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The challenges and opportunities of 3D printing implementation and sustainability performance: the double-edged sword of environmental uncertainty

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ABSTRACT

3D Printing (3DP) is a popular advanced technology that may revolutionise manufacturing practices, yet few studies have explored its impact on the Triple Bottom Line (TBL). In particular, many studies have failed to recognise that 3DP implementation does not happen in a vacuum; the environmental uncertainty in which it is applied matters greatly. This research employs Resource-Based Contingency theory to reveal how 3DP implementation levels influence sustainability performance, while considering the role of environmental uncertainty. Survey results from 266 responses indicate 3DP implementation in production positively contributes to TBL performance, encouraging managers on 3DP adoption; Environmental uncertainty acts as a double-edged sword: internal manufacturing uncertainty weakens the positive effects, but external supply uncertainty strengthens them. This highlights the importance of aligning 3DP implementation with firm's internal and external uncertainty. The findings suggest that 3DP helps firms mitigate external supply disruptions, presenting environmental uncertainty as both a challenge and an opportunity.

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3D printing; sustainability performance; environmental uncertainty; triple bottom line

1. Introduction

The manufacturing industry is constantly evolving, as advanced manufacturing technologies are developed that enable the production process to be not only more cost- and resource-efficient, but also more sustainable and resilient (Beltagui, Kunz, and Gold 2020b; Eyers et al. 2022; Ford and Despeisse 2016). This is in-line with the overarching goal of Industry 4.0 and the requirements of a post-COVID future (Asokan et al. 2022). One popular set of advanced manufacturing technologies is Additive Manufacturing (commonly known as 3D printing) which is 'a process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies' (ISO 2021). The process of 3DP enables the construction of three-dimensional objects through continuous or incremental layers, with the rapid nature of the process allowing for printing on demand (Ngo et al. 2018; Petrovic et al. 2011). The original 3DP processes were developed in the 1980s; since 2000 there has been much industrial adoption in both prototyping and manufacturing activities (Bade, Lasch, and Schneider 2025; Ernst & Young 2019; Eyers et al. 2022; Moradlou, Roscoe, and Ghadge 2022). Some industry reports have forecasted the market revenue will reach over $50 billion by 2030 (Molitch-Hou 2022); if the current growth of investment in 3DP continues, 50% of manufactured goods will be 3D printed in 2060, with this figure potentially achievable as early as 2040 in a scenario in which investment doubles every five years (ING 2017). The implementation of 3DP allows companies to have more control over production processes while simplifying production complexity and procedures, therefore causing significant changes in operations and performances (Kang, Li, and Bancroft 2020; Tziantopoulos et al. 2019; Weller, Kleer, and Piller 2015).

Whilst there is much enthusiasm for 3DP in the literature, it remains unclear whether 3DP can allow for more sustainable use of resources, and under which contingency this new technology is beneficial from a sustainability perspective (the Triple Bottom Line) (Despeisse et al. 2017; Ford and Despeisse 2016; Lim et al. 2024). Given the importance of sustainability for research, policy, and practice, such an omission is particularly significant when considering the future for 3DP. The majority of research focuses on topics such as the expansion of the 3DP techniques and available types of input materials (Beltagui, Rosli, and Candi 2020a; Chandima Ratnayake 2019; Zhai et al. 2025), comparisons and switch-over between 3DP and conventional manufacturing (Akmal et al. 2022; Attaran 2017; Peron et al. 2024), costs of 3DP adoption for manufacturing (Baumers et al. 2017; Heinen and Hoberg 2019; Ding et al. 2021), the role of 3DP in enhancing mass-customisation (Eyers et al. 2022; Shukla, Todorov, and

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Kapletia 2018), manufacturing flexibility (Delic and Eyers 2020; Eyers et al. 2018), and innovation (Candi and Beltagui 2019), influence on supply network configuration (Friedrich, Lange, and Elbert 2022; Kolter et al. 2025; Tziantopoulos et al. 2019), and process selection when adopting 3DP (Dohale et al. 2024; Eyers et al. 2022; Kabelitz-Bock et al., 2025). Here, the majority are based on interview or modelling methods (Chaudhuri et al. 2021; Corsini, Aranda-Jan, and Moultrie 2022; Huang et al. 2013; Kabelitz-Bock, Hoberg, and Meuer 2025). By comparison, research on the impact of 3DP technology implementation from an Operations Management (OM) perspective based on quantitative empirical data is still in its infancy. Even though Lam et al. (2019) have highlighted the positive correlation between the adoption of 3DP and stock returns by using a secondary dataset, and Delic and Eyers (2020) revealed that AM adoption positively relates to supply chain flexibility, a review from a sustainability perspective remains unwritten. Therefore, the first aim of this research is to reveal the impact of 3DP implementation on sustainability performance, providing redress for current omissions in literature.

It is important to recognise that the strategic implementation of a resource such as 3DP does not happen in a vacuum—the extent of environmental uncertainty and the appropriateness of the environment to which this resource is applied is crucial, as managers can only gain expected opportunities or competitive advantages when the strategic resource is used in the correct context (Rungtusanatham, Miller, and Boyer 2014; Wong, Boon-Itt, and Wong 2011). However, environments cannot be directly perceptible; rather, they are conditional on the level of certainty a firm carries about its current and future business operations (Ho et al. 2005). As such, prior research has distinguished environmental uncertainty as a contingency factor that may influence the effectiveness of organisational resource implementation (Aitken et al. 2016; Flynn, Huo, and Zhao 2010). Therefore, it is crucial to examine environmental uncertainty in studying the impacts of 3DP on sustainability performance; without such knowledge it is hard to determine realistic implications arising from the technology adoption. Previous research indicates that firms with varied operating environments tend to have different strategic implementations of resources, aiming for a fit to enhance organisational performance (Aitken et al. 2016; Donaldson 2001). In this article, we propose that 3DP implementation ought to be aligned with environmental uncertainty to facilitate sustainability performance. We therefore adopted a joint usage of Resource-Based View (RBV) and Contingency theory as the Resource-Based Contingency (RBC) in this study to investigate the impacts of 3DP implementation on sustainability performance by considering the moderating role of environmental uncertainty.

The RBV emphasises gaining competitive advantages through acquiring unique resources (Hart 1995). Meanwhile, the theory proposes that 'resources should be valuable, precious, rare, inimitable, and non-substitutable' in order to confer a sustainable competitive edge (Barney 1991). The resources can be intangible or tangible, including human resources, capital, equipment, technology, staff skills, information and so on (Hart 1995; Li et al. 2020a; Sarkis, Gonzalez-Torre, and Adenso-Diaz 2010). Therefore, 3DP is a valuable strategic technological resource to organisations (Eyers et al. 2022). Contingency theory argues that only the fit of an organisation's character to contingencies (size, strategy, and environment) can lead to higher performance (Donaldson 2001). It was popular to use contingency theory at a unit of organisation to see whether an organisational structure fit its business environment (Burns and Stalker 1961; Donaldson 2001). Nowadays, contingency theory has been widely applied to argue that organisational practices, resources, and capabilities need to fit their environment to contribute positively to performance in OM research (Chavez et al. 2013; Lam et al. 2019; Merschmann and Thonemann 2011; Wong, Boon-Itt, and Wong 2011). In essence, RBV focuses on sustaining competitive advantage(s) through resources, and contingency emphasises enhancing performance via the fit between resources and environments. Additionally, the RBV also highlights that technological disruptions or changes in external circumstances outside firms can drive companies to quickly develop new resources (Hart 1995; Tushman and Anderson 1986), which is actually an echo to the 'fit' concept of contingency theory. Furthermore, considerable research has thoroughly established the positive relationship between competitive advantages and corporate performance (Newbert 2008). All the clues above suggest RBV and contingency theory could be integrated and applied jointly building a contingent view of RBV as RBC, evidenced by existing research as examples (Choi et al. 2024; Homburg and Wielgos 2022; Lam et al. 2019), to form a nature that the 'match' between organisational distinctive resources, capabilities and characteristics to their associated implementation environments delivers competitive advantages and ultimately better performance, which serves as the groundwork for our moderation model that includes 3DP implementation, sustainability performance, and environmental uncertainty.

Building on these theoretical foundations we pose two research questions in this study:

RQ1. What is the impact of 3DP implementation in production on firm sustainability performance (triple bottom line)?

RQ2. How does environmental uncertainty affect the relationships between 3DP implementation and sustainability performance?

This study provides significant contributions both theoretically and practically. To our knowledge, this is one of the first research efforts to empirically examine the impact of 3DP implementation level on firm sustainability performance involving the role of environmental uncertainty. This contribution is particularly important, since it recognises the real-world challenges of 3DP that is affected by environmental uncertainty; our study therefore provides a fuller understanding of sustainability than has been possible in many previous articles. The research confirms the positive relationship between 3DP implementation and sustainability performance, meanwhile indicating a double-edged sword effect of environmental uncertainty within the relationship, thus revealing a new perspective that environmental uncertainty is a challenge but could also be an opportunity for firms. This observation has not been reported previously, and is therefore something that firms should be mindful of in their adoption of 3DP, from both pessimistic and optimistic perspectives. Our research findings further provide more convincing support for managers in terms of 3DP investment and implementation when aiming for green production, suggesting firms consider both internal and external environmental uncertainty to achieve benefits through 3DP implementation.

The paper is structured as follows. In Section 2, we provide a literature review and theoretical background, leading into a conceptual framework and associated hypotheses in Section 3. Section 4 explains the research methodology, followed by the results in Section 5. Next, Section 6 covers the results discussion, theoretical contributions and practical implications. Finally, the paper concludes with Section 7, discussing the research limitations and future developments.

2. Literature review

In this section we examine the relevant literature on 3DP development and implementation (2.1), sustainable performance (2.2) and environmental uncertainty (2.3), highlighting the current state of knowledge and elaborating on the research gaps while synthesising these three themes (2.4).

2.1. 3DP development and implementation

The technologies of 3D Printing (or Additive Manufacturing) enable the fabrication of various parts and complicated geometries from three-dimensional (3D) computer model data (Ngo et al. 2018). This technology has emerged as a general-purpose manufacturing technology that has motivated many manufacturers to reconceive their production systems to seek competitive advantages in the new Industry 4.0 era (Berlak, Hafner, and Kuppelwieser 2021; Caviggioli and Ughetto 2019; Tziantopoulos et al. 2019). The origins of 3DP are typically linked to the development of Stereolithography (Hull 1986); subsequently there has been extensive development and now there are seven distinct 3DP process types: Vat Photopolymerization, Material Jetting, Binder Jetting, Powder Bed Fusion, Material Extrusion, Directed Energy Deposition, and Sheet Lamination (BSI 2015). Each process type has its unique characteristics, benefits, and challenges, however there are common principles around design, pre-processing, manufacturing/fabrication, and post-processing (Eyers and Potter 2017), and thus it is commonplace in management research to consider 3DP as a holistic range of technologies where possible, rather than focusing on idiosyncrasies of individual process types or commercial implementations.

Following the development of techniques, materials, and equipment, 3DP has enjoyed rapid growth and has proved transformative for production and logistical processes in many manufacturing sectors, including automotive (Bade, Lasch, and Schneider 2025; Delic and Eyers 2020), construction (Berlak, Hafner, and Kuppelwieser 2021), aerospace (Wagner and Walton 2016), and electronics (Kabelitz-Bock, Hoberg, and Meuer 2025). Whilst 3DP is not a panacea for manufacturers, it does exhibit a range of characteristics which, if managed correctly, can offer some advantages over more traditional approaches. Table 1 provides a comparison between 3DP with traditional Injection Moulding, organised in terms of the classic competitive objectives of operations. Beyond this like-for-like comparison, 3DP offers opportunities to lessen costs and accelerate fulfilment times through simplified manufacturing procedures and localised production (Weller, Kleer, and Piller 2015; Akmal et al. 2022) that is easier to achieve than for Injection Moulding; likewise 3DP may offer improved environmental credentials too (Despeisse et al. 2017; Asokan et al. 2022).

2.2. Sustainability performance

The Brundtland Commission originally proposed the concept of sustainable development in 1987 as development that 'meets the needs of the present without compromising the ability of future generations to meet their own needs' (Brundtland 1987). Thereafter, researchers have proposed different definitions of sustainable development in microeconomic terms rather than the original macroeconomic style, which is hard for firms to follow. In doing so, Elkington (1998) proposed the idea of the 'triple bottom line' (TBL), which suggests firms simultaneously improve in terms of the economic, environmental, and social performance aspects of sustainable development.

Economic Performance considers the sustained financial performance of firms focusing on cost reduction in the entire manufacturing processes of purchasing materials, production (e.g. energy utilisation), waste disposal, as well as after-sale services (e.g. return/warranty) (Yildiz Çankaya and Sezen 2019; Paulraj 2011; Shepherd and Günter 2011; Zhu, Sarkis, and Lai 2012). Economic performance is typically one of most important goals that firms expect to achieve with implementing new technology and changes, especially for firms in developing countries such as China (Zhu and Sarkis 2004). Improving economic performance has been researched within substantial studies and commonly found production capability is a key contributor to it (Chavez et al. 2022). *Environmental Performance* refers to the organisation's effectiveness in using energy and natural resources efficiently, reducing negative externalities (e.g. pollution and emissions) and fostering a sustainable working environment (Alsawafi, Lemke, and Yang 2021; Chavez et al. 2022; Li et al. 2020b; Zhu and Sarkis 2004). There are mixed voices in literature regarding whether increasing environmental performance may detract from economic performance, given the green management practices could incur costs (Yildiz Çankaya and Sezen 2019; Zhu, Sarkis, and Lai 2012). Nonetheless, examining environmental performance remains essential due to the rising local and global focus on eco-friendly manufacturing (Paulraj 2011; Li et al. 2020b). Regarding *Social Performance*, it has generally been the most

Table 1. Comparison of 3DP and conventional Injection Moulding process.

Competitive objectives	3DP / Additive manufacturing	Conventional injection moulding	Relevant 3DP/AM literature
Cost	Economic production at low volumes; viable at medium-higher volumes	Economic production only achieved at higher volumes, but then overall much cheaper than 3DP	(Baumers et al. 2016; Huang et al. 2021; Eyers et al. 2022)
	On-demand production negates stockholding and thus lessens storage costs	Volume production drives stockholding and potential storage costs	(Pérès and Noyes 2006; Holmström et al. 2010; Demir, Eyers, and Huang 2021; Peron et al. 2024)
	Optimisation for weight reduction lessens manufacturing, transportation, and in-use costs	Process constraints limit opportunities for optimisation in part design	(Petrovic et al. 2011; Achillas et al. 2015; Joshi and Sheikh 2015; Di Lorenzo et al. 2024)
Quality	Products can be readily customised to meet exact user needs	Not suitable for individual customisation to meet exact user needs	(Tuck, Hague, and Burns 2007; Piller, Weller, and Kleer 2015; Peron et al. 2025)
	Surface finishes may be poor; post-processing necessary in most cases	Consistent finish though may be compromised by flow lines, burn marks, weld lines, and delamination	(Chohan and Singh 2017; Gibson et al. 2021)
	Mechanical characteristics of parts may be affected by process characteristics	Generally reasonably consistent, but may be affected by process characteristics	(Tanikella, Wittbrodt, and Pearce 2017; Baca and Ahmad 2020; Zhai et al. 2025)
Speed	Short lead time between design and manufacturing commencing due to no tooling	Long lead times between design and manufacturing due to need for tooling	(Holmström et al. 2010; Petrovic et al. 2011; Guo, Choi, and Chung 2022)
	Relatively slow printing process	Very fast moulding process	(Gibson et al. 2021)
	Ability to produce complex parts lessens part count and assembly requirements	Limits in geometric complexity for parts limits ability to consolidate to lessen assembly requirements	(Yang et al. 2019; Gibson et al. 2021)
Dependability	Fair repeatability and availability, although achieving consistency is sometimes challenging. But technology development is overcoming this.	Good repeatability, generally high availability, consistent production over time	(Basak et al. 2022; Peron et al. 2024)
Flexibility	High degrees of process flexibility and operations flexibility supports production of a wide range of products with minimal changeover penalties	Wide variety of products possible, but with larger changeover penalties and more fixed materials routes	(Rosen 2004; Eyers et al. 2018; Schulze et al. 2025)
	High degrees of design flexibility enable much creativity with lessened constraints for manufacturability	Design constraints around manufacturability well-established, requiring much consideration of design for manufacture	(Hague, Campbell, and Dickens 2003; Jin et al. 2013; Di Lorenzo et al. 2024; Peron et al. 2025)

neglected of the three dimensions of the TBL by enterprises (Yildiz Çankaya and Sezen 2019). However, its significance has gained recognition in light of global movements towards corporate social responsibility and its close ties to operational practices and efficiency (Li et al. 2020b). There is considerable debate on what comprises social sustainability, leading to diverse definitions of social performance across the literature (Yawar and Seuring 2017; Alsawafi, Lemke, and Yang 2021). In this research, we have collectively reviewed and synthesised these perspectives, concluding that Social Performance focuses on an organisation's practices in enhancing the well-being, satisfaction, and development of its stakeholders - such as employees, customers, and the wider community - through socially responsible practices (Yildiz Çankaya and Sezen 2019; Hong, Zhang, and Ding 2018; Li et al. 2020b; Paulraj 2011).

The TBL allows firms to employ and measure the sustainability concept in daily operational practices, which encourages firms' attention and efforts to be sustainable (Chavez et al. 2022; Le, Nguyen, and Cheng 2021; Miemczyk and Luzzini 2019). Furthermore, there is increasing research in sustaining long-term success, particularly after learning lessons from the Covid-19, for sustainability (Sarkis 2020). However, much research has found it rather difficult to simultaneously improve all three aspects of TBL (Chavez et al. 2022; Miemczyk and Luzzini 2019; Yu et al. 2020). Indeed, Elkington (2018) has indicated the triple bottom line could not be accomplished without breakthrough innovation and asymmetric growth. Hence production technology evolution is important for achieving sustainability performance (Yu et al. 2020).

2.3. Environmental uncertainty

Uncertainty refers to the incapability of assigning possibilities to future developments and the challenge of precisely predicting the consequences of decision-making (Wong, Boon-Itt, and Wong 2011). This research focuses on the uncertainty aroused from a focal company's internal and external environments as manufacturing uncertainty (MU) and supply uncertainty (SU). In operations management, most existing studies on environmental uncertainty adopt a holistic approach, blending factors from both the internal and external environments of the organisation (Lucianetti et al. 2018; Merschmann and Thonemann 2011; Wong, Boon-Itt, and Wong 2011). However, as per the phenomenological nature of uncertainty, it is essential to distinguish between internal and external uncertainties based on the attributes of the researched object (Kahneman and Tversky 1982). Examples of this distinction could be seen on uncertainty analysis for supplier selection in Chen et al. (2020) and for leadership credibility in Løhre and Halvor Teigen (2024). This perspective also aligns with theorical lens in this paper, which posits both internal and external implementation environments are matter for the technological resource (3DP) adoption, as discussed later in section 3.2. Given this research context of 3DP in production activities, particularly focusing on the upstream supply chain, sourcing and making represent the primary internal and external activities from which uncertainties arise. Accordingly, the research has employed SU to represent the external environmental uncertainty and MU for internal environment uncertainty.

Previous literature has highlighted the role of MU in relation to organisation structure, strategic planning, and market orientation (Rungtusanatham, Miller, and Boyer 2014). This paper considers MU as factors that are difficult to predict and control in the production processes (Davis 1993; Ho et al. 2005; Sreedevi and Saranga 2017). Previous studies have identified many factors of MU, such as the degree of process standardisation and/or interaction (Khurana 1999; Qi, Zhao, and Sheu 2011; Wong, Boon-Itt, and Wong 2011), stability caused by process (Ho et al. 2005), engineering redesign for accommodating variants (Ho et al. 2005; Sreedevi and Saranga 2017), and degree of modularisation of products (Ho et al. 2005; Sreedevi and Saranga 2017).

Failure to be supplied as planned is another source of uncertainty. This may be caused by a malfunctioning production process at the supplier side, late delivery due to unexpected weather conditions, or unacceptable quality of the delivered materials and/or components (Aitken et a., 2016; Davis 1993). Davis (1993) proposed this as supply uncertainty (SU) (Ho et al. 2005; Qi, Zhao, and Sheu2011). In this paper, we consider SU in the manufacturing industry as unpredictable and uncontrollable factors in the supply of resources from suppliers (Aitken et al. 2016; Davis 1993; Ho et al. 2005). It is especially critical to manage SU in the manufacturing industry, including delivery performance, accuracy, lead-time, and quality (Aitken et al. 2016; Bhatnagar and Sohal 2005; Ho et al. 2005). Therefore, the impacts of environmental uncertainly (including both MU and SU) have to be considered when implementing 3DP in production activities.

2.4. Synthesis of 3DP implementation, sustainability performance, and environmental uncertainty

As highlighted in the literature review above, 3DP has been widely adopted in manufacturing, playing a pivotal role in the advent of Industry 4.0. Along with the growth, firms use 3DP to produce increased numbers of parts, components and even finished products, and recently many major firms embraced the full potential of 3DP and implemented it in mass production, such as Adidas, Airbus, BMW, Ford, General Electric Aviation, Local Motors, and Honda etc. (33D Hubs 2019; Ernst & Young 2019; ING 2017). Forecasting predicts a 24% annual growth for the four years to achieve around $44.5 billion by 2026 (33D Hubs 2022).

However, the question regarding 'how much exactly the impacts of 3DP implementation on performances are' remains unanswered. One of the key reasons is, also as one of the established criticisms of literature, that the majority of the current research is over-reliance on qualitative assessments when evaluating impacts on performances. The empirical quantitative data is lacking due to the challenges and difficulties that could be faced in doing so. Therefore, Lam et al. (2019) have devoted efforts to highlighting the positive correlation between the adoption of 3DP and stock returns by using secondary datasets. However, stock return as performance is a general economic criterion, rather than within operations management. Delic and Eyers (2020) revealed that AM adoption positively relates to supply chain flexibility, only one dimension of operational performance.

More important, increasing attention has been paid to the sustainability of the technologies while 3D printing adoption increases (Lim et al. 2024). Especially as per Elkington's (2018) view of 'the triple bottom line could not be accomplished without breakthrough innovation and asymmetric growth'. It is sensible to estimate that the implementation of 3DP, an evolution technology, is essential for completing triple bottom line performance (Ford and Despeisse 2016). Therefore, it is rather necessary to explore the exact relationships between 3DP implementation on sustainability performance.

However, the integration of 3DP into manufacturing systems does not exist in a vacuum. It is essential to consider how the contingencies of environmental uncertainty influence the application of 3DP and its potential to contribute to sustainable outcomes. Manufacturing uncertainty (internal) affects strategic planning and can disrupt the expected benefits of 3DP's flexible and responsive production capabilities (Aitken et al. 2016; Ho et al. 2005). Similarly, supply uncertainty (external) can hinder the reliable procurement of materials essential for 3DP, impacting delivery performance and overall product quality (Bhatnagar and Sohal 2005; Qi, Zhao, and Sheu 2011). The challenge lies in managing these uncertainties to harness the full potential of 3DP for sustainable growth. Thus, this paper will hypothesise the correlations between 3DP implementation, sustainability performance, and environmental uncertainty. It will employ a theoretical lens and review of the literature to establish these connections, followed by empirical testing to elucidate the 'impacts' thoroughly.

In light of these dynamics, the role of 3DP in sustainable manufacturing emerges as both a driver and a response to the challenges posed by environmental uncertainties (Lim et al. 2024). Organisations adopting 3DP must navigate these complexities, leveraging the technology's strengths to foster resilience and adaptability in their operations. The interplay of development, sustainability, and uncertainty thus represents a fertile ground for further research, especially in the context of the global shifts in production paradigms post-Covid-19.

In summary, a comprehensive understanding of these interconnected relationships is pivotal for companies looking to implement 3DP as part of their strategic operations. It calls for a holistic approach that considers the technological capabilities of 3DP, the overarching goal of sustainability, and the pragmatic realities of environmental uncertainty. Only by recognising and addressing these interdependencies can firms fully capitalise on the transformative potential of 3DP for a sustainable and resilient future in manufacturing. Therefore, the next section will hypotheses the correlations between 3DP implementation, sustainability performance, and environmental uncertainty through both theoretical lens and literature, then empirically tested them.

3. Hypothesis development

Based on the explorations and critical insights from Section 2, this section provides individual subsections that clearly derive the hypotheses on the relationships between 3DP implementation and performance (3.1) as well as on the moderating role of environment uncertainty (3.2), that are used in subsequent conceptual framework development (3.3).

3.1. 3DP implementation and performance

Elkington's viewpoint (2018) is in-line with Resource-Based View (RBV) theory when explaining the potential relationship between 3DP implementation and sustainability performance. The RBV theory was initiated from the strategic management field, and further formed by taking the perspective of emphasising the importance of resources in sustaining competitive advantages (Hart 1995). In RBV, firms need to acquire valuable and non-substitutable resources to gain or enhance their capabilities to further sustain competitive advantages (Hart 1995). 3DP can be considered a type of strategic technology resource in companies, which equips them with distinctive competencies in design and manufacturing leading to competitive success with unique competitive advantages (Delic, Eyers, and Mikulic 2019). Moreover, corporate performance increases with such enhanced or distinctive competitive advantages (Newbert 2008), so it can be concluded that the implementation of 3DP in production will positively affect sustainability performance.

Although the manufacturing process of 3DP may use different printer technologies or printing materials, the common key feature of 3DP is the ability to integrate multiple conventional production processes to simplify production complexity and procedures with distinct materials utilisation efficiency and significant elimination of production waste (Davies et al. 2022; Janssen et al. 2014; Piller, Weller, and Kleer 2015; Mishra, Kr Singh, and Gunasekaran 2024). This helps to achieve much more production cost efficiency via reduction of costs of materials, energy utilisation, as well as waste discharge (Achillas et al. 2015; Berman 2012; Petrovic et al. 2011). Research shows that the waste of raw materials can be reduced by 40% when using additive technologies instead of subtractive (machining) technologies (Petrovic et al. 2011; Reeves 2008a). Some AM techniques maintain up to 97% material efficiency; conversely some subtractive technologies could even often produce material waste exceeding 90% in some industries (Reeves 2008b; Achillas et al. 2015). For example, in aerospace the 'buy-to-fly ratio' concerns how much of bought raw materials actually features on the part flying on the plane. In conventional manufacturing, buy-to-fly ratios are shown to be 20:1, with 19 kg of material going to waste for every 1 kg of flying end-product (Reeves 2008b; Achillas et al. 2015). Additionally, 3DP also allows companies to have full control over the entire production process of design, prototyping, and manufacturing (Lam et al. 2019; Li et al. 2019). This helps with the control and improvement of product quality, particularly obvious in health care industry such as 3-D printed implants and prosthetics (Attaran 2017, Peron et al. 2025), which in return results in cost reduction for after-sales e.g. warranty and return processing, and thus contributes to overall economic performance improvement (Baumers et al. 2017; Berman 2012; Chandima Ratnayake 2019). Therefore, this research hypothesises the level of 3DP implementation will help to improve the corporate economic performance, as stated in H1 below and shown in Figure 1.

H1: The level of 3DP implementation in production has a positive impact on firm economic performance.

Meanwhile, 3D printing technology has been identified as a key manufacturing technology that has the potential to enhance sustainable production, supporting this broader environmental goal (33D Hubs 2022; Huang 2013). Along with fewer and less complicated manufacturing procedures, fewer types and volumes whilst much greener materials would be used in 3DP production (Achillas et al. 2015; Huang et al. 2013). This is because 3DP does not require the use of fixtures, cutting fluids, coolants, casting release compounds, forging lubricants and other auxiliary resources inputs that are necessary in conventional manufacturing (Huang 2013; Peng et al. 2018). For instance, FDM, one of the most popular 3DP technologies, uses non-toxic thermoplastic materials with low melting points, requiring less energy for the build chamber and extrusion nozzle (Peng et al. 2018). In addition, 3DP enables the fabrication of lattice or spatial structures to reduce product weight (Di Lorenzo et al. 2024; Petrovic et al. 2011; Walachowicz et al. 2017). This not only reduces the consumption of materials in production, but also has significant benefits for fuel consumption (Petrovic et al. 2011; Huang 2013; Walachowicz et al. 2017). Furthermore, these benefits lead to less polluting emissions to the terrestrial, aquatic, and atmospheric systems. For instance, the cutting fluids, not required by 3DP production, are a very hazard wastes within conventional manufacturing (Huang 2013). Also, through simulation comparison, research indicates a 26.6% reduction in carbon emission if adopting 3DP in a centralised supply chain to produce spare parts compared to conventional production, and the reduction will come to 53.7% if AM is adopted in a decentralised supply chain (Li et al. 2017). In addition, implementing 3DP in production not only contributes to creating a cleaner working environment as discussed above, but also demands less human involvement in manufacturing (Attaran 2017), thereby minimising workers' exposure to hazardous or noxious conditions. These practices significantly decrease the frequency of health and safety accidents in the workplace, which are prevalent within the complex and harmful chemicals involved conventional production (Achillas et al. 2015; Matos et al. 2019). In summary, 3DP implementation in production could lead to the reduced consumption of harmful materials, energy, and resources meanwhile lessen pollutant emissions and decrease workplace accidents, therefore contributing to environmental performance (Achillas et al. 2015; Matos et al. 2019; Peng et al. 2018), as postulated in H2 and shown in Figure 1.

H2: The level of 3DP implementation in production has a positive impact on firm environmental performance.

In addition, some research also claims that 3DP can enhance production flexibility, reduce lead time, and allow more engagement with customers for customisation (Delic

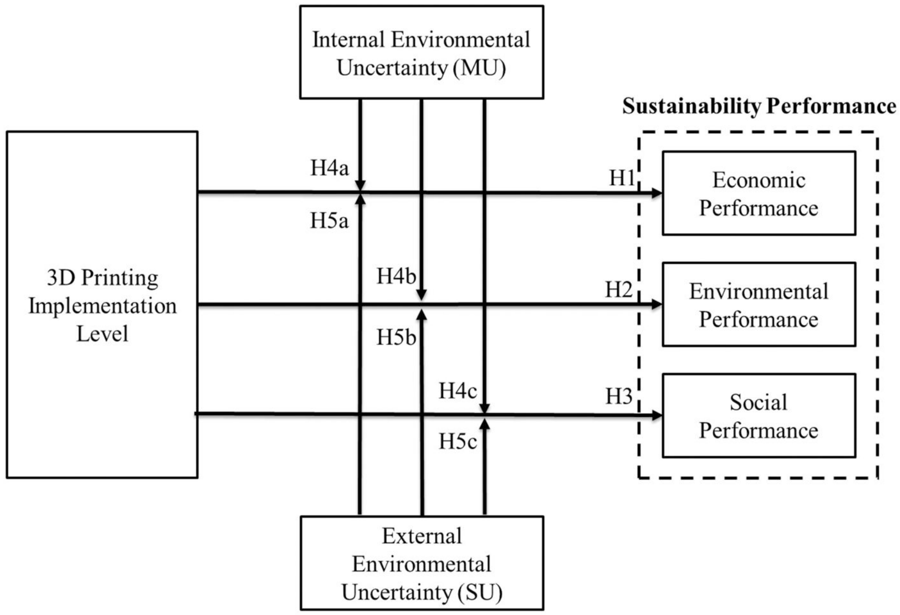

Figure 1. Conceptual framework.

and Eyers 2020; Eyers et al. 2022; Shukla, Todorov, and Kapletia 2018) to ultimately contribute to customer satisfaction. For example, the case of Active8 Robots shows the lead time reduction from 3-4 weeks to less than 12 hours via using 3DP (Create3D, 2023). Meanwhile, 3DP also brings in more opportunities for jobs, promotions, training and education, which maximises the benefits for staff in terms of income, knowledge and skills, as well as safety (Asokan et al. 2022; Bonekamp and Sure 2015; Leitao et al. 2020; Matos et al. 2019). The National Strategy report for Additive Manufacturing UK predicts 60,000 job opportunities generated by 3DP by 2025 (AM-UK 2018), which is in-line with the research finding of the positive relationship between AM technologies and employment at the industry level (Felice, Lamperti, and Piscitello 2022). These jobs will be skilled roles providing staff training and education, offering better salaries and greater opportunities for improved welfare and betterment (Leitao et al. 2020; Peron et al. 2025), in lower noise-level work environments than traditional factories for better healthy conditions (Asokan et al. 2022; Peng et al. 2018). Meanwhile, 3DP adoption increases corporate (social) reputation which can convert to stock return for beneficial to stakeholders (Lam et al. 2019). Therefore, 3DP implementation seems to increase the satisfaction of many groups including customers, staff and other stakeholders which boosts the corporate social performance, as proposed in H3 and shown in Figure 1.

H3: The level of 3DP implementation in production has a positive impact on firm social performance.

3.2. The moderating role of environmental uncertainty

As discussed in Section 1 this research has adopted a joint usage of RBV and contingency theory as the RBC to form the moderation role as shown in Figure 1. As per the argument above, when examining the acquisition of a new resource, it is necessary not only to look into the resource itself, but to also consider the environments where it is applied to successfully achieve the competitive advantage as expected, and ultimately improve performance. Following the contingency theory, one key dimension of contingencies is environmental stability (Burns and Stalker 1961; Donaldson 2001; Pennings, 1992), which forms the choice of moderator in this research as Environmental Uncertainty (EU) (Sousa and Voss 2008). This choice is also backed up by extensive volumes of existing research that has demonstrated the moderator role of EU in various scenarios (Downey and Slocum 1975; Qi, Zhao, and Sheu 2011; Wong, Boon-Itt, and Wong 2011). Meanwhile, RBV says that the existing competency base within firms could make it difficult to acquire new resources (Hart 1995), whilst technological discontinuities or shifts in external circumstances outside firms may promote companies to develop new resources rapidly (Hart 1995; Tushman and Anderson 1986). This indicates that when considering the implementation environment for a resource, it is worthwhile to examine both the environment within the firm, and also outside it. Therefore, in this research, the authors have adopted two dimensions under environmental uncertainty as a final choice of moderators: Manufacturing uncertainty (MU) reflects the 3DP implementation environment within the organisation, and supply uncertainty (SU) represents the 3DP implementation environment outside the organisation. Applying the contingency theory to a resource level in this research (RBC), it is the fit between a distinctive acquired resource (3DP) and its implementation environments (MU and SU) that can lead to higher performance. In other words, environmental uncertainty (MU and SU) will moderate the level of beneficial sustainability performance from the 3DP implementation.

It is well documented that environmental uncertainty usually disturbs business operations and thus decreases performance, so organisations always try to avoid it (Bhatnagar and Sohal 2005; Downey and Slocum 1982; Nguyen et al. 2023).

Regarding the moderating role of MU, the high MU refers to a manufacturing environment where a factory follows non-standardised processes for production, and has rather limited capability to cope with any changes in the production volume, meanwhile the products themselves have a low degree of modularisation (Ho et al. 2005, Qi, Zhao, and Sheu 2011, Sreedevi and Saranga 2017, Wong, Boon-Itt, and Wong 2011). Such a manufacturing environment usually faces higher rates of faulty operations, defective products, and higher risks of production rescheduling or progress delays (Aitken et al. 2016; Davis 1993; Ho et al. 2005), which will in turn decrease corporate sustainability performance. In detail, fault operations, defect products or any pause of production will certainly cause more material consumption and waste, which incurs additional costs to purchase these materials and discharge the wastes (Wong, Boon-Itt, and Wong 2011) and is also not friendly to the environment (Wang et al. 2023). Meanwhile, the issues above would result in more production which means more consumption of energy and emissions of pollution, again increases costs (Wong, Boon-Itt, and Wong 2011) and negatively impacts the environment (Wang et al. 2023). In addition, high MU could increase risks for quality control and product quality, which may dissatisfy customers, damage to stakeholders' benefits, and burn more costs for warranty and return processing (Ng et al. 2015; Wong, Boon-Itt, and Wong 2011), thus a decrease of both economic and social performances. Moreover, working in a high MU factory with messy and non-smoothy operations, the staff's work modes, passions, and motivations to adapt to new technology could be weakened therefore bringing opposite results towards their satisfaction, training and education, and welfare (Kafetzopoulos, Psomas, and Skalkos 2019; Wang et al. 2023) thus again decrease the corporate social performance. Last but not least, 3DP implementation within an organisation itself is another source of manufacturing uncertainty in the internal environment (Ho et al. 2005). Therefore, when 3DP is implemented in a high MU environment, the overall uncertainty level within the firm's manufacturing environment will be increased, which brings a greater negative impact on sustainability performance. In other words, 3DP implementation theoretically fits better within a low MU environment than a high MU environment. Therefore, this study hypothesises MU will weaken the positive impacts brought by 3DP implementation on sustainability performance, as proposed in H4a, H4b and H4c and shown in Figure 1:

H4a: The impact of 3DP implementation on economic performance is higher for firms operating in a low MU environment.

H4b: The impact of 3DP implementation on environmental performance is higher for firms operating in a low MU environment.

H4c: The impact of 3DP implementation on social performance is higher for firms operating in a low MU environment.

Similarly considering the moderation role of SU, higher supply uncertainty will negatively affect sustainability performance (Wang et al. 2023). This is because high uncertainty from suppliers represents a supply environment that suffers from high risks of unstable/poor quality of critical materials, the wrong volume of supplies, and failure in on-time deliveries (Bhatnagar and Sohal 2005; Ho et al. 2005; Merschmann and Thonemann 2011; Qi, Zhao, and Sheu 2011). Under this scenario, transaction costs associated with these sourcing activities will be increased, worsening purchase costs (Wong, Boon-Itt, and Wong 2011). Additionally, product quality may not be stable and lead time may be longer (Wong, Boon-Itt, and Wong 2011; Bhatnagar and Sohal 2005) causing customers concerns, reputation damage, as well as more costs for dealing with return and warranty (Lucianetti et al. 2018; Wang et al. 2023), thus reducing both economic and social performances. Moreover, these supply issues also disturb production plans and progress as production may have to be paused, delayed and rescheduled until the right materials and resources are received (Sreedevi and Saranga 2017). Therefore, the consumption and wastes of materials and energies will be increased as well as associated costs for disposal of the wastes, therefore reducing both economic and environment performance (Lucianetti et al. 2018; Wang et al. 2023). In return, hazardous material discharge and pollution emissions would add further influences on environmental performance (Wang et al. 2023). Moreover, production plan reschedules will consume a large amount of time and human resources which is against the stakeholder betterment of social performance (Lucianetti et al. 2018). Therefore, researchers suggest firms maximise mitigation and reduce supply uncertainty (Davis 1993; Ho et al. 2005). Furthermore, 3DP implementation in production could restructure and simplify the supply network configuration of the product-associated materials (Friedrich, Lange, and Elbert 2022; Roscoe and Blome 2019; Tziantopoulos et al. 2019), therefore may disturb the extant cooperations and integrations between the focal company and its suppliers, and thus further boost supply uncertainty. This in return negatively affects the triple bottom line performance (Sreedevi and Saranga 2017; Yang and Zhao 2016). Therefore, implementing 3DP in a high SU environment will also cause a greater negative impact on sustainability performance than implementing 3DP in a low one. Thus, this study hypothesises that SU will also weaken the positive impacts brought by 3DP implementation on sustainability performance, as stated in H5a, H5b, and H5c below and shown in Figure 1:

H5a: The impact of 3DP implementation on economic performance is higher for firms operating in a low SU environment.

H5b: The impact of 3DP implementation on environmental performance is higher for firms operating in a low SU environment.

H5c: The impact of 3DP implementation on social performance is higher for firms operating in a low SU environment.

3.3. Conceptual framework

To comprise the hypotheses deduction associated with the detailed literature review above, a conceptual framework is developed in this section as shown in Figure 1. The framework clearly shows the expected relationships between 3DP implementation level and sustainability performance (with three constructs) as the implications of H1- H3, also the moderator role of the environmental uncertainty with two constructs that manufacturing uncertainty (MU) serves as internal environmental uncertainty as proposed in H4a-H4c, and Supply uncertainty (SU) represents the external environmental uncertainty as postulated in H5a-H5c.

4. Methodology

In this section, we introduce the details of methodological design including data collection and sampling (4.1) and measurement items (4.2), and also demonstrate the reliability and validity of the dataset through analysis (4.3) and control of bias and endogeneity (4.4).

4.1. Data collection and sampling

Informed by the conceptual framework in Figure 1, an online survey approach was adopted to collect the primary data and test the hypotheses. The questionnaire is structured into two main sections, starting with background and profile questions, and then moving to the Likert-scale questions for all the constructs presented within the Figure 1 framework. The survey adopts a 7-point Likert scale to ensure a reliable dataset (Hensley 1999), and for the data collection purpose, the English version of it has been translated into Chinese and back-translated into English by independent scholars to ensure conceptual equivalence and accuracy.

The target participants for this survey come from managers of companies which are engaged in elements of the manufacturing services that employ 3DP technology. China is one of the top-ranking countries in terms of the use of 3DP in production (Ernst & Young 2016; 2019). Therefore, data were collected from manufacturing industries located in China with companies that undertake 3DP implementation at any of the seven below-mentioned levels. We strategically collected our primary data mainly from manufacturing companies located in the top three of the seven economic development regions in China, which are the Yangtze River Delta (YRD) area including Shanghai, Jiangsu, and Zhejiang provinces, the Pearl River Delta (PRD) area of Guangdong province, and also the Bohai Sea Economic area (BSE) contains Beijing, Tianjin, Hebei, Shandong, Shanxi, Liaoning, and Inner Mongolia provinces (Huo et al. 2018). These areas represent the most well-developed manufacturing areas in China (Huo et al. 2018; Li et al. 2020a) and are also in-line with the location configuration of the 3DP industry in China (3D Science Valley 2023). We randomly sampled companies listed under the manufacturing and service sections of the Firm Catalogue in these areas and sent out 1000 questionnaires (Huo et al. 2018; Li et al. 2020a). The survey was distributed to target participants via emails in the summer 2020, and 364 responses were received in total after up to two rounds of follow-up reminders. To minimise bias brought by missing data, the researchers have excluded all incomplete responses from the dataset prior to analysis following the 'complete case approach' (Hair et al. 2018). Then, after conducting further data cleaning and removing outliers, 266 usable responses were available as the sample for further statistical analysis, with a final response of 26.6% and a valid rate of 73.1% of the received responses.

The focus of this research is on the generality of the impact of 3DP implementation in production on corporate sustainability performance; therefore the analysis unit is based on firm level. As shown in Table 2 regards sample profile, most participants are senior or high-level managers within the companies and had been in their current position for five years or more, with the average respondents' tenure in their current firm being 8.3 years. Additionally, the sample has good coverage of firms in terms of industry types, number of employees, and turnover. In summary, the questionnaire has been completed by senior managers or above across a broad range of manufacturing industries with high awareness of firm manufacturing and performance status. Thus, it is reasonable to expect that the informants have sufficient knowledge to respond to the questionnaires.

4.2. Measures

The study uses survey data to measure the constructs of interest. Measurement items for each construct were adapted from established research. All the scale items are summarised in Table 3 and Table 4 below for all constructs.

In this research, as per hypotheses H1, H2, H3, the different 3DP implementation levels may impact the triple bottom line performances. Therefore, the clear recognition of different 3DP implementation levels is important. However, despite the considerable commercial interest in 3DP, it is interesting to note that there has been little formal emphasis on measures of the level or extent of 3DP within firms. In this study, we therefore draw upon work with a well-established measure considering technology implementations more generically, which provide precise terminologies that we used for a seven-level measure of 3DP implementation (Moersch 1995). The levels, covering from not applying at all to full implementation, are Non-use, Awareness, Exploration, Infusion, Integration (Implementation), Expansion, and Refinement (Moersch 1995). In this research, these classifications have been modified with clear definitions for each level to fit better into the context of 3DP implementation and form an ordinal measurement for it, as the details shown in Table 3.

To double-test the validity of this measuring scale for 3DP implementation, we have conducted interviews via focus group with three experienced academics and three industrial specialists with rich experience in the 3DP area in the UK (Fredendall, Letmathe, and Uebe-Emden 2016; Kwak, Seo, and Mason 2018). Further, the Q-sort method was employed to evaluate the appropriateness of validity for all constructs in this work including the 3DP implementation, in which the participants matched the items to the construct definitions (Fredendall, Letmathe, and Uebe-Emden 2016; Kwak, Seo, and Mason 2018; McKeown and Thomas, 1988). Through the tests above pre-data collection, the results show the designed measure for 3DP is valid according to the suggestion from Hair et al. (2018). Additional feedback from industrial specialists suggested that this measure is very useful to

Table 2. Sample profile.

Characteristic	Number	Percentage	Characteristic	Number	Percentage
Manufacturing industry			*Work years*		
Aerospace, defence and security	3	1.13%	Less than 5 years	60	22.56%
Automotive	9	3.38%	5 - less than 10 years	128	48.12%
Basic metals	6	2.26%	10 - less than 15 years	46	17.29%
Biomedical equipment	2	0.75%	15 - less than 20 years	13	4.89%
Capital projects & infrastructure	2	0.75%	20 year or above	19	7.14%
Chemicals	10	3.76%			
Clothing & footwear	14	5.26%	***Management Position***		
Coke and refined petroleum products	2	0.75%	Low-level manager	94	35.34%
			Middle-level manager	144	54.14%
Electrical equipment	16	6.02%	High-level manager	28	10.53%
Electronics	30	11.28%			
Energy, utilities & mining	13	4.89%	***Employee Size***		
Engineering & construction	8	3.01%	1-9	3	1.13%
Food & beverages	13	4.89%	10-50	21	7.89%
Forest, paper & packaging	1	0.38%	51-250	65	24.44%
Furniture & home furnishing	11	4.14%	251-500	50	18.80%
Health & beauty care	3	1.13%	501-1000	76	28.57%
Home appliances	16	6.02%	1001-5000	34	12.78%
Industrial and mechanical equipment	58	21.80%	5000+	17	6.39%
Other	2	0.75%	***Turnover***		
Pharmaceutical	23	8.65%	Less than £2 m	25	9.40%
Printing & publishing	3	1.13%	£2m - less than £25 m	67	25.19%
Rubber and plastic products	8	3.01%	£25m - less than £50 m	69	25.94%
Shipbuilding	1	0.38%	£50m - less than £100 m	65	24.44%
Textiles	8	3.01%	£100m - less than £500 m	26	9.77%
Toys	4	1.50%	£500m or above	14	5.26%

Table 3. 3DP Implementation level.

3DP implementation levels	Description
1. Non-use	No access to 3D printing technology or its implementation.
2. Awareness	The manufacturing organisation has only experts or a few employees who understand 3D printing technology.
3. Exploration	The manufacturing organisation has made investments in the physical machines and knowledge development of 3D printing technology.
4. Infusion	The manufacturing organisation has deployed the 3D printing for prototyping purposes.
5. Implementation	The manufacturing organisation has begun to implement 3D printing in daily production for parts or products, but only in a limited certain volume, e.g. small-scale production.
6. Expansion	The manufacturing organisation has implemented 3D printing to produce more and more parts or products, which account for a considerable amount of the total production volume. Or the manufacturing organisation has developed strong 3D printing based capabilities to produce large volume products.
7. Refinement	The manufacturing organisation regards 3D printing as the key production method, rather than traditional manufacturing. Half or more of the organisation's total production volume has been completed using 3D printing.

Table 4. Factor analysis results.

Measurements	Mean	S.D.	Item loading
Manufacturing Uncertainty (MU) (Cronbach's alpha = 0.65; CR = 0.79; AVE = 0.55)			
MU01: We tend to run standardised production process whenever possible	2.37	1.28	0.69
MU02: We are highly capable of variant scale of orders	2.39	1.21	0.80
MU03: The degree of modularisation of our main product is very high	2.77	1.22	0.74
Supply Uncertainty (SU) (Cronbach's alpha = 0.75; CR = 0.84; AVE = 0.64)			
SU01: The quality of critical material is very stable	2.57	1.22	0.76
SU02: We agreed upon on-time delivery for a large amount of our purchase volume	2.48	1.11	0.82
SU03: We agreed upon accuracy for a large amount of our purchase volume	2.41	1.06	0.82
Economic Performance (ECP) (Cronbach's alpha = 0.71; CR = 0.78; AVE = 0.47)			
ECP01: Decrease in cost of materials purchased	4.42	1.18	0.74
ECP02: Decrease in cost of energy utilisation	4.53	1.25	0.68
ECP03: Decrease in fee for waste discharge	4.68	1.27	0.62
ECP04: Decrease in costs of warranty/returns processing	4.32	1.23	0.69
Environmental Performance (ENP) (Cronbach's alpha = 0.77; CR = 0.80; AVE = 0.50)			
ENP01: Reduction in consumption for hazardous/harmful/toxic materials	4.80	1.23	0.81
ENP02: Reduction in energy consumption	4.64	1.10	0.60
ENP03: Reduction in pollutant emissions	4.82	1.29	0.71
ENP04: Decrease of health and safety accidents in workplace	4.97	1.29	0.68
Social Performance (SOP) (Cronbach's alpha = 0.77; CR = 0.80; AVE = 0.51)			
SOP01: Improvement in employee satisfaction (wages, benefits, safety)	4.82	1.19	0.69
SOP02: Improvement in customer satisfaction	5.15	1.12	0.66
SOP03: Improvement in employee training and education	4.96	1.19	0.76
SOP04: Improvement in overall stakeholder welfare or betterment	4.94	1.05	0.74

help them develop a clearer understanding of 3DP implementation levels, which is demanded practically but not available yet. Within the survey, participants are asked to tick the option that best describes their organisation's current overall 3D technology implementation level across all product lines. After data collection, the skewness and kurtosis values have been checked for normality, which are 0.108 and −.1.413 respectively, clearly passed the normality test as recommended by Hair et al. (2018). Therefore, the validity of construct 3DP is confidence, and more validity tests for other constructs and the whole model have been explained in sections 4.3 and 4.4 below.

During data collection, participants were also asked to indicate both manufacturing uncertainty and supply uncertainty as applicable to their organisation by answering the 7-point Likert-scale questions concerning to what extent they agree with each statement about the associated measurements for these two constructs (1= strongly agree; 7 = strongly disagree) (Bai, Sheng, and Li 2016; Huo et al., 2018). Manufacturing uncertainty (MU) in this research represents uncertainties within the manufacturing process inside of the business (Davis 1993; Ho et al. 2005). The measurements of it have been adopted from Ho et al. (2005), Qi, Zhao, and Sheu (2011), Sreedevi and Saranga (2017), and Wong, Boon-Itt, and Wong (2011), including production process standardisation, capability of managing variant scale of orders, and degree of modularisation of manufactured products. Supply uncertainty in this research focuses on the stability level of suppliers in the supply of critical resources (Davis 1993; Ho et al. 2005). The measurements have been adopted from Bhatnagar and Sohal (2005), Ho et al. (2005), Merschmann and Thonemann (2011), and Qi, Zhao, and Sheu (2011), include quality stability of critical material, on-time deliveries by suppliers, and supplier accuracy in filling orders.

To ensure the universal and effective measurement of the variable of corporate sustainability performance, this research has adopted the classic three dimensions of sustainability performance: economic, environmental, and social. Survey participants have required to indicate their organisation's current performances on these three dimensions within the industry compared to their major competitors again using a 7-pointed scale (1= worst in industry, 7 = best in industry) (Yu et al. 2020). Economic performance focuses on cost reduction include measurements of the decrease in cost of materials purchased, the decrease in cost of energy utilisation, the decrease in fees for waste discharge, and the decrease in costs of returns/warranty processing (Yildiz Çankaya and Sezen 2019; Paulraj 2011; Shepherd and Günter 2011; Zhu, Sarkis, and Lai 2012); Environmental performance focuses on reducing consumption and pollution, so that the associated measurements include the reduction in consumption for hazardous, harmful or toxic materials, the reduction in energy consumption, the reduction in pollutant emissions, and the reduction in health and safety accidents in the workplace (Alsawafi, Lemke, and Yang 2021; Chavez et al. 2022; Li et al. 2020b; Zhu and Sarkis 2004). Social performance refers to corporate social behaviour, which applies the measurements of the improvement in employee satisfaction (wages, benefits, safety), the improvement in customer satisfaction, the improvement in employee training and education, and the improvement in overall stakeholder welfare or betterment (Yildiz Çankaya and Sezen 2019; Chavez et al. 2022; Hong, Zhang, and Ding 2018; Li et al. 2020b; Paulraj 2011).

To eliminate undesirable variance and enhance the validity of the research results, two control variables have been taken into consideration within this study: management position and years of work in the organisation. As per the stakeholder theory, the managers, as one of the most essential stakeholders who lead the companies, have a great influence on corporate sustainability performance (Rebs et al. 2019). Research has demonstrated that the managers' support and attitude, which are influenced by the managers' characteristics, are the key drivers to corporate sustainability performance improvement (Tseng, Lim, and Wu 2018). Empirical findings further reveal that the characteristics of managers have significant correlations with sustainability performance (Huang 2013; Tacheva, Simpson, and Ivanov 2020), for instance, senior level managers have more influence on sustainable initiatives and practices than juniors thus produce higher impacts on sustainability performance (Tseng, Lim, and Wu 2018); and managers tenure is also positively associated with the sustainability performance (Huang 2013).

4.3. Reliability and validity

In examining construct reliability, this research follows the two-step method recommended by Narasimhan and Jayaram (1998). A factor analysis was conducted using principal component analysis with a varimax rotation (Huo et al. 2018). As shown in Table 4, each item had stronger loadings on constructs, which shows good coherence of the measurement items. Additionally, Cronbach's alpha was calculated and the values for all constructs were higher than 0.70, except for manufacturing uncertainty (0.65), indicating a high level of internal consistency. Moreover, composite reliability (CR) values are around 0.80, which demonstrates the high reliability of constructs. Therefore, it can be concluded that the measurement scales adopted are reliable.

Additionally, both convergent and discriminant validity were examined for construct validity. The average variance extracted (AVE) of all constructs was higher than 0.50 (with the exception of 0.47 for economic performance), also indicating high convergent validity (Huo et al. 2018). The discriminant validity test was conducted by comparing the squared root of AVE with the correlation between each pair of constructs (Huo et al. 2018). As presented in Table 5, the

Table 5. Square root of AVE value.

Constructs	1	2	3	4	5
1. Manufacturing Uncertainty	0.74[a]				
2. Supply Uncertainty	0.42**	0.80[a]			
3. Economic Performance	−0.22**	−0.18**	0.68[a]		
4. Environmental Performance	−0.31**	−0.31**	0.50**	0.70[a]	
5. Social Performance	−0.32**	−0.27**	0.48**	0.57**	0.71[a]
Mean	2.51	2.48	4.49	4.81	4.97
S.D.	0.95	0.92	0.90	0.95	0.87

*$p < 0.05$; **$p < 0.01$.
[a]Square root of AVE value.

square roots of AVE estimates were higher than all corresponding correlations. Therefore, discriminant validity was ensured in this study.

4.4. Bias and endogeneity

Two approaches were used to check common method bias. First, the results of Harman's single-factor revealed that the largest variance explained by any single factor was 27.34%. Thus, the common method bias is not a concern (Podsakoff and Organ 1986). Second, as all the variables were self-reported, including 3DP implementation level, MU, SU, ECP, ENP, SOP, an unmeasured common method factor was used to re-estimate the measurement model (Podsakoff et al. 2003). The results indicate a significant chi-square difference between the measurement model and the unmeasured common factor model ($\Delta\chi^2 = 17.239$, df $= 62$, $p < 0.001$). Therefore, common method bias is not an issue in this study.

There are potential endogeneity issues that could be a concern from two perspectives in the survey method: (1) selection bias, and (2) simultaneity. These potential issues were resolved in two ways within this research. First, we collected data from all possible manufacturers which implemented 3DP technology, rather than focusing on a specific segment in the manufacturing industry. As a result, the sampling covered 25 segments including automotive, food and beverages, toys, engineering, and construction, as shown in Table 2. Therefore, this approach reduced the impact of potential endogeneity, which may be caused by selection bias, to a certain degree. Second, the issue of simultaneity often occurs when two constructs affect each other simultaneously (Antonakis et al. 2014). The current study argues that the 3DP implementation level was associated with the sustainability performance of manufacturing firms. This is because, according to RBV theory and established literature, it is the 'resource' (3DP in this study) that enables the capability to gain a competitive advantage and ultimately improve performance (sustainability performance), rather than the other way round (Delic and Eyers 2020; Lam et al. 2019; Newbert 2008; Peng et al. 2018). This is in line with the view from Elkington (2018) that the triple bottom line could not be accomplished without breakthrough innovation, and that 3DP is an innovative technology that will revolutionise manufacturing (Berman 2012). Supportive empirical research outputs have demonstrated the same argument, for example, Lam et al. (2019) confirmed firms implementing 3DP gain higher stock returns for two years after the implementation and Delic and Eyers (2020) argued that 3DP adoption affects supply chain performance via supply chain flexibility. Therefore, 3DP implementation is essential for completing triple bottom line performance. To further ensure no endogeneity issue, we applied Durbin-Wu-Hausman via Stata 14, as suggested by Ketokivi and McIntosh (2017). We firstly regressed the independent variable (3D printing implementation level) with all controls (management position and years of work) to see whether adding the residuals from this model has any significant coefficient on the original model (Dong, Ju, and Fang 2016). Then, we applied augmented regressions for the residuals as additional independent variables and found the estimated parameters were not statistically significantly different from zero. Therefore, the simultaneity of 3DP implementation and sustainability performance is not an endogeneity concern in the current study. Therefore, by justifying the content theoretically, contextually, and statistically, we conclude that endogeneity is not an issue in our study.

5. Analysis results

In this section, we have conducted the hierarchical regression analysis to test the hypotheses with results display in 5.1 and further interpret the moderation findings via plots in 5.2.

5.1. Hypothesis testing

All the analysis data in the study is quantitative data returned from the participants to the researchers directly. The data were imported into the statistical software SPSS to obtain hierarchical regression analysis, aiming to exploit the correlation among the constructs as well as the moderation effect (Bai, Sheng, and Li 2016; Hair et al. 2018).

As shown in Table 6, the hierarchical regression results are presented using four models. Model 1 includes only the control variables. Model 2 adds the 3DP implementation level. Model 3 inputs the moderators MU and SU. Model 4 features all the interaction terms. We checked the variance inflation factors (VIF) associated with each regression coefficient and found that the largest VIF was 1.34, so multicollinearity was not a concern.

If taking the level of significance to be 0.05, it can be clearly seen from Model 2 that all the hypotheses about the main effects (H1, H2, H3) are supported with positive coefficient value of 0.300, 0.298, 0.325 respectively. In terms of moderating effects, as shown from Model 4, the interaction hypotheses for H4a, H4b, H5a and H5b are supported, but H4c and H5c are not. In detail, manufacturing uncertainty (MU) moderates the relationship between 3DP implementation and economic performance (ECP) with $\beta = -.228$ and $p < .01$. It also moderates the relationship between 3DP implementation and environmental performance (ENP) with $\beta = -.243$ and $p < .01$. However, it does not moderate for the relationship of 3DP with social performance. Regarding supply uncertainty (SU), it does moderate the relationship between 3DP implementation and economic performance (ECP) with $\beta = .127$ and $p < .05$; SU also moderates the relationship between 3DP implementation and environmental performance (ENP) with $\beta = .122$ and $p < .05$. Once again, this form of uncertainty does moderate the relationship of 3DP with social performance.

5.2. Moderation plots

To further facilitate the interpretations of these data, in Figure 2 the authors plot all the significant interaction effects found through this research (Aiken and West 1991; Dawson

Table 6. Hierarchical regression results.

	Economic performance			
Independent variables	Model 1	Model 2	Model 3	Model 4
Management Position	.142	.042	.058	.063
Year of work	−.200	−.073	−.023	.012
3DP Implementation Level (3DP)		**.300****	.271**	.255**
Manufacturing Uncertainty (MU)			−.131*	−.172**
Supply Uncertainty (SU)			−.100	−.113
3DP x MU				**−.228****
3DP x SU				**.127***
Adj R^2	.010	.090	.120	.149
ΔR^2	.017	.082	.037	.035
F change	2.332	23.986**	5.495**	5.484**
	Environmental performance			
Independent variables	Model 1	Model 2	Model 3	Model 4
Management Position	.188	.089	.114	.120
Year of work	−.104	.022	.101	.135
3DP Implementation Level (3DP)		**.298****	.251**	.232**
Manufacturing Uncertainty (MU)			−.187**	−.233**
Supply Uncertainty (SU)			−.213**	−.223**
3DP x MU				**−.243****
3DP x SU				**.122***
Adj R^2	.005	.084	.188	.221
ΔR^2	.013	.081	.109	.039
F change	1.713	23.440**	17.774**	6.598**
	Social performance			
Independent variables	Model 1	Model 2	Model 3	Model 4
Management Position	.085	−.023	.001	.003
Year of work	−.297*	−.159	−.084	−.065
3DP Implementation Level (3DP)		**.325****	.281**	.273**
Manufacturing Uncertainty (MU)			−.199**	−.221**
Supply Uncertainty (SU)			−.151*	−.157*
3DP x MU				−.119
3DP x SU				.067
Adj R^2	.018	.112	.191	.194
ΔR^2	.026	.097	.084	.010
F change	3.482*	28.833**	13.708**	1.581

*Significant at $p< .05$; **Significant at $p< .01$.

2014). Parts A and C in Figure 2 refer the plots results for H4a and H4b respectively, which shows that the MU weakens the relationships between 3DP implementation with ECP and ENP while MU increases from low to high. Parts B and D in Figure 2 are the plots for H5a and H5b respectively, which show, however, the relationships between 3DP implementation with ECP and ENP have been strengthened while the SU increases from low to high, and this is a conflict result compared to the hypotheses H5a and H5b.

6. Discussion and implications

This section discusses the results from data analysis in section 5 and associated contributions to both literature and theories (6.1), whilst indicate the practical implications that could be adopted by industrial specialists and police makers (6.2).

6.1. Theoretical contributions

This study makes significant theoretical contributions towards both existing research gaps and underpinning theories.

6.1.1. 3DP contributing to TBL

First, this work contributes to the 3DP literature by confirming a positive relationship between 3DP implementation and sustainability performance. To echo previous literature, as per the technique principle of 3DP, one of the key advantages brought by 3DP is to reduce production complexity (Davies et al. 2022; Li et al. 2019; Piller, Weller, and Kleer 2015; Wagner and Walton 2016). This can include having fewer production processes, using less and greener materials, and having better control resulting in better product quality (Achillas et al. 2015; Ford and Despeisse 2016; Huang et al. 2013; Kang, Li, and Bancroft 2020). From an economic performance perspective, with fewer production procedures, energy costs and waste discharge costs may be reduced; as less materials are needed, material costs decrease; better product quality reduced defect rates and the cost of warranties and returns (Achillas et al. 2015; Attaran 2017; Baumers et al. 2017; Chandima Ratnayake 2019). In terms of environmental performance, implementing 3DP in production minimised requirements for large varieties of materials meanwhile transit to more environmental-friendly materials (Achillas et al. 2015; Huang et al. 2013; Tziantopoulos et al. 2019), therefore lowering the consumption of rare or hazardous resources while also reducing energy consumption and pollutant emissions in both production and transportation (Di Lorenzo et al. 2024; Ford and Despeisse 2016; Huang et al. 2013; Peng et al. 2018). Besides, the 3DP production operations can reduce interaction with frontline dangers as well as workers' exposure to hazardous or noxious conditions

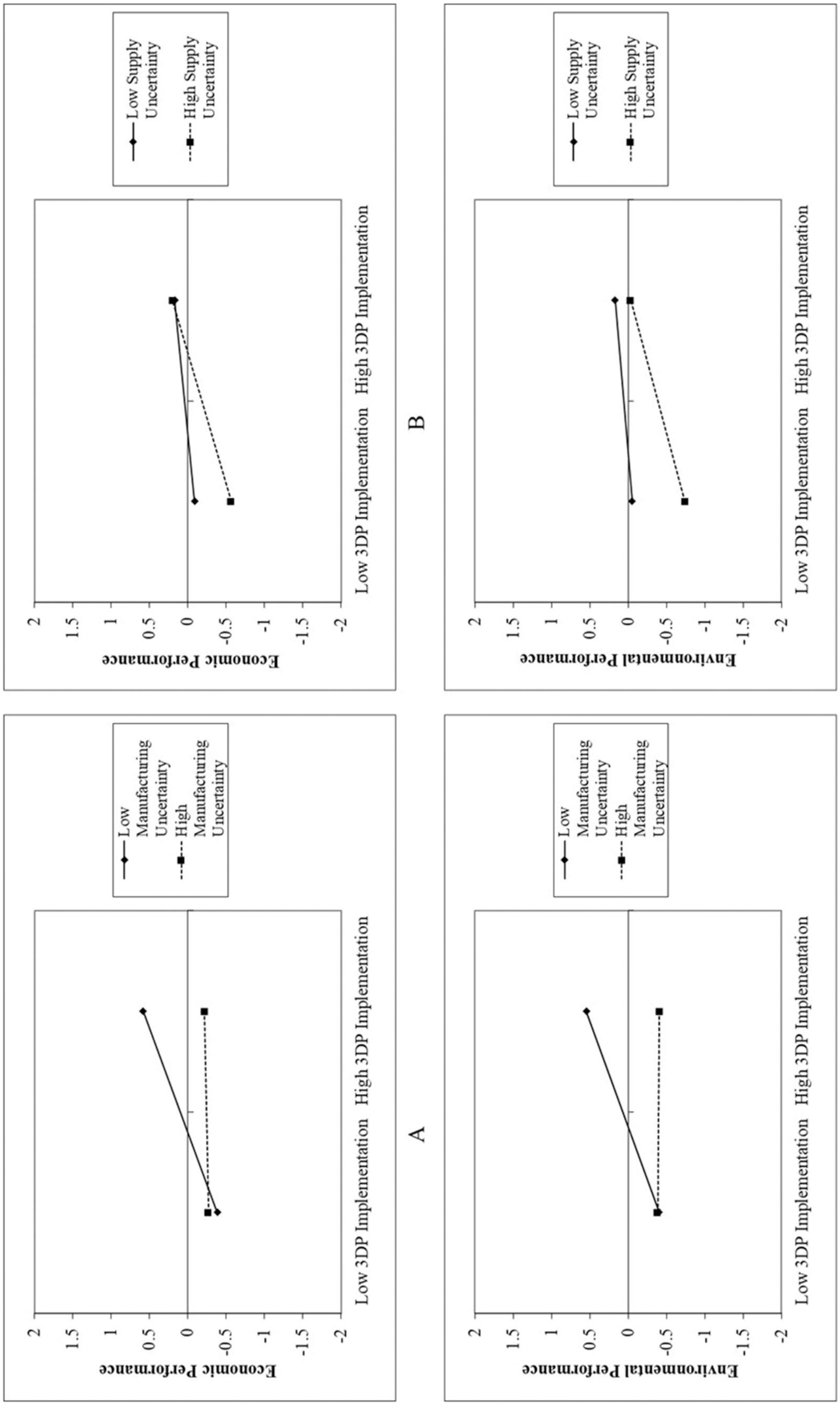

Figure 2. Interaction effect plots.

in the workplace, achieving a safer and healthier work environment (Achillas et al. 2015; Matos et al. 2019). Regarding the aspects of social performance, 3DP implementation can improve production flexibility and enhance customisation (Chandima Ratnayake 2019; Delic and Eyers 2020; Eyers et al. 2022), which reportedly contributes to customer satisfaction (Peron et al. 2025). Meanwhile, this adoption of advanced technology boosts firm reputation and improves the skill level of internal staff members (Bonekamp and Sure 2015; Leitao et al. 2020; Matos et al. 2019), which satisfies both employees and stakeholders. Therefore, as the RBV suggests, 3DP implementation helps enhance firms' manufacturing capabilities by reducing complexity and increasing quality, allowing the adoption of a more balanced and optimal resource supply structure, and improving production flexibility and skills level, thus strengthening the firm's competitive advantage in cost efficiency, resource efficiency, and social satisfaction, therefore contributing to the improvement of economic performance, environmental performance, and social performance respectively.

6.1.2. Environmental uncertainty: a double-edged sword

Moreover, this study is the first empirical examination of environmental uncertainty involving 3DP implementation. In contrast to the well-acknowledged role of environmental uncertainty acting as an often-negative moderator, this research found environmental uncertainty served as a double-edged sword when it came to moderating the level of benefits that brought 3DP implementation to sustainability performance. It suggests a new perspective: environmental uncertainty can be a challenge but also an opportunity for firms.

Specifically, internal environmental uncertainty MU plays a negative role when moderating the impacts brought by 3DP implementation on ECP and ENP, but the external environmental uncertainty SU acts as an accelerator. Which side of the double-edged sword that applies mainly depends on whether there is a good fit between the firm environment and acquired resources. For MU, in reflection to the literature, a negative correlation between MU with ECP and ENP has been well established (Bhatnagar and Sohal 2005; Ho et al. 2005; Nguyen et al. 2023). An increase in MU will often cause the production plan to be adjusted or even paused (Aitken et al. 2016; Davis 1993; Ho et al. 2005), which not only increases operational and production costs, but also reduces resource and energy efficiency (Ng et al. 2015; Wong, Boon-Itt, and Wong 2011; Wang et al. 2023). Meanwhile, 3DP implementation may bring more MU as a new production technology (Ho et al. 2005), though it can also sometimes improve production flexibility (Delic and Eyers 2020; Eyers et al. 2022) which may help to mitigate manufacturing uncertainty (Sreedevi and Saranga 2017). However, previous studies indicated that 3DP implementation in production is still in a developing stage and has not been widely accepted as a standard production technology to fully replace the traditional one (Davies et al. 2022; Tziantopoulos et al. 2019; Wagner and Walton 2016). Therefore, with two production methods maintained, firms may face even greater uncertainties and higher risks (Sreedevi and Saranga 2017), especially when the two methods have not been integrated well. Therefore, 3DP implementation and a high MU internal environment aren't likely to allow for a good fit, so according to contingency both ECP and ENP decrease.

Regarding SU, the results inherently show SU can strengthen the positive relationship between 3DP implementation and sustainability performance, even though SU individually normally negatively affects sustainability performance (Davis 1993; Ho et al. 2005; Yang and Zhao 2016). This different moderating role of SU compared to MU is reasonable because MU is generated by the focal company internally, but SU comes from suppliers externally. Part of the reason that SU acts as an accelerator is that, when implementing 3DP into an environment with a high level of SU, the supply uncertainty faced by the focal firm decreases rather than increases as hypothesised. This occurs when, as highlighted in the literature review, 3DP implementation simplifies the material supply configuration and makes the focal firm less dependent on suppliers by reducing the number of material transactions (Chandima Ratnayake 2019; Friedrich, Lange, and Elbert 2022; Petrovic et al. 2011; Tziantopoulos et al. 2019). The disturbances brought by 3DP implementation to the extant integration between the focal company and its suppliers may be the terminations of those unstable and risky relationships, so that eventually reduce the SU rather than boost it. Therefore, 3DP implementation would help more in mitigating or reducing uncertainty from suppliers in a high SU environment. Additionally, Delic and Eyers (2020) also found 3DP implementation helps achieve better sourcing flexibility, as it enables some of the key suppliers involved in the designing of components and finished products (Delic, Eyers, and Mikulic 2019). This can make transactions more transparent and boosts the trust integration between focal firms and their suppliers (Delic, Eyers, and Mikulic 2019), ultimately reducing SU during the collaboration whilst mitigating the impacts from SU (Merschmann and Thonemann 2011; Sreedevi and Saranga 2017). Therefore, 3DP implementation and a high SU external environment work as a good fit (Merschmann and Thonemann 2011; Sreedevi and Saranga 2017), so according to contingency both ECP and ENP increase.

However, there is no interaction significance found for SOP. This may be partially because MU and SU are more inclined to describe the operational environment so that does not directly affect the satisfaction of customers, employees, and stakeholders (Sreedevi and Saranga 2017). Therefore, it is possible that mediators exist in between to pass the effects of MU and SU to SOP. In other words, this may show that the positive relationship between 3DP implementation and SOP is more stable and primarily depends on the extent of 3DP adoption. Another possible explanation is that the improvement of SOP may need a bundle of resources and capabilities with complicated interactions among them, e.g. three-way or four-way interactions. However, companies may have not allocated sufficient attention or investment towards achieving this.

6.1.3. Contributions to underpinning theories

This work not only contributes to the RBV and contingency theories respectively by deploying them, but also contributes to both by developing a joint usage of RBC. In doing so, this study provides a comprehensive and complementary theoretical explanation of the impact of 3DP implementation on sustainability performance, which has been moderated by environmental uncertainty. The work deploys the RBV (Hart 1995) to theorise how 3DP implementation, a strategic technology resource, enhances firms' manufacturing capabilities through reducing production complexity, simplifying supply configuration and increasing manufacturing flexibility, ultimately leading to improved competitive advantage and resulting in positive improvements of triple bottom lines. In addition, this work adopts contingency theory at the resource level (Donaldson 2001; Lam et al. 2019; Sousa and Voss 2008) to critically examine the 3DP implementation and explore the possible fit between 3DP implementation and its applied environmental uncertainty. The paper also reviews the dimension of environment contingency from both an internal MU and external SU perspective, compared to the one-sided view in most extant research. We theorise how these different dimensions under environmental uncertainty represent different levels of environmental support and requirements for 3DP implementation, thus moderating the impact of 3DP implementation on sustainability performance. Taken together, this work identifies a match and connection between RBV and Contingency as RBC by emphasising the fit between distinctive resources with its implementation environment for optimal performance. Meanwhile, we believe this developed joint theory RBC can serve as a useful theoretical foundation for future 3DP-infused research, but also encourages future research to apply theories innovatively rather than applying 'the same old methodologies' (MacCarthy et al. 2013). In particular, it urges researchers to shift their focus from the discussion of 3DP's technological features and industrial applications (Attaran 2017; Dohale et al. 2024) to a more strategic view on impacts following 3DP implementation.

6.2. Managerial and policy implications

Our study represents one of the initial research efforts examining the impact of 3DP implementation from a TBL perspective, drawing on quantitative data sourced directly from a wide-range of industrial respondents. Such an approach is important yet is relatively uncommon in literature. As such, the study can make several important contributions to commercial practice.

Firstly, our study provides evidence that 3DP can make a positive contribution to the sustainability performance of firms. This is an important consideration; many firms are under regulatory and shareholder pressure to improve all aspects of their sustainability performance, and so such evidence can be useful to senior management in deciding their production strategies. From a practical sense, these observations may affect the degree to which managers choose to implement 3DP in their operations. Whilst 3DP has received extensive public attention in recent years, the current level of adoption is still relatively low (Davies, 2020; Thomas-Seale et al. 2018; Tziantopoulos et al. 2019), an issue often linked to lack of practitioner knowledge (Peron et al. 2025) and difficulties in understanding the impact of adopting the technologies (Ernst and Young, 2016; Leitao et al. 2020; Shukla, Todorov, and Kapletia 2018). Through our research, this study provides a detailed explanation of the technologies, their adoption, and importantly provides quantitative data over the potential positive impact they may have. Such evidence would be useful in making the case for adopting 3DP within operations, and also for defending when such choices would be inappropriate.

Secondly, our study offers an alternative perspective for managers in the strategic management and exploitation of uncertainty. Whilst uncertainty is typically considered as a negative factor to be avoided, this research has revealed a new view that environmental uncertainty is a challenge but could also be an opportunity for firms as a double-edged sword. We show that MU and SU play reversed roles when interacting with 3DP implementation to performance, meaning that firms will benefit more in terms of economic and environmental performance when 3DP is implemented in a low-level MU environment and/or a high-level SU environment. In terms of MU, this is particularly interesting since 3DP is often advocated in manufacturing wherever possible, which is harder for less flexible manufacturing processes to accommodate. Our findings here suggest that there are opportunities here for exploitation that firms may not be fully aware of, which in turn could form part of a distinctive competitive strategy. Furthermore, the moderation results of SU also indicate that the implementation of 3DP can help firms to guard against external environmental supply uncertainty, and thus firms could consider using it as an approach to achieve more resilience in response to external uncertainty. This extends existing research which suggests 3DP offers potential to increase resilience in the supply chain (Naghshineh and Carvalho, 2022), providing quantitative evidence to support this proposition. We can see practical examples of this from the Covid-19 pandemic, whereby 3DP was employed in industries where conventional supply was either unpredictable as a result of supply chain disruption, or had failed entirely (Tareq et al. 2021). This was particularly evident in examples such as healthcare, where firms employing 3DP could strategically deploy their technologies to gain access to previously inaccessible markets, capitalising on the SU (Huang et al. 2021).

We note also that there are associated implications arising from our work for policymakers. There has been much enthusiasm around 3DP for promoting economic sustainability through initiatives such as near-sourcing or reshoring etc (Moradlou and Tate 2018), however our findings extend to improvements for the TBL. Policymakers may wish to support adoption of 3DP through more helpful policies and regulations to accelerate firms moving into the digital production era. Meanwhile, these supportive policies contribute to creating more environmental friendly, safer, and healthier manufacturing sectors that promote high-skilled job opportunities, benefitting society. The non-significant findings of the moderating roles on social performance indicate that it is more difficult to improve social performance as the affecting factors are complicated. Other studies have already demonstrated the complexity of 3DP's relationship with social sustainability (Beltagui, Kunz, and Gold 2020b), however given the other positive results found in this work it may be worthwhile policymakers considering the opportunities to exploit potential social performance benefits through the promotion of 3DP (Matos et al. 2019; Asokan et al. 2022).

7. Limitations and future research

Whilst this paper has made several novel contributions to knowledge, as with all research it comes with several inherent limitations. Despite much enthusiasm in academia, and increasing commercial uptake, 3DP remains a fairly emergent technology. Industry is still getting to grips with how to best manage such technologies in practice, and so we recognise that respondents to our survey may have varying degrees of understanding of the concepts, which is a common criticism of survey methodology in any piece of research. Unlike a screwdriver or a wrench that has narrowly defined applications and modes of operation, 3DP offers enormous flexibility in deployment (Eyers et al. 2018), and so different managers may have very different perceptions of the technology. To counteract this, we insisted that respondents were au fait with 3DP, and that they actually employed the technologies within their operations. These precautions noted, we nevertheless highlight that perceptions on the technologies may vary, for which further work could explore different interpretations. Additionally, we indeed appreciate other factors that could be considered for control, e.g. property rights and design innovation, that is related to the 3D design process while adopting the technology, in future follow-up studies with an expansion of the scope.

The research draws upon the collection of data using a survey, for which 266 usable responses were received. In 3DP research such a response is quite large, and we were pleased to reach such a wide range of organisations. However, we acknowledge that each firm is represented by a single managerial response, and whilst we show in our work that there is no statistical evidence of a single-response bias, it would have been preferrable to collect the responses of multiple responses for each firm.

A third limitation concerns the temporal nature of the data collected. This is a cross-sectional study, and as such represents the perspectives of managers at a single point in time. Future research can try to collect longitudinal data or dyadic data with time-lagged either through multiple collection for several years or leave a time gap between data collection for independent variables and dependent variables.

The collection of data solely from China represents a further limitation of the work. As China is a dominant player in world manufacturing, collecting data from this region is helpful to form representative understandings of commercial manufacturing. However, we acknowledge that future studies would benefit from drawing on perspectives from a wider proportion of the world's manufacturing countries.

Finally, in terms of methodology, the selection of an online survey does result in several well-established constraints for the study. For example, whilst we enjoy a good number of results from a wide range of anonymous companies, and there would be challenges around maintaining anonymity, future studies might wish to be more prescriptive and could consider using follow-up interviews with respondents to complement the survey data.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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