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Virtual warehousing through digitalized inventory and on-demand manufacturing: A case study

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ABSTRACT

Novel digital on-demand manufacturing technologies provide a significant opportunity to support development of virtual warehousing and in turn improve supply chain performance. However, the implementation of virtual warehouse comes with a set of challenges, especially where the objective is to virtually warehouse standard or legacy parts that have been developed and verified initially for conventional (non-digital) manufacturing. In this paper, we explore the key elements required for successful implementation of a virtual warehouse for legacy parts based on a combination of part digitalization, on-demand manufacturing, and part validation. Our proposed framework for adoption of virtual warehouse includes development of a digital inventory which includes supply chain and manufacturability data, identification, and selection of suitable parts for on-demand manufacturing, selection of on-demand manufacturing technology, fit-for-purpose validation of the parts. Our framework is exemplified through a case study, and we conclude that the building of an effective virtual warehouse requires several enablers, including availability of digital data about technical and supply chain characteristics of parts, but also a suitable part identification tool. This part identification tool needs to be flexible to include comparison with reference parts already produced by different on-demand manufacturing technologies.

1. Introduction

Virtual warehousing can be defined as a collection of digitized parts that can be digitally manufactured on-demand to eliminate the need to store the parts physically in an inventory (Ayers and Malmberg, 2002). From this definition it follows that the storage capacity of the virtual warehouse (VW) depends on the digital inventory data storage available space (Hidayat et al., 2022) whereas delivery and fulfilment capacity depends on the availability of digitalized on-demand manufacturing (ODM) capacity. The VW builds on the digitalization of inventories and ODM to enable cost reductions, production optimization, supply chain resilience (Rarità 2021), environmental impact reduction and high quality customer service throughout the supply chain (Fung, 2005). Ensuring that parts produced using ODM are of sufficient quality is presently under-explored and represents a significant challenge in the implementation of VW.

Conventional supply chains depend on the warehousing of inventories to ensure agility and robustness (Asmussen et al., 2018). However, the warehousing of physical objects generates inventory costs and results in waste through stock obsolescence. VW may address these and other challenges by enabling manufacturers to procure or produce parts on-demand by means of virtualized ODM.

New digital manufacturing technologies, such as direct additive manufacturing (DAM) and indirect additive manufacturing (IAM), enable the manufacturing of parts on demand as they operate digitally and without the need for pre-defined, component-specific tooling. Furthermore, digitalized manufacturing resources may be brought together in virtual factory systems. This may be either internal (owned by, and dedicated to, meeting the needs of the company owning the resources), external (dedicated to supplying manufacturing-as-a-service to multiple companies) or hybrid (combinations of internal and external) (Akmal et al., 2022; Hedenstierna et al., 2019).

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DAM is a digital manufacturing technology that enables the user to produce complex geometry layer-by-layer directly from a digital model (Jiang, 2020; Petrovic et al., 2011; Mandolla et al., 2019), to potentially reduce or eliminate the need for production tooling. In IAM, a mold tool is additively manufactured, and a chosen material is injected into the mold in a digitalized workflow similar to traditional injection molding (IM), but does not require pre-defined, component-specific tooling. Both DAM and IAM may form part of virtual factory systems that may be either internal, external or hybrid.

In an ideal implementation of the VW, a desired number of parts can be sourced and delivered on-demand when needed. Such a VW would comprise a comprehensive digitalized inventory, seamlessly integrated with a virtual factory of ODM capacity and connected by a virtual network of just-in-time logistics. We use the term VW and not digital inventory to highlight the concept of a digital repository of a variety of parts from different products, which can be ordered as needed. Thus, such a VW contains digital inventory of different parts. The term digital inventory implies focus on inventory of individual parts and not to the entire repository of parts across products.

However, several challenges present themselves when the concept meets practice. A first key challenge in the establishment of the VW is the digitalization of inventories, where a lack of digital representations of the components to be digitalized may be a complication (Colli et al., 2022). This is specifically important for the virtual warehousing of legacy parts that have been manufactured with conventional manufacturing methods, and where no computer-aided design (CAD) files or digitalized manufacturing and quality assurance protocols may be available. To address this and other challenges, Kandukuri and Moe (2021) propose a data quality assurance (DQA) framework for VW. The framework answers questions related to whether digital drawings are available when needed, whether the parts can be made 'first time' when needed, whether the parts can be made at the same quality in different locations. Such DQA frameworks are perceived as essential for the successful digitalization of inventories in the implementation of VW in mature supply chains where supplies of legacy parts need to be supported.

A second key challenge that needs to be addressed in the implementation of the VW for legacy parts is the digitalization and virtualization of manufacturing and supply, and the subsequent product quality assurance (PQA). PQA provides assurance that the virtually manufactured parts are fit-for-purpose and thus fit-for-delivery from the VW. A key premise for a VW is that the parts virtually warehoused must be produced and delivered in a quality that meets requirements, and this aspect is important to consider in the selection of ODM technologies to be used for the virtualization. Where parts are manufactured for a new custom design, verified, and validated by means of a digital manufacturing technology such as described by Hedenstierna et al. (2019) and Khajavi et al. (2014). The task of quality assurance and fit-for-purpose validation is comparatively trivial. This is because the manufacturing method used in the virtual warehousing of a given part is equivalent to the method used in the development (post the initial printability check of the new custom design), verification and validation of the said part. However, for legacy parts, that may have been manufactured with non-digital manufacturing methods for decades, and with materials that have not been made available for digital manufacturing, the digitalization and virtualization of manufacturing, supply and quality assurance may require substantial efforts. The DQA framework proposed by Kandukuri and Moe (2021) is useful in the systematic review of available data and in the evaluation of ODM technologies to implement.

The framework proposed by Chaudhuri et al. (2022) explores two key enablers that may potentially facilitate the virtual warehousing of legacy parts, while at the same time providing increased support to the development and manufacturing of parts which are designed for digital manufacturing. One key enabler is IAM technologies, which allow the digitalization of a conventional high-volume manufacturing process – IM – to enable on-demand low-volume virtualized manufacturing of parts that are found to have substantial equivalence to parts manufactured with conventional IM. Whereas DAM provides manufacturers with a new digitalized way to convert raw material into finished products layer-by-layer, IAM provides manufactures with a new way to digitally make the IM tools that convert the materials, without changing the conversion itself. The substantial equivalence of IAM to conventional IM addresses some of the DQA and PQA challenges associated with virtualizing the manufacturing and warehousing of legacy parts as it reduces the risk of non-performance and the need to specify product fit-for-purpose acceptance criteria. Another key enabler is the implementation of a fit-for-purpose digital reference part inventory in a part selection search engine capable of fuzzy logic – based similarity analyses. The feeding of such a search engine with digitalized parts that have been virtually manufactured comprises the last step in the virtual warehousing of a part in the model proposed by Sharifi (2021b) and allows the continuous improvement of the VW itself.

Accordingly, the goal of this study is to explore how VW can be implemented in practice and how the ODM process such as IAM and freeform injection molding (FIM) may be applied in the virtual manufacturing and warehousing of fit-for-purpose legacy parts. The importance of VW, as well as possible routes to implementation, has already been studied (Fung, 2005; Meng et al., 2019; Ceschia et al., 2022). However, there is very limited literature on the actual implementation of VWs for (legacy) parts. Accordingly, this paper is focused on answering the following specific research questions:

1. How do we identify and select legacy parts that are appropriate for ODM and in turn for VW?
2. How do we ensure that legacy parts made with ODM technologies are fit-for-purpose / fit-for-delivery in a VW set-up?
3. How can the data gathered through fit-for-purpose validation of first parts be used to refine the identification and selection framework for subsequent parts and the selection of ODM technology?

In the present paper, we explore how a part selection methodology proposed by Sharifi et al. (2021b) can allow robust DQA and is suitable for the identification of part candidates for VW, as well as for the selection of suitable ODM technology. The paper also shows how the fit-for-purpose PQA of a (virtualized) manufacturing protocol is the critical last step in the virtual warehousing of a fit-for-delivery part. Finally, the paper shows how the implementation of a fuzzy logic-based part search engine in a VW of fit-for-delivery parts enables continuous improvement and expansion of said warehouse by continuously integrating data to improve selection. We conclude that novel IAM methods and the emergence of fuzzy logic and other machine learning frameworks may enable and substantially facilitate the virtual warehousing of parts.

The contribution of this research are as follows:

a) Development of a comprehensive framework for implementation of VW for legacy parts. This includes a part identification process, selection of an ODM process and a manufacturing process verification. The manufacturing process verification feeds information back to the part identification process through the development of a library of reference parts to drive further continuous process refinement based on a fuzzy logic-based part similarity mapping.
b) Application of the above framework using the data from a case company, with potential to create a VW comprising fit-for-delivery legacy parts that have been digitalized, selected, manufactured, and verified for compliance with requirements.

2. Literature review

The digitalization of inventories enables manufacturers to increase resilience and responsiveness in supply chain. This is done by improving the tracking of stock levels, streamlining the order fulfillment process, identifying trends and patterns in demand, and consequently improving forecasting accuracy regarding production levels and order quantities (Hompel and Schmidt, 2007). However, digitalized inventories alone do not eliminate the need for physical inventories/warehouses. In this study, it is shown how the digitalization of inventories, combined with the digitalization and virtualization of ODM enables manufacturers to virtualize warehousing and thereby reduce or eliminate physical inventories.

2.1. Key drivers for adoption of VW

The primary drivers for companies to explore the adoption of VW is to stay at the top of their business capabilities and technological advancements by digitalizing the value delivery system (Kohtamäki et al., 2019) to increase responsiveness and lower warehousing costs. Digital interoperability is the ability to achieve seamless, fast, reliable, and secure exchange of data and information between companies. One of the main goals of the digital interoperability is to connect the information in an effective and efficient way while maintain privacy (Pan et al., 2021). VW, in this context, enables companies to increase resilience in the supply chain, reduce costs associated to traditional warehousing and minimize the environmental impacts.

2.1.1. Supply chain resilience

Successful adoption of the VW may have a high impact on supply chain resilience (Zhao et al., 2023) and operational efficiency (Calatayud et al., 2019; Chavez et al., 2017; Dubey et al., 2019; Singh and El-Kassar, 2019). The VW can potentially build resilience into supply chains (Fiksel et al., 2015; Walter et al., 2004) based on ODM capability (Montes and Olleros, 2021). Moreover, the VW eliminates or significantly reduces costs associated with offshore production (Attaran, 2017), as well as multi-stage distribution and inventory costs (Kandukuri and Moe, 2021). Building resilience requires combining dynamic flexibility with the ability to respond to given circumstances by having integrated supply chain systems and structural flexibility to reconfigure supply chains according to changing circumstances. The VW, in this context, builds the foundations for both dynamic and structural flexibility, thereby contributing to operational efficiency in the face of disruptions and risk. Additionally, the VW can assist companies to quickly and cost-effectively identify and manage high-risk parts in the event of a supply chain disruption as well as help in the development of risk management strategies for new products. The VW also enables companies to identify alternative suppliers that can provide back-up stock during supply chain shortages, or to identify back-up manufacturing solutions when no back-up stock is available (Asmussen et al., 2018; Hidayat et al., 2022). Overall, the adoption of the VW can enhance supply chain resilience and operational efficiency, thereby providing companies with a competitive advantage in a dynamic and uncertain business environment.

2.1.2. Cost and time savings

Warehousing and inventory management are key elements in supply chain management via the ability to establish efficient and smooth logistic operations in the organizations. Such operations are vital in supporting company competitiveness as costs associated with logistics, storage and handling are important parts of overall production costs and overall fulfillment of performance criteria. To minimize the costs associated with traditional warehousing, many organizations are taking new solutions into consideration for running the warehouse more efficiently. Emerging technologies in the field of logistics and supply chain have had significant impact on cost reductions (Kamali, 2019). The VW is one example of an emerging platform technology, which can significantly reduce costs by minimizing the maintenance and inventory procurement costs (Hidayat et al., 2022). Moreover, stock-out costs may be fully or partially avoided if parts can be manufactured on demand.

As a step towards virtual warehousing, companies may create an inventory data sharing mechanism between manufacturing and distribution in order to provide better management of the flow of materials from suppliers to customers (Jung and Jeong, 2018). By sharing inventory information via the VW, the manufacturer can improve operational performance on several key measures including finished goods inventory reduction, degree of backlogs, parts purchasing quantity and total cost (Jung and Jeong, 2018).

In addition to cost saving, time savings may be realized by reduced inventory status check-ups and rationalizing of safety stock. The VW helps manufacturers to replace existing just-in-time and just-in-case supply chain capabilities with agile inventory management. This results in reductions of inventory costs.

2.1.3. Reducing environmental impact

VW potentially enables manufacturers to manufacture parts/products when and where they are needed (Ceschia et al., 2022). This may result in the minimization of scrap waste materials, transportation (FLEXE, 2019), inbound logistics, storage and hence contribute to a lower environmental impact. Environmental factors have a high impact on how quickly organizations accept digital technology (Yadegaridehkordi et al., 2018).

When implemented in a VW, tool-less ODM technologies such as DAM and IAM can significantly enhance the sustainability of short series production and product development (Hegab et al., 2023). Contributions include saved emissions from metal tool manufacturing, reduced emissions from production to stock and increased access to recycled materials. Several recycled materials have already been processed by selective laser sintering (SLS) and fused deposition modeling (FDM) methods, and IAM offers the developers an even wider range of recycled materials.

ODM-based VW can minimize the environmental impact of shipping by offering a de-centralized manufacturing model. This is specifically important during the market introduction stage and spare parts manufacturing in the later stages of product life-cycle management. Currently, de-centralized ODM facilities may be found in Asia, US, and several EU countries. In a virtualized manufacturing set-up, these facilities may be eligible to produce a given part according to the product specification with no start-up costs and delivery to the local customer with significantly reduced shipping time, cost, and environmental impact. However, this virtualized manufacturing approach may require that the quality or fit-for-purpose of parts supplied by means of a given ODM technology be verified before the part can be added to the "shelves" of a VW.

2.2. Challenges in adoption of VWs for legacy parts

To virtualize the (on-demand) manufacturing of parts, manufacturers initially need a systematic approach to identifying parts that are suitable for virtualization, and to determining which ODM technologies will be appropriate for their manufacturing.

2.2.1. Data availability

The first step in virtual warehousing is to ensure that the necessary product data is available in a digital format, as lack of such data may complicate the virtual manufacturing and subsequent PQA that is an essential prerequisite of delivery from a VW. As shown by Chaudhuri et al. (2022) companies frequently lack digitalized part files for legacy parts. And even where such digitalized part files are found, they often lack critical process, manufacturability, quality assurance and supply chain data. Evidently, such lack of product data may complicate the virtualization of part manufacturing that is needed for VW implementation, and robust processes are needed to compensate for lack of data. Even if data is available, companies lack suitable tools to assess which parts can be manufactured by ODM with required quality and hence can be offered for delivery through a VW.

2.2.2. Selection of individual parts suitable for ODM-based VWs

Digitalized on-demand manufacturing capacity is a critical part of the VW supply chain. ODM potentially allows the just-in-time manufacturing of parts without the need for pre-defined manufacturing tools, and therefore becomes a key enabler in the virtualization of warehouses. However, without an appropriate part identification and selection tool and a robust framework for the selection of appropriate ODM technologies, it is very difficult or impossible for manufacturers to identify the most suitable parts/spare parts for a given ODM supply chain. Considering the diversity of ODM technologies available, a systematic approach is necessary to facilitate the selection of suitable parts for ODM and the configuration of ODM supply chains to support a VW. In the part identification and selection, the availability of critical technical, technological and supply chain criteria for successful classification and identification of the parts appropriate to be manufactured is crucial. To support this work, several researchers have developed frameworks for part identification for AM (Lindemann et al., 2015; Chaudhuri et al., 2020; Knofius et al., 2016). Lindemann et al. (2015) explored a bottom-up methodology for part selection for AM. Knofius et al., 2016 used an analytic hierarchy process (AHP) to identify the most suitable spare parts to be manufactured by additive manufacturing (top-down approach). Recently, Chaudhuri et al. (2020) and Sharifi et al. (2021b) have developed a methodology for spare part selection for AM and IAM/FIM by combining the data-driven top-down and bottom-up approaches. They have used multi-criteria decision--making and cluster analysis techniques to identify the most suitable spare parts for ODM and have added part verification and fuzzy logics-based similarity mapping to complete the VW and drive continuous improvements in part and ODM identification and selection.

2.2.3. Selection of on-demand manufacturing technologies supporting VWs

Digital ODM is a production method where manufacturing may be initiated as soon as a customer makes an order without the need for pre-defined tooling and without any products being manufactured and stored in inventories in anticipation for future sales (Westkämpfer, 1997). By using ODM, a company can rapidly and easily change supply chain configurations, adjust product features based on customer desires, and direct manufacturing order fulfilment so that it happens close to local markets (Westkämpfer, 1997; Adamson et al., 2017).

Contrary to traditional manufacturing, ODM does not require pre-made tooling, extensive and diffused supply chains, costly storage, or long-distance transportation. Also importantly, it eliminates the risk of unsold inventories. Other important benefits of ODM are mass customization, high levels of flexibility, on-time production, distributed production, cloud-based manufacturing, no fixed costs or initial investment and reducing overproduction which can make less total resource wastage (Montes and Olleros, 2021; Unnu and Pazour, 2022). Moreover, ODM may enable manufacturers to reduce the number of components from several to one by adding new levels of design freedom to allow part consolidations. The consolidation of multiple parts into a single part eliminates the assembly process, which is usually time-consuming and complicated, and reduces costs associated with warehouse management (Sharifi et al., 2021a). Besides the obvious advantages of production on-demand, ODM has some shortcomings such as higher variable costs per unit, lower production throughput, as well as potential reliability, performance and quality concerns (Unnu and Pazour, 2022). Where external or hybrid ODM supply chains are used, capacity planning and quality assurance may require attention. Choosing the most appropriate ODM technologies which can produce the parts with the desired quality and cost efficiency remains a challenge for most companies. Though it is not the focus of the paper to review different ODM technologies, for the benefit of the reader, we provide a broad overview of DAM and IAM technologies below.

DAM and IAM are two ODM technologies that are emerging as alternatives/complements to conventional IM (Sharifi et al., 2021a). Fig. 1 summarizes the main DAM and IAM technologies and their main benefits.

As it can be seen in Fig. 1, DAM technologies increase flexibility and design freedom and enable manufacturers to shorten delivery lead times. Different DAM technologies have been studied in detail by (Ngo et al., 2018). Although DAM has been shown to be an attractive ODM method, it has some limitations that are discussed in detail in sub-Section 2.2.3.1. IAM technologies can address some of the drawbacks of DAM, as shown in Fig. 1 (Sharifi et al., 2021a), and supply chain

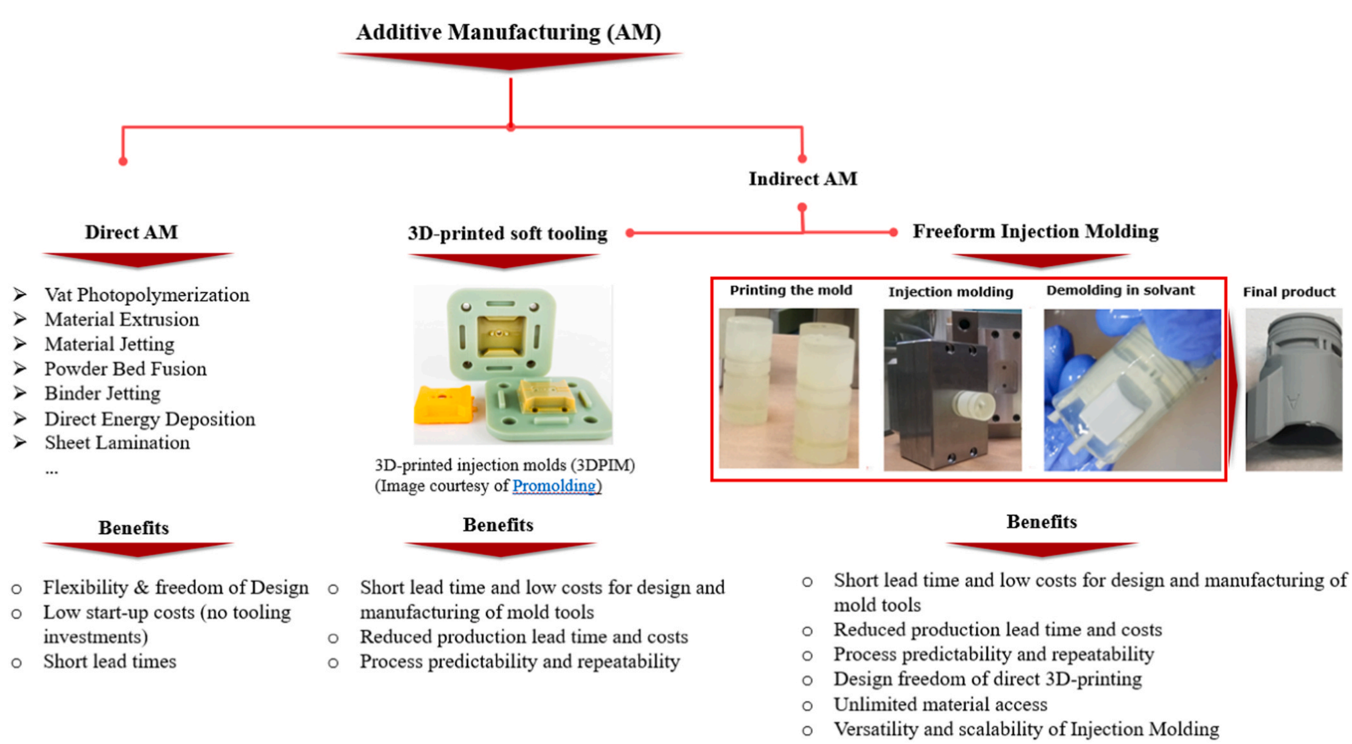

Fig. 1. Common DAM and IAM technologies. DAM: direct additive manufacturing; IAM: indirect additive manufacturing.

professionals need to consider benefits and limitations of these ODM technologies when selecting parts and setting up virtualized supply chains.

2.2.3.1. Direct additive manufacturing (DAM). The DAM process, also referred to as 3D-printing (Sharifi et al., 2021a), starts with slicing a computer-aided design (CAD) file or a scanned object into layers by means of a slicing software. Then each layer will sequentially be printed to manufacture the part (Pan et al., 2014). There are several studies in the literature regarding the manufacturing process, production efficiency, and design framework for DAM (Bikas et al., 2019; Kadkhoda-Ahmadi et al., 2019; D'Aniello et al., 2021; De Falco et al., 2019).

The benefits of DAM (Ribeiro et al., 2020) such as short lead times (Mashhadi et al., 2015), design freedom (Renjith et al., 2020), and low start-up costs (Gao et al., 2015) have already been studied by researchers and are summarized in Fig. 1. DAM has wide range of applications including rapid tooling, rapid prototyping, and end component manufacturing (Scott et al., 2012; Peron et al., 2024). DAM has been considered as an alternative for low-volume IM (Ribeiro et al., 2020; Achillas et al., 2017; Hällgren et al., 2016). However, DAM has some limitations that limit its usefulness as a direct alternative for traditional IM (Diniță et al., 2023). Some of these limitations are rough surface finish (Kumbhar and Mulay, 2018), anisotropic mechanical properties (Kok et al., 2018; Ziemian et al., 2012), poor dimensional accuracy (Islam et al., 2013), insufficient material properties and limited choice of materials (Ngo et al., 2018). Unpredictability and unrepeatability (Dowling et al., 2020), high process costs (Thomas and Gilbert, 2014), limits on the part size (Abdulhameed et al., 2019), slow process speed and limited scalability (Gokuldoss et al., 2017) are considered as some other limitations of ADM.

2.2.3.2. Indirect additive manufacturing (IAM). IAM has some benefits such as scalability (Meisel et al., 2012) and flexibility of material choice (Rosato et al., 2012). However, the suitability of IAM (Tosello et al., 2019) for low-volume ODM in a VW set-up has not been fully addressed. FIM and 3D printed soft tooling (PST) are two well-known IAM technologies that can address some of the limitations of DAM and IM for ODM-based VW applications. As it can be seen in Fig. 1, IAM combines the key benefits of DAM and IM. PST and FIM do not depend on pre-defined metal tooling, as they are based on 3D printed mold tooling that is manufactured on-demand and may be either soluble (FIM) or durable (PST). The rest of the toolchain – and the materials processed - are similar to those of traditional IM. The functional equivalence of IAM to conventional IM, and the digitalized nature of 3D printed molds, makes IAM an attractive technology for virtualized ODM. PST is based on molding tools that are durable and is suitable for simple part designs in commodity materials. FIM is based on single-use soluble molding tools and is suitable for complex part designs in engineering materials. The selection of IAM method thus requires an initial assessment of part design and part material, an exercise that is considerably facilitated if such data is included in a digitalized inventory. As shown in the research by Sharifi et al. (2021b), such part data may furthermore be included as parameters in a similarity search, if a fit-for-purpose reference library is established, to inform and refine the selection of parts and ODM methods.

2.2.4. *Verification, fit-for-purpose, and fit-for-delivery*

A key implicit assumption in ODM-based VW is that the parts that are digitally manufactured on-demand have a quality that is sufficiently close to the parts they are intended to replace. To achieve this goal, a good digital product model (digital inventory) and a reliable source of digital production capacity are needed. Furthermore, the fit-for-purpose of a given digital product model and ODM production process need to be verified before the resulting fit-for-delivery part can be added to the VW (Pedersen et al., 2019). Such verification can include simple dimensional measurements, functional testing under real working conditions, lifetime tests (accelerated test) and other relevant tests, as specified in the part specification or fit-for-purpose description (Vora and Sanyal, 2020).

For custom designs that are developed for ODM, fit-for-purpose and fit-for-delivery verification is comparatively easy to achieve, as product requirements are developed for the capabilities of the chosen ODM technology. In the ODM-based VW of legacy parts that have been manufactured with conventional manufacturing methods, fit-for-purpose verification is more challenging, as product requirements have been developed for the capabilities of the chosen manufacturing technology. Accordingly, manufacturers may need to carefully evaluate ODM technologies to find those that are most similar to the conventional manufacturing technologies to minimize capability differences and to maximize the success of the verification. Manufacturers should also evaluate how to identify potential economies-of-scale that may result from the reuse of quality assurance protocols developed for the legacy parts, and from the repetitive manufacturing and replenishment of the part, that is an implicit assumption behind a VW.

3. Methodology

We used a case study method to conduct the research. The data needed for this study were provided by the sourcing department of the case company, an original equipment manufacturer (OEM). The case company meets the growing need for infrastructure, food supply, energy efficiency, and climate-friendly solutions. The company's products and services are used in areas such as refrigeration, air conditioning, heating, motor control, mobile machinery, hydraulic systems, components for powering off-highway mobile machinery, air-conditioning, refrigeration industry, residential and commercial heating, district energy, low voltage AC drives, and power modules.

The case company has already started their digitalization journey for spare parts manufacturing, and they have implemented the part selection platform described by Sharifi et. al (2021b) to identify suitable parts to be manufactured by ODM. The motivation for basing our research on this company is the existing knowledge in the company and the company's willingness to explore how low-volume parts may be produced on-demand in a VW setting. The case company believes that VW may help increase resilience in supply chains and reduce costs associated with offshore production and inventory costs. Moreover, the case company believes it can minimize the scrap rate and consequently reduce waste materials and environmental impact. By implementing VW, the case company furthermore aims to identify alternative suppliers quickly for low-volume products with high risk of running out in case of a smaller or wider-spread supply chain event and to develop risk management strategies for new products. Finally, the case company aims to develop a framework that allows the proactive identification of alternative back-up manufacturing suppliers for parts where supply risk is high. In this context, the option of having both internal, external and hybrid ODM sources is perceived as attractive. Hence, the case company and a technology supplier with expertise in ODM using FIM came together and agreed to test the idea of the VW for feasibility for the purpose of this research. Fig. 2 illustrates the main elements in the proposed VW model. The digital information of the parts can be stored in a digital inventory, which contains the digital specifications of the products/parts to be manufactured at any given time, and against which product quality assurance can be performed. The digital inventory includes technical specifications, supply chain data about lead time, cost, safety stock etc. The digital inventory feeds a virtualized ODM system. This ODM provides the manufacturing resources needed to convert parts in the digital inventory into physical objects and defines the boundary conditions of the available manufacturing capacity. Those boundary conditions, and other relevant data are to develop a first set of selection criteria that are feed into the part selection framework to support

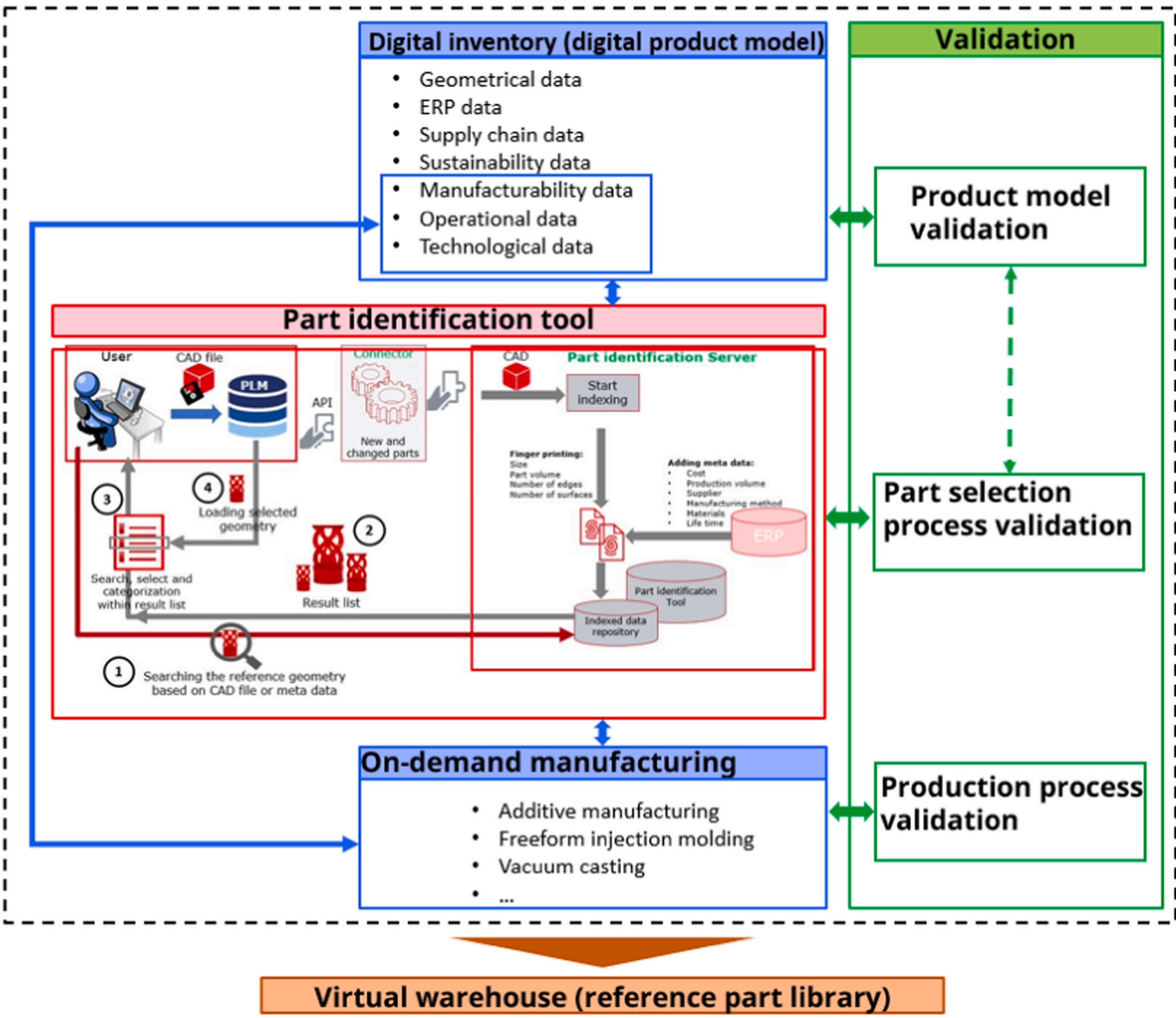

Fig. 2. Important elements of VW; a) digital inventory, b) part identification and selection tool (Sharifi et al., 2021b), c) Virtualized manufacturing and supply platform, d) verification of digital product model, part selection and production process, e) VW comprising fit-for-delivery (reference) parts that have been digitalized, selected, manufactured, and verified.

identification of parts that are suitable for ODM and inform the selection of ODM technology to use. After the identification and selection processes, there is a need to verify the ability to produce the selected parts on demand, in a fit-for-purpose quality. This verification allows us to add the verified part and associated protocol as a fit-for-delivery item in our VW. At the same time, it provides the part selection framework with a fit-for-purpose reference part that will inform the selection of similar future parts with more confidence.

The part identification tool (Fig. 2) is a key element in the virtualization of legacy parts warehouse as:

a) It connects the digital inventory and the virtualized ODM

b) It provides the interface that enables the end user to identify candidates for ODM

c) It provides the similarity assessment that allows us to exploit a library of reference parts to refine our identification and selection of parts.

Finally, a multi-step approach, which integrates the key elements referenced above to help companies build an ODM-based VW is proposed. Our proposed approach starts by data collection and part selection criteria definition. Then suitable parts for ODM are identified from a given part portfolio, and ODM technology is chosen for each selected part. Parts are manufactured by the chosen ODM technology, and manufacturing output is verified for fit-for-purpose. Parts fulfilling the case company quality criteria can be virtually warehoused as fit-for-delivery, and information about each successfully warehoused part will inform the identification and selection of new parts.

To enable the implementation of the VW depicted in Fig. 2, a systematic process is shown in Fig. 3. The process is developed in recognition of the fact that transitioning towards the VW is not simply a technical challenge, but also a strategic and organizational challenge. The VW implementation process includes conducting interviews and an awareness building workshop followed by quantitative data collection, developing, and using the part identification tool, manufacturing the identified parts and validating the digital product model, part selection and the manufacturing process. As shown in Fig. 3, the VW adoption process will be finalized by one or more change management workshops to align organizational requirements for the transition.

In support of this approach in the use case, the process of collecting

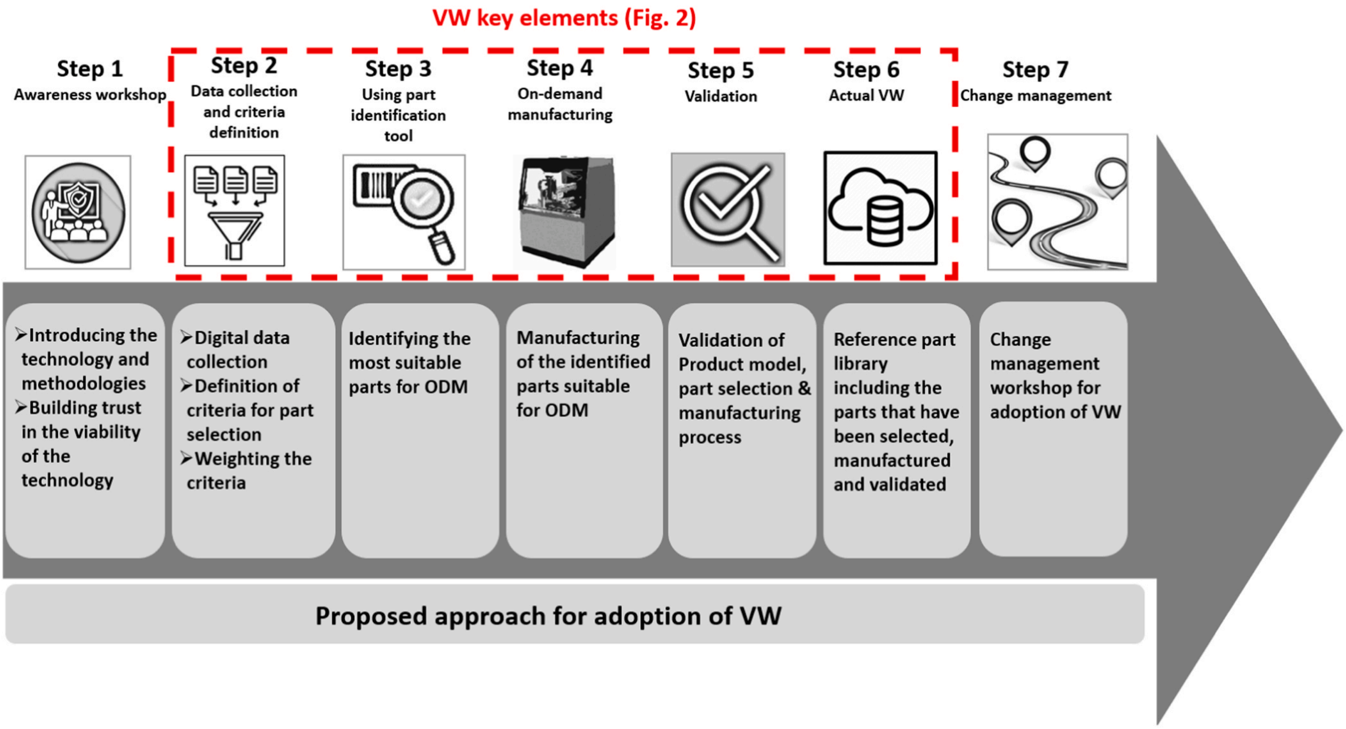

Fig. 3. Systematic approach for adoption of VW.

the relevant technical and supply chain data consisted of four interviews (with duration of approximately one hour each) and one workshops (half day). The interviews and workshop were conducted between the research team and the expert teams from the case company's supply chain, procurement, global advanced manufacturing, and value engineering. Fig. 4 shows the provided technical and supply chain data by the case company.

3.1. Part selection for VWs

Fig. 5 shows the steps followed to identify the most suitable parts for the VW. As can be seen in Fig. 5, the first step is to provide the technical and supply chain data that was discussed in a previous sub-section. In step two, all the data needed for part selection for VW is imported into Cadenas (https://partsolutions.com). Cadenas, an off-the-shelf software solution used by supply chain managers to aggregate demand across multiple locations and/or departments has already been used by Sharifi et al. (2021b) as a part selection engine. In step three, the objectives and weights of objectives are defined to inform the part selection for VW. Step four is to identify the similarity between objects or patterns by means of clustering techniques (Bateni et al., 2017; Kassambara, 2017). Clustering methods work based on 'like-to-like' comparison between the objects and assign similar objects into object groups. Steps five, six, seven and eight will help the user to rank the parts within each cluster, part sampling, compiling the screening results and finally selecting the best part candidate(s) for the VW, based on the defined criteria.

3.2. Building foundations for the VW: a case study

The potential impact of VWs on supply chain resilience, minimization of cost and environmental footprint has already been studied (Calatayud et al., 2019; Chavez et al., 2017; Dubey et al., 2019; Singh

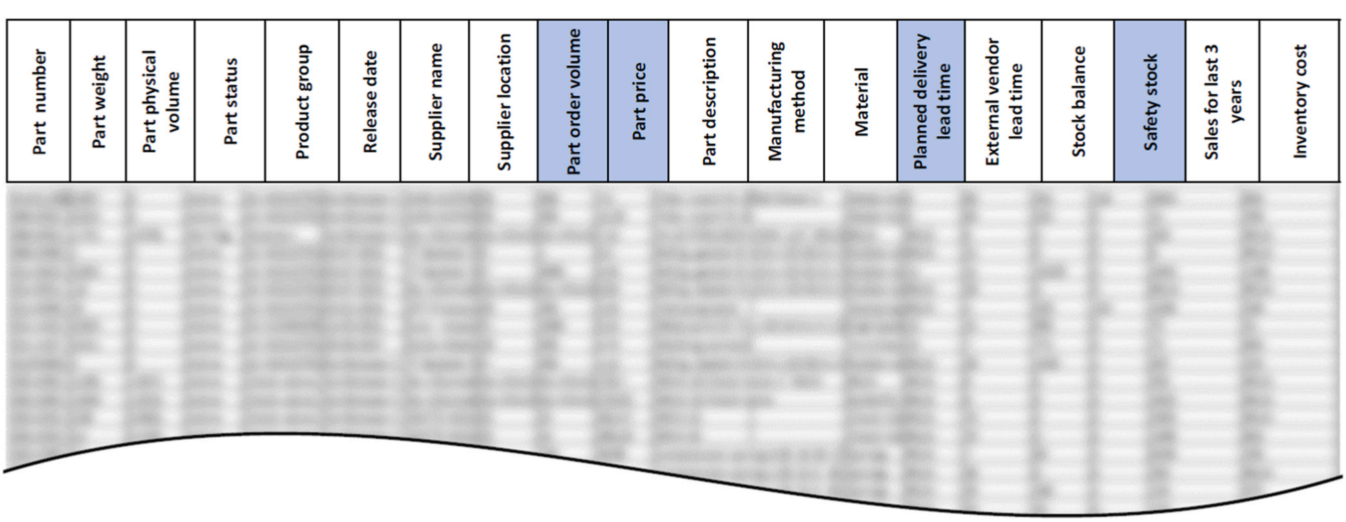

Fig. 4. Technical and supply chain data provided by the case company to be included in the analysis.

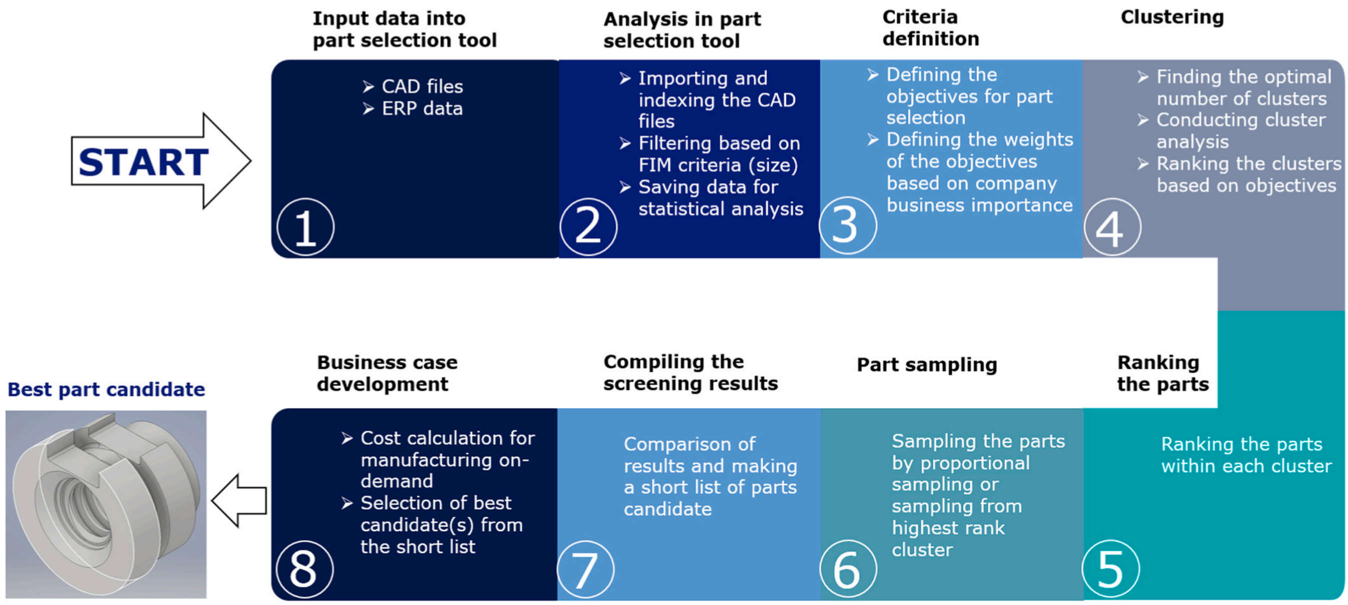

Fig. 5. Summary of the process for part selection for VW.

and El-Kassar, 2019; Hidayat et al., 2022; Ceschia et al., 2022). However, there is no literature about how to virtualize a warehouse in practice. Therefore, in this study the most important elements of the VW (Fig. 2) were explored and a systematic approach for implementation of the VW has been proposed and tested on a selected part in a case company.

Fig. 3 shows our proposed approach for the adoption of the VW. As can be seen in Fig. 3, steps 2–6 are the key elements of the VW shown in Fig. 2. These implementation steps are initially sequential, and step two may require involvement of experts from different disciplines such as enterprise resource planning (ERP) and product life cycle management (PLM), supply chain, logistics, material, after sale and procurement. Step three is intended to include a part selection tool, which enables the company to efficiently identify the parts having advantageous supply or stock profile for ODM based on the criteria defined in steps 1 and 2. Without such a tool, a company with a big parts portfolio will not be able to easily identify and select parts that are suitable for ODM. Several part identification methodologies (Lindemann et al., 2015; Chaudhuri et al., 2020; Knofius et al., 2016) have been developed to identify the most suitable parts for AM based on bottom-up and top-down approaches. However, both bottom-up and top-down approaches have limitations that constrain their use for part selection for ODM (Sharifi et al., 2021b). Therefore, in this study, we have chosen to proceed with an extended top-down part selection approach developed by Sharifi et al. (2021b). In step four, it is determined what ODM technology is most appropriate for the identified parts followed by development of digital product protocol for each identified part. In this study, we have used FIM as the ODM technique to keep scope manageable, but other ODM techniques may be just as appropriate for the virtual warehousing of a given part. To make sure that the ODM parts fulfill the quality / fit-for-purpose criteria defined by the case company, the quality of the output from steps 2–4 needs to be verified. Therefore, step 5 is a crucial step in the VW implementation framework. Finally, after step 5, the products/parts can be added to the VW (reference part library).

The case company started their digitalization journey several years ago and has used DAM mainly for prototyping and manufacturing of production tools to support production lines. Recently, the case company has started exploring the opportunities to use ODM techniques for manufacturing of short series production of end-component and spare parts to virtualize warehousing. They have, therefore, progressed beyond step 1 - awareness - and have started considering IAM as a complement to their existing DAM-based supply chains. In the following, we will be focusing on steps 2–5, which comprise the actual digitalization and virtualization of a component to be warehoused.

3.3. Digital data collection and definition of criteria for part selection for ODM

In this study, one part library consisting of 300 spare parts was selected as a representative sample for testing of the VW methodology. It should be mentioned that digitalizing the target inventory is not an easy task as the needed digital data are either incomplete or does not exist in some cases.

Following selection of this sample, the next step was to define the criteria to be used in the selection of the most suitable parts for ODM. In this study, part order volume, part price, planned delivery lead time and stock balance have been chosen as the most important supply chain objectives for part selection for ODM (shadowed in blue color in Fig. 4). FIM was chosen as ODM method due to the extensive use of engineering materials in the case company. The four objectives have been compared pairwise and have obtained relative weights of 0.56, 0.26, 0.12 and 0.06 respectively using the analytical hierarchy process (AHP) method.

3.4. Part identification for ODM

When manufacturing companies decide to implement a VW, one of the key questions is how the most suitable components to be manufactured on-demand can be identified, considering the ODM technologies available to the company within the supply chain infrastructure considered. There have been some attempts to develop methodologies for part selection for DAM and IAM (Lindemann et al., 2015; Chaudhuri et al., 2020; Knofius et al., 2016; Sharifi et al., 2021b). However, there is no research in the literature addressing the part selection methodology for ODM-based VW, where fit-for-purpose and fit-for-delivery are essential requirements. In this study, a top-down part identification methodology developed by Sharifi et al. (2021b) is used. The summary of part selection steps has been shown in Fig. 5. Eight parts out of 300 parts were identified as the most suitable parts for ODM and one out of those eight parts was selected as the best initial candidate to be manufactured by the chosen ODM method (FIM). Fit-for-purpose requirements were identified in dialogues with the case company, and it was determined that part material -polyetheretherketone (PEEK) - and dimensional requirements were critical to quality.

3.5. Manufacturing of identified parts using selected ODM

One of the key elements for building the VW is the capability to manufacture the parts on-demand. In this study FIM has been selected as the ODM technique. Before a specific part can be added to the VW as fit-for-delivery, it needs to be ensured that the part can be manufactured in a fit-for-purpose quality using the chosen ODM method. Accordingly, a baseline production protocol for the FIM-based ODM of the chosen part is compiled by the ODM supplier (an external vendor, in this case).

3.6. Verification, fit-for-purpose and fit-for-delivery

As previously described, ODM methods may differentiate substantially from conventional manufacturing methods in terms of achievable part quality and functional performance. This means that a critical last step in the virtual warehousing of a part is to verify that it is fit-for-purpose. The fit-for-purpose depends on a) the requirements defined for a given part, b) the completeness of digital data describing those requirements, and c) the method originally used for manufacturing of parts meeting those requirements. Therefore, the fit-for-purpose verification of the final ODM part may be very straightforward if the part is originally manufactured by a given ODM method where the digital representation is complete. On the other hand, it can be very complex if the part is originally manufactured by a non-digital manufacturing method where the digital representation is completely absent.

Depending on the nature and criticality of parts to be virtually warehoused, manufacturers will have to carefully consider the capabilities of available or target ODM methods and suppliers in the definition of criteria for the part identification and selection. A complete review of factors to consider is outside the scope of this paper, and we have chosen to apply FIM as ODM due to the compatibility of this method with the engineering materials used by the case company. Specifically for the part selected as first candidate, the material PEEK was required. Previous data compiled by the ODM supplier demonstrated base-line compatibility of the FIM method with PEEK and provided a high level of confidence regarding functional performance fit-for-purpose equivalence. The dimensional accuracy of the parts was identified as a critical fit-for-purpose requirements, and through the validation process, it was found that a specific process (cleaning of the FIM molds) needed to be improved to achieve compliance with dimensional requirements. After two iterations, the products manufactured passed dimensional accuracy testing, and the part and production protocol were deemed fit-for-purpose and added as a first fit-for-delivery item to the VW reference library.

It is important to note that the part selection process included comparison of the part portfolio of the case company with reference part libraries, which were deemed fit-for purpose by the ODM supplier. It is further important to note that even if it is technically feasible to produce a part using a particular ODM technology, it does not imply that it can be produced to the desired level of quality. Hence, parts need to be produced, verified for quality and further improvements made to the process to meet the quality requirements. If such quality cannot be achieved through simple process changes, unfortunately the part cannot be considered to be included in a VW. The selected sample part, which was tested for quality and validated. has now been added to the reference part library of the ODM supplier. When the part selection tool is used for other portfolio of parts by the case company or for any other company, the updated reference part library with the information of this particular part will be used.

4. Discussion, conclusion and scope for future research

The main purpose of this study has been to develop a framework supporting the virtualization of a warehouse comprising legacy parts, with subsequent application of the framework for a case company. A VW which exploits the digitalization of inventories and manufacturing to enable storage-less on-demand production and supply, is perceived as attractive to improve supply chain performance in terms of resilience, cost efficiency and sustainability.

While significant research has been carried out on the digitalization of inventories and the ODM of custom parts, the topic of on-demand based virtual warehousing of legacy parts – and in particular the topic of practical VW implementation – has received less attention.

In our research, we address this gap by proposing a framework for VW implementation that is based on the following key elements:

- The establishing and/or presence of a digital inventory comprising digital representations of parts and information about critical-to-quality / fit-for-purpose requirements.
- The establishing and/or presence of a part identification and selection framework comprising a part selection tool with a similarity search engine.
- The establishing and/or presence of virtualized ODM resources comprising specific ODM technologies with specific boundary conditions that may inform the definition of part selection criteria for the part identification and selection framework.
- The establishing and/or presence of a process for verifying that parts that have been identified, selected, and manufactured on-demand are fit-for-purpose and may thus be deemed fit-for-delivery from the VW.
- The presence of a reference library architecture which allows the part selection tool to integrate digital representation data from parts that have been deemed fit-for-purpose in the selection of new parts to drive a continuous improvement of the part selection process.

We proceeded to test the proposed framework through data collected from a case company in collaboration with an ODM supplier and demonstrate that a fit-for-purpose, fit-for-release legacy part may be virtually warehoused through the systematic execution of the framework proposed.

The framework proposed and verified in this study differs from previous research in its focus on legacy parts, and on factors that consider fit-for-purpose and fit-for delivery in the part selection tool. Moreover, our proposed part selection tool is capable of comparing the parts in the part portfolio with reference parts, which can be produced with the desired quality using different ODM technologies. The process also includes validation and process improvement to achieve the desired quality, which can feed back into the part selection process through an updated reference part. Thus, our proposed approach supports continuous improvement of the part selection process by continuously integrating data from verified fit-for-purpose parts in a fuzzy logics-based similarity search engine.

The case study underscores the fact that despite strong strategic interest in the adoption of VW, multiple operational challenges associated with 1) data availability, 2) an appropriate part and manufacturing process selection tool and 3) validation of selected parts for quality remain. It is a limitation of our study that we could not test our approach using a larger portfolio of parts due to data availability challenges in the case company. We also did not validate the 7 other parts which were identified in the initial selection. Similarly, we did not include assemblies in our evaluation and only considered individual parts.

The case study informed us that VW can be implemented in practice if digital data about parts' technical and supply chain characteristics are available, can be integrated into a common database which can be used by the part selection tool. Moreover, the part selection tool should be flexible to include comparison with reference parts which were already produced by different ODM technologies to desired quality and validation of parts before each individual part can be included in a VW. For companies lacking high quality digital data, expert driven process of part selection followed by quality validation must take place before parts can be considered for virtual warehousing.

Future research should explore how assemblies and sub-assemblies can be considered for evaluation for inclusion in a VW following guidelines provided by Stark et al. (2023). Future research should also explore ways to integrate virtualized ODM platforms in VW models. This will help to determine what factors may help supply chain managers determine use of internal (in-house manufacturing), external (use of ODM service provider) and hybrid supply chain configurations (combination of in-house and use of external service providers). This will help to achieve performance objectives in terms of costs, quality, reliability, responsiveness, sustainability, and resilience.

Disclosure statement

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

Authors statement

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CRediT authorship contribution statement

Elham Sharifi: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Saeed D. Farahani:** Writing – review & editing, Supervision, Resources, Project administration. **Atanu Chaudhuri:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology. **Brian Vejrum Wæhrens:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Funding acquisition. **Lasse G. Staal:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests Elham Sharifi reports administrative support and writing assistance were provided by Nexa3D.

Data availability

The data that has been used is confidential.

Appendix A. List of abbreviations

VW, Virtual Warehouse; ODM, On-demand manufacturing; FIM, Freeform Injection MoldingDAM, Direct Additive Manufacturing; IAM, Indirect Additive Manufacturing; IM, Injection Molding; SLS, Selective Laser Sintering; FDM, Fused Deposition Modeling; OEM, Original Equipment Manufacturer; CAD, Computer-aided Design; PST, Printed Soft Tooling; PLM, Product Lifecycle Management; ERP, Enterprise Resource Planning; AHP, Analytic Hierarchy Process; DQA, Data Quality Assurance; PQA, Product Quality Assurance; PEEK, Polyetheretherketone

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