Emerald Industrial Management & Data Systems

The Role of Service Providers in 3D Printing Adoption

Journal:	*Industrial Management & Data Systems*
Manuscript ID	IMDS-08-2018-0339.R1
Manuscript Type:	Research Paper
Keywords:	3D printing adoption challenges, industrial firms, service providers, Denmark, Germany, additive manufacturing

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Abstract

Purpose - 1) to identify challenges faced by industrial firms at different phases of adoption of 3D printing 2) outline how 3D printing service providers can help address these challenges.

Methodology - Separate interview questionnaires for 3D printing users and 3D printing service providers, were used to conduct semi-structured interviews.

Findings - The key 3D printing adoption challenges are: creating a business case, difficulty in using different materials, optimising the process for specific parts, lack of 'plug and play' solutions offered by equipment manufacturers, limited availability of training and educational support, poor end product quality, machine breakdowns and high cost of maintenance and spare components. Using the theoretical lens of the Technology Acceptance Model (TAM), results show lack of ease of use and technological turbulence impact companies' decisions to adopt 3D printing. 3D printing service providers can indeed attempt to alleviate the above challenges faced by customers through providing multiple 3D printing services across different stages of adoption.

Research implications - Future research should examine the role of 3D printing equipment manufacturers and design and modeling software solutions providers in improving adoption and how 3D printing equipment manufacturers could develop into more integrated service providers as the technology advances.

Practical implications - Service providers can help customers transition to 3D Printing and should develop a portfolio of services that fits different phases of adoption.

Originality/value - The paper outlines how 3D printing service providers can help address customer challenges in adoption of 3D printing across different stages of adoption.

Keywords 3D printing adoption challenges, industrial firms, service providers, Denmark, Germany.

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1. Introduction

Many firms across a diverse range of industries are exploring 3D Printing (3DP) for multiple applications including prototyping, tooling and component manufacturing. Conservative estimates consider 3DP to be still at an early diffusion stage, with room for further and rapid development (Anusci, 2015). However, 3DP has multiple potential advantages i.e. decrease in lead time (Mellor *et al.*, 2014; Chiu and Lin, 2016), reduction in transportation, logistics and inventory costs (Khajavi *et al.*, 2014; Chen *et al.*, 2015), weight reduction, energy consumption reduction and improvement in environmental sustainability (Petrovic *et al.*, 2011; Chen *et al.*, 2015; Holmström *et al.*, 2017), improved flexibility and customization (Khorram Niaki and Nonino, 2017; Holmström *et al.*, 2017; Deradjat and Minshall, 2017). Indeed, increasingly sophisticated 3DP technologies are expected to transform manufacturing and provide impetus to 3DP services, as well as applications of new business models (Gallouj *et al.*, 2015; Hannibal and Knight, 2018; Jiang *et al.* 2017).

Motivation to adopt 3DP depends on the perceived relative advantage of the technology and the resulting performance expectations (Schniederjans, 2016). Such motivations and the willingness to scale 3DP production may, however, differ depending on the firm's stage in the adoption cycle and their current level of maturity in adoption. Differences between expectation and satisfaction, expected and perceived service and utility differential between the selected alternative and a reference affect the intention of the user to adopt new technologies (Ha, 2018). However, only limited research is available on adoption of 3DP (Shukla *et al.*, 2018), particularly those employed by industrial manufacturing companies, the challenges faced by them in adoption, expectation mismatch concerning services bought and on ways to overcome such challenges.

3DP service providers offer a full spectrum of 3DP-related services. These include services for selling and servicing of additive manufacturing equipment, the design and/or manufacture of 3D printed products, as well as other consultancy and feasibility analysis services (Rogers *et al.*, 2017; Sasson and Johnson, 2016). The developments in 3D technology show no signs of abatement. Indeed, despite the interest in understanding and monitoring the growth and potential of 3DP (Berman, 2012; Mellor *et al.*, 2014, Weller *et al.*, 2015; Baumers *et al.*, 2016; Birtchnell *et al.*, 2017; Dwivedi *et al.*, 2017), there is no research which has analysed the roles of service providers in addressing the challenges faced by manufacturers in adopting 3DP. Thus, the specific research questions this study addresses are as follows:

1) What are the key challenges faced by Danish and German manufacturers in adopting 3DP and using 3DP services?
2) What is the role of 3DP service providers in overcoming the challenges associated with the adoption of 3DP?

Interviews were used to collect data to answer the above questions, conducted with three Danish firms and four German firms, as well as with one Danish and two German service providers. As a result, this study provides new insights into the practices of industrial firms implementing 3DP and insights into the challenges they face in doing so. The paper then discusses the roles of service providers, highlighting how they address those challenges. By identifying disparities between the needs of these firms and the types of services offered by 3DP service providers, the study suggests a portfolio of services that can be offered by such firms during the pre-adoption, adoption and post-adoption phases of 3DP. Such services are expected to improve the competitiveness of 3DP service providers but, more importantly, serve to overcome challenges faced by industrial customers and thereby act as a driving force in their adoption of 3DP technologies. In this paper, '3D printing services' refers to 3DP offered as a service on demand (Rogers *et al.*, 2017) as well as the auxiliary services supporting the installation, maintenance and configuration of 3D printers in the facilities of customers (Rogers *et al.*, 2016).

2. Literature review

2.1. Challenges in adopting 3D printing

New technology adoption is fraught with challenges (Lin *et al.*, 2018). Thus, despite technological advances, several limitations of 3DP are hindering widespread adoption. These include slow process speed (Merrill, 2014), poor dimensional accuracy compared to some conventional processes, rough surface finish (Petrovic *et al.*, 2011), problems with process predictability and repeatability (Baumers *et al.*, 2016; Chekurov et al., 2018) and restricted choice of materials (Berman, 2012). Other barriers are high capital investment, high material and maintenance costs (Chekurov et al., 2018), insufficient material properties, difficulties with material removal, high process costs and high energy intensity (Mellor, 2014; Gilpin, 2014; Oettmeier and Hofmann, 2016). While the above challenges emanate from the current limitations of the technologies and the manufacturing processes, these do not include issues like investment in the training required in materials, design, infrastructure and specialised software (Holweg, 2015), intellectual property and ethical concerns (Li *et al.*, 2014).

Lack of guidelines also makes it difficult for non-experts to optimise product designs and to obtain the necessary knowledge (Weller *et al.*, 2015). 3DP knowledge is built around three major domains—process and material related, design related and part related and companies lack knowledge in one or more of the above domains (Wang et al., 2018). Different types of 3DP technologies, along with availability of a large variety of equipment make it difficult for end-users to keep pace with the available choices and to be aware of the process capabilities of each system (Zheng et al., 2017). Thus, companies frequently face the problem of selecting the most appropriate additive manufacturing (AM) process to meet their specific requirements.

There is also a lack of understanding of different costs, particularly those associated with metal-based AM processes (Mellor *et al.*, 2014). Equipment vendors may also not inform potential customers about the full range of costs associated with operations and maintenance (Dwivedi *et al.*, 2017). Furthermore, the vendor can also be unwilling to disclose information that could expose weaknesses of the technology (Rahman and Bennett, 2009). Thus, the key challenges related to the adoption of 3DP, as identified from the literature, concern technological limitations, training and lack of expertise and high costs of investments, operations and maintenance. Regarding spare parts, Chekurov et al. (2018) identified other challenges such as 3D model unavailability, difficulty in making 3D models for obsolete or damaged components, file version management, piracy resulting from data leaks in the supplier network and variable raw materials quality.

2.2. Role of service providers in the adoption of new technologies

High customer-perceived quality requires that, apart from the core service, the service provider's offer must also include a relevant set of supporting services of the right quality, as seen from the customer's perspective. Hence the service represents added value for the customer and that the customer finds it easy to use (Edvardsson and Olsson, 1996). To enhance usage of services, service providers must gather input from customers, obtain customer feedback on the initial new service (Goldstein *et al.* 2002), focus on meeting the needs of a specific customer or market segment (Cooper *et al.*, 1994) and ensure that the service concept meets real customer or business needs - versus just using the latest technology (Edvardsson and Olsson, 1996).

To better understand the role of service providers in the adoption of new technologies, we reviewed the literature on adoption of advanced manufacturing and information technologies. Obtaining the services of knowledgeable advanced manufacturing technology consultants can be key to ensuring successful advanced manufacturing technology implementation (Mora-Monge *et al.*, 2008). But, while studying adoptions of shop floor manufacturing technology, Scannell *et al.* (2012) found that the support provided by technology service providers did not necessarily have a significant impact on the adoption decision.

Customers can choose to have their designs 3D printed for them at the facilities of a 3DP service provider, or may opt to conduct the 3DP process themselves by purchasing or renting equipment, or by alternatively booking a time slot at a service provider's location. Customers can also employ rapid prototyping or facilitative services to take care of the entire process from the initial design to the printing of the physical object (Rogers *et al.*, 2016). Rogers *et al.* (2017) provide a classification system for 3DP as an on-demand service, identifying three types of service models: generative, facilitative and selective services. A broad range of 3DP services, particularly generative and selective services require the active involvement of the customers into the 3DP process. In analysing online 3DP platforms, Rayna *et al.* (2015) determined that access to the means of production may eventually turn increasingly more consumers into prosumers. Varying levels of consumer involvement may provide unique opportunities for the configuration of service packages, as evidenced by the framework for consumer involvement developed by Rayna *et al.* (2015). There are also opportunities for consultants to help customers along the entire 3DP value chain (Holzmann *et al.*, 2017) concerning issues related to 3D design, technologies, or training. Other services with potentially higher numbers of customers, but higher costs, include the retail sale of 3D printers and the sale of 3D models through online platforms (Holzmann *et al.*, 2017).

2.3 Theoretical foundation of technology adoption and acceptance

Diffusion of technology (Rogers, 2004) is an important aspect of technology adoption and one can distinguish between four phases introduction to market, growth in market acceptance, maturity of market and decline with market saturation (Slack et al., 2016). Christensen (2006) mentions performance trajectories and the distinction between sustaining innovations and disruptive technologies. Unlike sustaining innovations, disruptive technologies often evolve at performance levels lower than market requirements, until they start to satisfy lower levels of required market performance. However, key performance objectives, as well as order qualifiers and order winners, are likely to change over the lifetime of a product and similarly over the lifetime of the utilization of a certain technology (Slack et al., 2016). Indeed previous order winners become order qualifiers and in the context of 3DP adoption, it is important to better understand the role of service providers as customers' order winners and order qualifiers change as the technology evolves and is adopted. Also, the technology acceptance model (TAM) can provide the core theoretical framework to understand the role of service providers in adoption of 3DP. TAM proposes two cognitive factors determine an individual's technological acceptance: perceived usefulness of the technology and its perceived ease of use (Venkatesh and Bala, 2008). Though originally used for understanding an individual's adoption of technology, Autry et al. (2010) applied and extended it in an organisation context for supply chain technology adoption. Autry et al. (2010) acknowledged that firm's knowledge resources needed to effectively implement technologies i.e. absorptive capacity plays an important role in adoption. Technological turbulence i.e. uncertainty in predictability in performance of the technology and current technological breadth of the company are also related to firm-level technology adoption. Thus, apart from perceived usefulness and ease of use, Autry et al. (2010) also considered technological turbulence and technological breadth in their model to explain supply chain technology adoption and implementation. Autry et al. (2010) showed that perceived usefulness of the technologies have a positive effect on adoption but increased turbulence and current technological breadth constrains the absorptive capacity of firms and inhibits adoption. Similarly, Gamal Aboelmaged (2010) considered TAM for e-procurement adoption, while Lee et al. (2013) applied it for Product-Lifecycle Management System adoption by a company.

We consider perceived ease of use, perceived usefulness along with technological turbulence to play an important role in 3DP adoption. Hence, it will be interesting to analyse how 3DP service providers can influence the above and facilitate their customers' adoption of 3DP. In summary, while the literature discusses challenges and barriers in adopting 3DP, there is limited research on exploring the role of service providers in addressing those challenges. Moreover, the technology acceptance model (TAM) has rarely considered the role of service providers to improve ease of use and perceived usefulness of technologies, while helping customers to navigate technological turbulence. The literature on adoption of new technologies focuses on the intra-organisational enablers and to a limited extent on the role of external partners. Moreover, there is little to no research on auxiliary 3D printer-related services. These services are a crucial component of any feasibility study for adopting 3DP and potentially significantly impact customers' experiences with the technology, thus leading to a long-run increase or decline in the adoption rate of the technology. We seek to address the above gaps.

3. Methodology and case descriptions

The exploratory interview and case study analysis approach (Remenyi *et al.*, 1998; Dubois and Gadde, 2002) employed here identifies to what extent the participating companies faced challenges in setting up 3DP facilities, both from the perspective of firms who attempted to do so (customers) and other firms providing support services beneficial to this endeavour (service providers). Two separate interview questionnaires – one for 3DP users and another for 3DP service providers, were developed based on the research gaps identified in the literature review. These questionnaires covered issues such as what specific benefits motivated the company to adopt 3DP technologies, the associated risks and barriers in their industry, for what applications 3DP is currently being used (e.g. prototyping, tooling, spare parts manufacture, small batch run manufacture) and how this is likely to change in the future, as well as the types of 3DP services currently being used. The questions also served as a guideline to conduct semi-structured interviews with both 3DP service providers and firms that have used such services in the past. The interview partners consisted of three service providers (one in Denmark and two in Germany) and seven user firms (customers) with three in Denmark and four in Germany (see Table 1). The interviews were carried out between January and May 2017. Interview sessions were recorded, analysed and subsequently shared with the interview participants.

The user firms represented a variety of industries such as medical devices, industrial products, jewellery, automotive parts, railway infrastructure, railways supplier and plastic products manufacturing. The objective here is to identify challenges faced by industrial users across different sectors in adopting 3DP, in buying the associated services and further how service providers can help in overcoming such challenges. Hence, a diverse set of user firms with varying levels of maturity in adopting 3DP were selected rather than focusing on a specific industrial sector.

The rationale for the country selection was twofold; firstly it was interesting to compare 3DP adoption in a large, market such as Germany with a small market such as Denmark. Secondly, the familiarity and proximity of the authors to these markets assisted with data collection and analysis. Alongside the USA and the UK, Germany has been a forerunner in the development and usage of 3DP technologies, driven by the automotive, aviation and machinery industries. Consequently it has a large number of 3DP service providers (190 were identified at the time this research was carried out). Manufacturing in Denmark is dominated by shipping, wind energy, pharmaceutical, medical devices industries and industrial product industries. This research identified 37 service providers (as well as a few large manufacturers who are driving 3DP adoption in Denmark).

3.1. Customers of 3D printing services

Table 1 summarises the case companies and their corresponding 3D printing related activities.

(Insert Table 1 here)

3.2. 3D printing service providers

Table 2 summarises the 3DP Service Providers (one Danish and two German) who participated in the study.

(Insert Table 2 here)

4. Analysis

The customers who participated in this research reported several practical challenges throughout the adoption process, i.e., during the decision phase of 3DP adoption, during adoption itself and in post-adoption applications. Table 3 provides an overview of the challenges faced by the user organisations, as well as the challenges that 3DP service providers perceived their customers were facing.

(Insert Table 3 here)

4.1. Pre-adoption challenges

During the decision phase, difficulty in creating a business case and difficulty in using different materials were key challenges. Business case development was considered as a challenge by four customers, while two service providers also acknowledged that customers face that challenge. Most customers indicated they were not able to create strong business cases but purchased the printers for the speed and flexibility they offered. The CG6 manager mentioned *"The machine costs money; the maintenance costs money, the person who operates the machine costs money. Thus, you always have to think about capacity utilisation."* For CD3 the business case for buying printers in-house was better than using service providers. Costs of using service providers were charged to the individual projects, and it made sense for them to invest in-house and amortise the costs over multiple projects. Three of the German customers (CG1, CG2, and CG3) specified that money was not an issue when deciding whether to adopt 3DP for a particular component or manufacturing process. Three customers and one service provider considered using different materials to be a challenge. Two service providers mentioned customers did not understand how to use the equipment and for what purpose. Two customers also highlighted such difficulties. The customers mentioned that the fast pace of technology development created confusion about whether to buy the equipment with the existing technologies or wait until the technology advances further. Customers also lack an understanding of the entire process and the overall cycle time. To illustrate this point service provider SD1 recalled an interesting anecdote: *"We had one company visiting our facilities, and they had already decided what to buy but wanted to see the post-production process. The manager from the company (who was responsible for buying) then took the tour. After the tour, he said that they are not going to use the particular equipment for the part as it takes a lot of time to clean the part. It was only after this that they bought the right system! I do not earn anything from helping them - the only thing I get is that I* *have a customer that has the right equipment."* Thus, allowing the potential customer to tour the facility and observe the processes led the customer to choose the right equipment and the processes and avoid future misunderstandings. Two German companies (CG2 and CG5) mentioned that it was difficult to get that the sourcing and purchasing people in their organisations to adopt a lifecycle-based Total Cost of Ownership approach while evaluating 3D printed parts. There was a lack of understanding of that approach as the purchasers usually evaluate suppliers based on price and quality. The above challenges demonstrated that difficulties in organisational decision making and lack of ease of equipment use have an impact on a company's decision to adopt 3DP, while fast pace of technology development or technology turbulence is further increasing complexity.

4.2 Adoption Phase Challenges

During machine set up, optimising the process for specific parts was identified as a key challenge. This challenge is in line with the findings of Deradjat and Minshall (2017). Another challenge faced was lack of 'plug and play' solutions by equipment manufacturers and little or no training or educational support being available. Service provider SG1 commented: "W*e noticed from all the different types of machines we have, that after the printer is delivered and deployed, the start-up engineer comes. He has his machine and his material, and he likes his job. But, in the end, you get a platform where you get parts that are incompletely printed or some that have defects. This gives you the feeling that you did not bet on the right technology. But it is mostly because of general parameters which are not optimised for specific parts. Basically, you have to optimise the process parameters fitted to a special part, and that is what we – as a service provider - can offer if the customer is not very experienced."*

Difficulty or lack of knowledge about design for 3DP was considered as a challenge by four customers but acknowledged by only one service provider. Lack of a trained workforce, that understands the equipment and the processes, was considered as a challenge by three customers and also recognised by one service provider. A CD3 manager considered that "*the biggest challenge for us is lack of knowledge at all levels and that is why training is so important. As soon as people know how to design with 3DP and know the benefits, then it is just a matter of either buying more machines or making agreements with external suppliers*." Service provider SG2 was right in acknowledging this challenge which was also noted by three customers. The SG2 manager stated: "*One issue is to understand the machines, another is to understand the process. You need employees, who understand AM, but no university and no training centres teach AM so far. AM apprenticeships also don't yet exist. At symposiums, the companies only talk about machines, i.e., how to make those bigger and faster, but what is neglected is the process. What is the use of the machine, if you don't have anything to support it, i.e., the additive thinking, the post-processing? That's a big challenge for serial production."*

Absence of absorptive capacity resulting from lack of a trained workforce and difficulty in usage owing to the need to understand both the equipment and processes with sufficient competency, highlights the challenges companies are facing in the adoption phase.

4.3 Post-adoption Challenges

For post-processing applications, poor end product quality and machine breakdowns were considered as challenges by eight customers, but interestingly none of the service providers acknowledged it. For example, CG2 explained that so far, the firm has not succeeded in producing identical objects when repeating the printing process with the same parameters and materials. The CG6 interviewee stated "*the big problem with prototypes is that although you can reproduce geometries very nicely, it all looks very good but no matter which 3DP technology you use, the material properties are not the same as in the traditional manufacturing processes, and that's where the first problem starts. Hence we cannot even think about it yet for serial production*". Given that repeatability and quality consistency are two of the key success factors of a modern manufacturing process, it is not surprising that most firms are hesitant to scale up additive manufacturing capacities for regular production. The high cost of maintenance and spare components and lack of trained workforce challenges three customers. But, the service providers do not seem to recognise these challenges. Two customers indicated that they faced difficulty in explaining the requirements for the service providers. Thus, service providers should develop expertise and capabilities to understand customer requirements better and engage with them to avoid unnecessary delays and quality problems. The post-adoption challenges also indicate poor quality and repeatability resulting from turbulence of the technology, lack of resources and lack of ease of use in explaining requirements to service providers.

4.4 Customer-service provider relationships

The service providers we interviewed seem to be unaware or unable to recognise quite a few challenges highlighted by the customers. These concerns such as poor end product quality, lack of reproducibility, breakdowns and high cost of maintenance and spares are often ignored. Customers' challenges related to optimising processes for specific parts, lack of knowledge of design for 3DP, lack of trained workforce and also difficulty in explaining requirements to service providers provide enough opportunities for the service providers to continuously improve their capabilities and to develop new services around those. The interviews also revealed that customers at different maturity levels of 3DP adoption have considerably different needs. For example, some customers (CD2, CG5) indicated that service providers should not try to sell all types of services to all customers. Some customers may be willing to buy low to mid-range printers to experiment and build internal capabilities in prototyping and tooling (CD1). For such customers, getting support in choosing the right equipment, in developing the business case and getting maintenance support is important. Some customers with higher levels of maturity and experience in using 3DP in-house (CD3, CG6) may want to get additional parts printed using the technologies they do not have in-house or if they do not have sufficient in-house capacity. Similarly, customers who have developed expertise in finding which spare parts are printable and which ones are not (CG5) may look to have some specific spare parts printed. For such customers, getting parts printed within reasonable time and cost and good quality with minimum post-processing is more important.

5. Discussion

Our research has revealed key challenges experienced by firms in adopting 3DP. The primary objective was to identify the possible challenges these firms faced and more specifically how 3DP service providers can potentially assist in overcoming them. These were a lack of knowledge about the potential of the technologies, uncertainties in the future development of the technologies, materials, training shortages and equipment and limited support from service providers. Such challenges can be mitigated by service providers developing services suited to the customer needs. The companies themselves should also develop enablers such as top management support and leadership, training and knowledge sharing within the organisation, a conducive culture to experiment and work on new ideas, etc. However, we did not specifically focus on the above enablers in this research.

Matthing *et al.* (2004) argue that by adopting a proactive approach and involving customers early and intensively, service firms can facilitate learning. Service providers have a critical role to play in understanding the challenges faced by manufacturers, addressing those collaboratively and thereby facilitating the adoption of 3DP by manufacturers. Fulfilling this role requires developing a portfolio of services suited to the customers' maturity levels and across adoption stages. More importantly, service providers must acknowledge that understanding and addressing customer challenges, while working closely with them (Rayna *et al.*, 2015) and equipment manufacturers can assist. The interviews revealed that several opportunities exist for service providers to offer stronger support (and hence spur demand) throughout all adoption stages. In the phase where customers are deciding to adopt 3DP, service providers could provide services related to analysing which manufactured parts are most suitable and in supporting the customer in conducting strategic investment evaluation before adoption (Mora-Monge *et al.*, 2008). For customers with higher levels of 3DP adoption maturity, service providers can support in redesigning the parts, while helping them select materials and appropriate additive manufacturing processes, equipment and technologies (Rahman and Bennett, 2009; Dwivedi *et al.*, 2017). Such services would thus not only assist customers in adoption decisions but would furthermore support them in attracting customers.

3DP comprises different technologies that can be considered at different maturity levels with varying requirements. Hence, pinpointing the general state of affairs concerning adoption is no easy task. However, we can apply the technology adoption literature to zoom out from the details of the analysis and provide a bridge to the subsequent discussion. When revisiting the above developments and challenges through the lens of technology adoption theory, it appears that the challenges resemble the adoption phases ~~labeled~~labelled by Slack et al. (2016). Firstly, the introduction to the market (characterised by innovative customers, few competitors, product/service as order winners, quality and range as order qualifiers, and flexibility and quality as dominant operations performance objectives) and to some extent the growth and market acceptance (characterized by early adopter customers; increasing numbers of competitors; availability as order winner; price and range as likely order qualifiers; and speed, dependability, and quality as likely dominant operations performance objectives. However, the introduction to market phase seems to resonate most with the data, given the emphasis on quality and flexibility challenges that service providers need to particularly focus on.

Using the lens of TAM, results show that though perceived usefulness is recognised, lack of ease of use compounded by technological turbulence is surely impacting the decision to adopt 3DP. Service providers have an important role to play in improving the ease of use, and by providing necessary training to improve absorptive capacity of the customers. Although technological turbulence cannot be avoided, service providers should provide customers with the latest technological developments. Such services should also consider specific customer needs, as well as their maturity in adoption and improve the ease of use and the usefulness of the technologies, demonstrated through specific use cases or pilot projects.

During the adoption phase, providing training and educational support, choosing materials and processes and calibrating the machines (for less experienced customers) and optimising the 3DP process for the manufacture of specific parts (for more advanced customers) are likely to be highly valued by customers. To assist in the post-adoption phase, 3DP service providers could focus on problem resolutions (Gangwar *et al.*, 2015) and establish a network of mobile servicing teams capable of providing on-demand, 24/7 support. These teams would require trained staff who can understand customer requirements, equipment and processes (Kim and Suwon, 2009). In the long-run, with the integration of the Internet of Things and sensors onto additive manufacturing equipment, there is potential for remote diagnostics, process optimisation, spare parts replenishment and automated material replacement. Figure 1 summarises the findings discussed above.

(Insert Figure 1 here)

6. Conclusions, implications and scope for future research

This paper uses an exploratory study of nine user organisations (customers) adopting 3DP and three 3DP service providers working towards improving the adoption of 3DP technologies amongst industrial companies. The findings reinforce the view from existing literature that the technology and business models are still immature for large-scale adoption. Companies planning to adopt 3DP face challenges on many fronts including lack of ease of use, technological turbulence, lack of resources and training. The study highlights the important role service providers can play in overcoming the above challenges. As Rogers *et al.* (2016) indicate, companies need to better understand how and to what extent to integrate service providers into their supply chains. This study furthermore identifies specific challenges faced by user organisations during the pre-adoption, adoption and post-adoption phases of 3DP. It also points out that service providers do not have a full understanding of all the challenges faced by their customers. Service providers can however play a critical role by helping customers in various ways: These include choosing the right technology, equipment and processes, and also by making them aware of future developments and by allowing them to experiment with the technology as well as training (Autry et al., 2010). In a study on the impact of 3DP on the hearing aid industry, Sandström (2016) noted that the initial technological uncertainty made it difficult to make the right decision concerning what technology to use, which is usually the case when a materially different technology is introduced (Utterback, 1994). Thus, firms should monitor the technology closely before the emergence of a dominant design and that they build an absorptive capacity (Cohen and Levinthal, 1990). It is not surprising that firms have raised similar concerns here.

3DP technologies permit experimenting with various business models at a much lower cost, testing new ideas or designs faster (Rayna and Striukova, 2015). Hence, several delivery models may emerge, whereby service providers, equipment manufacturers, consultants, industry experts and aggregator platforms dynamically adjust their service portfolio to individual customer needs. There is a potential to develop 3DP centric collaborative network and platform comprising various stakeholders (such as technology, raw material and equipment suppliers, service providers and educational institutions) to share challenges and develop solutions, which facilitates further development. Such networks can also be operated as an independent entity, as an industrial cluster-based organisation or led by universities, bringing in companies to test developments and to train engineers and business executives (Marri *et al.*, 2002). This potentially could support the widespread adoption of 3DP. For example, Combiworks in Finland offers the 'Factory as a Service', with agile capacity where customers can select a location and production method. Combiworks finds production facilities with available capacities and necessary capabilities to produce parts or products. Such network aggregators may emerge as separate business entities, connecting suppliers with buyers and pooling capacity, thereby enhancing asset utilisation (Connor *et al.*, 2014). These may be promoted by local industrial clusters and/or local governments to improve the local manufacturing competitiveness and/or by logistics service providers.

There is limited research on the role of service providers in 3DP adoption by industrial users. TAM literature has rarely included service providers in explaining customers' technology adoption. Thus, this study makes important academic contributions by 1) specifying how 3DP service providers can assist customers to overcome challenges in adopting 3DP across pre-adoption, adoption and post-adoption phases and also 2) by analysing the role of the service providers through TAM. The research will be of relevance to 3DP service providers who wish to increase the adoption of 3DP by their customers, as they will be able to identify specific services needed across adoption phases and the corresponding service delivery models. It will also be of relevance to industrial users to get acquainted with potential challenges in 3DP adoption and be prepared for that or demand such services from the service providers.

6.1 Scope for future research

Understanding the role of network aggregators, their business models and the dynamic process of experimenting with various 3DP business models are potential avenues for future research. Our study did not consider other stakeholders such as equipment manufacturers, design and modeling software solutions providers or raw material suppliers, etc. – reaching out to these players is an obvious next step to gain a more holistic view. Future studies could examine the interplay between the role of various stakeholders in 3DP adoption and success rates. The role of collaborative networks as a vehicle for widespread adoption of 3DP printing is a 'virgin' territory for further research. Most of the customer firms we interviewed lacked a well-defined strategy for digital manufacturing technology adoption – potentially another strand of future research.

We used TAM as a theoretical lens for this study, however, other theoretical perspectives could also be considered and explored. On the other hand, using the framework of TAM, further research is needed to validate how service providers can alleviate challenges faced in 3DP adoption by improving ease of use, emphasizing usefulness, helping customers to navigate the technological turbulence and the resource constraints they face. TAM research has to a large extent focussed on technology adoption by individual customers and later technology adoption by organisations and to a limited extent on the role of service providers in facilitating technology adoption. Hence, such research in the context of 3DP will also extend the body of knowledge on TAM.

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Figure 1: Mitigating strategies to overcome 3DP adoption challenges

Phase	**Challenges**	**Role of Service Providers in overcoming challenges**
Decision to adopt	Difficulty in creating a business case	• Offer business case development as a service • Support the development of options and scenarios and their potential viability
	Difficulty in using different materials	
Adoption	No plug and play solution, little or no training and educational support	• Machine manufacturers provide training and educational support for customers • Work with customers to adapt equipment and processes to their needs
	Difficulty in optimizing process for specific parts	
Post adoption	Difficulty or lack of knowledge in design for 3DP	• Provide design for 3DP services and training • Analyze product quality issues and work with equipment manufacturers to address customer problems • Service providers deliver performance based services throughout the product lifecycle
	Poor end product quality and machine breakdown	
	High cost of maintenance and spares	
	Lack of trained workforce who understands the equipment and process	

Table 1: 3DP Service Customers

Company	**Sector**	**3D printing (3DP) related activities**
Danish customers (D)		
CD1	Medical device manufacturer	CD1 develops products and services for people with personal and private medical conditions. The company uses 3DP for prototyping and tooling. They regularly develop prototypes of new products and some fixtures or moulds using 3DP. These items help R&D personnel in carrying out design iterations faster and allows them to experiment primarily in the early design phase to fix up the product's boundaries and also later in testing and validating the product. CD1 currently uses 3DP service providers for buying and servicing machines and occasionally use them as sub-contractors in a project for their 3D drawing capabilities.
CD2	Designer of jewellery, silverware, home decoration and accessories manufacturer	At the beginning of their 3DP implementation, no computer-aided design drawings of existing products were available. CD2 bought some sophisticated 3D printing equipment from another department in the company that realised that it was easier to use service providers. They are using cheaper desktop FDM printers. 3DP has enabled new products with more advanced designs produced with 3D printed processing aids and holders. The company uses external service providers for printing wax models for casting. In the future, the company would like to be able to 3D print silver, but this is a difficult material with which to work.
CD3	Industrial products manufacturer providing solutions used in refrigeration, air conditioning, heating, motor control and mobile machinery	CD3 uses 3DP for prototyping of plastic parts and tools and fixtures. It plans to use it for manufacturing small batches of advanced parts and spare parts. They first bought 3D printers in 2012 following earlier buying-in of 3DP parts. The machines have repaid in 2 years. CD3 commissioned the second machine in 2017, and both machines currently run at high levels of capacity utilisation. The only process that they have in-house is FDM. The company uses 3DP service providers for other processes, which may be needed for specific parts and fixtures as well as to get additional capacity.
German customers (G)		
CG1	Automotive parts supplier	CG1 is a large supplier of aerospace and automotive bearings and guidance systems. They currently use 3DP primarily for prototypes. As precision parts are their specialisation, they consider that the parts they manufacture cannot currently be 3D

		printed to a sufficient standard. A key motivator for purchasing 3D printers (SLS and FDM) was the opportunity to experiment more freely with the technology to expand usage from prototyping to production.
CG2	Automotive parts supplier	CG2 is a specialist in the production of doors, motors and seats for the automotive industry. They currently use 3DP primarily for tooling, jig construction, prototyping, as well as small batch production. The key reasons for purchasing printers were the acceleration of their learning curve for the technology, as well as to assess its potential commercial applications and hence value to the business.
CG3	Railway infrastructure manufacturer	CG3 is still in the developmental phase of 3DP applications, meaning 3DP parts are 'one-offs' and not yet used in the standard production process. For example, CG3 uses 3D printed versions of their products at trade fairs and sales meetings abroad, both to make cross-border transportation easier and to circumvent any legal hurdles and export/import tariffs for their products. Usage is however expanding, and the company is looking to invest in production scale 3DP technology.
CG4	Plastic products supplier	CG4 specialises in manufacturing 3D printed plastic parts for the automotive industry. In 2016, following an evaluation period using external service providers they purchased polyjet 3D printers and currently mainly use 3DP for producing prototypes. Increased flexibility in the face of uncertain demand (particularly with customer specific parts) and the opportunity to experiment more freely with the technology motivated the purchase.
CG5	Railway industry supplier	CG5 began exploring options for 3DP of spare parts in 2015. Rapid spare parts availability is the primary motivation for the company to explore 3D Printing. It uses a combination of local German service providers and a large non-European one for prototyping, component manufacturing and spare parts manufacturing. CG5 believes buying machines is not currently the right strategy and it prefers to work with the service providers.
CG6	Forklifts manufacturer	CG6 has been using 3D printing for over ten years at its headquarters in Germany. In 2016 it bought a small 3D printer. This means they can now 3D print some pre-series parts and pilot production parts with quantities of less than 50 in-house. The R&D department uses 3DP for prototyping of plastic parts. It uses local service providers based on how quickly they can deliver the parts and on price. The primary motivation for the

		company is to test and assemble products and to avoid costly tooling changes.

Table 2: 3DP Service Providers

SD1	Service provider primarily prints plastic prototypes and production parts for B2B customers	SD1 directs private customers to other service providers more in tune with their usually more straightforward demands. The company helps B2B customers choose and buy the right equipment. Prototypes concern a large part of the turnover but also the production of, e.g. glasses for customers constitutes a fair share of the business. The main obstacle for further use of 3D printing for production concerns quality validation of the utilised materials and final components. They provide training and advice and have experienced that it can be a long learning curve for customers to get into the habit of designing for 3D production (which entails combining different components otherwise injection moulded separately). Also, it is problematic with advanced machines that they break very easily, and the causes are difficult to find.
SG1	3DP business unit of a larger business group	The SG1 group is a specialist in metals, and hence the 3DP division also focuses on developing metal powders. The company started using 3D printing since 2012. The feasibility study for a customer and for conducting future development of an existing product within the company led to the decision to purchase a 3D printer and test internally. An internal start-up dealing with AM was founded in 2014 and integrated into the operational business as of January 2017. The company provides the right printing parameters to customers, i.e. support in design, small series production runs, post-processing and recycling. The AM division's customers come from five different industries: aerospace, medical, automotive, tooling and machine engineering and electronics.
SG2	A pioneer in 3DP mainly in stereolithography	SG2 is one of the most innovative and versatile companies that produces prototypes and small series in metal and plastics. SG2 offer a range of different technologies to customers. Besides offering services in 3D printing, SG2 also provides tool construction with conventional methods, construction of models, CNC machining and vacuum casting. By using both additive and conventional technologies, synergies are created, leading to the company's philosophy of connected prototyping. Currently, SG2 has an annual turnover of 13.5 Mn Euros of which 3D printing contributes approximately a third. Around 10 per cent of its employees work exclusively for the additive department. SG2's customers are mostly from the automotive industry, which contributes up to 75% to the annual turnover.

Table 3: challenges and barriers faced in adopting 3DP

		User Organisation											
		Customers									Service Providers		
		CD1	CD2	CD3	CG1	CG2	CG3	CG4	CG5	CG6	SD1	SG1	SG2
Decision to adopt 3D printing	Difficulty in developing a business case	X	X				X		X		X		X
	Difficulty in understanding what can be printed and for what purpose						X		X		X		X
	Lack of a specialised service provider		X										
	Difficulty/unwillingness to use other raw materials				X		X			X			X
	Need for multiple testing for materials and equipment								X				
	Lack of service provider post-processing capabilities								X				
	Difficulty in convincing sourcing/procurement staff					X			X				
Adoption	Equipment manufacturers offering no plug and play solutions/training or educational support	X			X				X				
	Difficulty in optimising the process for specific parts				X	X	X					X	
Post-adoption applications	Difficulty or lack of 3DP design knowledge	X		X		X		X				X	
	Poor end-product quality and machine breakdowns	X	X		X	X	X	X	X	X			
	Lack of reproducibility of parts			X					X				
	Difficulty in explaining company requirements	X	X										
	High cost of maintenance and spare components		X					X		X			
	Lack of understanding and trained workforce	X				X		X					X
	Difficulty in conducting tests and lack of test results										X		