This manuscript has been published in Technovation:
https://www.sciencedirect.com/science/article/pii/S0166497217308519
Please do not distribute or cite it without first contacting the authors.

Effective use of 3D printing in the innovation process

*Marina Candi[1] and Ahmad Beltagui[2]

*Corresponding author

[1]Center for Research on Innovation and Entrepreneurship, Reykjavik University School of Business, Reykjavik, Iceland, marina@ru.is

[2]Operations and Information Management Department, Aston Business School, Birmingham, United Kingdom, a.beltagui@aston.ac.uk

Acknowledgements

Part of the funding for this work was provided from the European Union's Seventh Framework Programme for research, technological development and demonstration under Grant agreement no. 324448 and from the University of Wolverhampton's Early Researcher Award Scheme. The authors are grateful to Abda Aslam for assistance with pilot data collection.

Abstract

Three-dimensional printing (3DP) is touted as a core element of a new industrial revolution, in which digitization, information and connectivity transform product innovation. However, while the purported benefits of 3DP are compelling, existing research suggests that expected benefits of advanced manufacturing technologies are rarely realized in practice. This research addresses the timely question of how to make effective use of a new digital technology. A theoretical framework based on Resource Orchestration Theory is used to analyze survey data collected from 177 US firms that use 3DP for innovation. Internal and external moderators of the relationship between the use of 3DP in innovation and performance are identified. Orchestration, measured as the level of coordination between information technology and manufacturing functions, and technological turbulence, are both found to act as positive moderators. These results indicate that adopting 3DP for innovation brings greater benefits to firms that orchestrate the functions involved in its implementation and use. In other words, how resources such as 3DP are used is at least as important as possessing them. Furthermore, 3DP is likely to be more effective in environments facing external uncertainty than under less turbulent conditions. With manufacturing becoming increasingly digitized, these results have implications for future innovations in manufacturing technology.

Introduction

Digitized manufacturing technologies are expected to bring dramatic benefits to companies and industries, but such benefits are seldom realized in practice. Therefore, an important research question is, *what differentiates firms that achieve performance benefits by using digitized manufacturing technology from those that do not?*

Faced with uncertainties in both demand and technology, product innovators are advised to turn to three-dimensional printing (3DP) to become flexible and agile (D'Aveni, 2015; Weller et al., 2015) and join the much vaunted *Industry 4.0* (Rüßmann et al., 2015; Lasi et al., 2014). The internet has changed business processes by altering patterns of communication (Overby, 2008; Mishra et al., 2007), as well as enabling new forms of collaboration in integrated and connected manufacturing ecosystems. 3DP is the latest in a long line of digital technologies—including Computer Numerically Controlled (CNC) machines and Enterprise Resource Planning (ERP) systems—which have promised to revolutionize the way new products are created. Nevertheless, despite the promise of such technologies, managers remain vexed by how to achieve the expected benefits, with most firms reporting no improvement in performance (Swink and Nair, 2007; Brandyberry et al., 1999). As 3DP is increasingly used in many industries, this research investigates how it can be *effectively* used in the innovation process. To this end, the research examines internal and external forces that may influence the extent to which firms are likely to realize performance benefits from 3DP and other digitized manufacturing technologies.

The term 3DP refers to a range of additive manufacturing processes, which create products by building up layers of plastic, metal or other material, directly from digital design files (Holmström and Partanen, 2014; Petrovic et al., 2011). This definition captures a broad spectrum of processes and technologies, most of which use light or heat to create physical objects from polymers, powders or filaments, without the cost penalties traditionally associated with tooling and low volume production (Weller et al., 2015). These processes include the laser hardening of liquid polymer (Stereolithography, SLA), laser melting of metal powder (Selective Laser Sintering, SLS) and extrusion of molten plastic (Fused Deposition Modelling, FDM) into solid objects. These processes all combine digital and physical elements, embedding information technology (IT) into manufacturing processes. Indeed, due to a complex combination of elements, 3DP is more effectively considered in terms of an ecosystem of innovations than isolated technologies (Piller et al., 2015). As such, adoption of 3DP extends the digital transformation of information based processes into the more challenging realm of the digitization of physical processes (Rindfleisch et al., 2017; Overby, 2008). Business processes such as design (Marion et al., 2015), procurement (Mishra et al., 2007) and supply chain integration (Liu et al., 2016) have been digitized through incorporation of ITs such as ERP, which demand a high level of coordination between functions (Gattiker and Goodhue, 2005). Adoption of 3DP demands even greater coordination and managerial effort because of the combination of digital and physical technologies involved.

In addressing internal forces likely to moderate the effectiveness of 3DP use in innovation, this research builds on two complementary perspectives from information systems and strategic management. The information systems literature argues that use of IT does not automatically ensure productivity improvements. Instead, the focus must be on understanding *effective use*, to achieve expected benefits (Orlikowski, 2000). IT can be used effectively only if it offers a useful representation of the physical process that it seeks to digitize (Burton-Jones and Grange, 2013). In the case of 3DP, the representation theory of effective use would require the IT to be capable of sufficiently representing physical product development and manufacturing, demanding alignment between IT and manufacturing capabilities. Secondly, the emerging Resource Orchestration Theory presents the parallel argument that firms' possession of capabilities (including IT and manufacturing capabilities) does not automatically produce competitive advantage (e.g. Liu et al., 2016; Helfat et al., 2007). Instead, managers' ability to structure, bundle and leverage resources and capabilities determines effectiveness (Sirmon et al., 2011). In the case of 3DP, this suggests that the alignment of IT and manufacturing capabilities drives the ability of a firm to obtain advantage from the adoption of these technologies.

In addition to internal forces, the characteristics of the competitive environment may moderate the effectiveness of new technologies. Turbulence in the competitive environment calls for flexibility (Beach et al., 2000), which is among the key advantages attributed to the use of 3DP (Weller et al., 2015). Flexibility here refers to the ability to cost-effectively adapt business, including the variety of products developed, when faced with uncertainty. Flexibility helps firms to cope with the rate of change and unpredictability of technology, referred to as technological turbulence (Sethi and Iqbal, 2008; Tatikonda and Montoya-Weiss, 2001). Therefore, this research considers the moderating influence of technological turbulence.

Using data collected from managers of 177 US firms that use 3DP, this research examines these firms' use of 3DP in their innovation processes and relationships with performance outcomes. Empirical evidence that the use of 3DP in innovation is positively related with performance is offered. Additionally, the moderating effects of the level of coordination between IT and manufacturing and perceived technological turbulence are taken into account and both are found to positively moderate the direct relationships. The results suggest that appropriate internal conditions in terms of functional co-ordination and challenging external conditions in terms of technological turbulence influence the effective use of this new technology.

The contributions of this research are threefold. Firstly, the Resource Orchestration Theory is empirically tested, supporting extant research about the importance of cross-functional integration in product manufacturing (Swink et al., 2007; Bharadwaj et al., 2007) in the novel context of 3DP. Resource Orchestration Theory implies that resources—including digital technologies—do not bring about competitive benefits unless they are appropriately managed and coordinated within the firm. This research contributes by empirically testing the moderating effect of manufacturing-IT coordination to explain effective use of 3DP in innovation. Thus, this research contributes to the growing literature on 3DP, which is contextualized through application of a theoretical framework to allow generalizability. Secondly, the research contributes to knowledge about flexibility and environmental uncertainty by testing the moderating influence of the external force of technological turbulence. Finally, by demonstrating positive relationships between the use of 3DP in the innovation process and performance outcomes, including innovation performance, important implications are offered for innovation theory and practice.

The rest of this article is organized as follows: In the next section the theoretical background for the research is presented. First, a summary of characteristics of 3DP that should be considered by managers is provided. Next, the Resource Orchestration Theory is examined as an explanation for differences in performance among firms adopting the same technology. The specific benefits of 3DP for innovation are discussed in relation to the literature on flexibility and technological turbulence. This is followed by the development of hypotheses based on these bodies of literature, which together make up the research model. The methodology used to test the research model is described, followed by a report of results. The article closes with a discussion of implications for theory and practice, limitations and directions for future research.

Background

3D Printing (3DP)

3DP processes differ from traditional manufacturing in a number of key ways. Firstly, 3DP is additive, i.e. it creates solid objects by adding material in layers, rather than removing material to create a desired shape. This characteristic offers the potential to reduce raw material waste, although energy use may be higher than for traditional processes (Huang et al., 2013). Secondly, 3DP goes directly from digital model to physical object, without the need for tooling. This enables on-demand production with very short lead times (Petrovic et al., 2011). It also facilitates distributed manufacturing, since resources can be shared through digital transfer of designs for production closer to their point of use (D'Aveni, 2015). This offers clear benefits when demand is low, intermittent, or geographically distributed, for example in spare parts supply chains (Khajavi et al., 2014). Thirdly, manufacturing using 3DP is not subject to the economies of scale that hold for traditional manufacturing since there is no cost penalty associated with low volume production (Mellor et al., 2014). As a result, on demand production of customized products to suit the needs of individual customers becomes economically viable (Weller et al., 2015).

3DP technologies were first patented and commercialized in the late 1980s and early 1990s by firms such as 3D Systems, Stratasys and EOS (Bandyopadhyay et al., 2015). For many years these technologies were referred to as rapid prototyping tools. Technology maturity and expiry of patents have stimulated development and adoption along with a growing belief that 3DP technologies can be used for rapid manufacturing, not just prototyping (Ruffo et al., 2006). As yet, however, the use of 3DP for end use products and components is largely limited to niche industries. For example, whereas producing tools on the International Space Station is a logical application, the commercial viability of doing so on earth is questionable (Holweg, 2015).

Resource Orchestration Theory

Adoption of 3DP in product development firms is believed to be approaching mainstream levels (D'Aveni, 2015), but resultant competitive benefits have not been widely evident. The Resource Based View of the firm suggests that developing or acquiring 3DP capabilities should bring about competitive advantage. This view fails, however, to account for synergies among capabilities (Liu et al., 2016) or for the role of management in extracting their benefits (Helfat et al., 2007). Resource Orchestration Theory addresses these issues by proposing that a combination of resources, capabilities and managerial acumen holds the key to performance (Chadwick et al., 2015). From this perspective, gaining performance outcomes from technological capabilities depends on alignment among activities in the organization. For example, a firm's ability to translate a supply chain management competence into competitive advantage can be dependent upon its ability to leverage IT competence (Liu et al., 2016; Chakravarty et al., 2013), while the IT and supply chain management functions alone may not generate improved performance without sufficient alignment between them (Yao and Zhu, 2012).

A considerable body of literature demonstrates that adopting managerial or technological innovations does not always result in success (e.g. Ketokivi and Schroeder, 2004). Possessing resources that are valuable, rare, inimitable and non-substitutable undoubtedly offers firms an advantage, but possession is not sufficient as firms with apparently identical resources can experience heterogeneous performance. Considering the distinction between productive and administrative resources made by Penrose (1959) allows the importance of managers' resource orchestration role to be taken into account. A firm uses its productive resources to create value and generate revenue, but its use of administrative resources allows these productive resources to be organized and used effectively. In other words, how resources are used is at least as important as what resources are possessed (Hansen et al., 2004). A key aspect is the synchronization of actions to deliver on strategy. Managers must match the level and type of resources needed for implementing strategy to the particular strategy adopted.

Helfat et al. (2007) argue that resource orchestration is particularly important where markets are not self-regulating through price effects on supply and demand, for example in markets for intangible assets that are not easily priced, or those affected by technological turbulence. In the absence of self-regulating markets, managers take on an important resource allocation role, which is not acknowledged by classic economic theory. This entails the two key processes of selection and deployment (Helfat et al., 2007). Firstly, managers identify resources, invest in them and design the organizational structures and business models to manage these resources. Secondly, they are required to build, align and adapt co-specialized resources, by providing a vision and nurturing innovation as a result. This perspective stems from a view that management is principally about the coordination of the activities of two or more people in an organization.

Resource Orchestration Theory posits that synchronization of processes and coordination of capabilities holds the key to competitive advantage. It therefore places emphasis on managers and how they manage resources, rather than on the firm's possession of resources alone. This has been investigated through the depth of the organization, examining orchestration across levels of hierarchy (Chadwick et al., 2015). It has also been studied across the breadth of the organization, examining synergies between functions, e.g., supply chain integration and IT competence (Liu et al., 2016). Such studies highlight how the combination of capabilities, rather than the capabilities alone, contribute to firm performance (Bharadwaj et al., 2007; Rai et al., 2006). In contrast to studies measuring direct impacts of technology on performance (e.g. Lu and Ramamurthy, 2011), the present research takes a resource orchestration perspective on 3DP by also examining how synergies between capabilities influence the effective use of technology.

Flexibility and Technological Turbulence

The value of 3DP, in common with other digitized manufacturing technologies, lies largely in its ability to increase flexibility, defined as the ability to react to uncertainty in the external environment (Beach et al., 2000). Environmental uncertainty refers to the rate of change and unpredictability of factors such as customer demand, competition and technology (Patel et al., 2012). Flexible manufacturing systems are those that cope with environmental uncertainty with little or no performance penalty (Upton, 1994; Mascarenhas, 1981). For example, if 3DP enables a supplier to react quickly to customer demand, regardless of place and timing (Khajavi et al., 2014), then it offers a valuable source of flexibility. Flexible systems have considerable implications for market structures and for the competitiveness of innovating firms (Bessant, et al., 2005), allowing them to create different outputs from the same inputs as rivals (Weller et al., 2015).

Flexibility can be utilized reactively, to accommodate unpredicted uncertainty. It may also be applied proactively, in order to gain a competitive edge over rivals and attract customers (Gerwin, 1993). The shortened development lead times 3DP offers can allow product developers to quickly alter or customize products to meet new market trends faster than competitors. While market uncertainty is important, the rate and unpredictability of technology in an industry, referred to as technological turbulence, is regularly a strong driver of flexibility (Candi et al., 2013; Sethi and Iqbal, 2008; Tatikonda and Montoya-Weiss, 2001). Managers' perceptions of technological turbulence encourage them to look for opportunities to innovate (Jaworksi and Kohli, 1993), to seek flexibility in their manufacturing systems (Oke, 2013), and to consider new technologies for their operations (Autrey et al., 2010). Where technology is relatively stable, it will be more advantageous to use established and more cost-effective manufacturing methods. For instance, polymer based 3DP provides a flexibility advantage since it does not require costly tooling as injection molding does. When customization of products is important, this may be an important factor. Conversely, when products are standardized and a large volume will be produced over time, it is generally practical to invest in tooling in order to achieve lower unit costs (Baumers et al., 2016). For example, 3DP has been applied to the production of hearing aids, but only for in-ear inserts, rather than the more sophisticated electronic components (Sandström, 2016). In contrast, the motorsports sector, where the degree of technological turbulence facing engineers has been compared to battlefield conditions (Cross and Cross, 1996), is a hotbed of 3DP activity. For example, the McLaren Formula 1 team announced a partnership with Stratasys, to enable trackside 3DP for parts and tooling during tests and races (Stratasys, 2017).

Hypothesis Development

While the proposed advantages of 3DP suggest that adoption of this technology could improve performance, there are challenges to be overcome and, as is common with new technologies, 3DP has not yet made much difference to performance (Sandström, 2016; Ketokivi and Schroeder, 2004; Brandyberry et al., 1999). Internal and external factors that may override or overcome the challenges are examined. Resource Orchestration Theory suggests that to achieve competitive benefits from new capabilities, there should be effective coordination between functions in the organization; therefore the moderating effect of internal manufacturing-IT coordination is examined. Meanwhile external technological turbulence helps to explain conditions under which a flexible but potentially expensive manufacturing technology such as 3DP could be of value. Therefore, the moderating effect of technological turbulence is also investigated. The following sections explain the empirical and theoretical justifications for the research model shown in Figure 1.

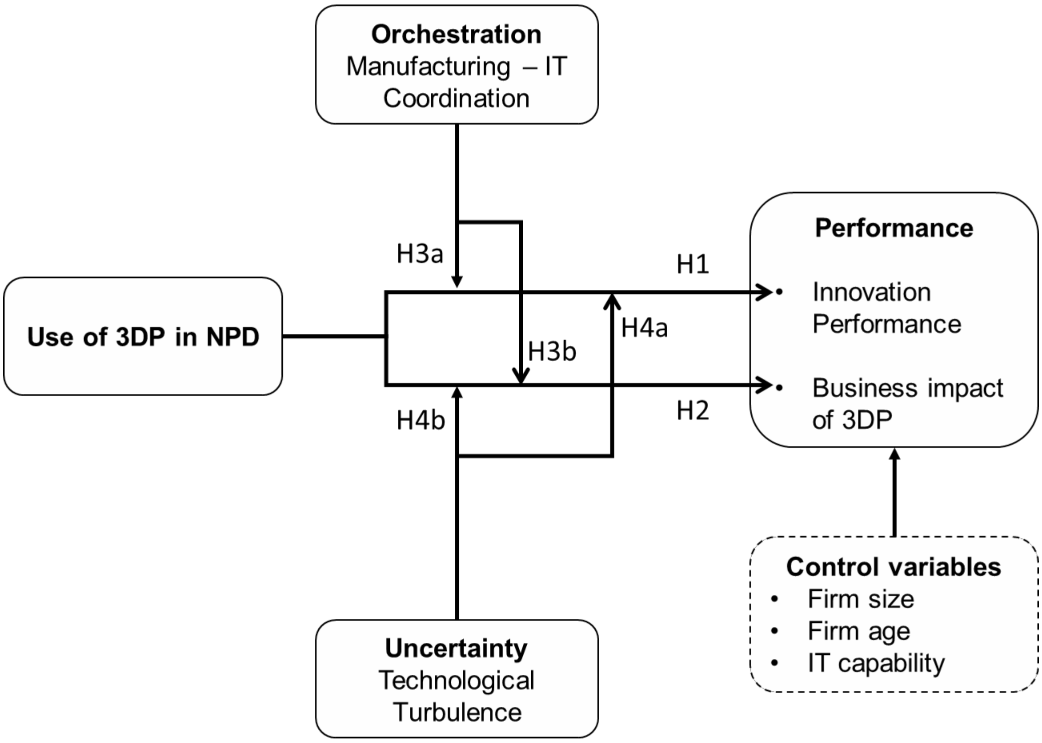

Figure 1: Research model showing hypothesized direct and moderating effects as well as control variables.

3DP use in innovation and performance

This research examines relationships between the use of 3DP in innovation and two performance variables. In the first place, in keeping with the focus on innovation, relationships with innovation performance are examined. In the second place, a broader view is taken, by examining relationships between the use of 3DP in innovation and overall business benefits stemming from the use of 3DP.

Digital technologies, such as 3DP, can contribute to innovation performance in at least two relevant ways. Firstly, conducting business processes digitally can improve efficiency and help cope with uncertainty (Mishra et al., 2007; Lu and Ramamurthy, 2011). Secondly, IT helps to coordinate and synchronize business functions such as innovation and product manufacturing (Bharadwaj et al., 2007). A particular concern for innovation is the integration between innovation and manufacturing, since the ability to develop successful products requires both (Swink et al., 2007; Chiva and Alegre, 2009). Innovation is increasingly reliant on the use of digital design tools, which in turn depend on the availability of suitable IT infrastructures (Marion et al., 2015). This is consistent with the growing recognition that IT should have a strategic rather than supporting role in business (Mauerhoefer et al., 2017; Bharadwaj et al., 2013).

Innovation is an information rich activity, which benefits from the use of IT to coordinate and manage digital data, for example offering access to information to all those involved in a project. By making the innovation process more digital, 3DP can help designers to share information at early stages of idea development, to quickly test working prototypes and share them with engineers in the development stage and to communicate with customers using physical models to elicit customer inputs or during product launch (Rindfleisch et al., 2017; Bogers et al., 2016; de Jong and de Bruijn, 2013).

Adoption of digital tools in innovation can help firms achieve successful outcomes from innovation projects (Marion et al., 2015). The connection between flexible manufacturing systems, such as 3DP, and product innovation is a logical one, which has also been empirically tested (Oke, 2013). As a result, the use of 3DP is expected to be related with higher innovation performance.

H1: The use of 3DP in innovation is positively related with innovation performance.

Theories developed in the field of Information Systems help explain how 3DP can contribute to business performance. The notion of process virtualization (Overby, 2008) highlights that processes may be performed more efficiently when IT is used to separate them from traditional physical or face to face methods.

This logic applies in the specific context of innovation, which often involves distributed virtual teams, rather than co-located ones, working together on projects. It is also evident in supply chain management, where digital tools are used for communication and integration between buyers and suppliers (Oh et al., 2012). A distinction can be made between using IT to make processes digital, and effective use of IT to achieve performance benefits. Drawing on representation theory, effective use is likely to occur when the IT offers an accurate representation of the physical processes it digitizes (Burton-Jones and Grange, 2013). 3DP helps to achieve this when it provides customers with accurate physical representations of products they might buy or offers engineers accurate digital representations of products they need to make. By going directly from digital to physical models, 3DP reduces the need for tooling, which in turn reduces the separation between a designed artefact and the corresponding manufactured one. As a result, the finished product should more closely resemble the envisaged design, while the lead time and cost of development should be reduced, thus contributing to product success. Thus, it is posited that the use of 3DP in innovation will be associated with the business impact that 3DP makes.

H2: The use of 3DP in innovation is positively related with the business impact of 3DP.

Resource Orchestration

Information systems can contribute to innovation performance in at least two relevant ways. Firstly, conducting business processes digitally can improve efficiency and help cope with uncertainty (Mishra et al., 2007, Lu and Ramamurthy, 2011). Secondly, IT can help to coordinate and synchronize business functions such as marketing, design and manufacturing (Bharadwaj et al., 2007). A particular concern for innovation is the integration between design and manufacturing, since the ability to successfully develop products requires both (Swink et al., 2007; Chiva and Alegre, 2009).

The ability of the manufacturing and IT functions to collaborate and to update or modify information systems is vital for effective use of technology. Bharadwaj et al. (2007) find that coordination between these functions contributes to a firm's IT capability, which in turn contributes to performance. Similarly, it can be expected that the effective use of 3DP in innovation is contingent upon the ability to coordinate manufacturing and IT functions, since 3DP is based on a combination of digital and physical processes relying on both IT and manufacturing expertise.

Gattiker and Goodhue's (2005) study of ERP provides insights for digitization. They find the ability to customize systems to be related to performance improvements and identify a time delay in achieving the benefits. The implication is that coordination with the IT function, which can support customization of information systems, will help benefits be achieved and that a closer working relationship between IT and other functions may help benefits to be realized more quickly.

As per Mishra et al.'s (2013) model, integration competence acts as a higher level dynamic capability, which enables a firm to develop and deploy a functional competence. They offer empirical results to demonstrate that procurement integration is an antecedent to digital procurement. Similarly, integration, in this case between manufacturing and IT, may be a necessary condition for gaining benefits from 3DP. Thus, the level of coordination between IT and manufacturing can be expected to moderate the relationships between the use of 3DP in innovation and performance outcomes.

H3a: IT-Manufacturing coordination positively moderates the relationship between the use of 3DP in innovation and innovation performance.

H3b: IT-Manufacturing coordination positively moderates the relationship between the use of 3DP in innovation and the business impact of 3DP.

Technological Turbulence

The dynamics of the competitive environment need to be taken into account in innovation management (Drejer, 2002), more specifically technological turbulence (Fernández, et al., 2010; Lee and Wong, 2011). Rapid changes in technology, commonly referred to as technological turbulence, create uncertainty, but also bring about new opportunities (Narver et al., 2004). Flexibility in innovation projects has been proposed as a means of coping with high levels of turbulence (Eisenhardt and Tabrizi, 1995; MacCormack et al., 2001; Li et al., 2010; Garud et al., 2008; Moorman and Miner, 1998). When managers perceive technological turbulence they attempt to adapt to the external pressures through flexibility (Candi et al., 2013; Buganza et al., 2009; Moorman and Miner, 1998). This is an area where the use of 3DP in innovation can be particularly beneficial (Weller et al., 2015) Flexibility can be achieved by using 3DP for rapid prototyping or advance testing with customers. This can, in turn, facilitate the adaptation of a new product to market conditions (Candi et al., 2013). Thus, because of its association with flexibility, technological turbulence can be expected to intensify the positive relationship between the use of 3DP in innovation and performance outcomes.

H4a: Technological turbulence positively moderates the relationship between the use of 3DP in innovation and innovation performance.

H4b: Technological turbulence positively moderates the relationship between the use of 3DP in innovation and the business impact of 3DP

Methodology

Data

To test the hypotheses, a sample of 321 managers (response rate 31%) in firms based in the United States was surveyed using a web-based survey. The sample was recruited by a panel research provider who sent the survey to a large number of potential respondents. Research has shown that results collected using panel surveys are not inferior to random samples as long as the respondents have the necessary knowledge to complete the survey (Krotki and Dennis, 2001; Pollard, 2002; Skinner, 2009). Taking this into account, a number of criteria were imposed to ensure that respondents were actually qualified to provide the information sought. The first criterion was that the firms they worked for should be engaged in developing products. The second criterion was that the firms should be interested in the use of 3DP or have actually used it. 3DP adoption is estimated to be below 20% in manufacturing firms, so the sample used is not representative of all firms (Schniederjans, 2017; D'Aveni, 2015). The purpose of the research is to examine factors related to effective use of technology, so the sample was deliberately drawn from firms that had used 3DP. The third criterion was that respondents should be knowledgeable about their firm's innovation and business operations. Without such knowledge, respondents would not be qualified to provide the required information. Finally, the firms should belong to one of the sectors listed in Table 1, which were expected to represent likely users of 3DP.

Table 1: Distribution of sample of firms surveyed among industry sectors.

Industry sectors	Proportion of sample
Aerospace & Defense	24%
Industrial Manufacturing	23%
Automotive	17%
Consumer Products Manufacturing	15%
Electronics Manufacturing	15%
ITC Equipment	6%

To test the hypotheses, only responses from those firms that were actually using 3DP for innovation (as opposed to only having expressed an interest in using 3DP) were used. Discounting cases with missing values, this resulted in a usable sample size of 177.

Variables and measurement model

As explained above, the hypotheses were tested using two dependent variables. First, three items to measure innovation performance were adapted from Griffin and Page (1996). Second, four items from Gattiker and Goodhue (2005) were used to measure the business impact of 3DP.

Innovation is generally seen to encompass three phases: idea generation, development and launch. Managers were asked about the extent to which their firms used 3DP in each of these phases and together these items were used to measure the extent of 3DP use in innovation.

Five items based on Bharadwaj et al. (2007) were used to measure the level of coordination between IT and manufacturing. Four items drawn from Jaworski and Kohli (1993) were used to measure technological turbulence.

Three control variables were included in the research model: firm size (number of employees), firm age (number of years from founding), and IT capability. Firm size may be related with a firm's ability to adopt new technologies, such as 3DP, and firm size is also likely to be related with the level of IT-manufacturing coordination needed. After all, in a very small firm, both functions may reside with the same people. Firm age may likewise be related with the focal variables. To bring the distributions of these variables closer to being normally distributed, the logarithms of the numerical values were computed. The overall level of IT capability present within a firm is likely to be related with the adoption of new digitization technologies and with improved innovation performance (Mauerhoefer et al., 2017) and so a control variable for IT capability was included in the research model, and was measured using four items based on Lu and Ramamurthy (2011).

Stata version 14.2 was used to conduct exploratory factor analysis with varimax rotation followed by confirmatory factor analysis to test the measurement model. The items included in the model are listed in Table 2. Measurement model fit statistics were very good (Shah and Goldstein, 2006) with a χ^2 of 382 (211 degrees of freedom), a root mean squared error of approximation (RMSEA) of 0.065, a comparative fit index (CFI) of 0.94 and a standardized root mean squared residual (SRMR) of 0.05.

Table 2: Variables, items and item loadings (λ). For all questions, answers ranging from 1 to 5 were offered.
χ^2 =382 (211 degrees of freedom), RMSEA=0.065, CFI=0.94, SRMR=0.05

Variables	Items	λ
Use of 3DP in innovation	Please indicate the extent to which your company uses 3D Printing in each of the following stages of innovation:	
	Idea generation phase	0.75
	Development phase	0.83
	Launch/commercialization phase	0.65
IT-manufacturing coordination	Please indicate the degree to which you agree or disagree with the following statements:	
	Our IT staff coordinate frequently with manufacturing to increase manufacturing's understanding of the information systems' capabilities	0.78
	Our IT staff coordinate frequently with manufacturing to help develop an understanding of manufacturing's technical requirements for the information systems	0.82
	Our IT staff work with manufacturing to customize information systems to our needs	0.81
	Our IT staff help manufacturing obtain relevant information and reports from the information systems	0.81
	Our IT staff provide ongoing training on the use of information systems	0.81
Technological turbulence	Please indicate the degree to which you agree or disagree with the following statements:	
	The technology in our industry is changing rapidly	0.86
	Technological changes provide big opportunities in our industry	0.78
	A large number of new product/service ideas have been made possible through technological breakthroughs in our industry	0.79
	Technological developments in our industry are substantial	0.92
IT capability	Please indicate the degree to which you agree or disagree with the following statements:	
	We constantly keep current with new information technology (IT) innovations	0.76
	We are capable of, and continue to experiment with, new IT as necessary	0.79
	We have a climate that is supportive of trying out new ways of using IT	0.88
	We constantly seek new ways to enhance the effectiveness of IT use	0.79
Business impact of 3DP	Please indicate the degree to which you agree or disagree with the following statements:	
	In terms of its business impacts, 3D Printing has been a success	0.80
	3D Printing has seriously improved this company's overall business performance	0.84
	From the perspective of this company, the benefits of 3D Printing outweigh the costs	0.95
	3D Printing has had a significant positive effect on this company	0.83
Innovation performance	Thinking about the last calendar year, please indicate the degree to which you agree or disagree with the following statements:	
	We played a leading role in market activities in our market	0.81
	We introduced more new products/services on the market than our competitors	0.79
	We adopted more technological innovations than our competitors	0.64

Data quality

Table 3 shows summary statistics and pairwise correlations between the variables. Some relatively high correlations between independent variables are noted, which raises the issue of potential multicollinearity. Grewal et al. (2004) offer a set of guidelines for detecting potential multicollinearity for various ranges of correlations between independent variables. For the range 0.41-0.59, of which there are three instances in Table 3—all with the control variable for IT capability—Grewal et al. show that provided reliability is strong (over 0.7), and R^2 is acceptable and sample size is sufficiently large, multicollinearity is not likely to be a problem. Variance inflation factors were checked and the highest factor noted was 3.96, which is below the conservative threshold of 5.00 suggested by Marquaridt (1970). Considered alongside the relatively large sample size, the highest variance inflation factor suggests that multicollinearity was not likely a serious problem.

Table 3: Summary statistics, composite reliabilities (CR), average variances extracted (AVE) and pairwise correlations between variables.

	Variable	Mean	Std.dev.	CR	AVE	1	2	3	4	5	6	7
1	Business impact of 3DP	3.30	0.65	0.92	0.73							
2	Innovation performance	3.42	0.69	0.79	0.56	0.44						
3	Use of 3DP in innovation	3.02	0.90	0.79	0.56	0.56	0.31					
4	IT-manufacturing coordination	3.22	0.90	0.90	0.65	0.46	0.35	0.40				
5	Technological turbulence	3.63	0.79	0.91	0.71	0.29	0.35	0.35	0.35			
6	IT capability	3.51	0.87	0.88	0.65	0.35	0.30	0.41	0.63	0.42		
7	Firm size (log)	3.49	1.19			-0.04	0.06	0.03	0.07	0.08	0.06	
8	Firm age (log)	1.63	0.39			-0.15	-0.05	-0.07	-0.03	-0.05	-0.08	0.60

The Breusch-Pagan test was used to check for potential problems of heteroskedasticity. The test yielded small χ^2 values for both regression models, indicating that heteroskedasticity was not likely a problem. This was further confirmed by examining residual versus fitted values plots.

The data were collected from single respondents, which raises the issue of potential common method bias. Since collecting data from multiple respondents was not possible using the data collection methodology employed, deliberate attempts were made to reduce the risk of common method bias in survey development and execution. In developing the survey, procedural remedies recommended by Podsakoff et al. (2003) were used. To reduce the propensity to respond in ways that might be considered to be more socially acceptable, the survey clearly stated that respondents would remain anonymous and that there were no right or wrong answers. To probe the issue of potential common method bias, items measuring a variable unrelated to the topic of this research were included in the survey (Bagozzi, 2011; Lindell and Whitney, 2001). The variable—having to do with the firm's social responsibility—was measured with three items. When included in factor analysis, these items loaded on one variable and did not have any cross-loadings with other variables. A Harman's procedure was conducted and resulted in the expected multiple factors with no single factor accounting for the majority of the covariance. Although no definitive test to rule out common method bias exists, the two examinations conducted along with the procedural remedies implemented provide reasonable confidence that the data did not suffer from common method bias.

Among the common sources of endogeneity are omitted confounders, which cause both the independent and dependent variables in a model. In the research model, one such confounder could be the availability, widespread acceptance or expectation of 3DP technology in a firm's competitive environment. In more colloquial terms, the mere prevalence of 3DP technology is likely to drive both its use and its favorable outcomes in terms of performance. Since the data were all collected from product development firms in the US, and hypothesis testing involved only those firms that had actually used 3DP for innovation, it can be assumed that 3DP technology was available and known to all participating firms. Thus, this does not need to be considered as a possible confounding variable. Since the focus of this research is not on what factors are related with the adoption or use of 3DP technology (e.g., Schniederjans, 2017) but on factors relating to effective use and performance benefits, it was necessary to restrict the sample used for analysis to firms that have used 3DP.

To test for potentially confounding effects of industry sector, additional regression analyses were conducted with industry sector dummies as reported in the next section. The result of this *post hoc* testing indicated that the results are robust across the manufacturing sectors included.

By including IT capability as a control variable, the research model accounts for the general level of IT savvy in the firms. This is a variable that is likely to be related with both the use of 3DP and performance outcomes. Another similar confounding variable, but one that could not be measured due the cross-sectional nature of the methodology employed, is past performance. Firms that have done well in the past are more likely than firms that have done poorly in the past to have funds at their disposal to invest in new technologies (Chen and Miller, 2007). Furthermore, managers might attribute past performance—whether good or bad—to their past levels of 3DP use, and this might influence future use (March and Shapira, 1992). This resonates with another common cause of endogeneity, namely causality loops between independent and dependent variables. However, since it was not the aim to test causality, but rather relationships among variables, endogeneity due to causality loops was not viewed as a potential problem.

Results

The hypotheses were tested using hierarchical moderated regression analysis (Arnold, 1982; Sharma et al., 1981) including the hypothesized interactions, followed by simple slope analysis (Aiken and West, 1991). This technique is regarded as a conservative method for testing interaction models (Arnold, 1982), which increases the likelihood of not detecting interactions when they actually exist. For this reason, a cut-off of p<0.1 was adopted for statistical significance. The results are shown in Tables 4 and 5. The independent variables were standardized and centered prior to analysis (Aiken and West, 1991).

Table 4: Results of hierarchical regression analysis with innovation performance as the dependent variable.

	Step 1: independent variables and control variables				Step 2: moderator variables added				Step 3: interactions added			
	Coef.	Std.err.	p		Coef.	Std.err.	p		Coef.	Std.err.	p	
Firm size (log)	0.06	0.04	0.16		0.03	0.04	0.44		0.04	0.04	0.27	
Firm age (log)	-0.04	0.13	0.76		-0.01	0.12	0.94		-0.05	0.12	0.67	
IT capability	0.12	0.04	0.01	***	-0.03	0.05	0.61		0.00	0.05	0.94	
Use of 3DP in innovation	0.14	0.04	0.00	***	0.08	0.04	0.05	*	0.09	0.04	0.03	**
IT-manufacturing coordination					0.11	0.05	0.03	**	0.10	0.05	0.04	**
Technological turbulence					0.22	0.04	0.00	***	0.23	0.04	0.00	***
Use of 3DP x IT-manufacturing coordination									-0.04	0.04	0.37	
Use of 3DP x technological turbulence									0.11	0.05	0.01	**
F	7.59 ***				11.27 ***				9.43 ***			
R^2	0.15				0.28				0.31			

** p<0.1 ** p<0.05 ***p<0.01*

Table 4 (Step 1) shows that hypothesis 1 is supported by a statistically significant relationship between the use of 3DP in innovation and innovation performance. In Step 2 we see that both the level of IT-manufacturing coordination and technological turbulence are positively related with the dependent variable at statistically significant levels. The results of Step 3 support hypothesis 4a, but not hypothesis 3a. Thus, it may be surmised that whereas the use of 3DP in innovation is related with innovation performance independently of the level of IT-manufacturing coordination, the relationship between the use of 3DP in innovation and innovation performance is stronger when technological turbulence is high than when it is low. The interaction diagram is shown in Figure 2.

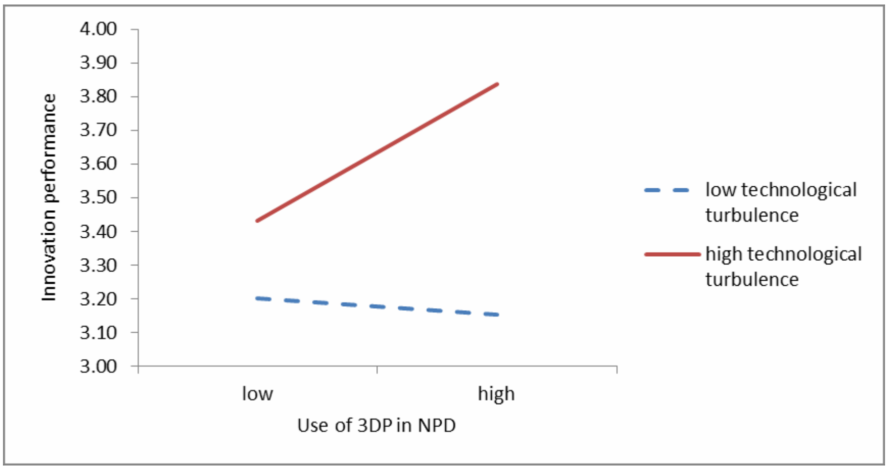

Figure 2: Interaction diagram showing the relationship between the use of 3DP in innovation and innovation performance for low and high values of technological turbulence. Low and high refer to values one standard deviation below and one standard deviation above the mean, respectively.

Simple slope analysis (Aiken and West, 1991) was used to further probe the results and revealed that the relationship between the use of 3DP in innovation and innovation performance is statistically significant at the mean of technological turbulence and upward, but the slope is not statistically significant below the mean. Thus hypothesis 4a is supported by the data.

Table 5 (Step 1) shows that hypothesis 2, about a positive relationship between the use of 3DP in innovation and business impact of 3DP is supported. In Step 2 we see that the level of IT-manufacturing coordination is positively related with the dependent variable at a statistically significant level. The results of Step 3 lend support to hypotheses 3b and 4b, since both interactions are statistically significant. Thus, the relationship between the use of 3DP in innovation and the business impact of 3DP is moderated by both the level of IT-manufacturing coordination and technological turbulence. The interaction diagrams are shown in Figures 3a and 3b.

Table 5: Results of hierarchical regression analysis with the business impact of 3DP as the dependent variable.

	Step 1: independent variables and control variables				Step 2: moderator variabless added				Step 3: interactions added			
	Coef.	Std.err.	p		Coef.	Std.err.	p		Coef.	Std.err.	p	
Firm size (log)	0.01	0.03	0.85		0.00	0.03	0.93		0.02	0.03	0.52	
Firm age (log)	-0.22	0.10	0.04	**	-0.23	0.10	0.02	**	-0.26	0.10	0.01	***
IT capability	0.11	0.04	0.00	***	-0.01	0.04	0.84		0.00	0.04	0.95	
Use of 3DP in innovation	0.27	0.04	0.00	***	0.23	0.04	0.00	***	0.23	0.04	0.00	***
IT-manufacturing coordination					0.19	0.04	0.00	***	0.18	0.04	0.00	***
Technological turbulence					0.05	0.04	0.14		0.07	0.04	0.06	*
Use of 3DP x IT-manufacturing coordination									0.07	0.04	0.10	*
Use of 3DP x technological turbulence									0.08	0.04	0.04	**
F	24.99 ***				23.03 ***				19.10 ***			
R^2	0.34				0.42				0.45			

**p<0.1 **p<0.05 ***p<0.01*

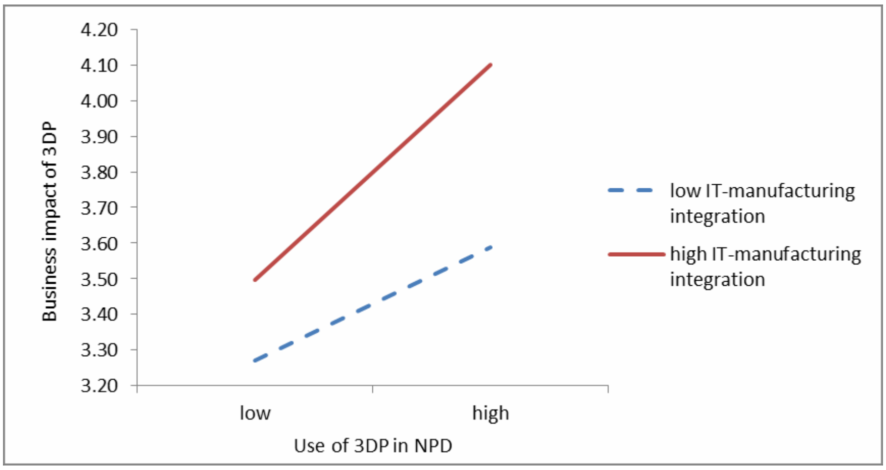

Figure 3a: Interaction diagram showing the relationship between the use of 3DP in innovation and the business impact of 3DP for low and high values of IT-manufacturing coordination. Low and high refer to values one standard deviation below and one standard deviation above the mean, respectively.

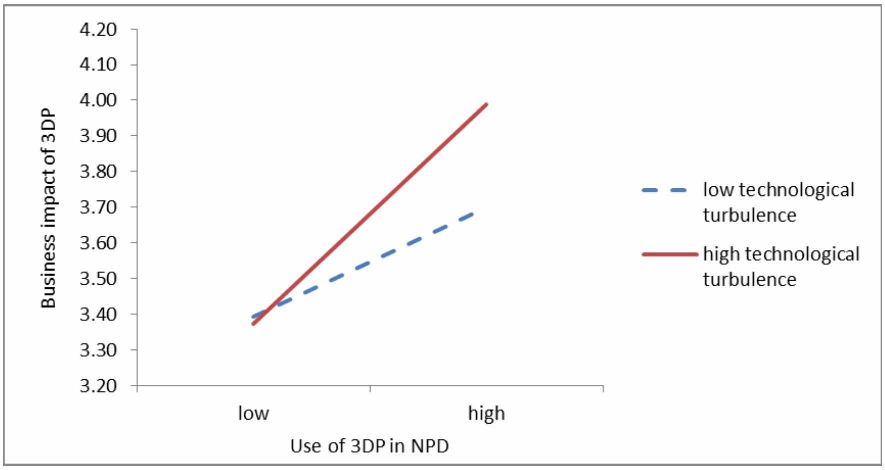

Figure 3b: Interaction diagram showing the relationship between the use of 3DP in innovation and the business impact of 3DP for low and high values of technological turbulence. Low and high refer to values one standard deviation below and one standard deviation above the mean, respectively.

Simple slope analysis (Aiken and West, 1991) revealed that the relationship between the use of 3DP in innovation and business impact of 3DP is statistically significant at the mean of IT-manufacturing coordination and upward, while the slope is not statistically significant when IT-manufacturing coordination is one standard deviation below the mean or lower. The results of simple slope analysis for technological turbulence were similar. Thus hypotheses 3b and 4b are supported by the data.

To check for potential confounding effects of industry sector, the regression analyses were repeated including dummy variables for the industry sectors represented (see Table 1). Only one of the sector dummies proved to be statistically significant (the one for the Electronics Manufacturing sector) and this was only the case in the regression analysis with innovation performance as the dependent variable. The coefficient was negative, indicating that belonging to the Electronics Manufacturing sector is related with lower innovation performance than being in other sectors. This is a potentially interesting finding, which might warrant further research, but for the purposes of this research these overall results for sector dummies indicate that the results are relatively robust across the sectors included. Furthermore, it should be noted that the regression results with respect to hypotheses remained consistent with the results reported above when the industry sector dummies were included.

Discussion

Implications for theory

This research commenced by asking what differentiates firms that achieve performance benefits from using digitized manufacturing technology from the majority that do not. To examine this issue, the research looks at whether and how firms can achieve performance benefits from using 3DP in innovation. Internal and external factors are examined, to empirically test conditions under which firms that use 3DP in innovation achieve effective use of the technology.

The research builds on Resource Orchestration Theory (Sirmon et al., 2011; Helfat et al., 2007; Hansen et al., 2004) and previous empirical results related to the coordination of IT and manufacturing (Liu et al., 2016; Gattiker and Goodhue, 2005). This is important because many prior studies that consider which resources and technologies are used do not examine how *effectively* they are used (Burton-Jones and Grange, 2013; Hansen et al., 2004) or explicitly measure how they are orchestrated and managed (Liu et al., 2016; Frohlich and Dixon, 1999). The results suggest that adoption of technology, without appropriate functional coordination, is less likely to result in expected benefits than if coordination is high. Specifically, coordination between IT and manufacturing functions is found to positively moderate the relationship between use of 3DP in innovation and the business impact of 3DP. This recalls Penrose's (1959) distinction between productive resources—in this case 3DP—and administrative resources used to coordinate functions, which Hansen et al. (2004) offer as explanation for the necessity of orchestration. Hence, this study supports the assertion that investment in technology is necessary but insufficient for competitiveness and that managers must create the conditions for the technology to be used effectively. So while a new technology may be useful, what counts is how it is used.

In contrast to business impact, no moderating effect of manufacturing-IT coordination was found on the relationship between use of 3DP in innovation and innovation performance. There are two possible explanations for this. First, since innovation performance is measured in terms of leading marketing activities, the number of new products launched and their technological novelty, it is conceivable that the manufacturing function of a business has a limited role as well as limited influence. Firms can be expected to create better products when their manufacturing and design functions collaborate on innovation (Chiva and Alegre, 2009; Swink et al., 2007), and since firms may emphasize innovation over manufacturing, the coordination between design and IT may also be more relevant than coordination between IT and manufacturing. Second, types of 3DP technology and equipment vary greatly. For example, a desktop FDM machine used to produce plastic models for exploring concepts and developing ideas is likely to require less technical knowledge and systems integration than an industrial SLS machine used to produce metal components. The business impact of 3DP is likely to be greater if it is used more widely, for example in manufacturing end use components and products (Baumers et al., 2016; Ruffo et al., 2006). The results suggest that, if this greater business impact is to be achieved, the technical knowledge and skills required—which are likely to be distributed in different functional units, such as IT and manufacturing—must be effectively orchestrated.

Previous studies of resource orchestration have conceptually outlined arguments around the importance of synchronization and management of resources. In particular, Sirmon et al. (2011) suggested how the task of orchestration may differ in various contexts. For example, they propose depth and breadth of organizations as contexts for orchestration. While Chadwick et al. (2015) examined depth, through a study of relations in the organizational hierarchy, the present study focuses on breadth, by examining the orchestration of organizational functions. Additionally, the level of competition and technological turbulence are proposed as factors that affect the nature of resource orchestration (Helfat et al., 2007). The present research is one of a small number that use Resource Orchestration Theory to explain empirical findings, thus contributing to this nascent theory. In particular, this research identifies a connection between resource orchestration and technology implementation. This suggests further avenues for research that combine the internal and external moderators identified here, or more explicitly, which deal with both strategic fit and environmental fit as measures of orchestration.

The research also draws on theory related to uncertainty and flexibility in innovation, relating the concepts of technological turbulence (Jaworksi and Kohli, 1993) and flexibility (Beach et al., 2000). Most arguments for the use of 3DP emphasize flexibility benefits, for example design freedom, elimination of tooling costs and affordable customization (e.g. Weller et al., 2015; Petrovic et al., 2011). Arguments for the use of flexible systems make a connection with both environmental uncertainty and product innovation (e.g. Oke, 2013). The results show that using 3DP in uncertain environments, where technological turbulence is high, makes its use more effective both in terms of innovation performance and for business impact. This is consistent with the belief that 3DP can be effective as a tool for customization and to help generate agile supply chains that respond to uncertainty through quickly developing and delivering innovative products (e.g. Bogers et al., 2016; Khajavi et al., 2014).

This research eschews theories of technology diffusion and acceptance, which are widely used in research on 3DP (Schniederjans, 2017). Instead, it builds on the assumption that use of technology does not automatically result in effective use (Burton-Jones and Grange, 2013; Orlikowski, 2000). Therefore, an important contribution of the research is its identification of factors related to effective use, which help to understand prerequisites for digitization. Some processes naturally lend themselves to digitization, for example replacing physical lectures with online videos (Overby, 2008). For innovation, however, the importance of adapting technologies to fit existing systems and processes (Frohlich and Dixon, 1999) and ensuring communication and coordination between different functional units (Bharadwaj et al., 2007; Rai et al., 2006; Cao and Dowlatshahi, 2005) cannot be underestimated.

As discussed earlier, two dependent variables are used to test the hypotheses: a variable that specifically measures innovation performance and a broader variable that measures the business impact of using 3DP. This second variable is made up of items adopted from Gattiker and Goodhue (2005) and explicitly refers to aspects of business impact stemming specifically from 3DP. In general, correlations between variables measured using a cross-sectional survey cannot be taken as evidence of causality. However, the method of explicitly asking respondents to evaluate the business impact of 3DP allows us to make cautious inferences about the contribution of the use of 3DP to business performance.

Managerial implications

For managers in product development firms, 3DP is likely to be viewed either with enthusiasm or suspicion. Excitement around technology frequently draws hyperbole, which in turn leads to raised expectations that cannot always be satisfied (Schniederjans, 2017; Holweg, 2015). For example, when managers are led to believe that products can be printed as easily as paper documents, they may become disappointed with the limitations of the technology, such as the setup and post-processing effort involved. Additionally, to make the most of these technologies demands the availability and orchestration of existing capabilities. As the results demonstrate, this includes effective coordination between manufacturing and IT functions.

This research offers evidence that the use of 3DP in innovation can have a positive impact on innovation. Moreover, it highlights the importance of orchestrating resources, particularly manufacturing and IT. There may be some prerequisites in terms of knowledge and experience in manufacturing required to make effective use of a new technology. Similarly, the digital aspects of technology demand a suitably skilled and coordinated IT function. While 3DP appears to be a new and revolutionary technology, it is important to learn from the mistakes of implementing digitized manufacturing technologies in the past (e.g. Ketokivi and Schroeder, 2004; Brandyberry et al., 1999; Frohlich and Dixon, 1999). In particular, it is unwise to assume that simply purchasing new technologies will automatically result in better performance. Instead, the competitive environment must be considered; digitized manufacturing methods such as 3DP will be better suited to turbulent environments in which rapid innovation is important than slower moving contexts where volume and cost are of primary importance (Baumers et al., 2016; Weller et al., 2015). Finally, the prerequisites for effective use of the technology must be put in place, which means the IT function must be well integrated with manufacturing as well as with the competitive strategy of the firm (Bharadwaj et al., 2007).

Finally, the results suggest the use of 3DP in innovation can help to generate competitive advantage. 3DP can be useful in the early stages of innovation for prototyping and testing designs. 3DP can also be useful after a product has been developed to help support product introduction, e.g. using physical models that will be more convincing to potential customers than digital representations. In this sense, 3DP helps to overcome limitations of digital processes that make digitization of manufacturing difficult. The use of 3DP therefore constitutes an untapped opportunity that product development firms should consider exploiting for improved performance.

Limitations and directions for future research

Innovation is generally viewed as consisting of three phases: ideation, development and launch. Rather than make a simple distinction between prototyping and manufacturing, the reflective variable for the use of 3DP in innovation combines the use of 3DP in all three phases. The use of 3DP can be related to representation (Burton-Jones and Grange, 2013) in all three. For ideation, 3DP helps to communicate and develop product ideas by creating physical representations that may be more effective than sketches and CAD models. In development, 3DP may enable better testing of form and function. And in the launch phase, 3DP helps provide customers with an accurate physical representation, for example to determine if the real product is either too large or too small. Furthermore 3DP models can be used to communicate with customers in the launch phase or to facilitate customer involvement in design (de Jong and de Bruijn, 2013). As the technologies improve, it is conceivable that more finished products will be produced directly using 3DP. Future research should build on this work by examining how 3DP is used in each phase of innovation. In particular, the effect that 3DP may have within innovation teams and its effect on communication between functions and organizations offer fertile ground for research.

While information systems researchers focus on the ability of IT to represent physical processes, the results of this research suggest 3DP may provide benefits by using physical processes to represent IT. Petrovic et al. (2011) suggest that design practice needs to change to enable 3DP to be used for manufacturing, but further research could also investigate the reciprocal relationship, i.e. how using 3DP in the ideation phase may change designers' practice.

Additionally, while examining the moderating effect of manufacturing-IT coordination, it may be of value to study coordination of both functions with design. The benefits of design-IT coordination are captured by studies of digital design tools (Marion et al., 2015; Barczack et al., 2007), while the benefits of close coordination between design and manufacturing are well established (Swink et al., 2007). As the results suggest that manufacturing-IT coordination may not influence the relationship between 3DP use in innovation and innovation performance, perhaps a more comprehensive examination of the design-manufacturing-IT triad could offer a more complete picture. A qualitative field study investigating how the orchestration of these three functions affects digitization could add value.

As discussed above, the treatment of the moderating effect of technological turbulence hinges on the relationship between perceived technological turbulence and efforts to increase flexibility. Previous research has identified several specific types of flexibility such as development, product mix, labor and machine flexibility (Oke, 2013; Beach et al., 2000). However, since the relationship between environmental uncertainty and flexibility is already established, variables for flexibility were not included in the model. Future research could examine the degree to which flexibility (as a strategic objective) might be an antecedent of 3DP use, or a consequence of effective use of 3DP.

In common with other studies of 3DP (e.g. Schniederjans, 2017; Rogers et al., 2016), no distinction is made between different 3DP technologies. The majority of studies that refer to 3DP or additive manufacturing, in common with industry reports and associations, continue to combine vastly different processes, which are suited to different applications, under the same title. This is because the different technologies share a set of characteristics, the principal one being their ability to build directly from a digital model. Despite these similarities, however, different technologies vary greatly in price, from less than $500 for consumer machines to nearly $1m for industrial ones. They offer different levels of performance and suit different applications. By focusing on the similarities, this study identifies results related to IT, but to give a more nuanced picture of orchestration, future studies should ideally focus more narrowly on specific 3DP technologies.

Conclusion

3DP is viewed by many commentators as an important part of a new industrial revolution. This vision appeals to all those who stand to benefit, including consumers, governments and industries, particularly in high wage economies. Questions remain, however, about low adoption rates for a set of technologies that are three decades old and low success rates for digitized manufacturing technologies in general. Therefore, this research examines internal and external factors that moderate the effective use of 3DP in innovation. The results show, firstly, that effective coordination between IT and manufacturing functions can intensify the benefits of using 3DP. Secondly, using 3DP in innovation is more likely to be effective for businesses that face greater turbulence in their operating environment. This is because the principal benefits of 3DP stem from its ability to enable flexible responses to uncertainty. These results contribute to the understanding of resource based competition and digitized manufacturing.

References

Aiken, L.S. and S.G. West. 1991. *Multiple regression: Testing and interpreting interaction*. Thousand Oaks, CA: Sage.

Arnold, H.J. 1982. Moderator variables: A clarification of conceptual, analytic, and psychometric issues. *Organizational Behavior and Human Performance*. 29: 143-174.

Bagozzi, R.P. 2011. Measurement and Meaning in Information Systems and Organizational Research: Methodological and Philosophical Foundations. *MIS Quarterly* 35(2): 261-292.

Bandyopadhyay, A., T.P. Gualtieri and S. Bose. 2015. *Global Engineering and Additive Manufacturing*. In S. Bose (Ed.), Additive Manufacturing: 1-18. CRC Press.

Baumers, M., P. Dickens, C. Tuck and R. Hague. 2016. The cost of additive manufacturing: machine productivity, economies of scale and technology-push. *Technological Forecasting and Social Change* 102: 193-201.

Beach, R., A.P. Muhlemann, D.H.R. Price, A. Paterson and J.A. Sharp. 2000. A review of manufacturing flexibility. *European Journal of Operational Research* 122(1): 41-57.

Bessant, J., Lamming, R., Noke, H and Phillips, W. 2005. Managing innovation beyond the steady state. *Technovation* 25 (12), 1366-1376.

Bharadwaj, S., A. Bharadwaj and E. Bendoly. 2007. The performance effects of complementarities between information systems, marketing, manufacturing, and supply chain processes. *Information Systems Research* 18(4): 437-453.

Bharadwaj, A., O.A. El Sawy, P.A. Pavlou and N.V. Venkatraman. 2013. Digital business strategy: toward a next generation of insights. *MIS Quarterly* 37(2): 471-482.

Bogers, M., R. Hadar, and A. Bilberg. 2016. Additive manufacturing for consumer-centric business models: Implications for supply chains in consumer goods manufacturing. *Technological Forecasting and Social Change* 102: 225-239.

Brandyberry, A., A. Rai and G.P. White. 1999. Intermediate performance impacts of advanced manufacturing technology systems: An empirical investigation. *Decision Sciences* 30(4): 993-1020.

Buganza, T., C. Dell' Era, and R. Verganti. 2009. Exploring the relationships between product development and environmental turbulence. The case of mobile TLC services. *Journal of Product Innovation Management* 26(3): 308-321.

Burton-Jones, A. and C. Grange. 2013. From Use to Effective Use: A Representation Theory Perspective. *Information Systems Research* 24(3): 632-658.

Candi, M., J. van den Ende and G. Gemser. 2013. Organizing innovation projects under technological turbulence. *Technovation* 33(4): 133-141.

Cao, Q. and S. Dowlatshahi. 2005. The impact of alignment between virtual enterprise and information technology on business performance in an agile manufacturing environment. *Journal of Operations Management* 23(5): 531-550.

Chadwick, C., J.F. Super and K. Kwon. 2015. Resource orchestration in practice: CEO emphasis on SHRM, commitment based HR systems, and firm performance. *Strategic Management Journal* 36(3): 360-376.

Chakravarty, A., Grewal, R. and Sambamurthy, V. 2013. "Information technology competencies, organizational agility, and firm performance: enabling and facilitating roles." *Information Systems Research* 24 (4): 976-997.

Chen, W.R. and K.D. Miller. 2007. Situational and Institutional Determinants of Firms' R&D Search Intensity. *Strategic Management Journal* 28(4): 369-381.

Chiva, R. and J. Alegre. 2009. Investment in design and firm performance: The mediating role of design management. *Journal of Product Innovation Management* 26(4): 424-440.

Cross, N. and A.C. Cross. 1996. Winning by design: the methods of Gordon Murray, racing car designer. *Design Studies* 17(1): 91-107.

D'Aveni, R. 2015. The 3-D Printing Revolution. *Harvard Business Review* 93(3): 41-48.

De Jong, J.P. and E. de Bruijn. 2013. Innovation lessons from 3-D printing. *MIT Sloan Management Review* 54(2): 42-52.

Drejer, A. 2002. Towards a model for contingency of management of technology, *Technovation* 22 (6), 363-370.

Eisenhardt, K.M. and B.N. Tabrizi. 1995. Accelerating adaptive processes. Product innovation in the global computer industry. *Administrative Science Quarterly* 40(1): 84-110.

Fernández, P., Del Rio, L., Varela, J. and Bande, B. 2010. Relationships among functional units and new product performance: The moderating effect of technological turbulence. *Technovation* 30(6), 310-321.

Frohlich, M.T. and J.R. Dixon. 1999. Information systems adaptation and the successful implementation of advanced manufacturing technologies. *Decision Sciences* 30(4): 921-957.

Garud, R., S. Jain and P. Tuertscher. 2008. Incomplete by design and designing for incompleteness. *Organization Studies* 29(03): 351-371.

Gattiker, T.F. and D.L. Goodhue. 2005. What happens after ERP implementation: Understanding the impact of interdependence and differentiation on plant-level outcomes. *MIS Quarterly* 29(3): 559-585.

Gerwin, D. 1993. "Manufacturing flexibility: a strategic perspective", *Management Science,* 39: 395-410.

Grewal, R., J.A. Cote and H. Baumgartner. 2004. Multicollinearity and measurement error in structural equation models: Implications for theory testing. *Marketing Science* 23(4): 519-529.

Griffin, A. and A.L. Page. 1996. PDMA success measurement project: recommended measures for product development success and failure. *Journal of product innovation management* 13(6): 478-496.

Hansen, M.H., L.T. Perry and C.S. Reese. 2004. A Bayesian operationalization of the resource- based view. *Strategic Management Journal* 25(13): 1279-1295.

Helfat, C.E., S. Finkelstein, W. Mitchell, M. Peteraf, H. Singh, D. Teece and S.G. Winter. 2007. *Dynamic capabilities: Understanding strategic change in organizations*. Malden, MA: Blackwell.

Holmström, J. and J. Partanen. 2014. Digital manufacturing-driven transformations of service supply chains for complex products. *Supply Chain Management: An International Journal* 19(4): 421-430

Holweg, M. 2015. The limits of 3D printing, Harvard Business Review, online forum, June 23. Available at [https://hbr.org/2015/06/the-limits-of-3d-printing], accessed 2nd April, 2017.

Huang, S.H., P. Liu, A. Mokasdar and L. Hou. 2013. Additive manufacturing and its societal impact: a literature review. *International Journal of Advanced Manufacturing Technology* 67(5): 1191-1203.

Jaworski, B.J. and A.K. Kohli. 1993. Market Orientation: Antecedents and Consequences. *Journal of Marketing* 57(3): 53-70.

Ketokivi, M.A. and R.G. Schroeder. 2004. Strategic, structural contingency and institutional explanations in the adoption of innovative manufacturing practices. *Journal of Operations Management* 22(1): 63-89.

Khajavi, S.H., J. Partanen and J. Holmström. 2014. Additive manufacturing in the spare parts supply chain. *Computers in Industry* 65(1): 50-63.

Krotki, K. and J.M. Dennis. 2001. Probability-based survey research on the Internet. In 53rd Conference of the International Statistical Institute, Seoul, South Korea.

Lasi, H., P. Fettke, H.G. Kemper, T. Feld and M. Hoffmann. 2014. Industry 4.0. *Business & Information Systems Engineering* 6(4): 239.

Lee, K.B. and Wong, V. 2011. Identifying the moderating influences of external environments on new product development process. *Technovation* 31(10-11), 598-612.

Li, Y., Z. Su and Y. Liu 2010. Can strategic flexibility help firms profit from product innovation? *Technovation* 30(5): 300-309.

Lindell, M.K. and D.J. Whitney. 2001. Accounting for common method variance in cross-sectional research designs. *Journal of applied psychology* 86(1): 114.

Liu, H., S. Wei, W. Ke, K.K. Wei and Z. Hua. 2016. The configuration between supply chain integration and information technology competency: A resource orchestration perspective. *Journal of Operations Management* 44: 13-29.

Lu, Y. and K. Ramamurthy. 2011. Understanding the link between information capability and organizational agility: An empirical examination, *MIS Quarterly* 25(4): 931-954.

MacCormack A., R. Verganti and M. Iansiti. 2001. Developing products on "Internet Time": the anatomy of a flexible development process. *Management Science* 47(1): 133-150.

March, J.G. and Z. Shapira. 1992. Variable risk preferences and the focus of attention. *Psychological Review* 99(1): 172-183.

Marion, T.J., M.H. Meyer and G. Barczak. 2015. The influence of digital design and IT on modular product architecture. *Journal of Product Innovation Management* 32(1): 98-110.

Marquaridt, D.W. 1970. Generalized inverses, ridge regression, biased linear estimation, and nonlinear estimation. *Technometrics* 12(3): 591-612.

Mascarenhas, M.B. 1981. Planning for flexibility. *Long Range Planning* 14(5): 78-82.

Mauerhoefer, T., S. Strese and M. Brettel. 2017. The impact of information technology on New Product Development performance. *Journal of Product Innovation Management.*

Mellor, S., L. Hao and D. Zhang. 2014. Additive manufacturing: A framework for implementation. *International Journal of Production Economics* 149: 194-201.

Mishra, A.N., P. Konana and A. Barua. 2007. Antecedents and consequences of internet use in procurement: an empirical investigation of US product development firms. *Information Systems Research* 18(1): 103-120.

Mishra, A.N., S. Devaraj and G. Vaidyanathan. 2013. Capability hierarchy in electronic procurement and procurement process performance: An empirical analysis. *Journal of Operations Management* 31(6): 376-390.

Moorman, C. and A.S. Miner. 1998. The Convergence of Planning and Execution: Improvisation in New Product Development. *Journal of Marketing* 62(3): 1-20.

Narver, J.C., S.F. Slater and D.L. MacLachlan. 2004. Responsive and Proactive Market Orientation and New-Product Success. *Journal of Product Innovation Management* 21: 334-347.

Oh, L.B., H.H. Teo and V. Sambamurthy. 2012. The effects of retail channel integration through the use of information technologies on firm performance. *Journal of Operations Management* 30(5): 368-381.

Oke, A. 2013. Linking manufacturing flexibility to innovation performance in manufacturing plants. *International Journal of Production Economics* 143(2): 242-247.

Orlikowski, W.J. 2000. Using technology and constituting structures: A practice lens for studying technology in organizations. *Organization Science* 11(4): 404-428.

Overby, E. 2008. Process virtualization theory and the impact of information technology. *Organization Science* 19(2): 277-291.

Patel, P. C., Terjesen, S. and Li, D. 2012. Enhancing effects of manufacturing flexibility through operational absorptive capacity and operational ambidexterity, *Journal of Operations Management*, 30(3): pp. 201–220.

Penrose, E.T. 1959. *The theory of the growth of the firm*. New York: Sharpe.

Petrovic, V., J. Vicente Haro Gonzalez, O. Jorda Ferrando, J. Delgado Gordillo, J. Ramon Blasco Puchades and L. Portoles Grinan. 2011. Additive layered manufacturing: sectors of industrial application shown through case studies. *International Journal of Production Research* 49(4): 1061-1079.

Piller, F.T., C. Weller and R. Kleer. 2015. Business models with additive manufacturing—opportunities and challenges from the perspective of economics and management. In *Advances in Production Technology*, 39-48. Springer International Publishing.

Podsakoff, P.M., S.B. MacKenzie, J.Y. Lee and N.P. Podsakoff. 2003. Common method biases in behavioral research: a critical review of the literature and recommended remedies. *Journal of Applied Psychology* 88(5): 879-903.

Pollard, D. (2002). *A user's guide to measure theoretic probability*, Vol. 8. Cambridge University Press.

Rai, A., R. Patnayakuni and N. Seth. 2006. Firm performance impacts of digitally enabled supply chain integration capabilities. *MIS Quarterly* 30(2): 225-246.

Rindfleisch, A, M. O'Hern and V. Sachdev. 2017. The digital revolution, 3D Printing, and Innovation as Data. *Journal of Product Innovation Management* 34(5): 681-690.

Rogers, H., N. Baricz and K.S. Pawar. 2016. 3D printing services: classification, supply chain implications and research agenda. *International Journal of Physical Distribution & Logistics Management* 46(10): 886-907.

Ruffo, M., C. Tuck and R. Hague. 2006. Cost estimation for rapid manufacturing-laser sintering production for low to medium volumes. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture* 220(9): 1417-1427.

Rüßmann, M., M. Lorenz, P. Gerbert, M. Waldner, J. Justus, P. Engel and M. Harnisch. 2015. *Industry 4.0: The future of productivity and growth in manufacturing industries*. Boston, MA: Boston Consulting Group.

Sandström, C.G. 2016. The non-disruptive emergence of an ecosystem for 3D Printing—Insights from the hearing aid industry's transition 1989–2008. *Technological Forecasting and Social Change* 102: 160-168.

Schniederjans, D.G. 2017. Adoption of 3D-printing technologies in manufacturing: A survey analysis. *International Journal of Production Economics* 183: 287-298.

Sethi, R. and Z. Iqbal. 2008. Stage-gate controls, learning failure, and adverse effect on novel new products. *Journal of Marketing* 72(1): 118-134.

Shah, R. and S.M. Goldstein. 2006. Use of structural equation modeling in operations management research: Looking back and forward. *Journal of Operations Management* 24(2): 148-169.

Sharma, S., R.M. Durand, O. Gur-Arie. 1981. Identification and analysis of moderator variables. Journal of Marketing Research. 16: 291-300.

Sirmon, D.G., M.A. Hitt, R.D. Ireland and B.A. Gilbert. 2011. Resource orchestration to create competitive advantage: Breadth, depth, and life cycle effects. *Journal of Management* 37(5): 1390-1412.

Skinner, D.C. 2009. *Introduction to decision analysis: a practitioner's guide to improving decision quality*. Probabilistic Pub.

Stratasys. 2017. McLaren Formula 1 Racing Deploys Stratasys Additive Manufacturing to Improve 2017 Car Performance. Available at: http://investors.stratasys.com/releasedetail.cfm?ReleaseID=1020520, accessed, May 8th, 2017.

Swink, M. and A. Nair. 2007. Capturing the competitive advantages of AMT: Design–manufacturing integration as a complementary asset. *Journal of Operations Management* 25(3): 736-754.

Swink, M., R. Narasimhan and C. Wang. 2007. Managing beyond the factory walls: effects of four types of strategic integration on manufacturing plant performance. *Journal of Operations Management* 25(1): 148-164.

Tatikonda, M.V. and M.M. Montoya-Weiss. 2001. Integrating operations and marketing perspectives of product innovation. The influence of organizational process factors and capabilities on development performance. *Management Science* 47(1): 151-172.

Upton, D.M. 1994. The management of manufacturing flexibility. *California management review* 36(2): 72-89.

Weller, C., R. Kleer and F.T. Piller, F.T. 2015. Economic implications of 3D printing: Market structure models in light of additive manufacturing revisited. *International Journal of Production Economics* 164: 43-56.

Yao, Y., Zhu, K. 2012. Do electronic linkages reduce the bullwhip effect? An empirical analysis of the U.S. manufacturing supply chains. *Information Systems Research,* 23(3): 1042–1055.