circular economy-oriented business model innovation is a new research frontier in sustainability (Bag, Gupta, and Kumar 2021) that incorporates principles or practices from circular economy as guidelines when designing business model (den Hollander, Bakker, and Hultink 2017). Circular economy is a multifaceted societal concept that extends beyond the material resources that further add complexity during the implementation process that requires a systemic and multidisciplinary perspective (Sakao and Brambila-Macias 2018). 3D Printing reconfigure companies' existing supply chain by breaking existing performance trade-offs fundamentally, which shift the current manufacturing production resources from labour-intensive to knowledge-intensive (Ford and Despeisse 2016). Knowledge-intensive signifies the advancement in firms access to new information and knowledge as strategic priority and translate into production process (Ghobadian et al. 2020). While transition to a circular economy requires knowledge development (van Buren et al. 2016), the introduction of 3D Printing under Industry 4.0 has provided firms with easier access to the knowledge and competence for firms to employ the circular economy principle in the production.

Next, 3D Printing is cost competitive technology with low capital required, it offers manufacturing flexibility with less capital required to achieve economies of scope. Economies of scope decide what and how products can be manufactured. The flexibility of 3D Printing allows more customised and creative products with green design and strong material properties but lower unit cost than traditional manufacturing technology. The leverage between capital and scale influences the production cost, whereas the leverage between capital and scope has impact on portfolio of products. The breakthrough effects altogether change the cost and production structure, which allows firms to provide innovative product and services with lower costs to serve the market while addressing the sustainability aspects. For example, green design and safe material selection lower the potential risk exposure of designers, workers and environment in the production process. Eventually, the exclusion of hazardous materials in the design stage could promise a safe manufacturing process; hence, the workers are free from handling dangerous or hazardous chemical products that might cause occupational chronic illness. Lastly, the organization commitment to sustainability requires the organizxation to examine the trade-off between short-term financial considerations and long-term social, environment and economic practices (Gualandris et al. 2015; Bansal 2005); this trade-off has prevented many enterprises from implementing sustainability. Theoretically, cost competitive technology like 3D Printing offer the potential to break through the long-standing trade-off perspective of sustainability. The existing studies conceptualize 3D Printing, circular economy and sustainability are disconnected and independently make the combination of three topic ripe for further inquiry. Drawing from current literature, we seek to contribute to the current literature by extending current understanding of 3D Printing with circular economy principle that foster sustainability outlook.

3. Research methodology

3.1. Research question

Based on the findings of the literature review we identified that there are limited knowledge on roadmap of how 3D Printing penetration to the manufacturing process, how circular economy work as a condition for sustainability. Our key research question is: How the nexus of 3D Printing and circular economy unlock sustainability (economic, environment and social) potential? Based on the key research question, we developed sub-questions to explore (1) the offerings of 3D Printing from different manufacturing industries in China from the point of view of circular economy principle and (2) how does 3D Printing base on circular economy principle in manufacturing process improve sustainability in Chinese manufacturing firms (3) What are the barriers to achieve circular 3D Printing economy.

3.2. Research design

As discussed above, our research is one of the first researches that connect industry 4.0 technology such as 3D Printing, circular economy and sustainability. In order to fully capture insights in addressing the above research questions, an explanatory manner and empirical qualitative approach is adopted. Among research methods in the qualitative research, we selected case study. Voss, Tsikriktsis, and Frohlich (2002) explain that 'the case method lends itself to early, exploratory investigations where the variables are still unknown and the phenomenon not at all understood' (Benbasat, Goldstein, and Mead 1987; Meredith 1998). Exploratory case study research is an essential step towards theory building (Eisenhardt 1989). Data were collected through 16 semi-structured interviews with companies, direct observations and other sources such as company websites to verify the evidence from the interview (Rowley 2002; Duarte and Cruz Machado 2019).

Table 2. The sample and description of interviewed companies.

Interview	Representative/delegates	Company location	3D Printing as complementary or main technology in the business?	Business scope	Years since established	Company size (number of employee)
1	Manager	Ningbo	Complementary	Marine spare parts service provider	>20 years	>100 employees
2	Manager of Public Relation Department	Ningbo	Complementary	automobile car light, car light dimmer, and other spare part provider	>30 years	>300 employees
3	Assistant to senior Doctor	Ningbo	Complementary,	Hospital's orthopaedic department	Since 2003	N/A
4	CEO	Hangzhou	Main	Private orthopaedic hospital with R&D	Since 2014	>50 employees
5	Manager	Ningbo	Main, mass customized	Sales of 3d printer and 3D scanners, souvenirs printing service provider	Since 2014	<10 employees
6	CEO	Ningbo	Main, with other diversified business	3D Printing software for education (platform)	Since 2013	~15 employees
7	CEO and founder	Hangzhou	Main, with other diversified business	3D modelling and online IP application agent	Since 2014	<10 employees
8	Senior engineer	Ningbo	Complementary	R&D and production of ophthalmic optic equipment	Since 2006	125 employees
9	Senior manager	Ningbo	Complementary	Manufacturing of intelligent safety box and library smart racks	Since 1996	40 employees
10	CEO and founder	Ningbo	Complementary	3d printer, robot production and intelligent fire alarm service system	Since 2013	11 employees
11	Professor	Shanghai	N/A	3d bioprinting research institution	N/A	N/A
12	CEO	Ningbo	Main	3D printer production and 3D maker online community	Since 2014	10–20 employees
13	CEO and founder	Beijing	Main	3D design and scanning	Since 2016	<10 employees
14	General manager	Shanghai	Main	Online 3D Printing community and online printing service provider	Since 2014	>30-50 employees
15	CEO and founder	Ningbo	N/A	Foreign 3D printer brand distributor	Since 2015	<10 employees
16	Operation manager	Ningbo	Complementary	Manufacturer of consumer spectacle frames	>15 years	<50 employees

3.3. Company selection process

Choosing which, and how many, cases to study are important methodological considerations (Yin 1989; Yin 2003). Table 2 provides detailed information of the interviewed companies. Considering the novelty and disruption of an innovation might differ across industry; therefore, in our sample of company selection, we intend to cover industry that has already established 3D Printing technology in the production process.

3.4. Data collection and analysis

The overall interview process and interview data analysis are described as below. First of all, we identified and contacted local 3D Printing enterprises and asked the counterpart to assign representatives whom are familiar with the operation of business. The interviewees of this study are either founder, CEO or engineers. On some occasions, details have been confirmed by respondents after the interview (e.g. through a follow-up telephone conversation). Multiple researchers have been involved in the project but have explored the interview data independently. Important themes from the literature, our own collective ideas and recurring themes in the data have been used to cross-reference, categorize and sub-categorize extracts. Key quotations from the interviews have also been abstracted, compared and clustered. All interviews were conducted in Mandarin, and the recorded interviews were transcribed. The transcripts were then translated, and the authors cross checked the interview data to make sure original meaning of the English translations are accordance with Mandarin interviews. The interview data are extracted following the standard content analysis procedures based on seven themes, which are 3D Printing application process, economic, society, environment, sustainability, opportunity and challenges to reflect the research questions.

4. Findings

Based on the interview questions, we generated different perspectives on 3D Printing technology and have gained promising insights from the interviewees from different industries. The result demonstrated in Figure 1, which we demonstrate the level of penetration of 3D Printing in the industry and sustainability performance based on the interview findings.

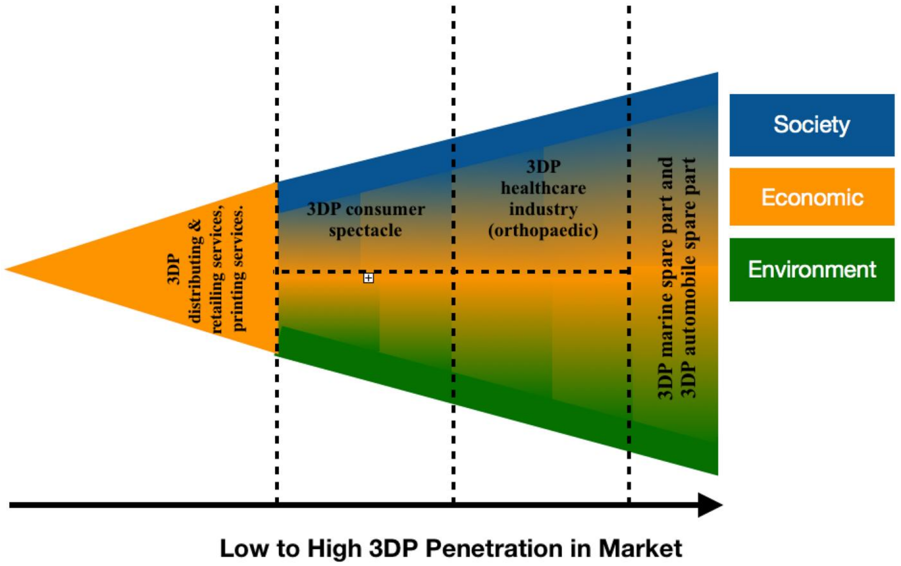

Figure 1. Level of penetration of 3D Printing against the three dimensions of sustainability performance.

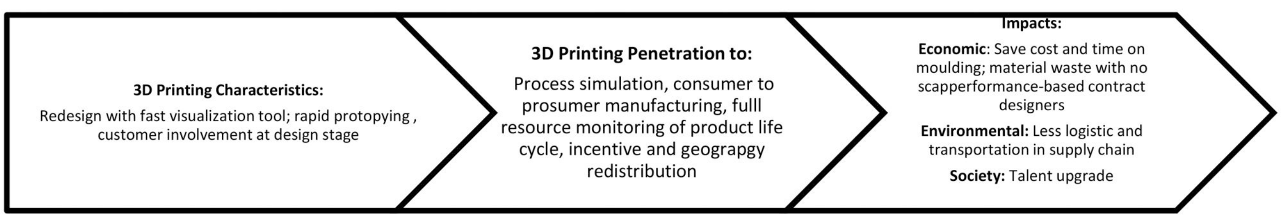

Figure 2. Roadmap of circular 3D Printing for full sustainability dimensions.

We explain our findings rooted with the economic dimension and expand diverging towards the social and environmental dimensions. We found that the firms realized economic factors as the main determinant for new technology adoption. When firms adapt the new technology and harvest cost–profit break-even performance in the new technology establishment stage, they will gradually improve societal and environmental dimensions. Although societal and environment impact might be the synergy of new technology adoption, the firms still play active roles to enhance the penetration rate of new technology adoption in the manufacturing process through circular 3D Printing. If the firms are able to identify the matching of 3D Printing characteristics with circular economy principle. Overall, we found that 3D Printing offers unprecedented impacts to the industry and end users in high-end industries like marine, automobile spare parts, and orthopaedics bio-printing industry. These market with characteristic of multiple product mix with low volume. On top of existing business model, sample firms from this group finds 3D Printing as a complementary tool to current manufacturing method, are aware of 3D Printing characteristic and circular economy principle fit in the production. However, in the sample group of consumer products such as souvenirs, with the market characteristic of high market volume, no large batch production requirement, numerous market players, the role of 3D Printing technology is seen as a market gimmick that attracts individual consumers or hobbyist. The adoption of 3D Printing technology was found does not complement with circular economy principle, thus limiting with potential of sustainability. We further discuss the findings in more details in the subsequent sections.

4.1. *Circular 3D Printing of product life cycle extension, redistribution, remanufacturing, recycling with full sustainability dimensions*

This is particularly relevant to traditional manufacturers who are sensitive to operations costs. High-level findings can be summarized in Figure 2. The characteristics of 3D Printing, such as redesign with fast visualization and rapid prototyping, allow the companies' product design team to enjoy flexibility to update the design at the customer's demand at any time, regardless of the complexity of the 3D model's geometry.

For example, Case Company 2 is specialized in manufacturing automobile spare parts, automobile headlights, and automobile light covers. The product design process is important and complex in the automotive industry, as it evaluates the design concepts before the new model automobiles are put into production. Interviewee 2 expressed that, as most of the company's products require assembly of different components, a slight change in a tiny component requires adjustment of different components as a whole. '*In the automobile industry, 3D Printing will be used to produce the prototype of a car spare part. For example, you want to produce a car headlight. In most cases, your customers will demand that you provide multiple designs of car headlights with different product characteristics and performance, and for each design, you need to produce a prototype for the*

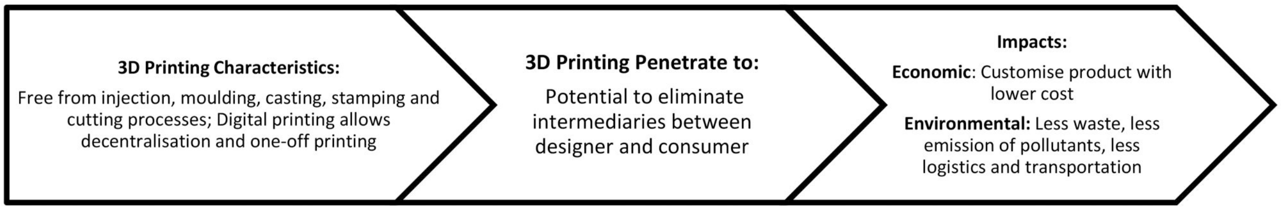

Figure 3. Roadmap of circular 3D Printing for economic and environment dimensions.

customers. The traditional method is time consuming, while your customers want to see the prototype urgently and give you no room to search for suppliers; you will need to fight between time and price in the past; however, with knowledge available online for instance open source which is at free cost or little cost, it could complement designer's expertise and shorten the design stage, also by using visualization tool, the design team is able to simulate product base on the input information'. The economies of one concept and one-off printing, where only variable costs, i.e. material costs, help the firm save up to approximately 50% of the moulding costs compared with the traditional manufacturing method, and they are able to enjoy 40% shorter lead time from the design to production stage. However, the company holds a conservative attitude for large volumes of production, as 3D Printing is still limited in the company's design and prototyping stage.

To complement the point of view that 3D Printing provides convenience in the design of complex spare parts, Interviewee 1, a manufacturer of spare parts for commercial ships, expressed that the introduction of 3D Printing helps the company to save costs from hiring long-term contractual designers. The designers who currently work for the firm are project-based; the salary they receive is based on the satisfaction of the customer. The shift to contractual designers are due to the design of spare parts is complex and normally takes a long time; a fixed salary is unlikely to motivate the employee to work overtime for the dedication of good design, whereas a project-based contract with incentive after completion of projects works as a mechanism for the designer to creatively and actively solve design issues for customers. '*We are happy to see our designers upgrade their capability after the introduction of 3D Printing in our business model. 3D Printing and the designer are complementary to each other, and neither could exist in isolation*'.

4.2. Circular 3D Printing of product life cycle extension, redistribution with economic and environmental dimensions

3D Printing has two key attributes that make it a 'sustainable' technology. First, 3D Printing produces less waste and less pollutants compared with traditional manufacturing techniques. Injection, moulding, casting, stamping and cutting processes are compulsory steps for a product to be manufactured, but 3D Printing is free of these steps. The second attribute is the transformation of the decentralized business model, where home communities are equipped with 3D printers. It can be achieved whenever a user receives digital design and proceeds to print it at a nearby community 3D printer. This on-site printing helps to eliminate the logistics that occur between the transportation of raw materials to the end user. In other words, fuel consumption as well as environmental impacts can be reduced. The result as illustrated in Figure 3.

However, in practice, the environment sustainability of 3D Printing still remains not clear, as none of the interviewed firms kept a record to trace the use of materials. According to Interviewee 13 from 3D Printing industry, '*once we try to look at the total electric consumption in the printing process and compare it with production via machines, we find that it is rather difficult to calculate because some temporary support structures are required in the printing process in order to prevent the printing objects from collapse;, we are not sure if the usage of printing materials is equal to the end product. We should not neglect the fact that the supporting structures are customised for the particular printed object, too, and there is no re-engineering into printing materials once it is printed*'.

Meanwhile, the interviewees express that environmental opportunity through decentralization is a 'utopia' that is not practically sound in 3D Printing. Interviewee 16 stated that '*the supply chain will not be simplified; it might introduce a new material supply chain. The vision of achieving decentralisation is when every home unit or community owns a 3D printer and produces its own needs at home. It is assumed that the 3D printer will become as ubiquitous as the existence as computers or laptops nowadays. However, this fact neglects the current bottleneck of 3D printers, where certain 3D printers accept certain types of materials … I am wondering how many 3D printers the home or community needs for this vision; also, the transportation costs might increase … as it involves transportation of different powders … some are explosive powders … the safety issue impacts this vision …. Also, when the industry is still finding the balance and fit of materials selection with 3D printer, remanufacturing of reused products or materials does not seem realistic, also, our company does not have the knowledge of handling waste materials …* '

On the other hand, most of the products currently manufactured through traditional manufacturing are convenient; for instance, spectacle frames. Interviewee 5 commented, '*the production scale for frames is big, and the current moulding is fast, convenient, and it is really cheap … the cost is per unit … if the consumers are pursuing customized spectacles for consumption upgrading that fit the shape of their face perfectly, 3D Printing can be an option for this, but the flexibility of printing materials is another issue*'.

4.3. Circular 3D Printing of product life cycle extension, redistribution, and recycling with economic and societal sustainability dimensions

In the literature review section, we can see that 3D Printing technology has straightforward implications on the economy and environment, but it is still ambiguous in the societal perspective. This statement does not support for high end industry such as healthcare that adopt bioprinting, we can see the result as illustrated in Figure 4.

The MSF Foundation, an international and independent medical humanitarian organization, where the teams consist of tens of thousands of health professionals that provide medical assistance to people suffering due to conflict, epidemics and disasters. The MSF project was officially launched in 2016, with an annual budget of $150,000, and is designed to provide a better alternative to traditional prosthetics through 3D Printing technology, for instance, 3D-printed prosthetics for people with disabilities after civil wars, including those in Syria, Jordan, Yemen, and Iraq. 3D Printing is a novel innovation to the healthcare industry. The controversial that holds with between innovation technology and privacy of consumers has impeded the penetration of 3D Printing in healthcare. Based on the findings from Interview 4, the 3D-printed prosthetic project uses a 3D scanner, where the 3D-printed prostheses are printed with higher precision that match the patient's bone structure. 3D-printed prostheses are also customisable to allow users to easily upgrade or replace the prosthetics with age and bone development. Hence, the 3D-printed prostheses provide the patient with greater comfort.

In the healthcare industry, 3D Printing can be classified into bio-printing and non-bio-printing. Bio-printing includes cell and organ printing and programmable-release drug-delivery capsules; non-bio-printing includes orthopaedic implants, dental implants and prosthetics. Drawing insight from Interview 3, although some local Chinese healthcare enterprises began to enter the 3D Printing field during a large investment in 2008–2012, the scale of the industry has yet to develop, and key material in 3D Printing such as metal powder that were required for bio-printing are imported from overseas. '*We acknowledged that bioprinted materials have implication to repair damaged organ, cells and tissue of human body. Also, the local government shows enthusiasm in pushing 3D bio-printing forward, but the certification for bio-printing is very strict. At the current stage, only four companies in China are CFDA-certified in non-bio-printing, and none is approved for bio-printing. This is why the development of 3D Printing in healthcare is very laid-back. We hope legislation in healthcare especially bioprinting could evolve with the pace of innovation*.'

Finally, the primary societal impact of 3D Printing is the change in labour structure from labour-intensive to a knowledge-based economy. 3D Printing is a technology driven by data and information; as expressed by Harari (2018), '*the merger of infotech and biotech might soon push billions of humans out of job market and undermine both liberty and equality … all power concentrated in the hand of tiny elite, and most people suffer something far worse—irrelevance*'. Conflict with technology drives humans from the job market, as Interviewee 15 pointed out. '*Each job lost is equal to one job created; I think we should hold an optimistic attitude towards this phenomenon because job loss would have happened with the introduction of computers, but it proves that the economy and welfare of the people is becoming better after the invention of computers*.'

Above evidences signify that despite the potential of 3D Printing, environmental sustainability is not always the priority to be tackled. In this sense, there is a need to first enhance the penetration of 3D Printing to some industries, and then environmental sustainability will come along.

4.4. Discussion of findings

4.4.1 Understanding the challenges of 3D Printing and sustainability in China

Although the 3D Printing technology has notable attention implications on sustainability, our investigation *via* semi-structured interviews demonstrated that though practitioners have foreseen the potential of 3D Printing in achieving sustainability, but it is limit to industry that adopt 3D Printing as a complementary tool to current production. The 3D Printing industry itself that sell 3D printed product does not seem to unlock economic benefit, hence, environment and societal implication are not found.

The 3D Printing industry as a whole in China is moving from low-value-added production to high-value-added production. For instance, R&D of 3D Printing technology is mainly concentrated on equipment, whereas materials and software constituting the core of 3D Printing technology, which are complementary to the printing machines are left behind, and rely on import from the United States and Germany. Based on the result of our interviews, we summarize some challenges of 3D Printing in China below for manager and policy maker, this finding may be an important guide in the decision-making of managers and policy-makers.

4.4.2. Low industrialization of 3D Printing

China's manufacturing sectors have relied heavily on low cost inputs (Lin et al. 2014) during the globalization era, which has led to low technical capacity of the industry to

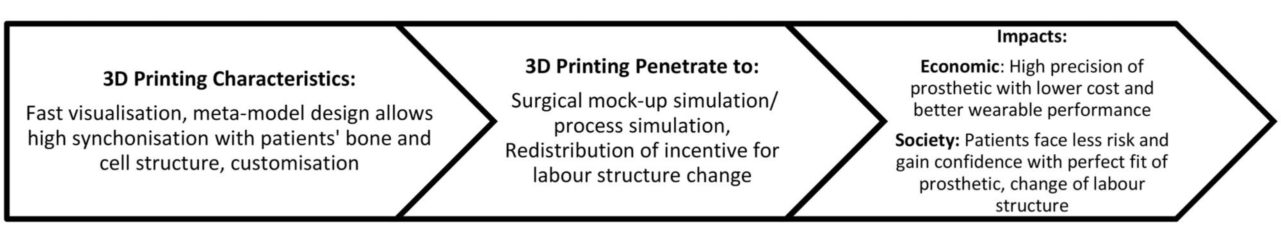

Figure 4. Roadmap of circular 3D Printing for economic and society dimensions.

adopt new technology. The government and authorized association could work as an accelerator to encourage the collaboration of triple helix, where more spin-off projects from universities and research institutions to industry are highly encouraged. Moreover, as R&D on 3D Printing technology is mainly concentrated on equipment manufacturing, a more comprehensive research strategy and guidelines on research of new materials and design software are required.

4.4.3. Low industrial supervision

The establishment of new technology is often entangled with new synergies on the societal scale, such as the ownership of intellectual property, and new rules and regulations, standards, and supervisory bodies. The establishment of the above-mentioned regulations increases the barrier of entry and constantly conducts qualification criteria to the existing market players to ensure the welfare of each stakeholder in the creative industry. For example, the association, experts and government should set up clear guidance on the intellectual property issue in 3D Printing. Chan et al. (2018) proposed that challenges of intellectual property infringement will slow down the penetration of 3D Printing technology, and legislation always lags behind innovation; hence, the guidelines should be made flexible enough to guarantee innovation growth and tight enough to punish the law-bypassing individuals and enterprises.

4.4.4. Education and training systems to develop talent

Rosenberg (1972) argued that the skill level of workers is an important determinant of the penetration of technology into industry, because the succession of a new implementation of technology demands complex new skills. Zahoor et al. (2022) revealed the importance of talents in managing digital technologies especially in developing countries. Lack of talents, or talents was slow to learn new skills alongside with the development of technology will impede technology penetration. This help to explain the low penetration of 3D Printing to some industries in China. The curriculum in high school and universities did not provide the 3D Printing industry with sufficient training courses related to engineering, materials, information technology, and other disciplines for 3D Printing. Meanwhile, 3D Printing-related skill upgrade courses for employees are not common in China. Most companies find it difficult to find the relevant courses and available talent to train their employees; although the skill upgrade courses are available in top-tier cities in China, it would be costly for firms from second- or third-tier cities to employ relevant trainers.

5. Contributions, limitations and future research directions

Under Industry 4.0 and Made in China 2015, the introductory of cost competitive cleaner technology such as 3D Printing has opened unprecedented opportunity for sustainability. However, research suggested a missing link between 3D Printing and sustainability (Gebler, Uiterkamp, and Visser 2015) and proposed circular economy as effective mechanism (Agrawal, Atasu, and Van Wassenhove 2019). Through the investigation of sixteen 3D Printing related companies in China, this study has unpacked the processes by which 3D Printing companies create and sustain sustainability with circular economy principle, especially in high end industry. For instance, companies from spare part industry unlock all dimensions of sustainability by realizing all 4Rs circular economy principle. This research findings corroborate with Roscoe and Blome (2019) that suggest that 3D Printing technologies can be complementary to existing production system with low volume, high margin personalized products. The sample interview companies that did not realize full circular economy principle such as healthcare industry and consumer spectacle industry achieved economic and societal benefits. On the other hand, companies that focused solely on 3D Printing related services has yet to develop environment and societal sustainability, as survival in the market remains the priority at current stage of business. Specifically, firms are facing 'liability of newness' after opting for strategic investment in new technology. Indeed, we show that circular economy with key four principles we describe is critical for 3D printing industry to achieve sustainability.

5.1. Theoretical contributions

Our research provides important theoretical implications. Our article draws on multidisciplinary literature and intends to make several contributions to researchers and practitioners by examining the complex links among circular economy, 3D Printing, sustainability. To the best of our knowledge, our research is one of the first empirical research that connect 3D Printing, circular economy and sustainability under the industry 4.0 umbrella. The contribution to the literatures is manifold. First, we summarized and proposed 3D Printing offering at product and process level base on circular economy principle based on current literatures. Second, this study confirmed the effective role of circular economy played in the link of 3D Printing and sustainability. Our empirical findings suggest the 3D Printing and circular economy principle fit provides the double marginalization effect that unlocks all dimensions of sustainability. Third, this study embraces all three dimensions of sustainability (economic, environmental and social) by studying the potential offering of 3D Printing and threats of new technology. To be specifically, the double edge sword of 3D Printing might replace the production labour because of straightforward supply chain that established between 3D Printing manufacturer and consumers. Also, the layoff of designers because 3D Printing offers product remixing base on existing designs or open design platform.

5.2. Managerial contributions

Important lessons for practice can be derived from this study. This empirical research suggests that managers can utilized the proposed 3D Printing offering at product and process level base on circular economy principle in their business model. For example, green material selection in the product design process enabling chemical separation are beneficial to recycling process and waste reduction (Liu et al. 2018). Next, our study addressed the opportunities and challenges of new technology adoption. As firms face resource constraints, managers can establish cost and benefit analysis by leveraging opportunity and challenges as discussed above alongside with new technology implementation within companies. Also, managers should understand their specific organizational context first before introduce 3D Printing into operation, as the research indicates that 3D Printing is a good complementary technology candidate for industry with low volume high margin personalized products. Lastly, the policy makers could establish technology roadmap to reveal the complexity of challenges for the 3D Printing industry.

5.3. Limitation and future research

Similar with other empirical study, we acknowledge our study subjects to several limitations. First, we explore the research questions with the data collected from the Chinese manufacturing firms. For greater generalizability, future research can consider sample firms from other industries, regions and countries. Next, future studies could extend this line of research to consider other new technologies as advocated in the Industry 4.0 to explore the potential benefits and threats contribute to sustainability literature. Also, due to the nature of research setting, we adopted case study to examine the research question other methodologies such as large scale survey can be adapted to generalize the result. Lastly, though 3D Printing has received great attention in the past decades for potential contribute to form sustainability, but the implementation of 3D Printing is still remain low. It is worth to investigate the implication of 3D Printing is matter in all industries or they specific in some industry. Overall, the fact that we are able to unpack the processes by which 3D Printing companies create and sustain sustainability alongside circular economy principle is the strength of this study through case studies method. We hope future research can build on abovementioned limitations to further develop studies within industry 4.0 technology, circular economy and sustainability.

In conclusion, after the investigation of different manufacturing industry who has adopted 3D Printing to complement manufacturing process, 3D Printing is undeniably perceived as a tool to transform or replace current traditional manufacturing, without full adoption of CE principle, firm realizes only economic benefit of 3D Printing; Vice versa, our investigation shows that firms will continue to achieve environmental and societal sustainability after they reap economic benefit when adopting full circular economy principle. This is evidence in the marine and automobile industry.

Acknowledgments

The authors would like to thank the editor and anonymous reviewers for the valuable and constructive comments, which have led to a significant improvement in the manuscript.

Research ethics approval

Research ethics of this work have been approved by the research ethics committee of the University of Nottingham Ningbo China.

Disclosure statement

The authors report there are no competing interests to declare.

Funding

This work was supported by the Major Project of the Ningbo-Chinese Academy of Social Science Strategic Collaborations Research Fund under Grant [NZKT201701]; Ningbo Research Base on Dual Circulation and Economic Development under Grant [JD5-FZ40]; and the Arts and Humanities Research Council under the Grant [AH/V015761/1].

Notes on contributors

Jia Jia Lim, PhD, is Assistant Professor at International Business School, Zhejiang University. Her research interests include digital transformation, buyer-supplier relationships, sustainability. Her research appears in International Journal of Operation and Production Management, International Journal of Production Economics, Journal of Business Research.

Jing Dai, PhD, is a Professor in Operations Management at Nottingham University Business School China. She is the recipient of Graduate Research Excellence Award at Iowa State University, USA where she earned a PhD in Supply Chain Management. Her research interest is in the fields of sustainable operations, green supply chain management and supply chain digitalisation. Prof. Dai has published extensively in leading international operations, logistics and supply chain management journals. She also received Best Paper Award in the Journal of Operations Management.

Carman K. M. Lee, PhD, is an Associate Professor at The Hong Kong Polytechnic University, where she obtained her PhD degree. She was awarded the Bronze Award of the 16th China National Invention Exhibition Award in 2006 and Outstanding Professional Service and Innovation Award. Dr Lee's current research areas include logistics information management, smart manufacturing, application of the internet of things and data mining techniques.

Hing Kai Chan, PhD, is a Professor of Operations Management at Nottingham University Business School China. He obtained his PhD degree from The University of Hong Kong. His research interest is in the fields of sustainable operations and supply chain, modelling and simulation and technology adoption. Prof Chan has published over 160 international papers in leading operations and supply chain management journals, such as Production and Operations Management.

References

Agrawal, V. V., A. Atasu, and L. N. Van Wassenhove. 2019. "New Opportunities for Operations Management Research in Sustainability." *Manufacturing & Service Operations Management* 21 (1): 1–12. https://doi.org/10.1287/msom.2017.0699

Atzeni, E., and A. Salmi. 2012. "Economics of Additive Manufacturing for End-Usable Metal Parts." *The International Journal of Advanced Manufacturing Technology* 62 (9–12): 1147–1155. https://doi.org/10.1007/s00170-011-3878-1

Bag, S., S. Gupta, and S. Kumar. 2021. "Industry 4.0 Adoption and 10R Advance Manufacturing Capabilities for Sustainable Development." *International Journal of Production Economics* 231: 107844. https://doi.org/10.1016/j.ijpe.2020.107844

Bai, C., P. Dallasega, G. Orzes, and J. Sarkis. 2020. "Industry 4.0 Technologies Assessment: A Sustainability Perspective." *International Journal of Production Economics* 229: 107776. https://doi.org/10.1016/j.ijpe.2020.107776

Bansal, P. 2005. "Evolving Sustainably: A Longitudinal Study of Corporate Sustainable Development." *Strategic Management Journal* 26 (3): 197–218. https://doi.org/10.1002/smj.441

Baumers, M., and M. Holweg. 2019. "On the Economics of Additive Manufacturing: Experimental Findings." *Journal of Operations Management* 65 (8): 794–809. https://doi.org/10.1002/joom.1053

Beltagui, A., N. Kunz, and S. Gold. 2020. "The Role of 3D Printing and Open Design on Adoption of Socially Sustainable Supply Chain Innovation." *International Journal of Production Economics* 221: 107462. https://doi.org/10.1016/j.ijpe.2019.07.035

Benbasat, I., D. K. Goldstein, and M. Mead. 1987. "The Case Research Strategy in Studies of Information-Systems." *MIS Quarterly* 11 (3): 369–386. https://doi.org/10.2307/248684

Bernon, M., B. Tjahjono, and E. F. Ripanti. 2018. "Aligning Retail Reverse Logistics Practice with Circular Economy Values: An Exploratory Framework." *Production Planning & Control* 29 (6): 483–497. https://doi.org/10.1080/09537287.2018.1449266

Birtchnell, T., and J. Urry. 2016. *A New Industrial Future: 3D Printing and the Reconfiguring of Production, Distribution, and Consumption.* Abingdon: Routledge.

Bourell, D., J. P. Kruth, M. Leu, G. Levy, D. Rosen, A. M. Beese, and A. Clare. 2017. "Materials for Additive Manufacturing." *CIRP Annals* 66 (2): 659–681. https://doi.org/10.1016/j.cirp.2017.05.009

Bruntland, G. 1987. *Our Common Future*, 45–65. UN: The World Commission on Environment and Development.

Cerdas, F., M. Juraschek, S. Thiede, and C. Herrmann. 2017. "Life Cycle Assessment of 3D Printed Products in a Distributed Manufacturing System." *Journal of Industrial Ecology* 21 (S1): S80–S93. https://doi.org/10.1111/jiec.12618

Chan, H. K., J. Griffin, J. J. Lim, F. Li Zeng, and A. S. F. Chiu. 2018. "The Impact of 3D Printing Technology on the Supply Chain: Manufacturing and Legal Perspectives." *International Journal of Production Economics* 205: 156–162. https://doi.org/10.1016/j.ijpe.2018.09.009

Chekurov, S., S. Metsä-Kortelainen, M. Salmi, I. Roda, and A. Jussila. 2018. "The Perceived Value of Additively Manufactured Digital Spare Parts in Industry: An Empirical Investigation." *International Journal of Production Economics* 205: 87–97. https://doi.org/10.1016/j.ijpe.2018.09.008

Corsini, L., C. B. Aranda-Jan, and J. Moultrie. 2020. "The Impact of 3D Printing on the Humanitarian Supply Chain." *Production Planning & Control* 33 (6–7): 692–704. https://doi.org/10.1080/09537287.2020.1834130

Delic, M., D. R. Eyers, and J. Mikulic. 2019. "Additive Manufacturing: empirical Evidence for Supply Chain Integration and Performance from the Automotive Industry." *Supply Chain Management: An International Journal* 24 (5): 604–621. https://doi.org/10.1108/SCM-12-2017-0406

den Hollander, M. C., C. A. Bakker, and E. J. Hultink. 2017. "Product Design in a Circular Economy Development of a Typology of Key Concepts and Terms." *Journal of Industrial Ecology* 21 (3): 517–525. https://doi.org/10.1111/jiec.12610

Despeisse, M., M. Baumers, P. Brown, F. Charnley, S. J. Ford, A. Garmulewicz, S. Knowles, et al. 2017. "Unlocking Value for a Circular Economy through 3D Printing: A Research Agenda." *Technological Forecasting and Social Change* 115: 75–84. https://doi.org/10.1016/j.techfore.2016.09.021

Duarte, S., and V. Cruz-Machado. 2019. "Green and Lean Supply-Chain Transformation: A Roadmap." *Production Planning & Control* 30 (14): 1170–1183. https://doi.org/10.1080/09537287.2019.1595207

Eisenhardt, K. M. 1989. "Building Theories from Case-Study Research." *The Academy of Management Review* 14 (4): 532–550. https://doi.org/10.2307/258557

Elkington, J. 1997. "The Triple Bottom Line." *Environmental Management: Readings and Cases* 2: 49–66.

EPA. 2022. "Sources of Greenhouse Gas Emissions." Environmental Protection Agency. Accessed February 21. https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions.

Faludi, J., C. M. Van Sice, Y. Shi, J. Bower, and O. M. K. Brooks. 2019. "Novel Materials Can Radically Improve Whole-System Environmental Impacts of Additive Manufacturing." *Journal of Cleaner Production* 212: 1580–1590. https://doi.org/10.1016/j.jclepro.2018.12.017

Faludi, J., Z. Hu, S. Alrashed, C. Braunholz, S. Kaul, and L. Kassaye. 2015. "Does Material Choice Drive Sustainability of 3D Printing?" *International Journal of Mechanical, Aerospace, IndustTial and Mechatronics Engineering* 9 (2): 216–223. http://waset.org/Publication/10000327

Fatorachian, H., and H. Kazemi. 2020. "Impact of Industry 4.0 on Supply Chain Performance." *Production Planning & Control* 32 (1): 63–81. https://doi.org/10.1080/09537287.2020.1712487

Ford, S., and M. Despeisse. 2016. "Additive Manufacturing and Sustainability: An Exploratory Study of the Advantages and Challenges." *Journal of Cleaner Production* 137: 1573–1587. https://doi.org/10.1016/j.jclepro.2016.04.150

Friesike, S., C. M. Flath, M. Wirth, and F. Thiesse. 2019. "Creativity and Productivity in Product Design for Additive Manufacturing: Mechanisms and Platform Outcomes of Remixing." *Journal of Operations Management* 65 (8): 735–752. https://doi.org/10.1016/j.jom.2018.10.004

Gao, D., Z. D. Xu, Y. L. Z. Ruan, and H. Y. Lu. 2017. "From a Systematic Literature Review to Integrated, Definition for Sustainable Supply Chain Innovation (SSCI.")*Journal of Cleaner Production* 142: 1518–1538. https://doi.org/10.1016/j.jclepro.2016.11.153

Gebler, M., A. J. M. S. Uiterkamp, and C. Visser. 2015. "A Global Sustainability Perspective on 3D Printing Technologies (Vol 74, pg 158, 2014)." *Energy Policy* 85: 511. https://doi.org/10.1016/j.enpol.2015.03.007

Geng, Y., and B. Doberstein. 2008. "Developing the Circular Economy in China: Challenges and Opportunities for Achieving 'Leapfrog Development." *International Journal of Sustainable Development & World Ecology* 15 (3): 231–239. https://doi.org/10.3843/SusDev.15.3:6

Ghobadian, A., I. Talavera, A. Bhattacharya, V. Kumar, J. A. Garza-Reyes, and N. O'Regan. 2020. "Examining Legitimatisation of Additive Manufacturing in the Interplay between Innovation, Lean Manufacturing and Sustainability." *International Journal of Production Economics* 219: 457–468. https://doi.org/10.1016/j.ijpe.2018.06.001

Greenhalgh, S. 2016. "The Effects of 3D Printing in Design Thinking and Design Education." *Journal of Engineering, Design and Technology* 14 (4): 752–769. https://doi.org/10.1108/JEDT-02-2014-0005

Gualandris, J., R. D. Klassen, S. Vachon, and M. Kalchschmidt. 2015. "Sustainable Evaluation and Verification in Supply Chains: Aligning and Leveraging Accountability to Stakeholders." *Journal of Operations Management* 38 (1): 1–13. https://doi.org/10.1016/j.jom.2015.06.002

Guo, S., T. M. Choi, and S. H. Chung. 2021. "Self-Design Fun: Should 3D Printing Be Employed in Mass Customization Operations?" *European Journal of Operational Research* 299 (3): 883–897. https://doi.org/10.1016/j.ejor.2021.07.009

Halassi, S., J. Semeijn, and N. Kiratli. 2019. "From Consumer to Prosumer: A Supply Chain Revolution in 3D Printing." *International Journal of Physical Distribution & Logistics Management* 49 (2): 200–216. https://doi.org/10.1108/IJPDLM-03-2018-0139

Hannibal, M., and G. Knight. 2018. "Additive Manufacturing and the Global Factory: Disruptive Technologies and the Location of International Business." *International Business Review* 27 (6): 1116–1127. https://doi.org/10.1016/j.ibusrev.2018.04.003

Harari, Y. N. 2018. *21 Lessons for 21st Century*. London: Penguin Random House UK.

Hedenstierna, C. P. T., S. M. Disney, D. R. Eyers, J. Holmström, A. A. Syntetos, and X. Wang. 2019. "Economies of Collaboration in Build-to-Model Operations." *Journal of Operations Management* 65 (8): 753–773. https://doi.org/10.1002/joom.1014

Hohn, M. M., and C. F. Durach. 2021. "Additive Manufacturing in the Apparel Supply Chain - Impact on Supply Chain Governance and Social Sustainability." *International Journal of Operations & Production Management* 41 (7): 1035–1059. https://doi.org/10.1108/IJOPM-09-2020-0654

Huang, Y., D. R. Eyers, M. Stevenson, and M. Thürer. 2021. "Breaking the Mould: achieving High-Volume Production Output with Additive Manufacturing." *International Journal of Operations & Production Management* 41 (12): 1844–1851. https://doi.org/10.1108/IJOPM-05-2021-0350

Janssen, R., I. Blankers, E. Moolenburgh, and B. Posthumus. 2014. "TNO: The Impact of 3-D Printing on Supply Chain Management." *The Hague, Netherlands: TNO* 28 (24). https://repository.tudelft.nl/islandora/object/uuid:cc288b1a-837c-4f24-8504-a45bb9636b70/datastream/URL/download

Jayakrishna, K., P. Sanjay Guar, R. Senthilkumar, and N. Aathis. 2017. "Sustainability Analysis of Prototyping Processes." *Applied Mechanics and Materials* 867: 290–293. https://doi.org/10.4028/www.scientific.net/AMM.867.290

Joshi, S. C., and A. A. Sheikh. 2015. "3D Printing in Aerospace and Its Long-Term Sustainability." *Virtual and Physical Prototyping* 10 (4): 175–185. https://doi.org/10.1080/17452759.2015.1111519

Kamble, S. S., and A. Gunasekaran. 2021. "Analysing the Role of Industry 4.0 Technologies and Circular Economy Practices in Improving Sustainable Performance in Indian Manufacturing Organisations." *Production Planning & Control* 34 (10): 887–901. https://doi.org/10.1080/09537287.2021.1980904

Kapletia, D., W. Phillips, N. Medcalf, H. Makatsoris, C. McMahon, and N. Rich. 2019. "Redistributed Manufacturing - Challenges for Operations Management." *Production Planning & Control* 30 (7): 493–495. https://doi.org/10.1080/09537287.2018.1540057

Kazancoglu, Y., Y. D. Ozkan-Ozen, M. Sagnak, I. Kazancoglu, and M. Dora. 2021. "Framework for a Sustainable Supply Chain to Overcome Risks in Transition to a Circular Economy through Industry 4.0." *Production Planning & Control* 34 (10): 902–917. https://doi.org/10.1080/09537287.2021.1980910

Kerin, M., and D. T. Pham. 2019. "A Review of Emerging Industry 4.0 Technologies in Remanufacturing." *Journal of Cleaner Production* 237: 117805. https://doi.org/10.1016/j.jclepro.2019.117805

Kreiger, M. A., M. L. Mulder, A. G. Glover, and J. M. Pearce. 2014. "Life Cycle Analysis of Distributed Recycling of Post-Consumer High Density Polyethylene for 3-D Printing Filament." *Journal of Cleaner Production* 70: 90–96. https://doi.org/10.1016/j.jclepro.2014.02.009

Kunovjanek, M., N. Knofius, and G. Reiner. 2020. "Additive Manufacturing and Supply Chains – a Systematic Review." *Production Planning & Control* 33 (13): 1231–1251. https://doi.org/10.1080/09537287.2020.1857874

Lam, H. K. S., Li Ding, T. C. E. Cheng, and H. Zhou. 2019. "The Impact of 3D Printing Implementation on Stock Returns a Contingent Dynamic Capabilities Perspective." *International Journal of Operations & Production Management* 39 (6–8): 935–961. https://doi.org/10.1108/IJOPM-01-2019-0075

Lin, J. T., D. Pan, S. J. Davis, Q. Zhang, K. B. He, C. Wang, D. G. Streets, D. J. Wuebbles, and D. B. Guan. 2014. "China's International Trade and Air Pollution in the United States." *Proceedings of the National Academy of Sciences of the United States of America* 111 (5): 1736–1741. https://doi.org/10.1073/pnas.1312860111

Liu, Y., Q. Zhu, and S. Seuring. 2020. "New Technologies in Operations and Supply Chains: Implications for Sustainability." *International Journal of Production Economics* 229: 107889. https://doi.org/10.1016/j.ijpe.2020.107889

Liu, Y., C. Blome, J. Sanderson, and A. Paulraj. 2018. "Supply Chain Integration Capabilities, Green Design Strategy and Performance: A Comparative Study in the Auto Industry." *Supply." Supply Chain Management: An International Journal* 23 (5): 431–443. https://doi.org/10.1108/SCM-03-2018-0095

MacArthur, E. 2013. "Towards the Circular Economy." *Journal of Industrial Ecology* 2 (1): 23–44.

Rehnberg, M., and S. Ponte. 2018. "From Smiling to Smirking? 3D Printing, Upgrading and the Restructuring of Global Value Chains." *Global Networks* 18 (1): 57–80. https://doi.org/10.1111/glob.12166

McDonough, W., M. Braungart, P. T. Anastas, and J. B. Zimmerman. 2003. "Applying the Principles of Green Engineering to Cradle-to-Cradle Design." *Environmental Science & Technology* 37 (23): 434A–441A. https://doi.org/10.1021/es0326322

Meredith, J. 1998. "Building Operations Management Theory through Case and Field Research." *Journal of Operations Management* 16 (4): 441–454. https://doi.org/10.1016/S0272-6963(98)00023-0

Nascimento, D. L. M., V. Alencastro, O. L. G. Quelhas, R. G. G. Caiado, J. A. Garza-Reyes, L. R. Lona, and G. Tortorella. 2019. "Exploring Industry 4.0 Technologies to Enable Circular Economy Practices in a Manufacturing Context a Business Model Proposal." *Journal of Manufacturing Technology Management* 30 (3): 607–627. https://doi.org/10.1108/JMTM-03-2018-0071

Peng, T., K. Kellens, R. Z. Tang, C. Chen, and G. Chen. 2018. "Sustainability of Additive Manufacturing: An Overview on Its Energy Demand and Environmental Impact." *Additive Manufacturing* 21: 694–704. https://doi.org/10.1016/j.addma.2018.04.022

Petrovic, V., J. Vicente Haro Gonzalez, O. Jordá Ferrando, J. Delgado Gordillo, J. Ramón Blasco Puchades, and L. Portolés Griñan. 2011. "Additive Layered Manufacturing: sectors of Industrial Application Shown through Case Studies." *International Journal of Production Research* 49 (4): 1061–1079. https://doi.org/10.1080/00207540903479786

Ripanti, E. F., and B. Tjahjono. 2019. "Unveiling the Potentials of Circular Economy Values in Logistics and Supply Chain Management." *The International Journal of Logistics Management* 30 (3): 723–742. https://doi.org/10.1108/IJLM-04-2018-0109

Roscoe, S., and C. Blome. 2019. "Understanding the Emergence of Redistributed Manufacturing: An Ambidexterity Perspective." *Production Planning & Control* 30 (7): 496–509. https://doi.org/10.1080/09537287.2018.1540051

Rosenberg, N. 1972. "Factors Affecting the Diffusion of Technology." *Explorations in Economic History* 10 (1): 3–33. https://doi.org/10.1016/0014-4983(72)90001-0

Rowley, J. 2002. "Using Case Studies in Research." *Management Research News* 25 (1): 16–27. https://doi.org/10.1108/01409170210782990

Sakao, T., and S. A. Brambila-Macias. 2018. "Do we Share an Understanding of Transdisciplinarity in Environmental Sustainability Research?" *Journal of Cleaner Production* 170: 1399–1403. https://doi.org/10.1016/j.jclepro.2017.09.226

Sanchez, F. A. C., H. Boudaoud, M. Camargo, and J. M. Pearce. 2020. "Plastic Recycling in Additive Manufacturing: A Systematic Literature Review and Opportunities for the Circular Economy." *Journal of Cleaner Production* 264: 121602. https://doi.org/10.1016/j.jclepro.2020.121602

Schniederjans, D. G. 2017. "Adoption of 3D-Printing Technologies in Manufacturing: A Survey Analysis." *International Journal of Production Economics* 183: 287–298. https://doi.org/10.1016/j.ijpe.2016.11.008

Sfetsas, T., S. Patsatzis, and A. Chioti. 2021. "A Review of 3D Printing Techniques for Bio-Carrier Fabrication." *Journal of Cleaner Production* 318: 128469. https://doi.org/10.1016/j.jclepro.2021.128469

Shukla, M., I. Todorov, and D. Kapletia. 2018. "Application of Additive Manufacturing for Mass Customisation: understanding the Interaction of Critical Barriers." *Production Planning & Control* 29 (10): 814–825. https://doi.org/10.1080/09537287.2018.1474395

Sodhi, M. S., and C. S. Tang. 2021. "Extending AAA Capabilities to Meet PPP Goals in Supply Chains." *Production and Operations Management* 30 (3): 625–632. https://doi.org/10.1111/poms.13304

Su, B., A. Heshmati, Y. Geng, and X. M. Yu. 2013. "A Review of the Circular Economy in China: moving from Rhetoric to Implementation." *Journal of Cleaner Production* 42: 215–227. https://doi.org/10.1016/j.jclepro.2012.11.020

Tang, C. S. 2018. "Socially Responsible Supply Chains in Emerging Markets: Some Research Opportunities." *Journal of Operations Management* 57 (1): 1–10. https://doi.org/10.1016/j.jom.2018.01.002

Thomas-Seale, L. E. J., J. C. Kirkman-Brown, M. M. Attallah, D. M. Espino, and D. E. T. Shepherd. 2018. "The Barriers to the Progression of Additive Manufacture: Perspectives from UK Industry." *International Journal of Production Economics* 198: 104–118. https://doi.org/10.1016/j.ijpe.2018.02.003

Tian, X., T. Liu, Q. Wang, A. Dilmurat, D. Li, and G. Ziegmann. 2017. "Recycling and Remanufacturing of 3D Printed Continuous Carbon Fiber Reinforced PLA Composites." *Journal of Cleaner Production* 142: 1609–1618. https://doi.org/10.1016/j.jclepro.2016.11.139

United Nations. 2022. "Transforming Our World: The 2030 Agenda for Sustainable Development A/RES/70/1." Accessed February 21. https://sustainabledevelopment.un.org/content/documents/21252030%20Agenda%20for%20Sustainable%20Development%20web.pdf.

Valenzuela, F., and S. Böhm. 2017. "Against Wasted Politics: A Critique of the Circular Economy." *Ephemera: Theory & Politics in Organization* 17 (1): 23–60.

van Buren, N., M. Demmers, R. van der Heijden, and F. Witlox. 2016. "Towards a Circular Economy: The Role of Dutch Logistics Industries and Governments." *Sustainability* 8 (7): 647. https://doi.org/10.3390/su8070647

Vazquez-Martinez, G. A., J. L. Gonzalez-Compean, V. J. Sosa-Sosa, M. Morales-Sandoval, and J. C. Perez. 2018. "CloudChain: A Novel Distribution Model for Digital Products Based on Supply Chain Principles." *International Journal of Information Management* 39: 90–103. https://doi.org/10.1016/j.ijinfomgt.2017.12.006

Voss, C., N. Tsikriktsis, and M. Frohlich. 2002. "Case Research in Operations Management." *International Journal of Operations & Production Management* 22 (2): 195–219. https://doi.org/10.1108/01443570210414329

Xiong, Y., H. Lu, G. D. Li, S. M. Xia, Z. X. Wang, and Y. F. Xu. 2022. "Game Changer or Threat: The Impact of 3D Printing on the Logistics Supplier Circular Supply Chain." *Industrial Marketing Management* 106: 461–475. https://doi.org/10.1016/j.indmarman.2022.03.002

Yin, R. K. 1989. "Research Design Issues in Using the Case-Study Method to Study Management-Information-Systems." *Information Systems Research Challenge: Qualitative Research Methods* 1: 1–6.

Yin, R. K. 2003. "Designing Case Studies." *Qualitative Research Methods* 5 (14): 359–386.

Yoo, B., H. Ko, and S. Chun. 2016. "Prosumption Perspectives on Additive Manufacturing: reconfiguration of Consumer Products with 3D Printing." *Rapid Prototyping Journal* 22 (4): 691–705. https://doi.org/10.1108/RPJ-01-2015-0004

Zahoor, N., M. Christofi, A. C. Nwoba, F. Donbesuur, and D. Miri. 2022. "Operational Effectiveness in Post-Pandemic Times: Examining the Roles of Digital Technologies, Talent Management and Employee Engagement in Manufacturing SMEs." *Production Planning & Control* 1–14. Advance online publication. https://doi.org/10.1080/09537287.2022.2147863

Zangiacomi, A., E. Pessot, R. Fornasiero, M. Bertetti, and M. Sacco. 2020. "Moving towards Digitalization: A Multiple Case Study in Manufacturing." *Production Planning & Control* 31 (2–3): 143–157. https://doi.org/10.1080/09537287.2019.1631468

Zhang, A., V. G. Venkatesh, J. X. Wang, V. Mani, M. Wan, and T. Qu. 2021. "Drivers of Industry 4.0-Enabled Smart Waste Management in Supply Chain Operations: A Circular Economy Perspective in China." *Production Planning & Control* 34 (10): 870–886. https://doi.org/10.1080/09537287.2021.1980909