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# Digitalisation of spare parts provision: co-evolution of digital service providers and original equipment manufacturers

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**ABSTRACT**

Original Equipment Manufacturers (OEMs) face challenges associated with spare parts provision, such as high inventory, and missed deliveries due to inventory obsolescence or long supplier lead times. Digitalisation of spare parts, enabled by additive manufacturing, address some of these challenges. In this digitalisation of spare parts the roles of digital service providers (DSP) and the OEMs co-evolve. We examine three DSPs developing services for their OEM customers and their value offering from the perspective of three user organisations, as well as two OEMs not using the services. We find that OEMs turn to the service providers for support to overcome a gap in their information processing needs and internal capabilities in the exploration stage. The use of the DSP addresses a large initial capability gap in information processing for identifying the opportunity to digitalise spare parts. Over time, once digital spare parts operations have been established, OEMs can begin to digitalise their spare parts during the product design stage. This reduces the demand for the exploration services initially offered by the DSP, such as digital scanning of parts and reverse engineering. To adapt, DSPs must explore new service opportunities as OEMs develop their digitalisation capabilities in the product design process.

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Digital spare parts services; information processing; original equipment manufacturers; service providers; co-evolution

## 1. Introduction

Service provision of spare parts is a crucial source of revenue and profit for many original equipment manufacturers (OEMs) (Oliva and Kallenberg 2003). Over the product's lifecycle, OEMs must carry sufficient inventory of spare parts to ensure high service levels, which results in high inventory carrying costs (Cohen, Agrawal, and Agrawal 2006). Despite carrying high levels of stock, OEMs may not be able to deliver the right spare part at the right time to customers because of distant inventory locations or due to parts degradation (Huiskonen 2001) and obsolescence risk (Li and Mishra 2022).

A challenge for many OEMs is that the demand for spare parts extends well beyond when products are actively manufactured (Inderfurth and Kleber 2013). The conventional approach used by OEMs is to acquire spare parts for the final phase of the service period by placing a sizeable final production order or last-minute purchase when the product is ramped down in production (Behfard et al. 2015; Inderfurth and Kleber 2013). This is typically sufficient to fulfill demand up to the end of the service period. However, this approach results in high inventory levels being held over long periods, which incurs inventory carrying costs and high obsolescence risk (Inderfurth and Kleber 2013). Orders for spare parts inventory after manufacturing ramp-down can often only be fulfilled by a single or limited few suppliers, resulting in long lead-time and high costs. In the case of multiple sourcing, there may also be risks of variations in the quality of the supplied spare part (Chekurov et al. 2018). However, conventional approaches, such as keeping stock and last-time buys from suppliers, are increasing costs for OEMs while not effectively minimising missed deliveries and lower service levels due to the reasons mentioned above. Thus, OEMs actively explore opportunities to address the above challenges and make their spare parts business competitive.

One approach to improving spare parts provision is to predict when components will likely fail through real-time data collection and plan maintenance services and the needed spare parts. Such an approach has been the focus of Product-Service Systems (PSS), which allow manufacturers to offer industrial product-service offerings, such as comprehensive remote services that combine digital and physical systems (Fargnoli and Haber 2023; Lerch and Gotsch 2015).

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The alternative approach, becoming increasingly feasible and available to OEMs, is the digitalisation of the spare parts supply chain, which focuses on manufacturing and delivering spare parts rather than predicting the demand for spare parts and managing inventory (Peron 2024). Digitalisation of spare parts appears both as a strategic opportunity and a threat for many OEMs, as the focus of the competition increasingly shifts away from the price and quality of the offerings toward delivering *value* to customers (Khajavi, Partanen, and Holmström 2014). The concept of on-demand manufacturing of spare parts was introduced by Walter, Holmström, and Yrjöla (2004) and elaborated by Pérès and Noyes (2006) for settings in which producing spare parts using conventional means or storing inventory is not feasible. Lately, research has investigated novel ways of monetising service businesses that rely on additive manufacturing (AM)-produced digital spare parts (Salmi et al. 2018). For such service businesses, a spare part's computer-aided design or CAD-data is saved in a digital file and transferred to be produced on demand through AM (Ballardini, Ituarte, and Pei 2018). Digitalisation of spare parts involves transferring and storing data on spare parts digitally, implying that spare parts can be manufactured according to users' needs using 3D printers that can be located geographically close to the end-user or in distribution centers along the supply chain (Holmström et al. 2010).

Hence, digitalising spare parts provision can support OEMs in catering to spare parts demand without keeping inventory. The benefits of digital spare parts include significant cost savings, improved availability of spare parts, and reduced delivery lead times (Salmi et al. 2018). Specifically, manufacturing individual parts or small batches on time becomes cost-effective. For many parts, the costs of downtime are so significant that ensuring availability becomes far more critical than the price of the part itself (Akmal et al. 2022; Salmi et al. 2018)

Indeed, OEMs can leverage the digitalisation of their spare parts operations to deliver spare parts on demand to their customers. For example, Gerhard Schubert GmbH, a global market leader in top-loading packaging machines, offers a 3D printing solution for various tools that allow its customers to print tools and parts on-demand and in-house. This also creates a decentralised setup wherein the service provider does not need to be present. Instead, the customer takes over the operation on an 'as-needed' basis. When clients need new tools or parts, they can browse an online library that functions as a digital warehouse and immediately print what they need. This decreases lead times for new parts and eliminates the need for extra space to store a repository of spares for Schubert's clients (see Schubert example on ultimaker.com). Similarly, oil and gas company Shell's 3D printing strategy is not to manufacture parts but to develop a digital warehouse that stocks all the information required to print components whenever needed. This is done through partnerships between Shell's technology department, OEMs, and local partners. A digital warehouse can potentially reduce lead times and promote responsible use of resources (van Keulen and Goh 2021).

Despite the potential to have digital spare parts and to get the parts produced using AM on-demand, few OEMs have implemented digitalisation of spare parts as part of their supply chain strategies (Chekurov et al. 2018). Reasons for that are that such an implementation requires capabilities that most OEMs lack (Roscoe, Cousins, and Handfield 2019) and lack of expertise in designing operating, controlling, and monitoring a digital spare parts supply chain (Peron 2024).

To get started, OEMs can collaborate with a DSP, a service provider specialising in digitalising spare parts (Salmi et al. 2018). By partnering with a DSP, an OEM can seek access to capabilities needed to digitalise spare parts. Service providers like Spare Parts 3D (https://spare-parts-3d.com/), Dimanex (https://www.dimanex.com/), FieldMade (https://fieldmade.no/services/) are emerging that offer end-to-end services starting from digitalisation of spare parts portfolio to feasibility assessment for production using AM part production and certification of parts based on industry standards. There is limited research on how DSPs can support OEMs in addressing challenges associated with spare parts provision through digitalisation and the capabilities that both DSPs and OEMs need to develop to digitalise spare parts.

Hence, this paper explores how DSPs operate while supporting OEMs in digitalising their spare parts. The specific objectives are to understand (i) why OEMs seek support from a DSP to address challenges related to spare parts provision, (ii) how the DSP develops its service operations over time to address the changing needs of the OEM, and (iii) identify the capabilities that OEMs need to develop for digitalisation of spare parts. To achieve these objectives, we investigate the value proposition of service providers and the operational problems OEMs face in digitalising spare parts. We examine three service providers, three OEMs using the services of the DSPs, an equipment operating organisation, and two OEMs relying on in-house capabilities. Contributing to the theory, we find that the information processing requirements and capabilities significantly change for OEMs as the digitalisation of spare parts is implemented, opening possibilities for the development of new enabling services by the service provider. The scope narrows, resulting in a more specialised value proposition potentially of interest to OEMs that have relied on developing in-house capabilities.

## 2. Literature review

To understand the evolving roles of DSPs and their OEM customers in the digitalisation of spare parts provision, we will start by reviewing the literature on the opportunities of digitalisation for spare parts, describing the challenges faced by the OEMs and the emergence of service providers, and addressing the gap between information processing requirements and capabilities.

### *2.1. Digitalisation opportunities in spare parts provision*

To improve the profitability of spare parts businesses, a systematically managed digitalised spare parts supply chain has been recognised as an increasingly feasible opportunity (Salmi et al. 2018). Critical steps in managing digitalised spare parts supply networks involve identifying a product portfolio, selecting the appropriate business model, modifying existing after-sales organisational structures, and designing and managing after-sales service supply chains. These steps correspond to systematically managing conventional spare parts supply (Cohen, Agrawal, and Agrawal 2006). Digitalisation can enable OEMs to offer on-demand spare parts services, which can help customers achieve their goals instead of supporting the products themselves (Schroeder et al. 2020). Digitalisation of spare parts helps alleviate some of the challenges associated with after-sales service by producing parts on-demand at locations closer to the point of demand with reduced need to store physical inventories. However, the decentralised configuration of the AM supply chain may not always be desirable for faster delivery of spare parts, and centralised and hybrid configurations are also possible (Cantini et al. 2024). Such choices will depend on the waiting time penalty, production rate, demand, and the investments needed for the AM equipment (Li et al. 2019).

A comprehensive implementation of the digitalisation of spare parts requires identifying and storing 3D printable parts in digital libraries. Fulfilling customer requirements requires choosing the appropriate 3D printing process and associated materials and considering pre- and post-processing steps in manufacturing and finishing that ensures high levels of quality assurance (Salmi et al. 2018). Therefore, it is essential to consider both technical and supply chain characteristics for spare parts to be produced by AM. An exhaustive review of technical and supply chain-related factors needed to classify and rank spare parts to assess their suitability for AM was recently reported (Frandsen et al. 2020). Similarly, Chaudhuri et al. (2021) developed a methodology (using cluster analysis and multi-criteria decision analysis) to classify spare parts in a portfolio to identify spare parts that are most suitable to be manufactured by AM.

Based on focus group interviews with industry experts, Chekurov et al. (2018) concluded that digital spare parts could be deployed for a specific product type in the long tails of company spare part catalogs. However, improvements in AM, company ICT infrastructure, data mining, and 3D model file formats are needed for more extensive deployment of digital spare parts (Chekurov et al. 2018). The high cost of obsolescence in parts in inventory shifts the advantage of deploying digital manufacturing in an on-demand production mode (Khajavi, Partanen, and Holmström 2014). This shift relies on reducing obsolescence costs through on-demand production and digital manufacturing unit costs that tend to be fixed, i.e. unrelated to the length of production runs (Holmström et al. 2010). To minimise long-run average system cost, Song and Zhang (2020) determined which parts to stock and which to print and showed that AM potentially results in significant cost savings, suggesting complementarity between stocking and printing to minimise costs. Using data from a material handling manufacturer, Heinen and Hoberg (2019) found that up to 8% of stock-keeping units (SKUs) and 2% of total units supplied could be produced using AM, even if unit production costs are four times higher than those using conventional manufacturing. This result can be traced to low demand, high fixed costs, and minimum order quantity stipulations in traditional manufacturing. Analysis by Sgarbossa et al. (2021) showed that the profitability of AM generally increases for small parts and for long procurement lead times of parts produced using conventional manufacturing and long review periods. For complex parts, the AM options outperform the conventional manufacturing options for small parts (Sgarbossa et al. 2021). By adopting AM, a spare parts supply chain can potentially reduce overall variable costs and carbon emissions, even though the initial fixed costs may be higher (Li et al. 2017).

Thus, encapsulating design and manufacturing data into a unique digital artifact enables the organisation to revisit the role of inventory in high-variety, low-volume settings (Holmström et al. 2019). Hence, incremental replacement of high-variety, slow-moving spare parts produced via batch manufacturing processes with on-demand parts production using AM can lead to significant cost savings without sacrificing customer service.

### 2.2. DSPs in the AM ecosystem

The OEM-centric provision of spare parts suits products involving major liability issues, such as safety-critical applications (e.g. medical equipment and aerospace), where a service provider may lack the desired technical expertise and the ability to meet the stringent requirements. It may also create opportunities for specialised digital service providers, who can offer services suited to the needs of such regulated industries. However, for most OEMs producing consumer and industrial products, introducing digital spare parts involves many hurdles outside an OEM's core competence, creating opportunities for service providers (Salmi et al. 2018). The other alternatives, enabled by AM, are centered on maintenance service providers, 3D database operators, 3D printing service providers, and end users (Salmi et al. 2018). In the alternative, the value added and value capture move away from the OEM, desensitising the role of the OEM in after-sales (Finne and Holmström 2013)

Digitalising spare parts, particularly parts of products with long life cycles, is challenging due to the problem of missing or non-existing computer-aided design (CAD) files (Beiderbeck, Deradjat, and Minshall 2018). Without CAD files, the desired spare parts are to be redesigned or reverse-engineered, which is costly and time-consuming, compromising the business case for digitalisation. Chekurov et al. (2018) found that even when a part could technically be manufactured with AM, there is a business case only if the distribution and logistics advantages outweigh the increased costs associated with AM. Digitalising is seldom needed when standard parts are efficiently manufactured with conventional manufacturing methods. Distrust in quality levels, insufficient material, design knowledge among critical stakeholders, and poor availability of design documentation on spare parts are additional considerations limiting the use of AM to produce spare parts (Chekurov et al. 2021). In adopting AM for spare parts, the difficulty in formulating the business case and material selection were identified as obstacles for OEMs (Chaudhuri et al. 2021).

Digitalising spare parts, OEMs can rely on different types of services, from consulting services helping with the business case to fully outsourcing the entire process of spare parts digitalisation from business case and initial design to printing the physical object and quality assurance. Rogers, Baricz, and Pawar (2016) provide a classification system for AM services, which include generative, facilitative, and selective services. Generative services focus on generating 3D printable models and include, for instance, scanning and construction services. Facilitative services involve suggesting 3D print objects without generating the model itself, while selective services aim to create large databases of 3D printable models from which customers can choose. Generative and facilitative services are most relevant in digitalising OEM's spare parts operations.

OEMs' many uncertainties in delivering digital spare parts to their customers include demand and supply-related uncertainties, lack of knowledge about reverse engineering needed when 3D designs are unavailable, difficulty choosing appropriate technologies, and estimating costs for producing a part on demand. This is particularly challenging because of rapid advancements in materials and manufacturing technology development and uncertainties associated with changing regulatory and standardisation requirements. To address these uncertainties, niche service providers have begun to emerge. AM service providers bring the desired flexibility for OEMs, help them leverage the technological options of AM, and provide opportunities to learn (Friedrich, Lange, and Elbert 2022).

AM adoption is highly collaborative, requiring the involvement of multiple ecosystem partners (Piller, Weller, and Kleer 2015 and Pfähler, Morar, and Kemper 2019). In the digitalisation of spare parts, an AM ecosystem is frequently created. AM service providers produce spare parts on demand. AM software service providers focus on designing for AM and automating the part selection process. Quality assurance services specialise in validation and standardisation. DSPs offer generative and facilitative services such as part selection, business case development, reverse engineering and scanning, part production, quality assurance, and validation.

### 2.3. Information processing and digitalisation of spare parts

The portfolio of services offered by DSPs helps OEMs address the uncertainties that digitalisation of spare parts introduces (Figure 1). The literature proposes three distinct sources of uncertainty -environmental, task, and inter-organisational (Tushman and Nadler 1978). For the OEM, considering the digitalisation of spare parts, these uncertainties generate information processing requirements to bridge the necessary information and the available information (Premkumar, Ramamurthy, and Saunders 2005).

The driver of demand for digital spare parts services is the need for information processing to deal with different types of uncertainty that OEMs face in the spare parts supply chain. OEMs face inter-organisational uncertainty regarding a lack of information about future demand for

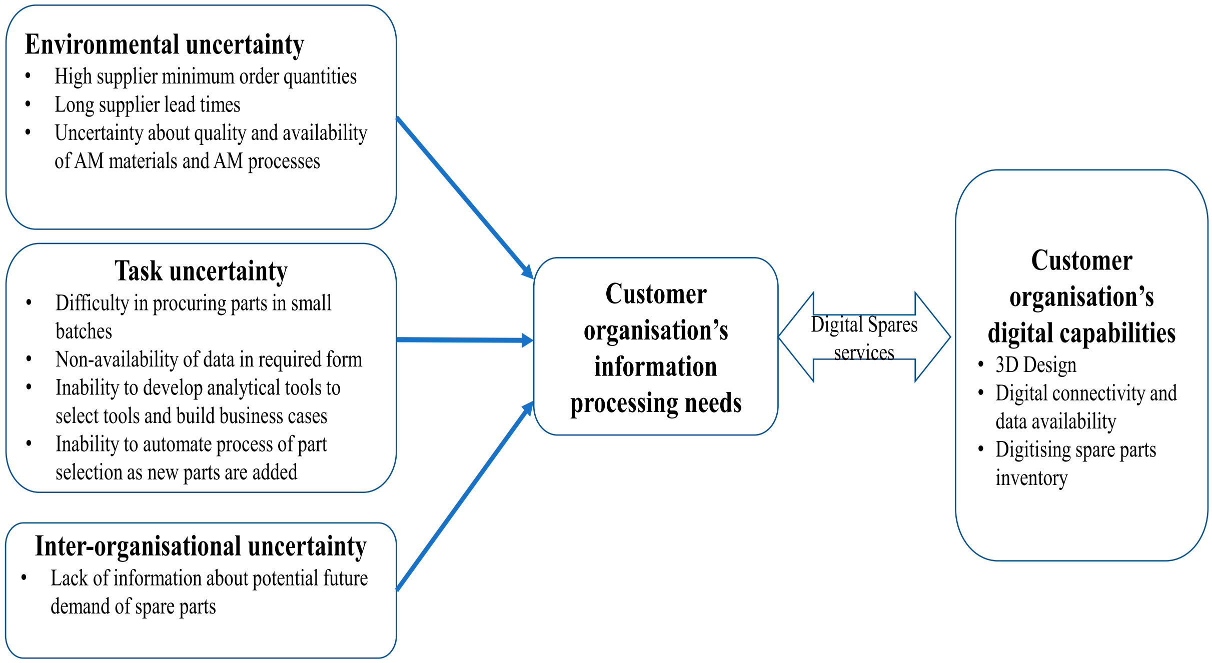


**Figure 1.** Digital spare parts services for overcoming customer's information processing gap.

On the left side, text box and arrows diagram showing the factors affecting customer organisation's information processing needs: Environmental uncertainty, task uncertainty, interorganisational uncertainty. On the right-side text box and arrows diagram showing that organisation's information processing needs is supported by the digital spares services that augment the customer organisation's digital capabilities.

spare parts. To address inter-organisational uncertainty in a conventional spare parts supply chain, the OEM seeks to forecast demand to ensure available inventory and avoid over-stocking. Before digitalising spare parts, the OEM must also forecast future demand when deciding which spare parts to digitalise (Chaudhuri et al. 2021). After digitalising, inter-organisational uncertainty and the need for forecasts can be reduced, as spare parts can be produced on-demand without the need to carry any inventory.

Developing better AM technologies and new materials suitable for AM expands the scope of spare parts that OEMs can consider for digitalising (Chekurov et al. 2021). However, this expansion of scope also introduces new uncertainties for OEMs, requiring information processing. OEMs face environmental uncertainties about the quality and availability of AM materials, the quality of AM processes, and their suitability for specific applications. It is not just an initial challenge to identify the printable parts that can be produced using AM (Chaudhuri et al. 2021). However, an ongoing and recurrent challenge imposed by the changing availability of materials and processes prompted the reconsideration of previously identified parts as non-printable. From the currently printable parts, which previously did not have a business case, information processing is needed to identify parts that have become viable.

The availability and format of information needed to conduct a printability analysis increase task uncertainty. Are 3D models available, or perhaps a 2D drawing? Is there sufficient information to locate the part for scanning when no drawing is available? OEMs also face task uncertainty when developing analytical procedures and tools to categorise parts from large spare parts portfolios into currently printable and non-printable parts. Repeating the printability analysis when new parts are added to the portfolio faces the same task uncertainties as the initial analysis.

### 2.4. Co-evolution of spare parts digitalisation and service provider's role

On the industry level, for the servitization of OEM operations, previous research has examined how the environment shapes the development, as well as investigated the changing role of the OEM in the servitization and de-servitization of the operations (e.g. Finne and Holmström 2013; Turunen and Finne 2014). More recently, the co-evolution of industrial services, solution architecture, and platform governance has been investigated (Jovanovic, Sjödin, and Parida 2022). However, the servitization of spare parts provision as a co-evolutionary process between OEMs and service providers, enabled by developments in manufacturing technology, has not been investigated.

The role of service providers in digitalising manufacturing is recognised in the literature (Rogers, Baricz, and Pawar 2016) but not explicitly examined for digitalising spare parts. The use of AM for spare parts and the need for decision support systems for the selection of spare parts suitable for AM is described (Chaudhuri et al. 2021) in the literature, as well as the challenges faced by an OEM in the switchover from conventional manufacturing to AM for spare parts (Heinen and Hoberg 2019). However, no prior study investigates the role of DSPs in the digitalisation of spare parts and the changes in the service provider role over time driven by the provider's and OEM's information processing capabilities.

## 3. Methodology

### 3.1. Research design

The focus is on service providers supporting OEMs in digitalising spare parts. To understand the role of the service provider in the operations of an OEM digitalising service provision, we examine examples where a service provider has been involved and examples where a service provider has not. Examining the digitalisation of spare parts supported by a service provider and digitalisation by an OEM relying on in-house capabilities pinpoints the role of the service provider. To understand the changing role of the service provider over time, we investigate the offerings of different service providers and their plans for further development.

### 3.2. Data collection

The data collection process was comprehensive, ensuring a robust foundation for our research. We collected data from three DSPs, three OEMs using one of the three service providers, and two OEMs not using DSPs (Table 1). The collected data consists of transcribed interviews and written materials provided by interviewees and from public sources. The recorded and transcribed interviews with the service providers totaled 6 h and 50 min, providing a wealth of insights into their operations. The interviews with the two OEMs digitalising spare parts in-house were recorded and transcribed, totaling 1 h and 40 min, offering a detailed understanding of their experiences.

The digital service providers are called DSP1, DSP2, and DSP3. DSP1 has already developed digital spare parts services over an extended period, allowing us to examine the change and evolution of the solutions. Secondly, it has been willing to engage with research and discuss its solution development and challenges. Since its founding in 2015, it has developed and used an inventory analysis and management software to assess parts printability, the economic viability of AM production, and the construction of digital spare parts catalogues ready for production. DSP2, founded in 2020, provides part identification considering components' total cost of ownership, technical, economic, and (re)design potential, cost, and pricing simulation to support make or buy decision making, qualifies the selected parts, and also allows ordering the part through its cloud-based platform. Its primary customers are providers of manufacturing services, such as machine shops with conventional manufacturing costs and 3D printing. Then, they provide them with a tool to do rapid assessments to serve their customers. DPS3, founded in 2015, offers a digital platform that identifies the right parts for on-demand manufacturing, designs the parts, matches the order with

**Table 1.** Data collection.

| | Selection criteria | Data collection | Data description |
|---|---|---|---|
| DSP1 | Digital service provider, established, focused on OEMs | 4 Interviews (69, 55, 63, 64 min), Secondary data | Interviews with CEO and founder, VP of Business Development, Openly accessible material |
| DSP2 | Digital service provider, start-up | 1 Interview (47 min), Secondary data | Interview with Senior Consultant, Openly accessible material |
| DSP3 | Digital service provider, established, focused on manufacturing subcontractors | 2 Interviews (48, 64 min), Secondary data | Interview with founder and consultant, Openly accessible material |
| Durable | OEM pursuing spare parts digitalisation supported by DSP1 | Secondary data | Customer case descriptions by DSP1: Openly accessible material |
| Transport | OEM pursuing spare parts digitalisation supported by DSP1 | Secondary data | Customer case descriptions by DSP1: Openly accessible material |
| Industrial | OEM pursuing spare parts digitalisation supported by DSP1 | Secondary data | Customer case descriptions by DSP1: Openly accessible material |
| RailCo | Operator of equipment from many OEMs. Pursuing spare parts digitalisation supported by DSP3 | Secondary data | Customer case descriptions by DSP3: Openly accessible material |
| MobilitySolutions | OEM pursuing spare parts digitalisation without digital service provider support | 1 Interview (68 min)<br>Secondary data | Interview with the Head of AM<br>Openly accessible material |
| BusCo | OEM pursuing spare parts digitalisation without digital service provider support | 1 Interview (32 min)<br>Secondary data | Head of AM Competence Center Openly accessible material |

its additive manufacturing partners, manages the quality control process, and delivers the parts when needed.

Through DSP1 and DSP3, we accessed secondary data describing how service providers support OEMs in digitalising spare parts. We collected secondary case data (presentations, reports, news articles) on digital spare parts solutions implemented by three OEMs: *Durable, Transport, Industrial,* and an operator of railway equipment from many OEMs, *RailCo.* 'Durable' primarily operates in the consumer durables industry and designs, produces, and sells products like washing machines, refrigerators, dishwashers, etc. 'Transport' designs and manufactures critical braking subsystems for railways, trucks, and buses. 'Industrial' provides essential components for automotive, marine, and other stationary engines. RailCo operates passenger and freight trains within the country and neighbouring European countries.

The digital maturity level of Durable is moderate as it has all 2D drawings but a limited number of 3D designs, limited accessibility to structured part specifications, moderate accessibility of parts metadata in digital format, and moderate digital integration of the part qualification process. Its risk level is low as the safety-related risk of parts is low, and the company faces the risk of spare parts shortages with the financial cost of replacing the machine. Its relationship with DSP was at an early exploration stage in response to challenges faced by the OEM.

The digital maturity level of Transport is low, as only hand-drawn 2D drawings are available, and there is a low availability of parts specification and metadata and part qualification process. Its relationship with DSP was at an evolving stage, moving beyond early exploration. The risk level is high due to the safety criticality of the parts, and the lack of availability of the parts ensures that the train is not available for service. The digital maturity level for industrial design is moderate, as 2D and 3D designs are available, with moderate availability of parts specifications, metadata, and qualification. The risk level is high as components are predominantly safety-critical, and the impact of the parts not functioning is high for customers. Its relationship with DSP is mature and has a more strategic nature.

The digital maturity level for RailCo is moderate. It has 2D and 3D designs available, and parts specifications, metadata, and qualification are moderately available. The risk level is high as components are predominantly safety critical. Its relationship with DSP is mature, more strategic, and developed over multiple years of working together.

The digital maturity assessment of the OEMs is shown in Table 2.

Two OEMs, *MobilitySolutions and BusCo*, played a crucial role in our research. These companies, which digitalised spare parts without the support of a service provider, *provided valuable ins*ights into their experiences. MobilitySolutions, a leader in the railways equipment industry, and BusCo, a major automotive company bus subsidiary, shared their perspectives on the challenges and opportunities of spare parts digitalisation.

While collecting data, we focused on operational problems in digitising spare parts delivery and how a service provider can support its customers in the implementation. Focusing on operational problems allowed the practitioners to present and share detailed contextual insights and solutions. The interviews with the service providers focused on the service design, addressing uncertainties faced by the customer organisations and supporting their key objectives, understanding how and why these service solutions were developed, and the value provided to customers along with their understanding of the capabilities needed by both service providers and their customers to adopt digital spare parts. Interviews were supplemented with secondary material on OEMs' digitalisation of spare parts.

### 3.3. Data analysis

The data is analysed using a critical evaluation framework considering problem context, generative mechanisms, triggering interventions, and expected and actual outcomes (Denyer, Tranfield, and van Aken 2008; Pawson and Tilley 1997). The object of the evaluation is the digital service provision in a specific problem context, the digitalisation of spare parts by OEMs. The first part of the analysis focuses on the context of the problem, which is the challenges OEMs face in digitalising spare parts and their requirements for information processing. Based on the contextualisation, we seek to describe the mechanism for value capture by the OEMs (both users of DSPs and non-users). Analysing the non-users, we strive to understand the constraints the service providers face. The outcome of the service provision, in terms of digitalisation and impact on uncertainty/ improved information processing, is evaluated. Finally, the providers' service offerings and their development plans are analysed to understand the changing role of DSPs. The steps of our analysis are presented in Figure 2.

## 4. Analysis and results

### 4.1. Problem context and service offering

Implementing digital spare parts requires specific capabilities (Roscoe, Cousins, and Handfield 2019). OEMs

**Table 2.** Digital maturity assessment of OEMs using DSPs.

| | Durable | Transport | Industrial | RailCo |
|---|---|---|---|---|
| Accessibility to design data | | | | |
| Level 0: Nothing | | | | |
| Level 1: 2D drawing | X | X | | |
| Level 2: 2D drawing + 3D models | | | X | X |
| Level 3: 2D drawing + 3D models arranged in a PLM | | | | |
| Accessibility to structured part specifications in digital format | | | | |
| Level 0: Nothing | X | | | |
| Level 1: having a validated specifications reverse engineering process with quality assurance over the data (engineering/qualification process) | | X | X | X |
| Level 2: having a defined and structured functional specification process at the equipment level | | | | |
| Level 3: having a defined and structured functional specification process at part level | | | | |
| Level 4: having the functional specifications integrated into one information system (PLM) | | | | |
| Accessibility to parts metadata in digital format: | | | | |
| Level 0: Nothing | | | | |
| Level 1: having the data accessible | | X | | |
| Level 2: having the data consolidated in one single information system (ERP) | X | | X | X |
| Level 3: being able to interface easily with 3rd party applications via API | | | | |
| Integration with the ordering process: | | | | |
| Level 0: Nothing | | | | |
| Level 1: Having a standardised referencing and ordering process | | | | |
| Level 2: reference AM service provider and deploy ad-hoc RFQ on obsolete parts | X | X | X | |
| Level 3: integrate a systematic decision making process to source AM parts for reorder needs | | | | X |
| Digital integration of parts qualification process: | | | | |
| Level 0: Nothing | | | | |
| Level 1: identify and appoint engineering resources for spare parts requalification | | X | X | |
| Level 2: having a pre-qualification for all part categories with validated technical solutions (material + process) and QC standards to apply | X | | | X |
| Level 3: having this deployed in a part Digital quality passport | | | | |

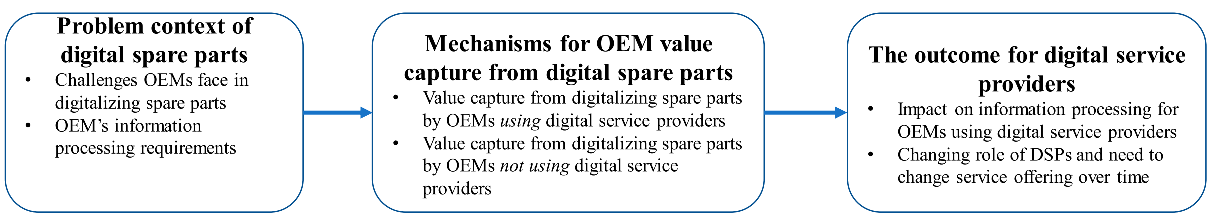


**Figure 2.** The steps of our analysis.

Text box and arrows diagram showing the sequence of research activities: problem context of digital spares, mechanism for OEM value capture, outcome for DSP.

either need to develop the necessary digital capabilities themselves or find service providers that can provide the capabilities as a service. Initially, the problem faced by the OEM is both a lack of information and a lack of ability to acquire the required information. When introducing digital spare parts, the OEM must identify which spare parts could be digitalised using AM and which are profitable. Figure 3 illustrates DSP1's current and evolving understanding of an OEM's information collection and processing requirements. The material selection step addresses environmental uncertainty, the business case development is constrained by inter-organisational uncertainty, and printability analysis focuses on reducing task uncertainty.

DSP1 started in 2015 with a service exploring whether AM is a viable spare parts solution for OEM customers. The initial service offering was an information collection and analysis process that involved many manual steps. To improve efficiency, the printability analysis was first automated. However, because available materials for 3D printing are limited but continuously expanding, DSP1 next developed their process for AM material selection based on functional specifications. The DSP1 maintains a database of conventional materials used by OEMs (1,300 materials) to conduct part selection and printability analysis based on functional specifications. It specifies these materials' functional requirements (e.g. temperature, fluids, and pressures in the environment where the materials operate). These functional specifications of conventional materials are then mapped against the functional specifications of the available 3D printing materials. This material selection process effectively identifies the parts

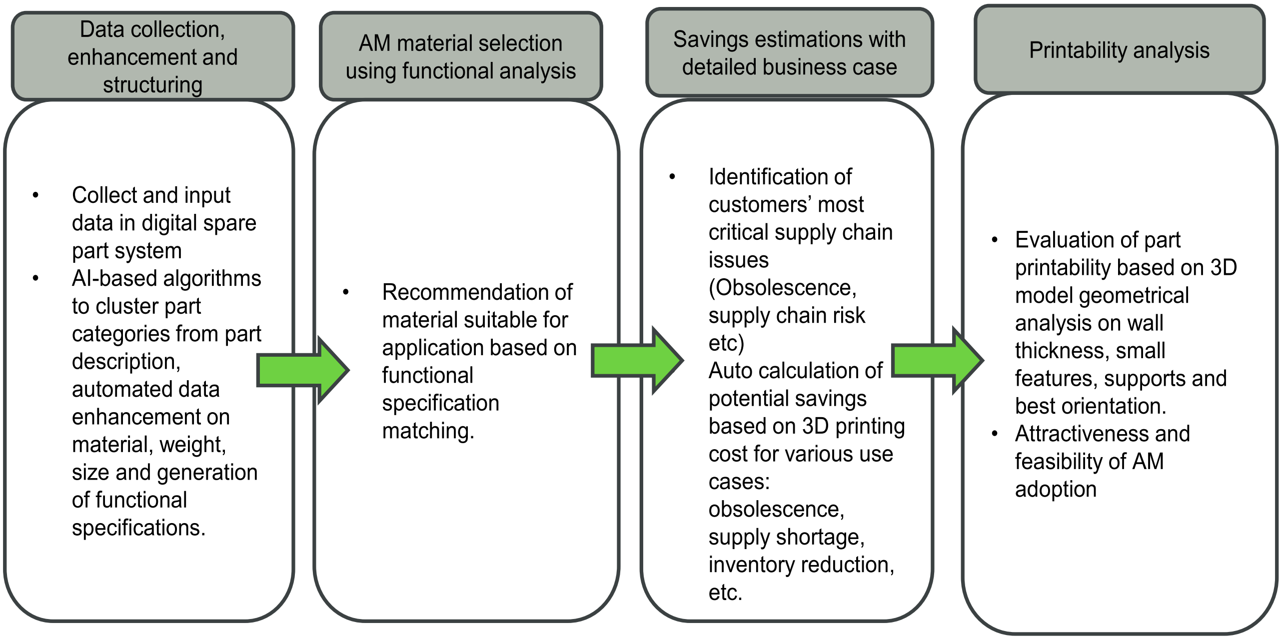


**Figure 3.** Information processing requirements for selecting spare parts for digitalisation.
Text box and arrows diagram showing the sequence of activities for determining the information processing requirements for selecting spare parts for digitalisation.

to be considered in the business case printability analysis stages. DSP1's service provision currently starts with a sample of 10,000–100,000 parts, extracted data from the OEM's Enterprise Resource Planning (ERP) and Product Lifecycle Management (PLM) systems.

DSP3 provides a comparable service to DSP1, but DSP1's information processing capabilities are more advanced. Hence, DSP 1's services are used in Figure 1. Both service providers examine the part-specific case before the printability analysis is performed. This reduces the required effort to generate missing 3D models for printability analysis.

> But, 3D geometry is not needed to evaluate a business case. Whenever a business case is evaluated, and it is favourable, then you do the reverse engineering – Co-founder of DSP 3

The service provided by DSP3 to *RailCo* is different. *RailCo* is not an OEM but a user of equipment. Consequently, *RailCo* has used the services of the specialised provider to create a procurement platform of 85000 parts, from which maintenance and procurement functions can identify parts that can be printed and access the information needed to ask for quotes and order the parts. As AM and materials capabilities continue to improve over time, specialist providers' services are required to update the information.

The information needed for business case development is purchase or production cost for conventional parts, supply lead time, minimum order quantity, stock levels, storage locations and storage costs, transportation cost, yearly consumption, and selling price. For part-specific business cases, the total cost of ownership models is defined by comparing the conventional and digitalised spare parts. The DSPs provide detailed cost models for the use case of each digitalised spare part, enabling the OEM to take account of the dynamic cost structures for both spare parts demand and 3D printers (cf. Akmal et al. 2022).

The business case development differs significantly between individual spare parts and different OEMs. The business case varies depending on whether parts in inventory deteriorate or perish, e.g. requiring scraping and re-ordering after 3 or 5 years in inventory, enabling a reduction of the total cost of ownership by switching to AM; whether cost savings are available from inventory reduction or purchasing parts on-demand; whether reduced lead-times for digitalised parts delivery create sufficient value to increase part price.

DSP1 distinguishes between short-term and long-term business cases. For example, a short-term business case for the switchover to AM can be made based on reducing reorder value through radically reduced reorder quantity. However, the long-term business case for a part can differ significantly from the short-term when parts are slow-moving but have a long shelf-life from the perspective of the total cost of ownership. Thus, the business case can be formulated differently depending on whether the OEM prioritises the short or long-term, emphasising cash release through reduced inventory or total cost. Contrasting the short-term (reorder value) vs. long-term (total cost of ownership) allows OEMs to release cash or seek to improve operating performance indicators, followed by financial market-based performance indicators (like ROI).

### 4.2. Mechanisms for value capture by OEMs

The mechanisms for OEMs' value capture from digitalis ing spare parts are a combination of financial (cashflow, total cost) and operational (lead-time reduction, alternative sourcing) mechanisms. The constraint is technological (quality, certification).

Digitalising spare parts allows for reducing the reorder value of previously high minimum order quantity (MOQ) parts with low demand but high prices. OEM *Industrial* found a set of 1,000 such spare parts, totaling about 4M€ in annual purchasing value and an inventory value of 9M€. From this initial set, 143 spare parts were identified that could be produced on-demand using AM. Switching to digital spares for all these parts would reduce 1.3 M€ worth of inventory compared to conventional parts' reorder value over the next 5 years.

Reducing inventory holding costs for slow-moving parts with high MOQ is another mechanism for value capture. The high MOQ of conventional manufacturing slows down the flow of spare parts. The ability to reduce the MOQ using AM is a mechanism to mitigate high inventory carrying costs for slow-moving spare parts. *Industrial* found in its exploratory study 1,630 low-demand parts with a current inventory value of more than 22 M€, but only a forecasted 5-year reorder value of 95,000€. Scrapping these parts and re-ordering them as digital spare parts on demand represents an opportunity to reduce total costs significantly. Avoiding the inventory holding cost by scrapping and replacing it with digital spare parts and inventory carrying costs of 5% of inventory value would allow for a reorder value of 1.1 M€. Furthermore, avoiding obsolescence due to the limited shelf-life of spare parts inventory also enables total cost reductions. Thus, OEMs with extensive spare parts inventories can seek millions of dollars in potential savings by scrapping inventory and switching over to digital spare parts using AM.

Reducing lead times and the number of subcontractors can be a mechanism for value capture. OEM *Transport* benefited from digitalising spare parts by introducing AM as a viable alternative to conventional manufacturing. The lead-time reduction mechanism is articulated by the service provider DSP1 as follows:

> The OEM can find a supplier for a metal machined part. However, if there are multiple process steps, it takes time and much effort for the OEM to coordinate many suppliers, especially for small production batches. Therefore, a good strategy on those small batches is to use AM to reduce the production steps, thereby saving many set-up costs. – CEO of DSP1

The value capture mechanism for OEM *Durable* also reduces lead time. Conventional spare parts reorder lead times are three months. Introducing digital spare parts procures the parts in 10 business days. OEM Durable identified 2,000 stock-out situations where procuring an alternative AM spare part would enable the company to fulfill warranty obligations more cost-effectively, corresponding to 1.2 million Euros in annual savings.

The obstacle or constraining mechanism for digital spare parts' value capture is regulated industries' quality and certification requirements. As OEM Mobility Solutions points out, information processing capability alone (as provided by DSPs) is insufficient here.

> … even when we have the digital files needed, it would be very fortunate to have the same powder as the original material. Normally, it is slightly different, so we have slightly different material characteristics. Moreover, we must adapt the design to make it cheaper when we adopt AM and ensure that the part has the same stiffness and strength, especially durability over time. Moreover, you will have to have much industry-related knowledge, and we combine both, enabling us to do this redesign process and the evaluation – Head of AM at MobiltySolutions

### 4.3. Outcome of OEM spare parts digitalisation efforts

We now compare the outcome of the spare part digitalisation efforts between OEMs relying on service providers and OEMs developing internal capabilities. The two OEMs developing in-house (*MobilitySolutions* and *BusCo)* are more advanced, incrementally increasing the digital spare parts by including them already in new product development.

> … we started with spare parts to show the so-called quick wins. However, the great potential will only be realized if the parts are designed directly during product development. A digital spare parts inventory is already created during the product creation process. It is being expanded to more and more products. – Head of AM Competence Centre at BusCo

OEMs relying on service providers do not have the capabilities to create digital spare parts at the product development stage, nor have they developed their services to support digitalisation at this stage. The focus is scanning existing spare parts portfolios and identifying the most impactful subset of spare parts to digitalise first.

As a result, DSPs can not currently offer *MobilitySolutions* and *BusCo* support for digitalising spare parts.

For OEMs lacking internal capabilities, DSPs have information processing services that can reduce uncertainty and enable exploration, as illustrated by OEMs *Durable, Industrial, and Transport*. For *RailCo*, a company using and maintaining equipment supplied by many different OEMs, the services of a DSP are valuable beyond initial exploration for systematically spotting more spare parts that can be digitalised as technology and materials improve.

### 4.4. Co-evolution of OEM digital spare parts operations and DSP service provision

The common challenge for OEM's digital spare parts operations and the DSP's service development is responding to the changing environment, tasks, and inter-organisational relationships. Digitalising parts by scanning from physical inventory or 2D drawings for legacy spare parts can cost hundreds of euros per part. Here, digitalisation is an information-processing intensive task, where automating the process of converting a 3D design to a digital spare part can bring down the costs of digitalisation. As AM technologies and materials continue to improve, it presents the opportunity to design digital spare parts that can be sourced on-demand, reducing inventory investment. It could be provided as a service by a DSP by combining the 3D design databases of OEMs with materials and AM process-related databases of the DSP and analytical tools to verify whether AM can produce parts quickly. This type of service would also enable OEMs to revisit which parts can be made by AM periodically and, over the product lifecycle, recalculate the part-specific business case.

> Companies need to prepare data to do top-down analysis and part identification. That is also fine if they want to stay in a bottom-up system. But if they want to transition to doing assessments at the inventory level, then definitely data infrastructure, data quality, the merging and integrating ERP systems, PLM systems, that need to happen in an in a different scale. – Co-founder of DSP 3

Where OEMs initially rely on the digitalisation of legacy spare parts, requiring expensive conversions of 2D designs or scanning of physical parts, the creation of digital spare parts can become part of product development over time. Still, not all spare parts are economical to digitalise during product development, presenting an opportunity for DSP to develop services that identify the opportunity to digitalise as it emerges. This is potentially a service that more advanced OEMs, like *MobilitySolutions* and *BusCo,* could find helpful. It resembles the service provided by DSP3 to *RailCo* in that the digitalisation of the spare parts is an ongoing information process. However, it differs in that the foundation is provided by the digital product design of the OEM. The service providers recognise the opportunity:

> The dynamic nature of an AM-ready inventory means that it can be regularly updated with new materials and technologies as they are developed, so parts previously identified as not printable could become printable as innovations come to light. –VP-Business Development of DSP1

AM cannot consistently manufacture parts to tight tolerances as a manufacturing technology. OEMs must develop in-house capability to address repeatable quality in industries with stringent safety requirements, such as railways or aerospace.

> We cannot rely on the service providers regarding the quality they deliver. Especially not in the railway industry because the norms we must comply with are stringent, and additive manufacturing as a whole industry is not yet on the quality level. Thus, we concluded that as a company, we should implement processes before and during printing and after the printing that enable us to produce the same quality with additive manufacturing equipment repeatably, be it in polymer or metal. This is necessary to deliver parts onto a train or into the infrastructure – Head of AM at MobiltySolutionsCo

To support the OEMs in adopting digital spare parts beyond the initial exploration stage, the DSPs need to develop new capabilities themselves or through a network of partners. These will include the ability to verify that a digital spare part is produced to the required quality and repeatability and engage with multiple functions in the OEM organisation. Unless repeatability and consistent quality are achieved, OEMs cannot adopt digital spare parts. Engaging with various functions within the customer organisation requires the inclusion of new key performance indicators in the business case developments. A function has limited incentive to embrace digital spare parts unless their interests are also addressed. Though it may be time-consuming, DSPs cannot rely on one key person; instead, they must seek and engage with multiple decision-makers across functions.

Results also showed that OEMs need an internal champion for AM-related initiatives, with top management support and a team of experts across functions to spearhead the initiatives around the digitalisation of spare parts. These organisations also need to develop their change management capabilities and include the digitalisation of spare parts as part of a more extensive digital transformation programme.

> We are still faced with what we call the necessity for change management, and it is really to do within the head of the organization. You have to start with a minimal proof of concept to convince people that you can do something. Here is what it can do. Here's what it shouldn't do: pick one or two things that are fairly stable

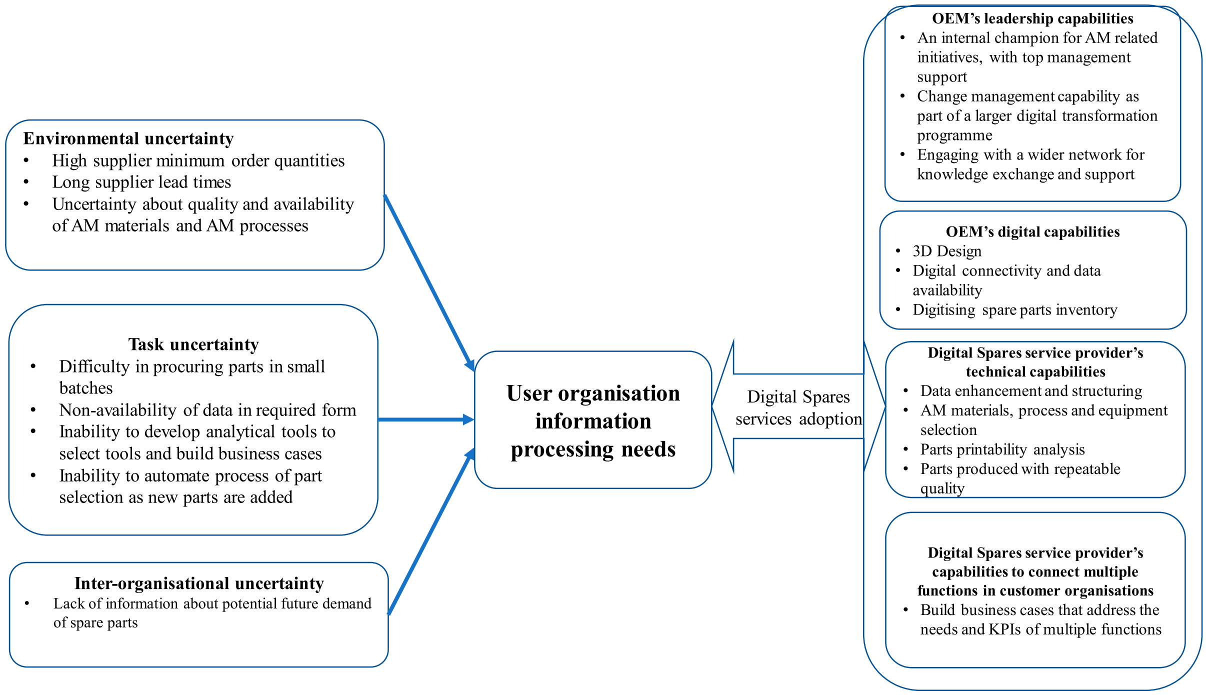


**Figure 4.** Digital spare parts adoption capabilities for OEMs and service providers.

The same figure as figure 1, except that the capabilities are detailed in the text box on the right: OEM's leadership capabilities, OEM's digital capabilities, DSP's technical capabilities, DSP's capabilities to connect to OEM's functions.

> so that you've got that convincing argument. You can see not just the burning platform but also the solution. Then, the next step is to start addressing scalability and, whilst doing that, start addressing things like data quality, process, group work, and governance. And that becomes almost like a center of excellence type journey where you've got initially a means to identify what the next thing is and prioritize it and also address all the changes that you need in process in culture, in training, procurement as well. – Founder DSP 3

A stand-alone initiative or project involving a few interested people will fail to get momentum and the necessary resources within their organisations. Finally, they should engage with a broader network for knowledge exchange and support. The OEMs we interacted with benefited from their association with their network members, who regularly shared their experiences of using AM in general and digitalising spare parts, in particular. Hence, based on this research, we update the conceptual framework shown in Figure 1 with a comprehensive framework of digital spare parts adoption capabilities (Figure 4)

## 5. Discussion

OEMs need different digital spare parts services at various stages of development and levels of digital capability to achieve the outcomes possible through digitalising spare parts. Information processing theory allowed us to explain how OEM needs change with the implementation of digital spares and to identify future opportunities for DSPs to develop the service offering to support the OEM as needs change. OEMs seeking to explore the possibilities offered by digital spare parts face a significant gap between the information processing requirements and information processing capabilities. DSPs have developed digital spare parts services to address the gaps, providing the OEM with the information processing capabilities to explore digital spare parts opportunities. Such services include both generative (including scanning and 3D modeling) and facilitative (selecting parts to scan and model) (Rogers, Baricz, and Pawar 2016). According to Galbraith (1977), firms can either increase their information processing capabilities or reduce their need for information through organisational means. OEMs have begun considering digitalising spare parts in new product development to minimise the need for information processing. This change significantly changes the role of DSPs and the need for supporting services. We also demonstrate how the DSPs and the OEMs need to develop capabilities to facilitate the adoption of digital spare parts.

### 5.1. Academic contribution

We contribute to the nascent literature on the use of AM for providing digital spare parts (Chaudhuri et al. 2021; Chekurov et al. 2018; Heinen and Hoberg 2019;

Salmi et al. 2018; Sgarbossa et al. 2021) by specifying the role of DSPs, and how they bridge the changing information processing needs and capabilities of digitalising OEMs. These responses to changes in need and capability are congruent with the observations of Kroh et al. (2018) on information processing in servitization. They concluded that information processing capabilities are needed to start the servitization, but increasing digitalisation results in a reorganisation that, over time, reduces the need for information processing. Digitalising spare parts follows this pattern of initial high requirements for digitalising legacy parts, which can be reduced when the digitalisation of spare parts is combined with new product development.

Our primary contribution is to the literature on digital spare parts, examining the role of the DSP over time. We contribute to research on the co-evolution of digital technology and digitalised operations (Jovanovic, Sjödin, and Parida 2022) by identifying the capabilities needed by the DSPs as the technologies mature and OEM capabilities develop. Examining the change in the spare parts operations, from digitalising legacy spare parts to digitalising spare parts within new product development, the potential role of the DSP narrows and becomes specialised. The trajectory for service delivery mirrors the de-servitization of new product delivery identified by Finne and Holmström (2013) as the technology matures.

### 5.2. Managerial implications

The findings from this research will help the DSPs in identifying the capabilities they need to develop over time, such as data structuring, choice of materials, processes, and equipment, conducting printability analysis and ensuring repeatable quality, developing business cases that take into account the needs of multiple functions within OEMs as OEM capabilities develop and the technologies mature. Similarly, it also provides OEMs with an understanding of the information processing needs for digital spare parts. It engages with DSPs to bridge those gaps, if needed, and continues to develop its capabilities in digital design, digitalising spare parts inventory, digital connectivity, and data availability, as well as in developing capabilities in change management, engaging with a broader network for knowledge exchange and developing an internal champion.

### 5.3. Limitations and future research opportunities

The research is based on three DSPs, three OEM customers, one equipment operator organisation, and two non-customer OEMs. Given the nascent stage of development of digital spare parts, getting access to actual world firms with experience is essential. We were fortunate to have access to both DSPs and OEMs. Nevertheless, future research should investigate in closer detail how OEMs develop their digital spare parts portfolio over time, the capabilities they need for this development in-house, and how DSPs can facilitate the development. In parallel, we also need to understand which DSP services OEMs will continue to rely on and which become redundant over time. There is also a need to know how DSPs can develop their portfolio of services in response to changing customer needs. Finally, the digitalisation of spare parts and servitization can perhaps co-evolve (Chen et al. 2021; Jovanovic, Sjödin, and Parida 2022). OEMs adopting digital spare parts will improve inventory, lead times, and service level outcomes. Still, it could support OEM servitization efforts and enable new business models through product-service systems (Baines and Lightfoot 2014). How 3D printed spare parts can act as an enabler for OEM servitization efforts, providing a platform for novel business models of OEMs is an avenue for future research. Moreover, the redesign of parts for AM (Lindemann et al. 2015; Vaneker 2017) has not been explicitly considered for spare parts in this research. As OEMs develop capabilities and digitalise their spare parts portfolio, they are expected to incur additional costs for redesigning the parts for AM, where digitalising may not provide the desired benefits unless such redesign is done. Hence, for legacy spare parts, such redesign costs must be considered while preparing the business case for a transition to digitalisation.

We interviewed DSPs who did not explicitly consider IP protection and cyber security threats as part of their services, nor are they considering existing patents on parts while considering parts that can be printed. Similarly, OEMs that are using the services of DSPs have also not raised these issues.

There are possible explanations for these. Firstly, as pointed out by Ballardini, Ituarte, and Pei 2018, there are challenges associated with interpreting traditional patent infringement doctrines in the context of AM and digital representations of spare parts. Furthermore, there are issues related to the nature of CAD files, as well as protecting CAD files through patent law. Hence, the DSPs may be reluctant to consider IPR issues because of a lack of clarity in patent law around digital spare parts and whether CAD files can be regarded as a means for transferring information about patent-protected parts as the patent law has traditionally been interpreted only about physical goods and not to digital or virtual representations (Ballardini, Ituarte, and Pei 2018). Moreover, DSPs may consider it is the responsibility of OEMs to inform them about possible patent protection and not feel those parts for printability evaluation and digital spare provision. OEMs using DSPs may have either already considered IPR aspects or not considered those for printability analysis or are unaware of the threats.

Interestingly, one of the OEMs, which is not using a digital spare parts service provider but is developing digital spare parts services on its own, did mention IPR. For example,

> The approach that you often hear in the market and from some software providers is we have excellent software. Please give me your CAD data on the parts or the 2D drawings. Then, I will import all these data into my software, and then the software will tell you which part is straightforward to print.
>
> In reality, this is not so easy. First, of course, we are not a company that will give our IP here to a third party so quickly. Yeah, this is not our intention. Others do not want to do that normally. So, the restriction is that the software has to run on our servers. And many startups providing the software have not considered this. – Head of AM, Mobility Solutions Co

Thus, loss of IP is one reason this OEM did not engage with a digital spare parts service provider.

We acknowledge that some new generation service provider, such as Autentica car parts (https://autentica-carparts.com/), are emerging, which address the issue of IPR protection through their solution based on non-fungible tokens (NFT). In contrast, others like Autentise (https://www.authentise.com/) emphasise data protection as part of their unique offering. While DSPs may consider IPR protection and data security while offering their services, OEMs should request data protection from DSPs. They may develop internal capabilities or seek legal help if they have concerns about IPR protection. Future research on digital spare parts can consider contracts between DSPs and OEMs while considering quality, cost, IPR protection, and cyber security risks. Designing, operating, controlling, and monitoring a digital spare parts supply chain involving OEMs, DSPs, and end-users, as discussed by Peron in 2024, can be an active domain for future research.

## 6. Conclusion

As the digitalisation of OEM's product design processes evolves, the digital service providers' offerings must co-evolve. Based on our field study, we have developed an understanding of why OEMs seek support from a service provider and why they do not. Furthermore, we have been able to outline how the service provider can develop its service operations over time to address the changing needs of the OEM. As the capabilities of the OEM improve, the service provider needs to focus its services on the digitalisation of spare parts in the OEM's product development process.

## Disclosure statement

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

## Data availability statement

The interview notes and transcribed interview data are available from the first author upon request.

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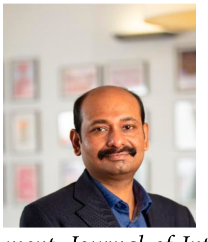

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## Appendix

**Questions for digital spare parts service providers**

(1) Please provide an overview of your company and the services your organisation provides
(2) Do you produce 3D printed spare parts on your own or use other AM service providers?
(3) Why do customers consider using your company's services?
(4) What is your company's value proposition to customers?
(5) What is your process from getting a customer request to delivery?
(6) For the specific OEM customers, explain the problem and the context which motivated the customer to approach your organisation
(7) What was the request you received from the OEM?
(8) What options did you discuss with the OEM to address its problem?
(9) What approach/intervention did you agree to deliver for the OEM?
(10) Why did the OEM find your approach suitable and convincing?
(11) How did you go about planning the intervention for the OEM?
(12) What specific activities did you do as part of the intervention?
(13) What outcomes did you deliver for the OEM?
(14) Can you explain why and how the different activities in the intervention generated the outcomes for the OEM?

**Questions for OEMs**

(1) What motivated your company to provide digital spare parts?

(2) How did you identify the spare parts that can be printed and the business case?
(3) What challenges did you face, and did you engage with a service provider in this journey?
(4) If you have not used a service provider, why did your organisation decide to provide digital spare parts services on its own?
(5) If your organisation used a service provider, what intervention did they carry out?
(6) What outcomes did your organisation achieved from adopting digital spare parts?
(7) Is your organisation planning for digital spare parts at the product development stage? If so, why?