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Different strokes for different folks: Comparative analysis of 3D printing in large, medium and small firms

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ABSTRACT

Industry 4.0 technologies such as 3D printing have radically transformed innovative outcomes for firms in terms of product design and offerings in the recent past. Acknowledging the impact, existing scholarship has delved into different dimensions of this technology and outcomes of its adoption, yet when compared with the scale of industrial activity globally and the varied possibilities associated with the adoption of this relatively new technology, the literature is woefully lean. Discussions and conversations on facilitators and inhibitors of adoption and continued usage are still nascent, particularly when one ponders upon specific insights related to sectors and firm size. The present study seeks to address this paucity by using the lens of firm size. Specifically, the study examines how firm size impacts various positive and negative outcomes of industry 4.0 innovation adoption and usage using 3D printing as an exemplar. Toward this end, we conducted a qualitative study to collect responses from 46 managers, 23 each from large-size and small-size enterprises operating in the United Kingdom. Thematic coding of responses revealed five aggregate dimensions representing facilitators and four aggregate dimensions representing inhibitors. Analysis of the findings revealed differences in outcomes with firm size, indicating that the adoption and optimal use of innovations such as 3D printing were indeed incumbent on firm size in the case of disruptive, technology-driven innovations that are generically presumed to have positive outcomes. Overall, the findings of this study provide new insights into various facilitators and inhibitors of the adoption of 3D printing technology, which can help firms to make better strategic decisions on the effective usage of this technology.

1. Introduction

3D printing is the colloquial name for additive manufacturing (Weller et al., 2015). It creates objects layer-upon-layer from 3D model data (ASTM, 2012). To explain further, 3D printing entails the direct manufacturing of physical products based on digital files, making the production process highly flexible and offering freedom to experiment with product design (Kyriakopoulos et al., 2016). The additive fabrication logic of 3D printing, as opposed to the subtraction logic of traditional manufacturing, makes tooling and dedicated parts inconsequential in production processes (Weller et al., 2015). The additive manufacturing facility offered by 3D printing has made it possible for firms to make physical products from a diverse catalogue of materials, including filaments, ceramics, polymers, and biological components, without any dedicated assembly plant (Yeh and Chen, 2018).

The preceding discussion establishes that 3D printing is a revolutionary technology with the potential to catalyze an industrial transformation (Holmström and Partanen, 2014). However, despite all growth estimates, it does not yet constitute even one percent of the manufacturing market globally (Ukobitz and Faullant, 2022). This indicates that adoption of 3D printing is still relatively low, all the positive

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outcomes notwithstanding. In addition, the latest scholarly literature has noted that even in the sectors and firms that have adopted 3D printing, all has not been positive, with disparate stories ranging from tremendous success to dismal disillusionment resulting from the failure of the technology to live up to the expectations (Beltagui et al., 2023). Obviously, there are anomalies and unknowns in the adoption trajectory that are not yet fully understood and in need of further diagnosis.

A search of the words "3D printing" and "adoption" on the Scopus database returned 71 studies published by leading publication houses. Less than 50 percent of these studies have specifically discussed the drivers/inhibitors of adoption; instead, they focus largely on specific contexts such as public housing projects (Won et al., 2022), 3D-printed prosthetic hands (Kim et al., 2022), logistic suppliers (Xiong et al., 2022), footwear manufacturing firms (Ukobitz and Faullant, 2022), healthcare 3D printing services (Chaudhuri et al., 2022), small-scale manufacturing in home settings (Wang et al., 2016) and so on. When this volume of research and the contexts addressed are superimposed on the almost immeasurable size of global manufacturing, the insights appear to be substantially inconsequential. Delving deeper into the literature, the contemplative examination of what is impeding the adoption of 3D printing is even less forthcoming, with only limited attempts (e.g., Chekurov et al., 2021; Durach et al., 2017; Lupton and Turner, 2018; Naghshineh and Carvalho, 2022). Furthermore, despite diverse stories of success and failure (Beltagui et al., 2023), academic research has yet to move beyond a narrow focus of quantitative, technology acceptance theory-driven investigations to broader and more pertinent concerns. For instance, there is a need probe the potential role of firm size in driving the multitude of experiences with 3D printing and the potential reasons for its lack-luster rate of adoption.

The present study responds to the need and call for advancing the research on the drivers of adoption of 3D printing by using the lens of firm-size to uncover not only the facilitators but also the inhibitors of its uptake in firms operating in different sectors. The motivation behind expanding the research to include both facilitators and inhibitors in the same space is driven by the contention within existing scholarship that 3D printing is a complex innovation ecosystem that needs to be nurtured through complementary relationships (Kwak et al., 2018) by overcoming both soft and technical barriers (Durach et al., 2017). Our intention to examine both facilitators and inhibitors is also consistent with the theoretical auspices of the dual factor theory (Cenfetelli and Schwarz, 2011), which is driven by the dominant logic that these factors of technology acceptance are not mere opposites and thus need to be considered together to present a clearer understanding of adoption/non-adoption. The idea behind examining the dual aspect of technology acceptance is also consistent with prior findings suggesting that the presence of enablers does not necessarily result in positive outcomes while using a certain innovation, since the antipole of enablers is the continuous framing of adverse scenarios based on the potential risks associated with innovation implementation (Hachicha and Mezghani, 2018). At the same time, anchoring the examination in firm-size variation is justifiable, with past studies noting the impact of firm size on technology adoption and use (e.g., Chan et al., 2019; Chittipaka et al., 2022; Street et al., 2017), such that the present lack of insight on the role of firm size represents a significant gap hindering the development of an effective strategic and operational action plan to ensure the optimal use of 3D printing. The need to understand the role of firm-size differences becomes all the more critical in light of observations that, for a long time, 3D technologies remained restricted to niche markets and were largely seen as the domain of the largest of firms, only recently becoming more accessible to smaller firms and new ventures (Rayna and Striukova, 2021).

We synthesize the preceding discussion and the present study's orientation to articulate two research questions (**RQs**): **RQ1**. What are the facilitators and inhibitors to the adoption and continued usage of 3D printing perceived by managers based on their experience of using it in their own firms and observing implementation across different firms? **RQ2**. What are the similarities and differences in facilitators and inhibitors impacting the adoption and continued usage of 3D printing based on firm-size (large versus small) variation?

We responded to the two questions by conducting a qualitative study entailing the collection of written responses through open-ended essays from individuals working in firms of different sizes operating in the United Kingdom (UK). We analyzed the responses, 46 in all, 23 each from large-size firms and small-size firms, using the Gioia method (Gioia et al., 2013). Our choice of conducting a qualitative study is motivated by our objective to probe varied nuances of the perceptions and implementational experiences of managers closely and deeply. A qualitative study was also considered necessary given the evolutionary phase of the development trajectory of 3D printing in mainstream manufacturing.

The key contributions of this study are (a) bringing the facilitators and inhibitors of 3D printing adoption and usage into the same space, thus presenting a more complete picture of 3D printing as a complex and dynamic innovation ecosystem, (b) underscoring and bringing forth the significant role of firm size in innovation adoption and performance, and (c) using an exploratory approach of a qualitative research design to analyze data collected directly from managers having experienced 3D printing in their firms, thereby generating fine-grained insights that a quantitative study could have missed.

The study is particularly relevant in the present environmental context, where sustainability concerns are of paramount importance. By uncovering the factors that can facilitate or inhibit the adoption of 3D printing/additive manufacturing, our study can help managers ensure better diffusion of this technology, which is acknowledged to be a manufacturing method that promotes sustainability by eliminating waste, saving time, and reducing the need for long distance transportation and storage facilities.

2. Theoretical background

3D printing is a radical and contemporary form of manufacturing enabled by digital technologies (Rayna and Striukova, 2016). It holds great transformative potential, with scholars going to the extent of suggesting that in the near future this technology would enable consumers to produce electronics as per their own customization at home (Potstada and Zybura, 2014). 3D printing is remarkably distinguished from the traditional production process due to differences in manufacturing logic, physical product creation, and production volume (Candi and Beltagui, 2019). While the interest of academic research in the area has varied, from how these technologies can help entrepreneurs and new ventures overcome barriers and challenges related to new product development, financial resources, business models, and markets (Rayna and Striukova, 2021) to the economic viability of adopting 3D printing (Mellor et al., 2014), the impact of market structures on firm performance in the wake of adoption of this technology (Weller et al., 2015), the factors responsible for its successful implementation within organizations (Yeh and Chen, 2018), and the sustainability aspect of these technologies (Naghshineh et al., 2021; Zhao et al., 2021), a rise in the examination of different factors supporting or hindering the adoption and usage of 3D printing has been observed in the recent past.

A comprehensive review of the literature reveals that very few studies (e.g., Yeh and Chen, 2018) have explicitly mentioned examining the drivers of adoption; however, a comparatively larger number has implicitly examined both facilitators and inhibitors in this context. We have extrapolated their findings to categorize the key discussions related to supporting/facilitating conditions under four headings: (a) *market-related aspects* such as product innovation and creative designing (Candi and Beltagui, 2019; Tsai and Yeh, 2019), customization (Niaki et al., 2019), ease of market entry (Tsai and Yeh, 2019; Yeh and Chen, 2018), and speed of reaching markets (Chaudhuri et al., 2019; Tsai and Yeh 2019; Schniedeijans & Yalcin, 2018); (b) *production-related aspects* such as direct manufacturing (Ford and Despeisse, 2016; Weller et al., 2015), supply chain efficiencies (Chaudhuri et al., 2019; Marak et al., 2019; Niaki et al., 2019), on-demand production (Ford and Despeisse, 2016; Oettmeier and Hofmann, 2017; Weller et al., 2015), and flexible manufacturing (Niaki et al., 2019; Schniederjans and Yalcin, 2018; Weller et al., 2015); (c) *performance-related aspects* such as improvement in key performance indicators (Candi and Beltagui, 2019; Niaki et al., 2019), ease of usage (Attaran, 2017; Marak et al., 2019), and environmental sustainability (Niaki et al., 2019; Weller et al., 2015); and (d) *miscellaneous factors* such as competitor behavior and perceived value (Ukobitz and Faullant, 2022), competitive push (Conner et al., 2014; Yeh and Chen, 2018), employee-related benefits (Candi and Beltagui, 2019; Schniederjans, 2017), and organizational readiness (Cohen, 2014).

Similarly, based on both explicit and implicit discussions on reasons that may hinder the adoption of 3D printing technologies by firms in the scholarly literature, we have grouped the inhibitors under four headings: (a) *human resource-related* issues such as lack of vision in the leadership team (Wang et al., 2016; Yeh and Chen, 2018), rigid perceptions (Ford and Despeisse, 2016), lack of a skilled workforce (Candi and Beltagui, 2019; Oettmeier and Hofmann, 2017), and employee/managerial resistance (Conner et al., 2014); (b) *technology-related issues* such as integration with existing structures (Mellor et al., 2014; Tsai and Yeh, 2019; Ukobitz, 2020) and evolving technology (Durach et al., 2017; Niaki et al., 2019; Schniederjans and Yalcin, 2018; Ukobitz, 2020); (c) *internal operational issues* such as a low quantum of manufacturing (Attaran, 2017; Ford and Despeisse 2016; Mellor et al., 2014), absence of quality standards (Ukobitz, 2020; Weller et al., 2015), and high costs (Baumers et al., 2016; Chaudhuri et al., 2019; Heath, 2015; Marak et al., 2019; Thomas, 2016); and (d) *external impediments* such as low consumer awareness and acceptance (Ford and Despeisse, 2016; Niaki et al., 2019; Ukobitz, 2020), environmental uncertainties (Ford and Despeisse, 2016; Ukobitz, 2020), skewed channel relationships (Candi and Beltagui, 2019; Ukobitz, 2020; Yeh and Chen, 2018), and regulatory ambiguity (Mellor et al., 2014; Weller et al., 2015).

At a glance, it would appear that the literature has a rich accumulation of insights on factors impacting the adoption or non-adoption of 3D printing. However, a deeper probe uncovers some visible gaps: firstly, the findings are limited and narrow when the size of the global manufacturing sector is considered; secondly, no one study provides a comprehensive assessment of drivers and inhibitors a single space, resulting in findings scattered across multiple studies; thirdly, most studies are focused on a specific context; fourthly, most studies have identified these factors by examining only a specific sector or firm; and finally, granularities such as firm size have not been taken into consideration while examining these aspects. The present study seeks to remedy these gaps by examining facilitators and inhibitors of adoption and implementation of 3D printing in both large and small size firms across different sectors.

3. Data and methodology

3.1. Data collection

When 3D printing surfaced as an innovation almost three decades ago, there were high expectations that it would invoke a manufacturing revolution, but now there is a certain amount of disillusionment with the outcomes achieved (Beltagui et al., 2023). Despite the extensive attention received from industry leaders and scholars, additive manufacturing has not yet witnessed the anticipated widespread adoption in many sectors, such as construction (Khosravani and Haghighi, 2022). A review of literature reveals that while discussion on why the diffusion is slow-paced has increased since 2014, the insights available are limited in volume, scope, and coverage. To explain further, the literature on reasons that have supported or hindered the adoption of 3D printing does exist, as discussed in the preceding section; nevertheless, it is far from comprehensive and slightly dated. Given the evolution of the technology and changes in the business environment, there is a need for a fresh examination of the facilitating and inhibiting factors that are impacting the adoption and implementation of 3D printing technologies. Also, with smaller firms experimenting with 3D printing, which was earlier considered the domain of the largest of large firms, their experience needs to be captured as well. As a result, we have chosen a qualitative research design, which will allow us the flexibility to explore the experiences and perceptions of a range of firms that have implemented 3D printing or are contemplating using it. Specifically, we utilized the open-ended essay method to extract information on facilitators and inhibitors in the adoption of 3D printing. Open-ended essays are a popular data collection technique in management and social science research since they help generate qualitative, rich insights from data (Salahuddin and Romeo, 2020; Talwar, Dhir et al., 2021). The method entails the collection of written responses from the participants to a set of questions. We developed these questions for our study by thoroughly reviewing the existing body of research on 3D printing technology. To ensure that the questions were relevant and aligned with the unfolding realities, we recruited a three-member panel comprising experts from academia, research, and industry to review the questions and suggest changes as required.

The final set of questions used to collect data comprised two distinct parts, one pertaining to the demographic and professional details of the respondents and the other comprising questions aligned with the study's objectives. Broadly, these questions focused on the reasons for adopting 3D printing technology, the advantages or affordances offered by 3D printing, various shortcomings and limitations of 3D printing technology, and different challenges or obstacles faced by firms since the adoption of 3D printing. Participants in the study were invited through an online crowdsourcing platform to ensure reach and relevant responses. Further, to ensure robustness, data collection was conducted in two phases, wherein in the first phase questions related to facilitating conditions were asked, and in the second phase questions related to inhibiting conditions were asked. Study participants comprised employees of firms operating in the UK.

Participation was voluntary, and the respondents were compensated for the same as per the policy of the platform. Along with assuring complete anonymity of responses and information, we informed the participants about the subjective nature of the survey questions and encouraged them to answer the questions freely, openly, and honestly. Doing so helped us to control for any issues related to responses as a result of biases such as social desirability bias (Nederhof, 1985).

In both the phases, we continued with data collection until theoretical saturation was reached. As a result, a total of 58 responses were received, of which 12 were discarded since these were incomplete and repetitive. Of the 46 retained, 23 were classified as responses from large scale enterprises (LSEs; based on the number of employees being more than 250) and the rest were classified as small-scale enterprises (SMEs; 10−250 employees). The average age of respondents from the LSEs was 37 years, and their average work experience was 12 years, with 15 belonging to the male gender. Their products included airplanes, satellites, helicopters, paper and plastic products, household paper and intimate hygiene products, lighting solutions, medical equipment, food and beverages, furniture, electric appliances, bathroom products, heavy duty trucks, cement, and packaging.

In the case of SMEs, the average age of respondents was 39 years, and the average work experience was 12 years, with 18 belonging to the male gender. Their products included tie downs, strapping, bed liners, roof lights, electrical connectors, food packing machines, rubbers, plastics, adhesives, staircases, furniture, decking, dog leads and harnesses, muzzles, training aids, screw pumps/generators, engineering kits, clothes, spectacles, cutting tools, acoustic insulation, position transmitters, sensors, electrofusion welding, mobile medical trailers, trailing equipment for transportation, HVAC air conditioners, material testing equipment, and consumables.

3.2. Data coding and analysis

To extract commonalities from the qualitative responses, two researchers independently coded the data collected through the open-ended essays as per the principles of grounded theory (Beyer and Holtzblatt, 1998). We performed open, axial, and selective coding to analyze the responses in line with the recommendations of Gioia et al. (2013). As a quality control measure, we adhered to a stringent, iterative approach for coding the data. Furthermore, since our objective was to uncover differences in facilitators and inhibitors of 3D printing adoption in LSEs and SMEs, we bifurcated the data and coded the responses separately. In the initial phase, two researchers independently coded the open-ended responses, while in the second phase, they interacted frequently to discuss the generated codes so as to achieve inter-coder reliability. After many such discussions, the discrepancies in codes were resolved to reach consensus, as suggested by Gilgor and Autry (2012). Coding of responses was undertaken using QDA Miner, a popular qualitative data analysis software, as it allowed the researchers to independently code the data and subsequently merge all separate files into one text to facilitate comparison. The memos option was actively used by the researchers to record their reasons for coding a particular text in a particular theme. The codes so generated were then manually analyzed by another member of the author team, such that the reported results are robust.

4. Results

Coding of the collected responses revealed five facilitating conditions that the employees of LSEs associated with the adoption and continued usage of 3D printing and four facilitating conditions that the employees of SMEs associated with the same, as presented in Fig. 1.

Coding of the collected responses revealed four inhibiting conditions that the employees of LSEs associated with the adoption and continued use of 3D printing and four inhibiting conditions that the employees of SMEs associated with the adoption and continued use of 3D printing, as presented in Fig. 2.

4.1. Facilitators driving adoption of 3D printing

Analysis helped us filter the raw data, moving from much broader first-order codes to narrower second-order themes and finally to the aggregate dimensions representing the five facilitators in the case of LSEs and four in the case of SMEs. The movement across these three levels is illustrated visually through the data structure diagram given in Fig. 3a and b for LSEs and Fig. 4a and b for SMEs.

The five facilitators that positively drive adoption and continued usage in LSEs are agility, versatility, efficiency and effectiveness, strategic leverage, and sustainability-orientation. The four facilitators that positively drive adoption and continued usage in SMEs are agility, efficiency and effectiveness, strategic leverage, and sustainability-orientation.

Agility, a facilitator perceived to exist in the case of firms of all sizes, can be defined as the 3D printing technologies' pace of response, lead-time, and turnaround time in developing new products, iterating designs, evaluations, amending specifications, and satisfying ad hoc needs, resulting in fast designing and prototyping, a short feedback loop, and flexibility in production.

In this regard, one participating employees noted that, "*The cost of prototype components is lower, and [they are] produced much faster—time is money after all. It reduces proof of concept times by roughly 75%, more if there a numerous tweaks and alterations*" [LSE, P4, Male, 44]

Another participant noted:

> "*The ability to quickly produce prototype products in house. We can then test, amend the design, and reproduce all in a number of hours or days. This process would normally take weeks if outsourced. We can also create quick solutions for bespoke tooling which helps in emergency situations. This gives us a huge cost saving as outsourced manufacturing on an urgent basis is very expensive*" [SME, P46, Male, 38]

Versatility, a facilitator perceived to exist in the case of LSEs only, captures how 3D printing can enhance the innovation performance of firms in terms of variety in design and diversified product offerings. The variety in design is enabled through empowering firms to design bespoke solutions and making more time available for research and design such that unique, detailed, and efficient designs can be created. Diversified product offering is supported through enabling firms to

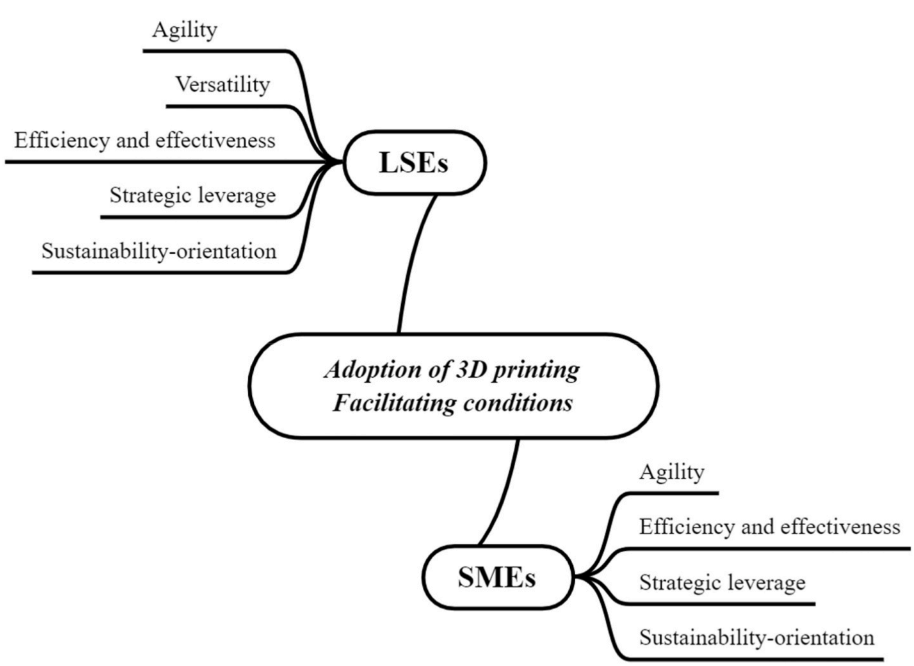

Fig. 1. Facilitators.

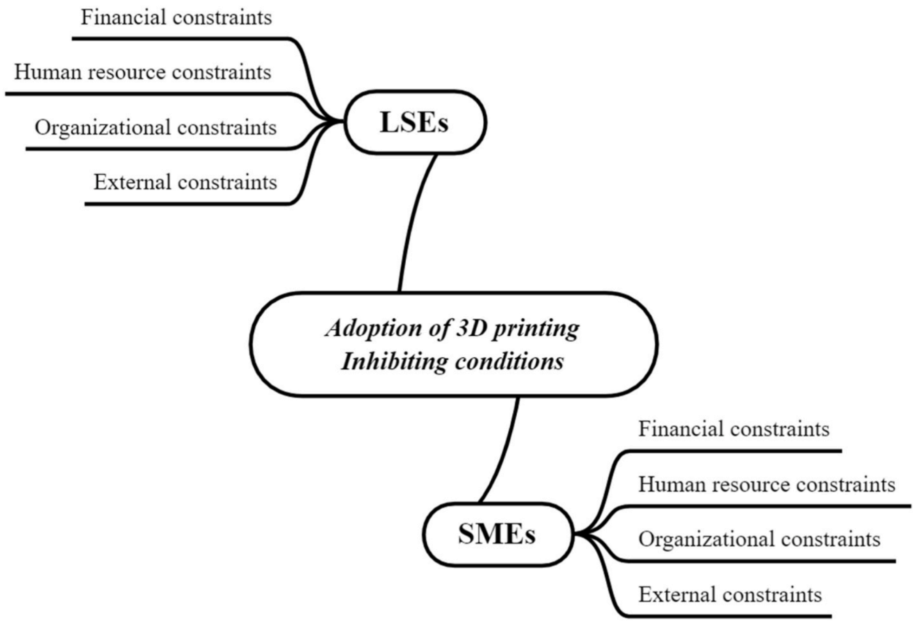

Fig. 2. Inhibitors.

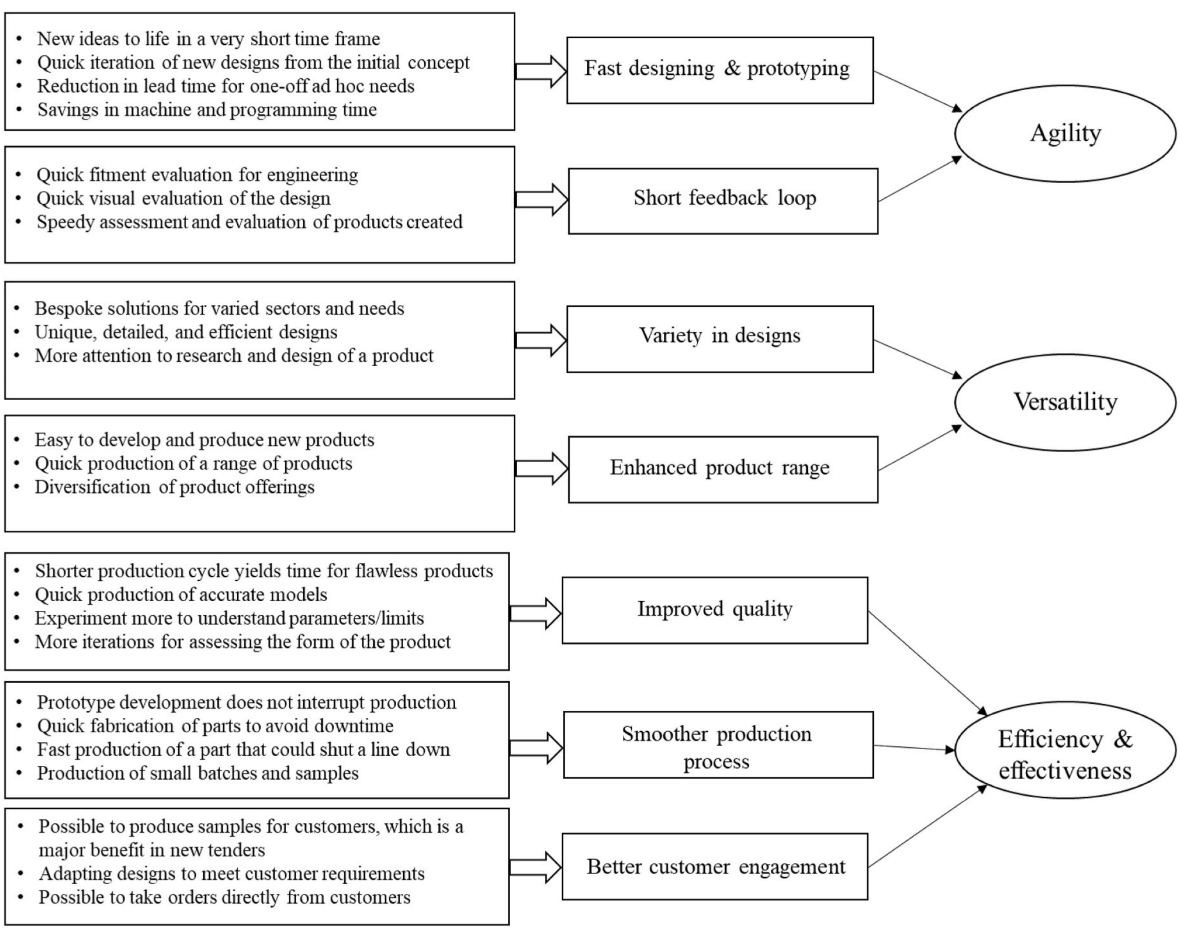

Fig. 3a. Data structure of facilitators (LSEs).

experiment with new product developments and prototypes quickly for testing. Employees of LSEs noted this to be a distinct benefit of 3D printing, as evidenced from the following responses:

"*Main drivers are for innovation in new designs and speed of creation. this enables us to bring ideas to life and trial much quicker than we could previously*" [LSE, P1, Male, 44]

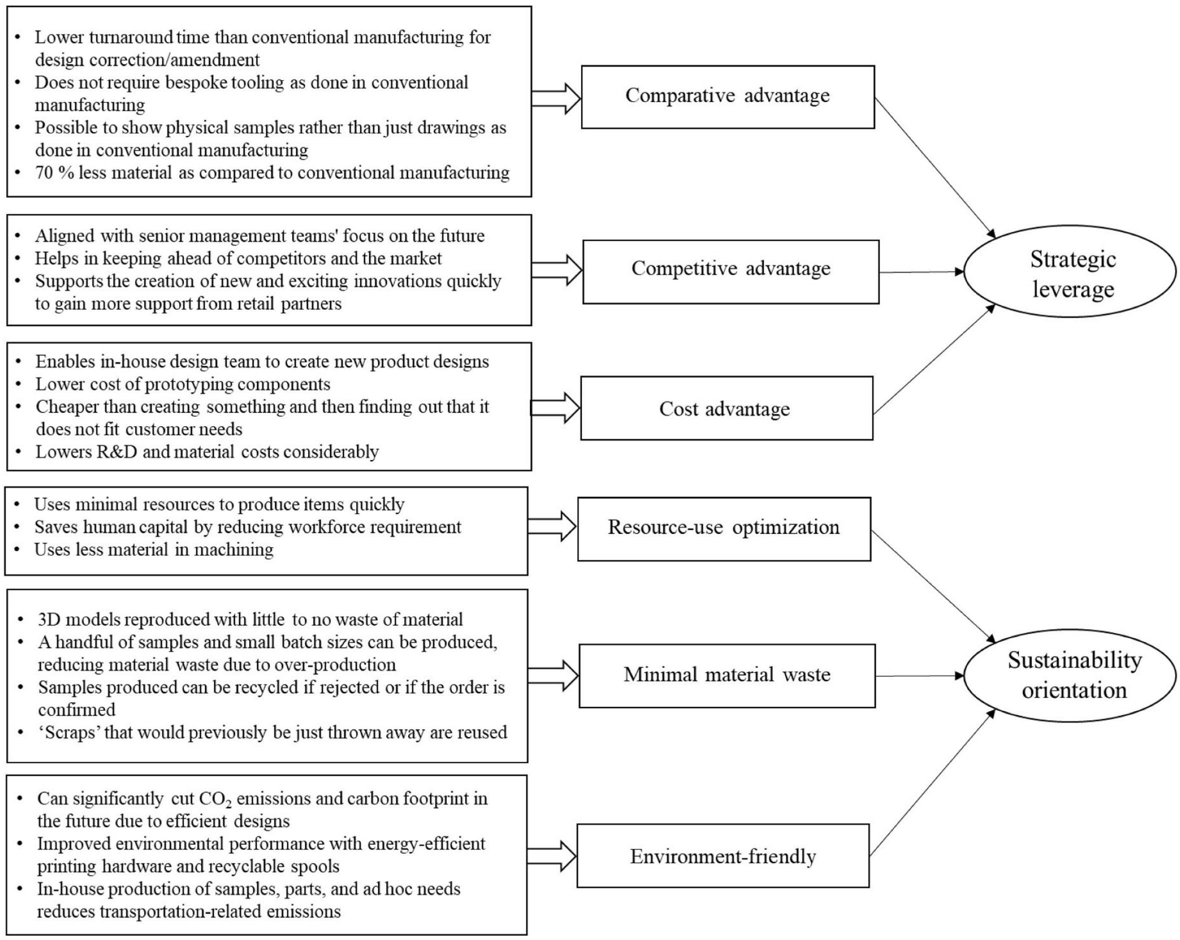

Fig. 3b. Data structure of facilitators (LSEs).

"*Primarily to support development and NPD activities - to speed up development work and reach final design more efficiently*." [LSE, P13, Male, 57]

Efficiency and effectiveness, a facilitator that employees of large as well as small size firms perceived to be a positive influence on the adoption and continued usage of 3D printing, is a gauge of how 3D printing contributes towards improvements in quality, operations, and customer engagement. The improvement in quality comes from precise measurements and sizing to create flawless products, robust prototypes that can survive vigorous testing, better internal quality control, the production of accurate models, and iterating until the desired form is reached, as shown in the words of respondents from both LSEs and SMEs.

"*For our internal business use it is very important to have the ability to quickly produce an accurate model which provides proof of concept to any design or prototype which we have developed in house, or to check a design or concept that was provided to us externally by a supplier or partner*" [LSE, P11, Male, 36]

"*3D printing will allow us to be more responsive, with a tool body that would previously have had to have been ordered from a subcontractor with a lead time of several weeks now available very quickly. It would also allow us to reduce costs and control quality better internally*" [SME, P38, Male, 43]

With regard to operations, 3D printers are perceived to have a positive impact by making the production process smoother in terms of supporting the fabrication of a critical part immediately in the event of breakdown, enabling the production of small batches and samples, and accommodating prototype development without impacting normal production processes. At the same time, they improve operations by simplifying the manufacturing process and making it consistent. The study participants confirmed this in these example observations:

"*3D innovations give a differentiated product and a bespoke solution. We generally use 3D printing to produce parts required urgently and that where waiting for long lead time parts from a supplier could lead to delays to customers. For example we have also used to fabricate door handles to*

Make our building Covid secure" [LSE, P5, Female, 50]

"*3D printing the components for our frames makes things so much easier for our welders as each part is identical rather than the variance you have when they're fabricated by a human. Even in the assembly area, the consistency from 3D printing the components make for a smoother operation with fewer flaws in the end-product after assembly*" [SME, P44, Male, 44]

The results of our data analysis also confirmed that 3D printing supports firms of all sizes in engaging their customers—both existing and potential—more efficiently and effectively by enabling companies to customize products to meet specific customer requirements, show physical samples rather than just drawings, reduce lead times to meet emergency demands, and improve on-time delivery rates. The enhanced capability to take orders directly and deliver a quality product on time was seen by respondents as a significant facilitating condition that increased the adoption and continued usage of 3D printing. At the same time, respondents from SMEs particularly noted how the use of 3D printing made them self-reliant as a firm. Some respondents asserted this quite emphatically, as quoted below:

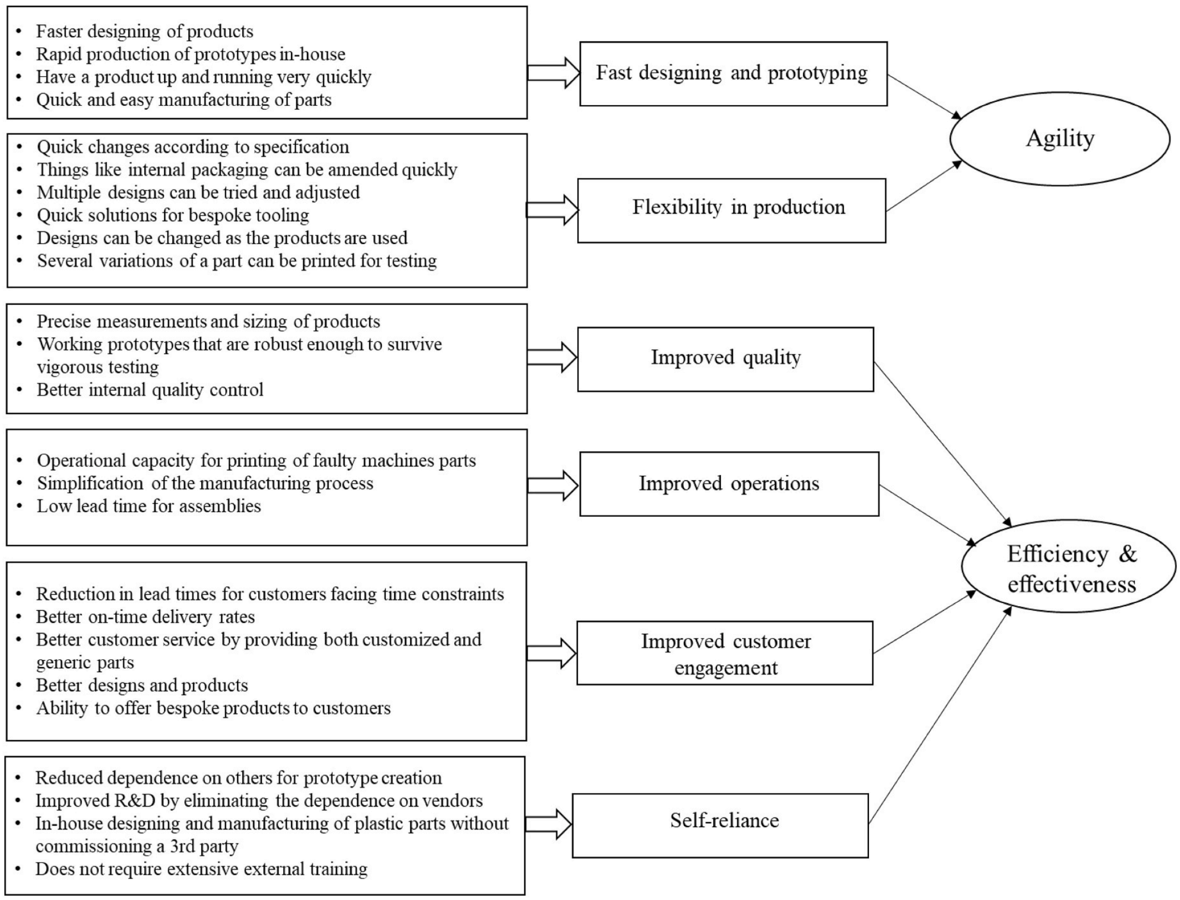

Fig. 4a. Data structure of facilitators (SMEs).

"*We are able to produce any product. We can take orders directly from customers. We can make anything from face visors to syringes. We can adapt designs to meet specific requirements. We are able to produce large quantities and therefore are able to sell the products at a lower price. We can also produce new designs for companies so they dont have to do so themselves*" [LSE, P7, Male, 31]

"*It offers us a quick, inexpensive and flexible to meet our customer's demands. Every part we sell is unique and designs change a lot; having the ability to alter a design and print it that day is invaluable. Otherwise we might be waiting 2-3 weeks for a simple tool, or longer for something more complex. That lead time is built in normally, but the ability to offer a part within a few days is a huge benefit and USP for us*" [SME, P39, Male, 44]

The *strategic leverage* offered by 3D printing has been noted unanimously by employees of both large and small enterprises. The key discussions hinged on the comparative, competitive and cost advantages offered by 3D printing. To begin with, respondents discussed how 3D printing was superior to conventional manufacturing by way of being faster, more flexible, and more versatile while requiring less input material. To quote some respondents:

"*We switched to 3d printers several years ago. We previously used long production line and specialised in infection moulding. The invention of 3d printers was driven largely by the current pandemic. We produce medical visors and the demand for these has increased by over 500 percent. We can produce these much easier on a 3d printer than the old production line. It is much more efficient and cost effective, as well as being less harmful to the environment*" [LSE, P7, Male, 31]

"*3D printing can help provide solutions for components that are difficult to manufacture in traditional ways and allows trying a variety of designs without the expense of large manufacturing runs that may produce redundant designs*" [SME, P32, Female, 33]

The strategic edge that the adoption and continued usage of 3D printing offered in terms of staying ahead of the competition or catching up with the first-movers was duly acknowledged by respondents from firms of varied sizes. 3D printing kept the adopting firms ahead of their peers by offering innovative and differentiated products that were attractively priced. The inherent features of 3D printing helped the firms as well in meeting customer demands faster than their competitors and developing the capability to beat the competition not only at the national but at the global level. As these respondents confirm the contention:

"*We have managed to win 30% more tenders from new customers by presenting 3D models that none of our competitors have been utilizing*" [LSE, P20, Female, 38]

"*The HVAC industry is very competitive and it is very difficult to compete on anything other than price and delivery time. Introducing 3D printing gives the company a slight edge over its competitors as you are able to produce your own components, perhaps not as cheaply as buying from China, but are less likely to be have delays*" [SME, P45, Female, 28]

Finally, the analysis of the qualitative responses brought forth the most intrinsic yet most critical strategic advantage offered by 3D printing—cost. Respondents employed in large as well as small size firms noted the fact that 3D printing lowered both the design and production costs for both routine manufacturing and one-off samples/ad hoc needs. In addition, it facilitated customization and research and development at much lower costs. As some respondents asserted:

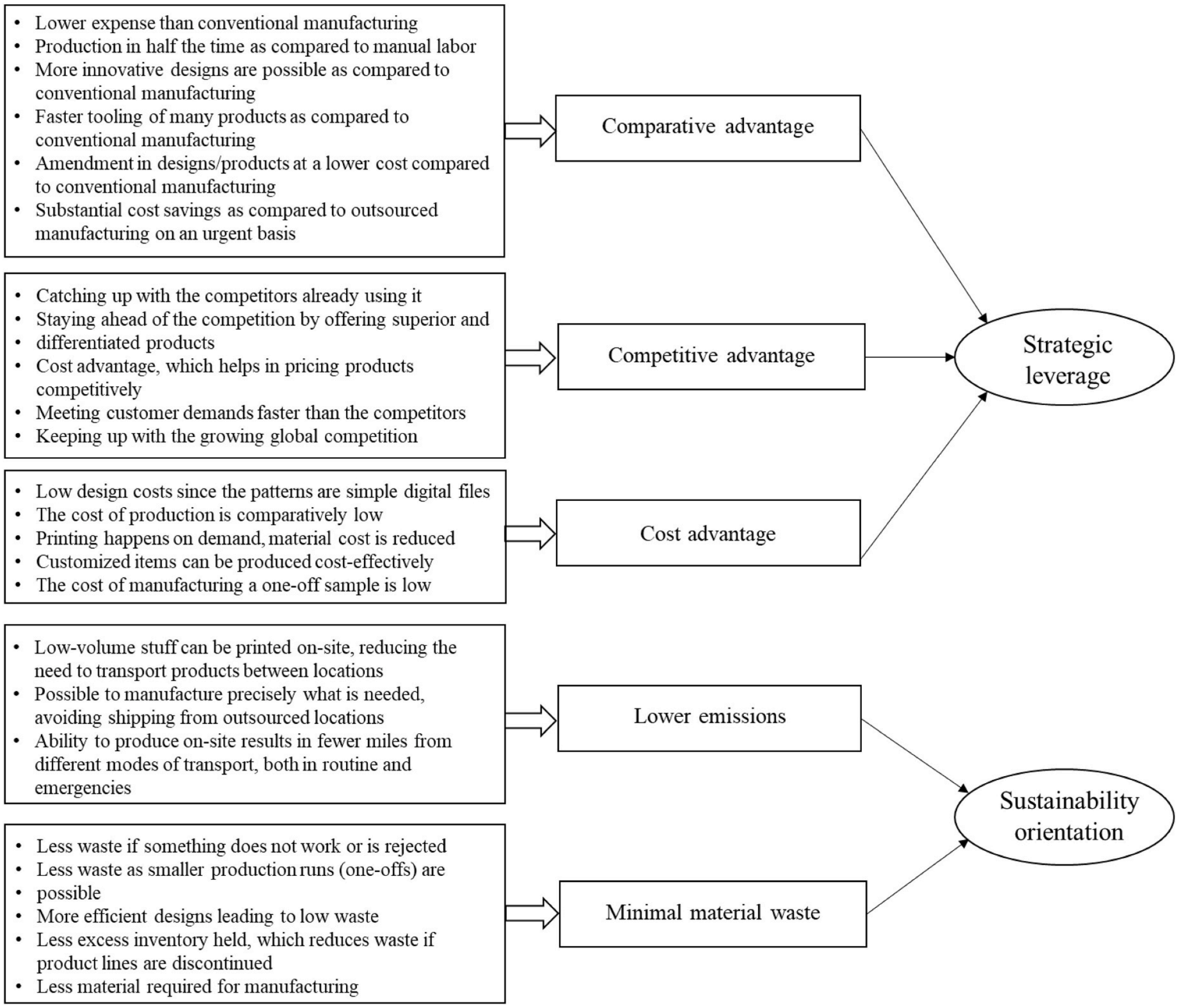

Fig. 4b. Data structure of facilitators (SMEs).

"*3D printing is used a lot for rapid prototyping. Its very effective and creating sample parts in a cost effective manor lowers R&D costs considerably. I can create a concept and that same week or even day be holding what I created in CAD. Due to this lot of prototype parts are ran through a 3D printer*" [LSE, P14, Male, 26]

"*We can design and manufacture plastic parts ourselves, without commissioning a 3rd party. Design costs are cheap as the patterns are simple digital files, not moulds that need to be tooled. The designs of our products can be changed as the products are used, while with moulded products we would have the expense of commissioning a new mould or be stuck with the first design*" [SME, P42, Male, 48]

As in the case of most industry 4.0 radical technologies, 3D printing is also considered to be one of the most sustainability-oriented technologies. This was apparent from the collected data, where employees of both LSEs and SMEs expressed appreciation for the sustainability-orientation of 3D printing and considered it a remarkable facilitating condition that positively drove adoption and continued usage of 3D printing. They particularly emphasized its contribution towards lowering emissions, reducing one's carbon footprint, enabling resource-use optimization and minimizing material consumption and waste. Some of the responses are quoted below.

"*Firstly 3D printing helps to cut down waste by as much as 70% as it uses only materials needed compared to conventional construction. Secondly it helps facilitate efficient designs with reasonably reduced carbon footprint. It is also presumed that 3D printing can significantly cut C02 emission in future*" [LSE, P15, Male, 30]

"*Environmental aspects e.g. disposal of waste product. But generally less materials needed, less transportation if requesting samples from manufacturer's warehouse, less waste as smaller production runs (one-offs) possible*" [SME, P32, Female, 33]

4.2. Inhibitors impeding adoption of 3D printing

Coding of the collected data to find the first-order codes, second-order themes, and the aggregate dimensions revealed four inhibitors/barriers in the case of LSEs as well as SMEs. The data structure for the same is presented in Fig. 5a and b, and 6a and 6b.

The four inhibitors that impede the adoption and continued usage of 3D printing in the firms of both sizes are financial constraints, human resource constraints, organizational constraints. and external constraints.

Financial constraints, an inhibitor found to exist in the case of both LSEs and SMEs, implies barriers and inhibiting factors arising from prohibitively high initial costs and funding challenges arising from the required investment. High initial costs arise not only from the cost of equipment but also from the cost of facilities to accommodate the equipment, ascertaining design functionality and durability, and the high cost of initial training. Funding challenges arise from concerns that investors have about the amount of funds to be committed,

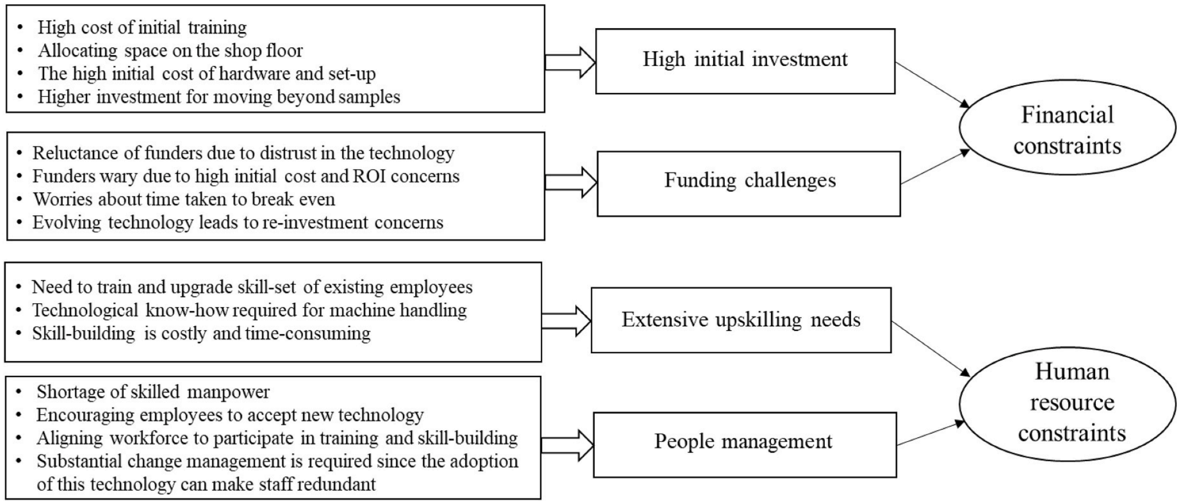

Fig. 5a. Data structure of inhibitors (LSEs).

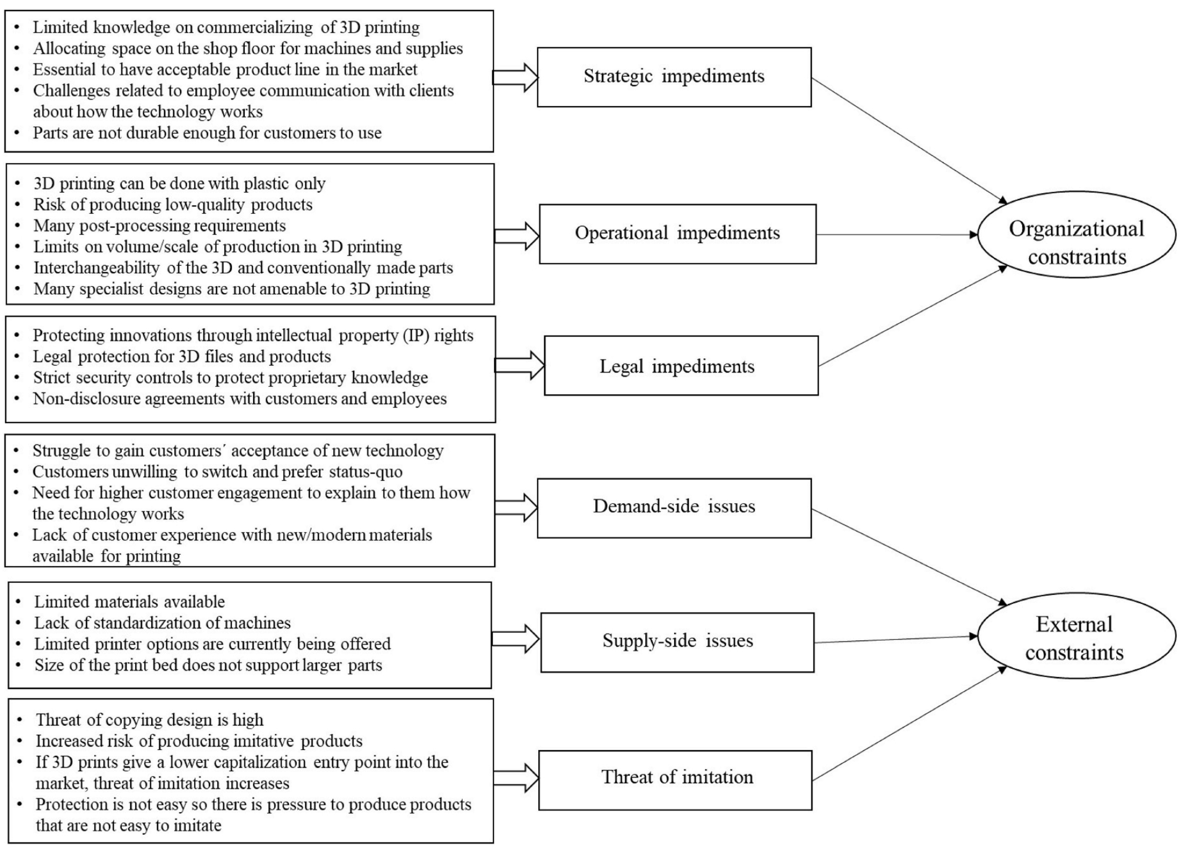

Fig. 5b. Data structure of inhibitors (LSEs).

distrust in the technology's potential, long payback periods, the time taken to break even, and concerns about return on investment (ROI). As some respondents noted:

"*The main barriers I would say are initial cost and skills, it can take time to secure budgets for this sort of technology and skills training can take time. other than this there are no other real barriers*" [LSE, P1, Male, 44]

"*The barrier is the initial cost of equipment, and the ongoing running costs. If the technology proves to be very expensive to run and not able to produce tools at a realistic cost then it will not be suitable*" [SME, P38, Male, 43]

Human resource constraints capture the personnel-related challenges that arise for LSEs and SMEs from the adoption and continued usage of 3D printers. One part of this inhibitor comes from the extensive upskilling training required to enable employees to operate and manage the new technology, and the second part comes from personnel issues regarding change management. As respondents observed:

"*Barriers are initial set up cost, training and also encouraging change within the workforce. The change management with the team is a barrier*

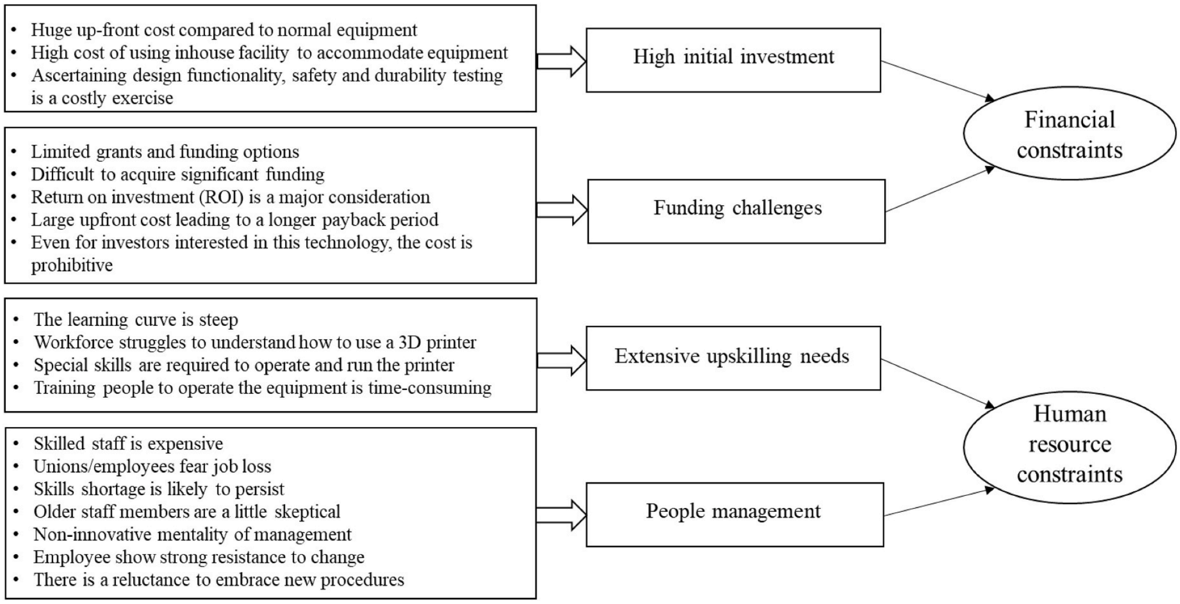

Fig. 6a. Data structure of inhibitors (SMEs).

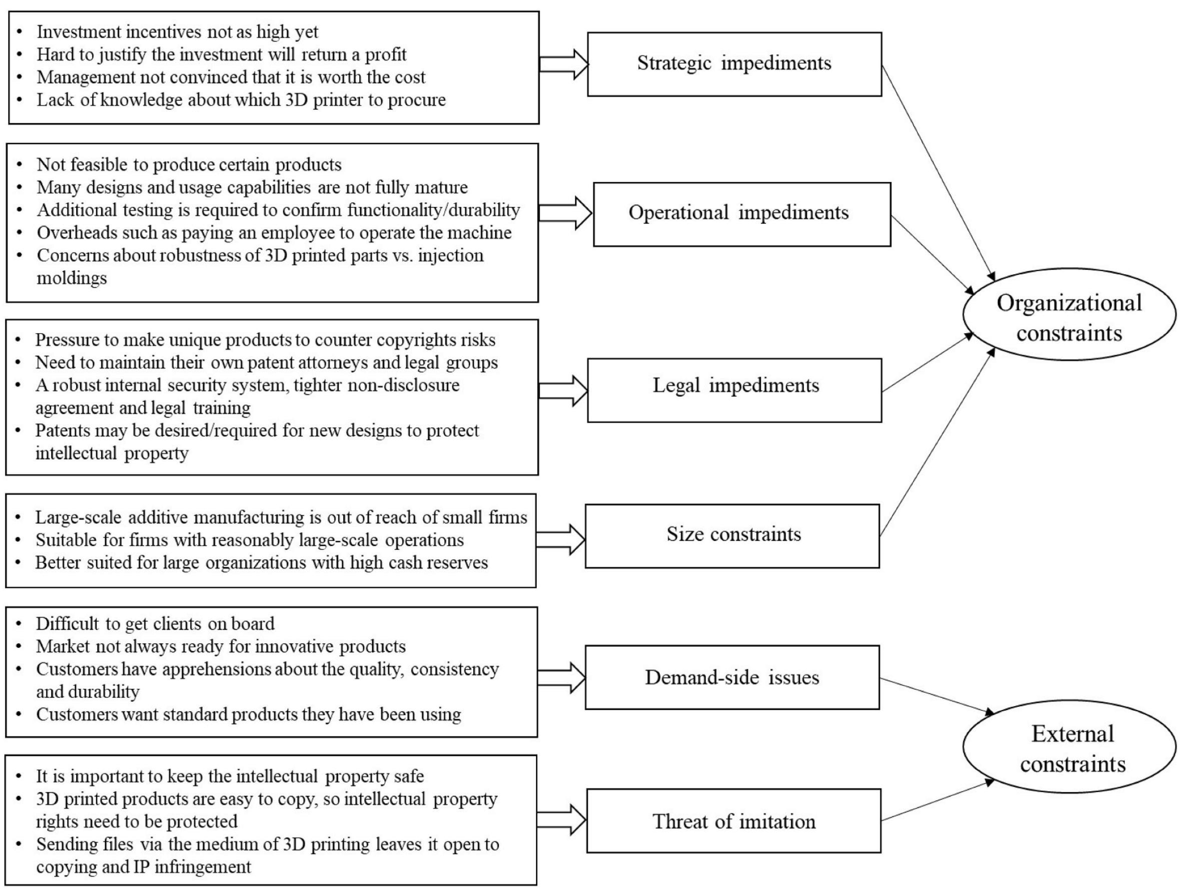

Fig. 6b. Data structure of inhibitors (SMEs).

as adopting this type of technology can mean a reduction in workforce and that needs to be very carefully managed" [LSE, P5, Female, 50]

"*The union that runs our shop is a big barrier. We are very limited in what we can do as far as 3-D printed parts in actual production or sold to customers. It's the opinion of the union that the 3-D printer is taking the job of a machinist, right or wrong, they do have some control and what we can do*" [SME, P27, Male, 46]

Organizational constraints capture the impeding factors that firms of all sizes face due to internal deficiencies, issues, or challenges comprising strategic, operational, and legal aspects. In the case of SMEs, an additional organizational impediment was observed in the form of the constraint imposed by their small size, making it difficult for them to make the noticeable transition to additive manufacturing and arranging the required funds.

The key strategic impediments that firms have to counter include limited knowledge of how to leverage 3D printing commercially to drive profitability, a lack of clear understanding on the optimal configuration of hardware and facilities, doubts about the sturdiness of products and the richness of product lines, and confusion in employee−customer communication. This is confirmed by the respondents, some of whom said,

"*Parts are not durable enough to use for customers. Also cost to print large enough items for customers is not practical*" [LSE, P9, Male, 47]

"*Lack of knowledge of which specification of 3D printer to procure. Changing the mindset of some of the older members of the team*" [SME, P46, Male, 38]

The operational impediments faced were related to the feasibility of producing all products through 3D printing, design, robustness and testing issues, material used, scale/volume of production, and the problem of interchangeability of the 3D parts with conventionally made parts. In the words of some respondents:

"*Barriers include capabilities in terms of meeting structural integrity requirements of the part along with the speed of manufacture for making parts that are required at significant volumes.*

Other inhibitors could be the total cost and interchangeability of the 3D parts versus a conventionally made part. If the parts are not exactly like for like in terms of dimensions and physical properties between printed parts and traditionally machined parts they cannot be used as alternatives or spares" [LSE, P2, Female, 49]

"*The type of equipment we produce. Its just not feasibly possible for a screw pump to be 3D printed as of yet. There may be an opportunity in the future but as of yet no*" [SME, P33, Female, 26]

The legal impediments experienced by both LSEs and SMEs are related to protecting their intellectual property from the vulnerability of the designs being imitated. Extensive efforts in the form of maintaining their own patent attorneys and legal advisers, having stringent non-disclosure agreements, and instituting tight security protocols act as barriers for firms of all sizes. This is apparent from the responses quoted below:

"*We have to keep our intellectual property protected, we do this by having NDA's for customers and employees. If we are working on a particular project, we keep it internal only, we don't flash it around on social media. Once the item is really produced, we may share that we did a 3D print of the bottle first, but it's really not necessary to share this information*" [LSE, P17, Female, 32]

"*Our company does many ITAR and maintains its own patent attorneys and legal groups. If we were to find a process that makes our parts better, faster, and cheaper that is NOT patented, our team would absolutely push to get it patented to protect our legal right to produce parts with that method*" [SME, P40, Male, 26]

External constraints capture the demand-side issues, supply-side issues, and the threat of imitation that firms face when they use 3D printing. However, supply-side issues are not perceived to exist in SMEs, such that their external constraints comprise only demand-side issues and threat of imitation. Herein, the prominent demand-side issues experienced by both the LSEs and SMEs include issues pertaining to gaining the acceptance of customers who are hesitant in adopting the new technology and prefer the status quo. Most customers are suspicious of new technology, and a high level of customer engagement may be required to convince them to switch to mostly or only 3D printing solutions. The respondents have expressed the difficulties involved quite emphatically, as seen in the sample responses given below:

"*As the technology is new, there is little proven use/case studies to work from. The technology needs to be developed collaboratively with the supplier. Customers are naturally suspicious of a new technology in a field where not much has changed in 30 years, and would worry about the quality and durability*" [LSE, P22, Male, 29]

"*As the technology is new, there is little proven use/case studies to work from. The technology needs to be developed collaboratively with the supplier. Customers are naturally suspicious of a new technology in a field where not much has changed in 30 years, and would worry about the quality and durability*." [SME, P38, Male, 43]

Coming to supply-side issues, only LSEs were perceived to face these. In this regard, the respondents noted factors such as the lack of standardization of machines, and availability of limited variety and material. As one respondent said,

"*The challenges presented by 3D printing should be understood by manufacturing leaders, in order to overcome them. One of the main problems of 3D printing is the lack of standardization of machines, and the potential for low-quality products*" [LSE, P10, Male, 33]

"*Limited options can currently be offered by suppliers. At the moment we can only source very simple equipment/solutions from suppliers and they must be food safe, which some suppliers cannot supply*" [LSE, P23, Female, 26].

LSEs as well as SMEs face a very serious risk of their innovations produced through 3D printing being copied and key data being breached. The employees stated this quite categorically, as produced verbatim below:

"*Yes, in short, I do believe that 3D printing has increased the risks of producing imitative products. In terms of securing the designs from being imitated and passed off as others, cyber security must be tight within the business to make it difficult for anybody to steal designs, and as for accidental imitations, I think some sort of database to look at current designs would be useful to ensure nobody accidentaly takes an idea that isnt theirs*" [LSE, P21, Male, 28]

"*This is something else that we need to strongly consider. Again, a lot of our materials that we move around are bespoke for specific customers. Sending these via the medium of 3D printing leaves it open to copying and IP infringement. Presumably there would be strong security put in place*" [SME, P29, Male, 37]

5. Discussion

We addressed **RQ1** regarding the facilitators and inhibitors to the adoption and continued usage of 3D printing by conducting a qualitative study through open-ended essays. Analysis of the data thus collected revealed five facilitators and four inhibitors as perceived by respondents working in various sub-sectors of the manufacturing industry that impact the adoption and continued usage of 3D printing. The five facilitators we identified are agility, versatility, efficiency and effectiveness, strategic leverage, and sustainability-orientation. The facilitators identified by us are in congruence with past findings but are not limited to them. In fact, the scholarly literature has not directly discussed facilitators for the most part; rather, past studies have deliberated upon the benefits of 3D printing. These can also be considered drivers of adoption, which have been mentioned by previous studies, but not by many. It is also important to note that past discussions have been more micro-focused and narrower, limited to specific benefits such as product innovation and creative designing (Candi and Beltagui, 2019; Tsai and Yeh, 2019), customization (Niaki et al., 2019), on-demand production (Ford and Despeisse, 2016; Oettmeier and Hofmann, 2017; Weller et al., 2015), and environmental sustainability (Niaki et al., 2019; Weller et al., 2015). In comparison, our findings offer a macro-level and more-inclusive categorization of facilitators of the adoption and continued usage of 3D printing, providing comprehensive coverage of all potential benefits that serve as facilitating conditions.

In examining inhibitors, our study identified four barriers that are perceived to be factors that can lower adoption or exacerbate the non-adoption of 3D printing by firms of different sizes. The four barriers we identified are financial constraints, human resource constraints, organizational constraints, and external constraints. These barriers are largely in consonance with the prior findings, wherein the scholarly literature has discussed issues such as the lack of a skilled workforce (Candi and Beltagui, 2019; Oettmeier and Hofmann, 2017), and employee/managerial resistance (Conner et al., 2014; Ford, 2014), which are similar to the human resource constraints identified in our study. At the same time, issues such as evolving technology (Schniederjans and Yalcin, 2018; Ukobitz, 2020), low quantum of manufacturing (Attaran, 2017; Ford and Despeisse 2016), low consumer awareness and acceptance (Niaki et al., 2019; Ukobitz, 2020), and high costs (Chaudhuri et al., 2019; Marak et al., 2019) identified by our study also provide a validation of prior findings and provide the literature a continuity. However, our study did not find some of the barriers discussed in the past, such as environmental uncertainties (Ford and Despeisse, 2016; Ukobitz, 2020) and regulatory ambiguity (Mellor et al., 2014; Weller et al., 2015). A potential reason for this could be that our study setting is in a developed country, where the business and regulatory environment is more settled. It is also quite possible that with the ongoing evolution of the technology, business and regulatory environments have become more settled.

To respond to **RQ2**, which queried the similarities and differences in facilitators and barriers impacting the adoption and continued usage of 3D printing based on firm-size (large versus small), we bifurcated the data into responses from employees of LSEs and SMEs before analyzing the responses. This enabled us to identify distinct sets of facilitators and barriers for each, making comparison possible and easy.

With regard to facilitators, broadly we observe that both LSEs and SMEs perceive agility, efficiency and effectiveness, strategic leverage, and sustainability-orientation as the key facilitating conditions, with LSEs also reporting versatility as an additional facilitator. However, a closer look at the first-order concepts and second-themes (see Figs. 3 and 4) shows that many of these are perceived to constitute different outcomes for LSEs as compared to SMEs. For instance, for SMEs, agility comprises fast designing and prototyping and flexibility in production whereas for LSEs, it implies fast designing and prototyping and a shorter feedback loop. Similarly, while efficiency and effectiveness from the LSE perspective include outcomes such as improved quality, a smoother production process, and better customer engagement, for SMEs, in addition to improved quality and customer engagement, it also implies improved operations and self-reliance. In the case of sustainability-orientation as a facilitator, it is apparent from first-order concepts and second-order themes that for SMEs, it has a narrower implication in terms of lower transport-related emissions and the minimization of material waste, whereas in the case of LSEs, it has a broader connotation to cover optimization of human resources in addition to materials. Similarly, LSEs perceive that 3D printing not only helps lower transport-related emissions but also the carbon footprint of the concerned firm by enabling efficient designs, the use of energy-efficient printing hardware, and recyclable spools. While significant, these differences are not as radical as a very prominent difference that becomes obvious when we see versatility as a facilitating condition. To elaborate, versatility, comprising variety in design and enhanced product range, is a facilitator perceived to exist only in the case of LSEs. This may be interpreted to indicate that SMEs are still in the stage of operationally implementing 3D printing and have yet to reach a stage where they are able to use this technology to make a marked difference in their product range and design. In the case of similarities, both LSEs and SMEs perceive the adoption of 3D printing as offering a strategic leverage through comparative, competitive, and cost advantages.

With regard to barriers, at a glance it appears that both LSEs and SMEs face similar inhibiting factors, captured in our study as financial constraints, human resource constraints, organizational constraints, and external constraints. However, a closer look at the first-order concepts and second-themes (seeFigs. 5 and 6) shows that many of these are also perceived to constitute different outcomes for LSEs as compared to SMEs. For instance, for SMEs, as opposed to LSEs, high initial investment comprises a prominent concern for ascertaining design functionality, safety, and durability testing. In comparison, LSEs are more concerned about the space allocation and high cost of initial training. Similarly, for LSEs, human resource constraints related to people management are more about change management, workforce alignment, and meeting skilled staff shortages, while for SMEs, they are largely about employee resistance and redundancy. In the case of strategic impediments, which constitute the larger organizational constraints, LSEs have more focus on commercialization and product line issues, whereas SMEs tend to be more concerned about the technical specifications of product and management support. Most marked differences between the two are related to size constraints, which constitute the perceived organizational constraints experienced by SMEs, and supply-side constraints, which constitute the perceived external constraints experienced by LMEs. Employees of SMEs distinctly considered the small size of their firms to be a constraint in resource-mobilization and scaling their operations. This finding is very important since it lends credence to the very motivation of our study to examine the differences in facilitators and inhibitors experienced by LSEs versus SMEs when it comes to 3D printing. Another dissimilarity was that the employees of SMEs did not perceive their firms to be experiencing supply-side issues, such as a limited variety of printers and materials currently available in the market. In terms of similarities, both LSEs and SMEs have similar funding, skill upgradation, intellectual property protection, demand-side, and threat of imitation concerns. Since this is the first study to undertake a comparative analysis of facilitating and inhibiting conditions that promote or impede the adoption and continued usage of 3D printing by LSEs and SMEs, there is no a priori evidence for us to compare our findings with.

6. Conclusion

The key motivation behind our study was to examine the facilitators and inhibitors that have been instrumental in impacting the present state of adoption or non-adoption of 3D printing by firms operating in different sub-sectors of the manufacturing industry. Despite some existing findings in this regard, the need for a more nuanced examination of the driving and inhibiting factors was felt due to certain theoretical and practice-level gaps. From the theoretical perspective, we observed that the volume of research and the evidence offered by the scholarly literature was limited and evolving, leaving many questions unanswered. From the practice perspective, recent reports and statistics indicated that the adoption rates of 3D printing were still quite dismal, the much-discussed benefits of usage not notwithstanding. In addition, despite 3D printing leaving the elite space of the largest of large firms and witnessing adoption by small-sized firms in the recent past, academic research had yet to contemplate the differences and similarities in the experienced facilitators and barriers due to variation in size and, consequently, resources. As a result, our study examined the facilitators and inhibitors of the adoption and continued usage of 3D printing, anchoring the examination in firm-size differences (large versus small). We articulated our objectives through two specific research questions, which we answered using a qualitative approach. The qualitative study sought responses from employees of manufacturing firms operating in the UK. We used a stringent approach to data analysis, as prescribed by Gioia et al. (2013), wherein we coded the data to generate first-order concepts, second-order themes, and aggregate dimensions. The results comprising a distinct set of facilitators and inhibitors for LSEs and SMEs separately were reported following the standard protocol of visual presentation through a data structure diagram and verbatim reproduction of sample responses. Our analysis revealed five facilitating conditions that the employees of LSEs associated with the adoption and continued usage of 3D printing and four facilitating conditions that the employees of SMEs associated with the adoption of 3D printing, as presented in Fig. 1. Similarly, coding of the collected responses revealed four inhibiting conditions that the employees of LSEs associated with the adoption and continued use of 3D printing and four inhibiting the same for SMEs, as presented in Fig. 2. The study offers meaningful implications, as discussed below.

6.1. Theoretical implications

We enumerate three notable contributions of this study as follows: First, our study attempted to address the issue of the paucity of insights in the scholarly literature on the adoption of 3D printing, which, despite more than two decades of first diffusion, has not reached the anticipated level of adoption (Ukobitz and Faullant, 2022). The available scholarly literature has not only given limited attention to the issue of slow adoption but has also kept a narrow focus on discussing drivers or inhibitors of adoption in specific contexts such as logistic suppliers (Xiong et al., 2022), footwear manufacturing firms (Ukobitz and Faullant, 2022), and healthcare 3D printing services (Chaudhuri et al., 2022). The discussion of inhibitors is especially sparse. Towards this end, we uncovered a broad set of facilitators—agility, versatility, efficiency and effectiveness, strategic leverage, and sustainability-orientation—which bring together all the potential factors that can drive adoption and continued usage of 3D printing by various sub-sectors of the manufacturing industry. Similarly, we identified inhibiting factors—financial constraints, human resource constraints, organizational constraints and external constraints—from the perspective of a broad set of manufacturing firms producing diverse products ranging from satellites, airplanes, and helicopters to food and beverages, furniture, and bathroom products. The consolidation of such a comprehensive set of facilitators and inhibitors relevant for a large set of firms can serve as a useful platform for scholars to build and expand upon. In sum, addressing the need for more research in the area, our study appreciably advances the current understanding of the adoption of 3D printing by offering a complete picture, with facilitators that may enhance adoption on one hand, and inhibitors that can reduce adoption or continued usage on the other.

Second, our study offers comparative analysis of how the facilitators and inhibitors differ with firm size. To our knowledge, this is the first study that has explored these differences through rigorous analysis of qualitative data collected from employees of these firms. The value of our contribution increases in light of the fact that despite mixed feedback on success and failure resulting from the adoption of 3D printing (Beltagui et al., 2023) and the more recent adoption of 3D printing by smaller firms and new ventures (Rayna and Striukova, 2021), the amassed knowledge of facilitators and inhibitors is not fine-grained, with the lens of firm-size variations remaining under-researched. Since the impact of firm-size variations in outcomes of technology adoption and use has been confirmed by past studies in different contexts (e.g., Chan et al., 2019; Street et al., 2017), the lack of discussion around it within the 3D printing context was a serious gap that we have uncovered and addressed, thereby not only providing novel insights but also opening an interesting and practically useful research path for future studies.

At the same time, the latest scholarly literature has noted that even in the sectors and firms that have adopted 3D printing, all has not been positive, with disparate stories ranging from tremendous success to dismal disillusionment resulting from the failure of the technology to live up to the expectations (Beltagui et al., 2023). The need to understand the role of firm-size differences becomes all the more critical in light of observations that 3D technologies had once remained restricted to niche markets, being largely seen as the domain of the largest of firms for a long time, but have recently become more accessible to smaller firms and new ventures (Rayna and Striukova, 2021).

Finally, our study makes a methodological contribution by not only identifying the facilitators and inhibitors, but also offering potential items that can be used to measure each of the factors identified. To explain further, the first-order concepts found through data analysis can be used to collect quantitative data for measuring the second-order themes and the aggregate dimension. Admittedly, we have not gone through the formal process of scale construction, yet these preliminary items can serve as a basis for scale development and testing in future studies. In addition, the distinct and comprehensive facilitators and inhibitors identified in our study can serve as basis for theory development. Given that 3D printing is evolving into an ecosystem of technologies (Candi and Beltagui, 2019), such theorization and measurement scales can be of great value in motivating and guiding research in the area.

6.2. Practical implications

Our study offers three useful implications for marketers, managers, manufacturers of 3D printers, and policymakers. First, through extensive mapping of facilitating conditions valid for a large variety of manufacturing firms having varied products and size, our study offers a strategic input for the relevant stakeholders, such as managers seeking to adopt or promote the use of 3D printing in their respective firms. For instance, recurring cost savings and the advantage of flexibility in producing the smallest of batch sizes and one-off samples can be used as strong counter argument to offset the concerns about high initial investment and scale of operations. At the same time, the categoric feedback of LSEs and SMEs that adoption of 3D printing is a key strategic lever in beating or catching up with the competition can help managers, marketers, and manufacturers still struggling to convince senior management about 3D printing being a reasonable business proposition.

Second, the barriers related to concerns about imitation and protection of intellectual property perceived to exist by LSEs and SMEs indicate that regulators can contribute to increasing the diffusion of 3D printing by formulating stringent policy measures and introducing robust preventive statutes that would act to dissuade copyright infringements. In addition, our findings that demand-side issues largely comprising consumer resistance to new technology still exist, provide inputs to concerned stakeholders that they need to increase awareness and information efforts at different levels. Given that 3D printing technologies are high on sustainability-orientation, supporting the diffusion of 3D printing will also help regulators in advancing their sustainability agendas to be greener than other conventional technologies, which is an added advantage.

Finally, we provide input for research and development firms by revealing that despite being around for nearly three decades, 3D printing is still considered to be a nascent technology in its evolutionary phase. Firms also feel that limited options are there, both as far as 3D printers and printing materials are concerned. This implies that research focused on improving the product features, sizes, variety of material used, and so on can be fruitful to develop 3D printers more aligned with industry requirements.

6.3. Limitations and future directions

Our study's contributions need to be considered in the light of certain unavoidable limitations of scope and methodology. These limitations are also important to acknowledge since they provide basis for determining future research directions. First, the study results are based on data collected through single qualitative method—open-ended essays—which involves written responses to a series of open-ended questions. As a result, there is a risk of bias or missing out more granular information that could have been captured through using multi-method approach combining qualitative and quantitative data collection, or even more than one approach to collect qualitative data. However, the study results can be considered robust since open-ended essays have been used quite effectively in past studies in different contexts such as food waste (Talwar, Kaur et al., 2021), healthcare (Iyanna et al., 2022), etc. Future studies can further extend our findings by using research designs comprising multiple approaches. Second, the LSE and SME firms examined in the study were based in a developed, Western country, which implies that the findings may not be portable to countries at different stages of economic development or even a developed country that is culturally different. This limitation is easily remediable by future researchers who can replicate our study in different settings, making comparative observations. Finally, our study had an exploratory orientation to uncover the facilitators and inhibitors experienced on the ground by LSEs and SMEs. We did not anchor our study's conceptualization in any known theories. While this helped us discover the facilitators and inhibitors as experienced, grounding our results in theory could have enhanced the takeaway. The facilitators and inhibitors identified by us indicate that organizational behavior theories, particularly those focusing on motivation, change management, and leadership can add interesting dimensions to the conceptualization and discussions. For instance, the eight-stage process for transformational change (Kotter, 1996) can be used as theoretical framework, especially since it has been found to be effective in examining the adoption of technological innovations (Campbell, 2008).

Data availability

Data will be made available on request.

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