Hybrid digital manufacturing: Capturing the value of digitalization

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Hybrid digital manufacturing: Capturing the value of digitalization

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Abstract

A chasm is growing between the advanced technologies available for improving manufacturing operations and those effectively used in practice. The vision of Industry 4.0 is to mobilize industry to seek out these possibilities for improvement and to close the gap between opportunity and reality. However, when compared with more established improvement opportunities such as lean manufacturing, the digitalization of manufacturing lacks in both paradigmatic examples and an understanding of how to achieve the benefits. This lack is a complication of concern: Without an appropriate operations strategy to capture the value of digitalization, manufacturing companies will be unable to focus on technological investments and operational changes. To address this concern, operations management academics must develop new theory through active engagement in the practice of digitalization in manufacturing. This research presents a paradigmatic example, based on engaged scholarship, focused on effectively combining novel object-interactive and conventional manufacturing syntax for benefiting from digitalization in internal operations and the wider supply chain. The contribution to literature is a novel operations strategy—hybrid digital manufacturing—for capturing the value of Industry 4.0 technologies.

KEYWORDS

digitalization, direct digital kitting, hybrid digital manufacturing, Industry 4.0, manufacturing syntax, object-interactive syntax, operations strategy

1 | INTRODUCTION

Prior research on the digitalization of manufacturing has resulted in a broad range of promising applications of direct digital manufacturing, including prototyping, tooling, customization, spare parts manufacturing, bridge manufacturing, and kitting for assembly (Holmström et al., 2010; Khajavi et al., 2015, 2018; Rosochowski & Matuszak, 2000; Tuck et al., 2008; Yan & Gu, 1996). However, from an operational perspective, the digitalization of manufacturing is challenging (Harris et al., 2021; Machado et al., 2019; Mittal et al., 2018), with digitalized islands, such as 3D-printing, subordinate parts of otherwise conventional operations and supply chains (Holmström et al., 2017). Based on our study, we argue that the full benefits of digitalization in manufacturing materialize—and persistent operational challenges are overcome—when operations switch from a conventional procedural syntax to a novel object-interactive syntax.[1] To illustrate the latter, consider (conventionally challenging) product engineering change in an object-interactive production system: Once a component has been selected for manufacturing, its digital counterpart is created according to its (modified) digital design and granted control of its own production, which it exerts by requesting object-interactive services from production resources.

In this study, we investigate the component manufacturing and direct digital kitting solution at Väderstad, a Swedish manufacturer of agricultural equipment. We derive insights into the design principles of the digitalized manufacturing system and analyze the benefits of the resulting object-interactive operations. Väderstad has digitalized the manufacturing of its metal components, for which it once relied on suppliers. We demonstrate how digitalization enables object-interactive services in Väderstad's component manufacturing and explicate the mechanisms through which this digitalization produces significant operational effects for the company. Furthermore, we discuss potential effects on the wider supply chain.

Building on established hybrid manufacturing (HM) theory (Peeters & van Ooijen, 2020), we identify hybrid digital manufacturing as a new type of HM strategy that combines procedural and object-interactive syntax in production control. The object-interactive services for the automated manufacturing of component kits keep the operational sequence open, thereby reducing the need for component inventory and production scheduling. Each component of the kit can be manufactured from different materials and according to a different design. When components are added to the kit in the automated kitting warehouse, each component can be added according to a different logic, with some components added by pull logic to complete a kit needed in assembly, and other components by push logic to complete nesting and improve efficiency. With both laser cutting and direct kitting controlled through object interaction, the procedural alternative, in which components are manufactured in batches by suppliers and kitted from inventory by Väderstad, becomes obsolete.

Our engaged scholarship (van de Ven & Johnson, 2006) on hybrid digital manufacturing has allowed us to identify key mechanisms through which digitalization adds value to manufacturing and how manufacturers can proceed with digitalization to achieve the benefits. We elaborate on the purpose and principles of hybrid digital manufacturing for realizing the vision of Industry 4.0. We build our narrative around the core idea of object interaction, describing it as a generic mechanism and discussing how it can be combined with conventional procedural control in an HM system. Our narrative presents the new operations strategy of hybrid digital manufacturing, outlining its key design principles and specifying its potential outcomes, both for an implementing manufacturer and for the wider supply chain. Before describing the new operations strategy for digitalization and its theoretical implications, we review the literature necessary to understand the digitalization of manufacturing and our collaboration on the design and implementation of the solution at Väderstad.

2 | LITERATURE REVIEW

In building an understanding of the systemic change that could be achieved through the digitalization of manufacturing, we must draw on several knowledge bases. First, we define the novel concept of manufacturing syntax, relating it to prior research in operations management. Through the concept of manufacturing syntax, we explain how digitalized manufacturing can operate in a structurally different way from conventional manufacturing that uses procedures to manage operations. Changing the manufacturing syntax redefines the relationship between a physical manufacturing system and an information system, creating a cyber-physical manufacturing system that relies on digital counterparts and object-interactive services to manage operations.

Recognizing that both procedural- and object-interactive syntax have their benefits and drawbacks, we identify the need for a new type of operations strategy. We ground this strategy in prior research on operations strategies for digitalization, HM, and solutions for component supply for assembly. Together, these different streams of research provide a foundation on which we build our narrative and frame our contribution, conceptualizing hybrid digital manufacturing as an operations strategy that combines procedural control and object-interactive services for beneficial internal operations and external supply chain outcomes.

In our discussion, we identify commonalities and contrasts between our findings to further literature not reviewed here in detail. These include production planning and control (PPC) of digitalized manufacturing systems (Bueno et al., 2020; Derigent et al., 2021; Hedenstierna et al., 2019; Helo et al., 2021; Jiang et al., 2022), generative design for additive manufacturing (Bendoly et al., 2021) and Digital Twin (Cimino et al., 2019).

2.1 | Manufacturing syntax: Digitalized manufacturing is fundamentally different

Through the concept of manufacturing syntax, we seek to explain how digitalized manufacturing can operate in a fundamentally different way from conventional manufacturing, with digital counterparts and object-interactive services replacing procedural control. We introduce the concept of syntax from programming theory, which describes how elements in programming languages are structured and related (McCracken & Reilly, 2003).

Programming languages using object-oriented syntax were introduced in the 1980s, with object interaction gradually replacing the initially dominant procedural control (Wegner, 1997). The introduction of object interaction has enabled new systems architectures of distributed and parallel systems as well as loosely coupled systems and system components, including multi-sided platforms and systems of systems (Mattila et al., 2021). Through object interaction, the functionality of digital entities has expanded incrementally (Van Lamsweerde & Letier, 2002), first enabling highly interactive visual interfaces between computers and human users, then allowing the creation of digital entities that automatically collect and organize information about human users, and most recently, permitting digital counterparts representing and facilitating interaction between autonomous physical objects (Derler et al., 2011). The last type of interaction is the very basis of novel cyber-physical systems in manufacturing and supply chains (Monostori et al., 2016).

The syntactic difference between procedural and object-interactive programming forms the basis for understanding how digitalizing manufacturing changes the way in which manufacturers and their suppliers can operate. Although most computer systems used in conventional manufacturing today are programmed using object-oriented languages, the structure of manufacturing processes and operations remains procedural. Procedural manufacturing syntax differs from object-interactive manufacturing syntax in how information is used and how operations are conducted (cf. Meyer et al., 2011; Musa et al., 2014).

Conventional manufacturing and supply chains are structured using procedures, separating physical processes (e.g., sourcing, making, and delivering) and information systems (e.g., planning and control; Stewart, 1997). For example, manufacturing is scheduled in information systems, and equipment is set up in the physical process to produce batches of specified products. Manufacturing a new product or changing the product requires production engineering and retooling. Sourcing and delivering new parts from suppliers also involve the setup of separate informational and physical processes.

By contrast, through object interaction, cyber-physical manufacturing operations combine product design, process design, and the automation of operations (e.g., Sierla et al., 2018). In direct digital manufacturing, the manufacturing syntax is inherently an interaction between production resources and product objects; digitalized equipment produces a part without setup and tooling as specified by the digital design model (Holmström et al., 2019). Adding functionality to the design model needed for interactions in further operational tasks creates a digital counterpart for the physical part (Meyer et al., 2011). This digital counterpart (Främling et al., 2003, 2007) is the cornerstone for the interactive manufacturing syntax, allowing us to extend object-interactive services from direct manufacturing to interactive handling and logistics. Cyber-physical objects consisting of a physical part and a digital counterpart can interact with manufacturing and handling equipment through service requests (Khajavi et al., 2018). With a procedural syntax, both the handling and the moving of products and components are controlled through inventory transactions and accounting the number of items of a given type in pre-defined locations (Rönkkö et al., 2007). Based on a digital counterpart, object-interactive services can track the movement of individual items and control their handling in any location (Holmström et al., 2011). This way, component handling can be individualized, both in manufacturing (Meyer et al., 2011) and in logistics (Arnäs et al., 2013). These are examples of how digitalized and conventional manufacturing rely on different syntaxes for operations. We summarize the key differences in Table 1.

Moreover, in Appendix A, we specify the terminology and illustrate the difference between the procedural and object-interactive syntax in manufacturing. With procedural control, digitalization is optional, whereas it is necessary for object-interactive services. In conventional manufacturing, procedures such as scheduling, tooling, and setup tightly couple physical resources and products, limiting the impact of digitalization. By contrast, in direct digital manufacturing, object-interactive services loosely couple physical resources and products. The resulting cyber-physical process relaxes the procedural constraints for changing products and individualizing operations that are present in conventional manufacturing, thereby increasing the impact of digitalization.

2.2 | Operations strategy for digitalization

The literature on the digitalization of manufacturing (e.g., Holmström et al., 2019) and Industry 4.0 (e.g., Parente

TABLE 1 Manufacturing syntax—The differences between procedural control and object-interactive services

	Procedural control (in conventional manufacturing)	Object-interactive services (in digital manufacturing)
Digitalization of physical objects and processes	Digitalization plays a limited role. Coordination of separate information processing and physical operations using orders, setups, and retooling.	Digitalization plays a key role. Object-interactive services in manufacturing cannot be used without digitalization. Digital counterparts are the foundation for object-interactive services for manufacturing and handling.
Control of manufacturing resources	Resources are controlled by procedures such as work orders. Procedures trigger tasks (e.g., setup, production) in the correct sequence for the resources to convert the material into components and components into products.	Physical resources interact digitally with physical products, making manufacturing a cyber-physical system. Resources and products are active objects that provide services to other objects upon request.
Relationship between product and process	Procedures tightly couple ("integrate") product and process. The need for tooling requires designs and operations to be frozen (standardized). Product generations ramp up and ramp down planning.	Services loosely couple ("interact with") product and process. Loose coupling between design and manufacturing allows for frequent changes in designs, operations, and plans.
Information systems	Information systems and the physical process are separate. The physical process can operate without the digital system after the process has been set up and the work order has been issued.	Information systems are part of the physical process (cyber-physical). Physical items have digital components (digital counterparts). Physical processes are part of the information system, and vice versa.

et al., 2020; Rüßmann et al., 2015) takes advanced technologies[2] as the starting point. While productivity and growth are identified as the ultimate purpose of investing in these advanced technologies, the key argument for Industry 4.0 is that valuable improvements can be achieved from novel combinations of technologies (Rüßmann et al., 2015). Many possible combinations lead to potential benefits such as decentralized and autonomous decision-making (e.g., autonomous robots); the leveraging of big data for real-time modeling of machines, products, and humans; simulation for testing alternative scenarios; and integration of not only companies, suppliers, and customers but also products, shop floor processes, and resources (Parente et al., 2020). However, the ways in which a manufacturer should invest and operate to achieve these benefits remain unclear.

Instead of directly identifying a purpose for digital technologies, operations management researchers can indirectly do this by addressing the obstacles and constraints of current manufacturing (e.g., Buer et al., 2021; Cifone et al., 2021). This is an approach based on identifying valuable solution–outcome pairs, originally proposed for facilitating digital innovation (Nambisan et al., 2017). Researchers seek to determine what the digitalization of manufacturing should accomplish, identify the problematic relationships and inefficiencies, and pinpoint the solutions necessary for achieving "... isolated, optimized cells coming together as a fully integrated, automated, and optimized production flow, leading to greater efficiencies and changing traditional production relationships among suppliers, producers, and customers—as well as between human and machine" (Rüßmann et al., 2015).

The digitalization of manufacturing has successfully addressed the following specific challenges of conventional manufacturing: prototyping, customization, on-demand spare parts, and on-demand kitting for assembly (Holmström et al., 2010; Khajavi et al., 2018; Tuck et al., 2008). Conventional manufacturing struggles to produce prototypes, customized parts, and spare parts because of the need for tooling (Holmström et al., 2017). Kitting parts for assembly is another major challenge for tool-based manufacturing, requiring extensive warehousing and handling (Lyly-Yrjänäinen et al., 2016). The mechanism of direct digital manufacturing that addresses the constraint of conventional manufacturing is the on-demand use of a digital design model to manufacture a physical component, eliminating the need for tooling and batching. The outcome is the ability to respond more quickly to demand without the need to constrain variety.

However, solutions are rarely one-size-fits-all. In their investigation of the introduction of on-demand digital spare parts manufacturing using additive manufacturing, Heinen and Hoberg (2019) found that, for most spare parts, conventional manufacturing is more efficient than digital manufacturing. For mass production, the use of direct digital manufacturing technologies is mostly infeasible due to higher costs compared with conventional

TABLE 2 Hybrid manufacturing typology and performance trade-offs (based on Peeters & van Ooijen, 2020)

Type of HM system	Description	Strategic management decisions	Tactical management decisions	Performance trade-off (performance frontier)
Sequential hybrid	Characterized by a series of production steps, starting as MTS and switching over to MTO at the CODP	CODP placement and inventory management strategy of MTS production	Order acceptance, release, and scheduling policies	Product change leads to inventory obsolescence in the MTS part of the system. The delivery lead time to the customer is constrained by perishable MTO capacity.
Parallel hybrid	Characterized by a production system or resource that is responsible for processing both MTO and MTS products	MTO versus MTS decision for products and dedicated production resources	Order acceptance, release, and prioritization at shared capacity	The production system must be capable of both MTO and MTS processing, thus increasing technical complexity.
Floating hybrid	Characterized by a series of production steps, where the CODP is variable, as orders are matched to work in progress (WIP)	Pipeline search and order matching strategy as well as capacity allocation	Order acceptance and release	The production, planning, and control system must be able to identify and control individual products in the process, thus increasing control complexity.

Abbreviations: CODP, customer order decoupling point; HM, hybrid manufacturing; MTO, make-to-order; MTS, make-to-stock; WIP, work in process.

manufacturing (Khajavi et al., 2015). Even when a novel and promising way of digitalizing manufacturing is identified, the required changes in manufacturing equipment may not be of interest to equipment manufacturers who focus on incremental improvement of conventional manufacturing rather than on novel ways of operating. This consequently forces digitalizing manufacturers to innovate and develop parts of the solution in-house (Lyly-Yrjänäinen et al., 2016). In this situation, an operations strategy for effectively spanning digitalized and conventional manufacturing would be useful.

2.3 | HM strategy

Divergent customer requirements concerning lead time and customization (Romsdal et al., 2014) allow few real-world production systems to follow a pure make-to-stock (MTS) or make-to-order (MTO) production strategy (Soman et al., 2004). A recent review by Peeters and van Ooijen (2020) revealed various ways in which real-life production systems combine MTS and MTO. In the literature, such combinations are presented as either HM (Peeters & van Ooijen, 2020) or assemble-to-order, positioned between MTO and MTS (Akinc & Meredith, 2015; Meredith & Akinc, 2007).

HM production systems seek to shift the performance frontier (Akinc & Meredith, 2015) by changing the trade-offs between push and pull production (O'Reilly et al., 2015). In practice, the shift is achieved either by repositioning the customer order decoupling point (CODP) to a different physical location in the production process or by differentiating the process (Kalantari et al., 2011; Lin & Naim, 2019; Perona et al., 2009). The combination of MTS and MTO can sometimes be achieved by identifying and designating the products manufactured in a common process as either MTO or MTS products (Beemsterboer et al., 2017; Chang et al., 2003; Soman et al., 2004, 2007; Zhang et al., 2013).

Peeters and van Ooijen (2020) distinguished between three types of HM systems with distinct production, planning, and control challenges (summarized in Table 2): sequential, parallel, and floating hybrid. These HM systems can be created using CODP, special or general-purpose resources, and scheduling for MTS or MTO. Each of these three types of HM systems has a different performance trade-off.

The variety of HM systems presented in empirical work (Peeters & van Ooijen, 2020) indicates that established production theory (Meredith & Akinc, 2007) offers only a partial theoretical conceptualization of HM systems. Its illustrative merits aside, the literature on generic production strategies—and, by extension, the CODP—typically equates job shop production to MTO. However, Peeters and van Ooijen (2020) found examples of all three types of HM systems in job shop research.

With increasing digitalization, manufacturing process control based on digital counterparts and object-interactive services also presents opportunities for strategic innovations for operations. Here, distinguishing procedural and object interaction as alternative ways of structuring operations creates a fourth class of HM—hybrid digital manufacturing—capable of combining object-interactive and procedurally controlled manufacturing, seeking to reap the benefits while avoiding the drawbacks. Even though hybrid digital manufacturing does not fit the description of sequential, parallel, or floating hybrid systems, similarities exist across several dimensions. In terms of production control, hybrid digital manufacturing, like the floating hybrid system, is product-centric; however, in contrast to the floating hybrid system, hybrid digital manufacturing achieves this through object-interactive services. In terms of order processing, hybrid digital manufacturing, like the parallel hybrid system, is capable of processing orders in parallel; however, in contrast to the parallel hybrid system, hybrid digital manufacturing achieves parallelization through an object-interactive service, namely direct digital kitting.

2.4 | Digitalizing component supply for assembly

Kitting is an established material-feeding practice in the assembly industries. It is defined as the supply of all the necessary components for a single assembly task in preconvened containers (Bozer & McGinnis, 1992). Direct digital kitting is an object-interactive service in manufacturing and an emerging topic in the literature (Khajavi et al., 2018; Lyly-Yrjänäinen et al., 2016). Conventionally, components for kitting come from inventory, a process that has been studied extensively (Bozer & McGinnis, 1992; Brynzer & Johansson, 1995; Hanson & Medbo, 2012). However, the process of collecting the components for a kit from warehoused batches of components is mostly manual. This warehouse kitting is both inefficient and prone to error, motivating recent proposals for automating the process (Caputo et al., 2015, 2021; Caputo & Pelagagge, 2011).

In assembly, kits can be used in stationary and non-stationary modes on assembly lines as well as in assembly cells. Feeding components as kits is a substitute for line-stocking, where components are stored in batches along the assembly line (Hanson & Medbo, 2012). The benefits of kitting in the assembly have been studied extensively in various industrial settings (Caputo & Pelagagge, 2011; Engström et al., 1998; Hanson & Brolin, 2013; Hua & Johnson, 2010; Johansson & Johansson, 1990). Conversely, some researchers have found that kit preparation can be a drawback (Fansuri et al., 2017; Hanson & Brolin, 2013; Hanson & Medbo, 2012; Vujosevic et al., 2012). Nevertheless, these studies are limited to warehouse kitting, leaving the potential impact of direct digital kitting unexplored.

Procedural-based attempts to improve the effectiveness of warehouse kitting processes seek economies of scale by batching the kitting of similar orders. Automating the preparation of kits is often physically constrained by the order-picking equipment. Warehouse kitting automation has been introduced for small parts (Caputo et al., 2021; Johansson & Johansson, 1990). Order batching is required for these solutions, which limits efficiency improvement to settings with repetitive final assembly schedules. Recent studies on warehouse kitting have explored the use of semi-automated systems to improve kitting efficiency and reduce the errors caused by humans as they sort and fetch parts (Boudella et al., 2018; Hu et al., 2020; Kootbally et al., 2018).

Fully automated robotic systems for warehouse kitting have long been present in the literature (Sellers & Nof, 1989; Tamaki & Nof, 1991) but have long remained in the experimental stage in practice (Berg, 2019). A reason for the slow progress in practice is the high capital investment and complexity of robotic systems for inventory-based parts kitting (Caputo et al., 2021). Currently, there begin to be some real-world implementations, but the literature still lacks studies of such leading-edge practice. The recent significant studies that address inventory-based and semi-automated kitting processes focus on the modeling and optimization of a robot-operator system (Boudella et al., 2018; Maderna et al., 2020); planning of an inventory-based kitting and component supply (Hu et al., 2020); identification and recovery from robot task failure in a kitting process and dynamic replanning of tasks (Kootbally et al., 2018); cost analysis (Caputo et al., 2018, 2021); and experimentation with new technologies, including computer vision and digital twinning (Agrawal et al., 2021; Comand et al., 2019; Ramírez et al., 2018).

Direct digital kitting is an object-interactive method for kitting that relies on manufacturing rather than on inventory to assemble the kits. It combines direct digital manufacturing technology and digital counterparts to specify the placement of a component in the kit (Khajavi et al., 2018; Lyly-Yrjänäinen et al., 2016). This method of kitting is enabled by the direct manufacturing and digital design of manufacturing kits, eliminating the error-prone manual process of parts fetching. The supply chain-related benefits of direct digital kitting are simplified operations planning and reduced inventory (Khajavi et al., 2018). In the object-interactive manufacturing syntax, direct digital kitting resolves the challenge of converting the output of parallel and interactive component manufacturing services to input for procedurally scheduled and controlled assembly operations, enabling hybrid digital manufacturing from a material flow perspective.

3 | METHODOLOGY

This study, which is a collaboration between practitioners and academic researchers, seeks new practical and theoretical knowledge, exemplifying engaged scholarship in operations management (van de Ven & Johnson, 2006). A group of academic researchers with diverse backgrounds works with the designers of the Väderstad manufacturing solution and its information system. One of the designers is a co-owner of the company, and the other is the automation system designer from Binar Solutions, a company specializing in digitalizing manufacturing and material handling. The two designers jointly developed and introduced the solution for manufacturing components on-demand and by counterpart using laser cutting. They were invited to be co-authors of this paper during the course of the study, reflecting their central role not only in designing effective solutions but also in recognizing the mechanisms for seizing improvement opportunities through digitalization. The group of academics includes three researchers who have worked extensively with conventional kitting and assembly solutions, two researchers with a background in direct digital manufacturing, and one researcher specializing in design science research. The researchers' role in the collaboration is to develop a theory that explains how the solution design achieves the observed benefits from the digitalization of manufacturing and the introduction of Industry 4.0 technologies.

3.1 | Case company

Väderstad makes custom-order agricultural equipment, such as sowing machines, for a global market. The company is a leader in product innovation and, at the time of this writing, holds the world record for sowing 502 hectares (1240 acres) of maize in 24 h. Customers are large-scale grain farmers around the globe, who rely on Väderstad's high-performance agricultural machines for productivity and responsiveness to changing weather conditions. However, as conditions and requirements vary widely, the machines are configured to the customer's order. Different variants are needed for different soils, field sizes, and crop types. The customized machines are produced to order and shipped with a lead time of 3 weeks. From 2007 to 2021, the period for the solution design and digitalization of manufacturing, the turnover of the company has grown from SEK 1400 million to SEK 4200 million, a sustained growth rate of 9% per year.

The nature of customer demand, the scope of customization options, and frequent product changes and innovations have prompted Väderstad to develop unconventional manufacturing solutions over the past decades. The welding and assembly processes are partly fed with batches of components in a traditional manner but are increasingly fed with component kits, where each kit is specified for a particular product configuration. This approach to material supply has led Väderstad to incrementally substitute conventional batch manufacturing of components and warehouse kitting with direct digital manufacturing of kits based on solutions developed in-house.

Väderstad began developing its highly automated solution for direct digital kitting with tube components (made from pipes and rods) in the 2000s. The technological enabler for the solution is laser cutters, a digitally controlled and widely used manufacturing technology—almost general purpose (Bresnahan & Trajtenberg, 1995)—for cutting metal. Initially, tube components were mostly cut in-house, using bandsaws. However, due to the advantages of laser cutting, the components were increasingly being purchased from suppliers. The new workshop for the direct digital kitting of tube components was ready in 2009, resulting in a dramatic reduction in required warehousing and material handling of components (initially for 300 part numbers and currently for 1300 part numbers of tube components). The development resulted in a patented process innovation (Stark, 2018) for material handling of individually manufactured components and direct digital kitting.

In 2018, the technology for laser cutting of sheet metal had improved enough for Väderstad to take the next step, seeking to transfer the sheet metal components for 3000 part numbers needed in welding assembly to one-piece (make-by-counterpart) manufacturing and direct digital kitting. Previously, these components were sourced from suppliers using laser cutting technology in conventional batch manufacturing. The new workshop was completed in June 2021, with the digitalization of sheet metal components ongoing in October 2022.[3]

3.2 | Case selection and data collection

The research was initiated by two senior academics as a spin-off of an earlier research collaboration on direct

TABLE 3 Data collection

Type	Date	Focus (*academics/practitioners participated*)
Plant visits, Väderstad	06-09-2016	Study of the tube workshop; during the visit, we were informed about the plans for the new sheet metal workshop (*2/1*)
	01-11-2017	Further study of the tube workshop (*2/1*)
	09-05-2018	Further study of the tube workshop (*4/1*)
	01-16-2019	Visit to the new sheet metal workshop, then under construction (*1/1*)
	11-06-2019	Visit to the new sheet metal workshop, still under construction; explanations of the concepts, processes, equipment, and control (*4/1*)
	11-30-2021	Visit to the sheet metal workshop in operation/ramp-up (*5/1*)
Phone calls, Väderstad	04-11-2017 to 10-21-2022	Fourteen phone calls, at relatively regular intervals, mainly for status updates regarding the development of the sheet metal workshop (*1/1*)
Video meetings, Väderstad	11-12-2020	Investment logic, current issues with original equipment manufacturing, an opportunity for on-demand parts sales to outsiders (*1/1*)
	11-13-2020	Review of current status, an opportunity for parts sales to outsiders (*1/1*)
	03-02-2021	Data verification and update (*2/1*)
	12-21-2021	Discussion of impact evaluation (*4/1*)
	05-26-2022	Explanations of the control of the materials and processes in the sheet metal workshop (*2/1*)
Video meetings, Binar	01-22-2021	Data verification and status update regarding the sheet metal workshop (*2/1*)
	01-28-2022	Issues and approaches related to production equipment providers supporting only procedural control (*2/1*)
	05-31-2022	Clarifying where procedural control is replaced and where it remains in the hybrid setup (*2/1*)

digital kitting (Lyly-Yrjänäinen et al., 2016). One of the senior academics recognized that the innovative direct digital kitting solution they had been investigating shared many characteristics with another example a colleague had been discussing: Väderstad's manufacturing of tube components. The research commenced with the academic researchers visiting the Väderstad factory to view the direct digital kitting solution in operation. During this initial visit, the designer of the digitalized tube component manufacturing at Väderstad shared his plans for a new, ambitious expansion of direct digital kitting to also include sheet metal components. The solution designer expected that the expanded use of direct digital kitting would radically reduce the need for warehousing and external component supply.

The longitudinal data collection consisted of field observations; face-to-face interviews; Zoom meetings; and documentation such as investment plans, patents, and patent application materials. The engaged scholarship covers the sheet metal workshop design from early planning (in 2016), through construction (started in 2018) and commissioning (in 2021), to continued ramp-up and operation at the time of writing (in 2022). Table 3 details the data collection and the main phases of the implementation project. The initial contact between the authors and Väderstad was for curiosity rather than for purposeful research and dedicated data collection. Later, in June 2018, we decided to conduct an engaged scholarship study and write an academic paper. From then onward, data collection occurred in a more systematic and structured manner than before. Field observations at the Väderstad factory were complemented by video meetings and phone calls. We held video meetings with the system designers to verify observations, discuss mechanisms, and confirm conclusions. We also recorded field observations and video meetings, and we took notes. Furthermore, publicly available documentation of the case includes one patent (Stark, 2018) and two pending patent applications (Lindberg & Stark, 2018; Stark & Lindberg, 2020).

3.3 | Theorizing through design

The research collaboration focuses on the design, theorizing of the design, and implementation of Väderstad's digitalized component manufacturing. Seeking to understand what the design consists of and how it works we adopted a design science approach (Holmström et al., 2009). Participating researchers and practitioners contributed methodologically, albeit in different ways (vom Brocke et al., 2021). Through the collaboration, the participating researchers have discovered the ways in which the design and its implementations are novel and how this understanding contributes to operations management theory. Additionally, the solution designers have developed a deeper understanding of what they are doing and the opportunities that their design provides for manufacturing operations, and by extension, the supply chain.

Theorization of the Väderstad solution was a joint effort of the solution designers and researchers. Iteratively, over the course of several meetings, researchers presented their findings and conclusions to solution designers in a dialogue that aimed for a shared understanding of the solution's mechanisms and outcomes. Additionally, the Väderstad designer participated in a master-level course on innovation in operations, presenting the solution and challenging students to contemplate further opportunities to develop and benefit from the digitalization of the component supply.

4 | HYBRID DIGITAL MANUFACTURING AT VÄDERSTAD

In this section, we describe how the digitalization of component manufacturing has proceeded at Väderstad following a hybrid digital manufacturing strategy. First, we present the digitalization of component manufacturing and the scope of object-interactive syntax in the operations. Next, we compare the effects of digitalizing the tube components against the viable alternative, followed by a similar comparison with the sheet metal components where the introduction of object-interactive syntax is ongoing and still in ramp-up. Finally, we describe what the design principles for object-interactive component manufacturing are, how they explain the observed effects, and how object-interactive syntax is combined with procedural syntax to implement hybrid digital manufacturing at Väderstad.

4.1 | Digitalization of component manufacturing and scope of object-interactive syntax

The end product is configurable but standard. Figure 1 presents the breakdown of required components for an example product. The example illustrates how Väderstad has introduced digital manufacturing and object-interactive manufacturing for tube and sheet metal components. For the example product, the digitalization of tube components includes 15% of the total number of components and 16% of part numbers. The digitalization of sheet metal components, when completed, will include 30% of the total number of components and 41% of part numbers.

The overall material flow through the supply chain and manufacturing plant after the digitalization of tube and sheet metal components is presented in Figure 2. The figure highlights the hybrid structure of the manufacturing system, combining object-interactive services (marked with gray shading) for some types of

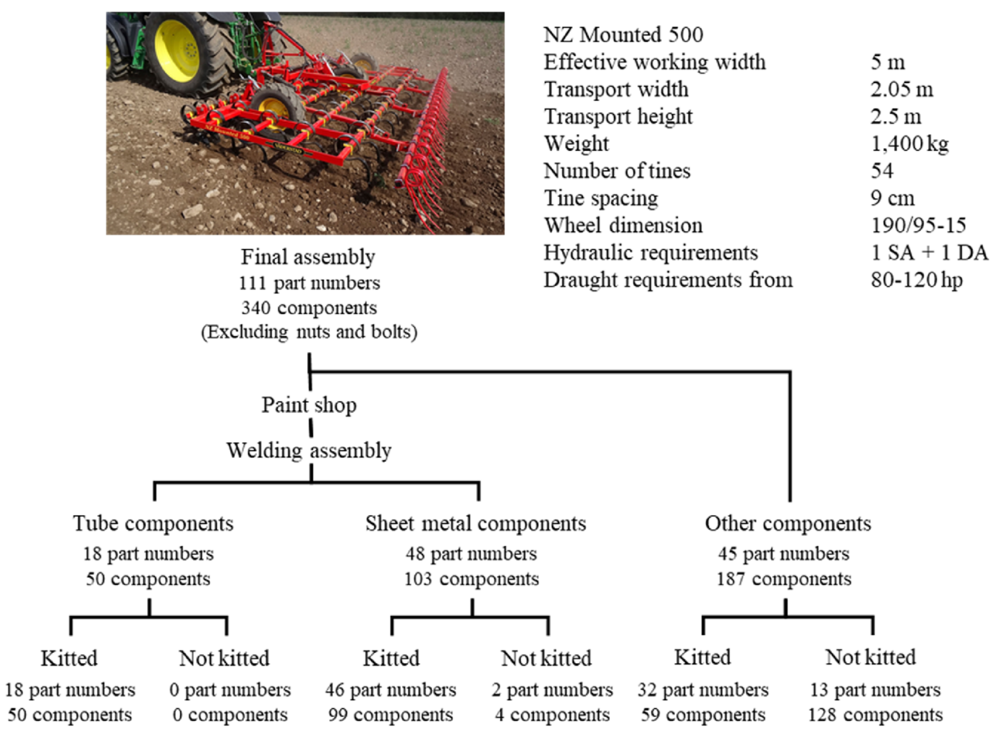

FIGURE 1 Make-to-order manufacturing at Väderstad—Kitting and batching of different types of components for an example product

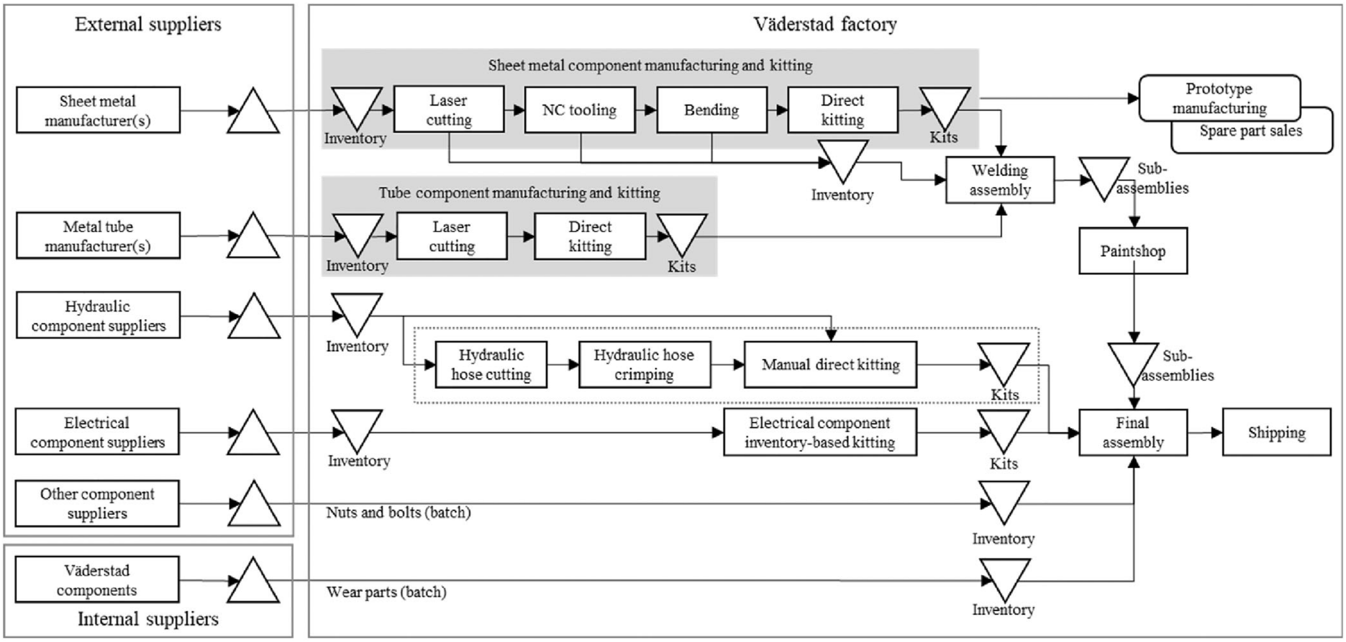

FIGURE 2 The material flow of Väderstad's hybrid digital manufacturing. The extent of digitalization using digital object-interactive services within the conventional and procedural controlled manufacturing is indicated by the gray shading. The extent of the manual object interaction in the direct manufacturing of hydraulic hose assembly kits is indicated by a dotted line

component manufacturing with the procedural control of assembly and sourcing of the rest of the needed components. The manufacturing and kitting of the tube and sheet metal components are object-interactive parts of an otherwise conventionally organized MTO manufacturing and MTS supply chain. For both tube and sheet metal components, 60% of the component volume is kitted for welding assembly, while 40% is supplied as batches. Welding assembly is conventional and tool-based using jigs and fixtures. Final assembly and component purchasing are also conventional and procedural.

The combination of procedural and object-interactive syntax is presented in more detail in Section 4.4. Next, we examine the effects of the digitalization of component manufacturing, as well as the design principles of the solution.

4.2 | Effects of object-interactive digitalization

At Väderstad, the digitalization of tube component manufacturing and that of sheet metal component manufacturing are two distinct events, separated by 10 years. The intended scope of direct manufacturing and automated handling is for a total of 4300 part numbers. Based on the first phase, all 1300 tube part numbers are currently digitalized along with a comprehensive digitalization of the production resources needed to process and handle the tube components. When fully realized, the scope of the second phase will include the digitalization of an additional 3000 part numbers. We describe the effects of the digitalization for tube components first, and the full effects of the ongoing digitalization of sheet metal components thereafter. An overview of the effects is included in Appendix B, where we compare the impact of Väderstad introducing object-interactive manufacturing and the handling of digitalized components with the alternative of supplying components using conventional manufacturing and handling procedures.

4.2.1 | Digitalization of tube component manufacturing

Before object-interactive manufacturing and direct digital kitting were developed and implemented, kitting was inventory-based at Väderstad. Both purchased and in-house manufactured components that were to be kitted were reliant on batch manufacturing and warehousing before kit preparation. In warehouse kitting, all part numbers required for each kit underwent a process in which a pallet of each part number was fetched, one at a time, using a forklift; the required components were selected, and the pallets were returned to storage using the forklift. Warehouse kitting required a considerable amount of inventory, both in terms of space and capital, along with a sizable warehouse workforce. The current investment required for the procedural alternative, with in-house batch-based laser cutting and conventional inventory-based kitting, is estimated to be SEK 83–100 million.

As a result of the introduction of direct digital kitting, all manufacturing of tube components has moved in-house, and tube component suppliers are no longer needed. Furthermore, the component inventory is no longer needed, and the workforce tied to warehouse kitting and supply logistics (purchasing, receipt of goods, etc.) can be assigned to other tasks. The overall impact on lead times as well as logistics and purchasing costs is considerable. For tube components, digitalization and object-interactive manufacturing and handling reduce the need for warehouse and production facilities to one-third, from 7500 to 2500 m^2. The required personnel are reduced to one-sixth, from 37 people to 6. The inventory is reduced to 1300 tons of raw material and 40 tons of ready (kitted) components, compared with 1300 tons of raw materials, 850 tons of batched components in inventory, and 40 tons in kits. The throughput time from raw material to welding assembly is 24–48 h for digitalized tube components, compared to 4 weeks, on average, for the alternative with a yearly inventory turnover of 12. The cost in terms of scrapped inventory from urgent engineering changes is estimated to be a factor of 10 times higher for the conventional alternative.

4.2.2 | Digitalization of sheet metal component manufacturing

In contrast to tube components, where we compared object-interactive manufacturing and direct digital kitting to the alternative of in-house batch manufacturing, the conventional alternative for providing welding assembly with sheet metal components relies on suppliers for component manufacturing. In the alternative, all sheet metal components would be sourced from suppliers in batches and warehoused. Once needed, they would then be kitted using a similar warehouse kitting process as described in the tube component alternative in Section 4.2.1. In a similar vein, this would require a considerable amount of inventory and space, along with a sizable workforce tied to kitting and logistics. However, with manufacturing at component suppliers, the investments in machinery and equipment for Väderstad would be smaller, an estimated SEK 4.5 million.

Compared with the conventional alternative, the object-interactive manufacturing and handling of sheet metal components at Väderstad require approximately half the facilities (2200 m^2 compared with 4000 m^2). The effect on personnel is a reduction to less than one-third (from 25 people to 7). The most significant effect is on the value of component inventory, which is reduced from SEK 27.4 million for purchased components in inventory to SEK 4.4 million for raw materials and components in the digitalized component manufacturing. The throughput time from raw material to welding assembly is currently 24–72 h for digitalized sheet metal components. Väderstad's investment in machinery and equipment, however, is considerably higher—SEK 160 million compared with SEK 4.5 million for the alternative.

To complete the digitalization of sheet metal components, an extensive effort is ongoing to include part numbers that require bending. Modifying the press brake to provide bending as an object-interactive service is a challenge, requiring in-house technology development. This obstacle to digitalization is delaying the realization of part number-driven benefits of digitalization, allowing us to compare the performance effects of partial and comprehensive object interaction (see Figure S2 in the Supporting Information for the comparison).

4.3 | The object-interactive solution and its design principles

Next, we examine the Väderstad solution design and its design principles. The Supporting Information details the solution and its implementation. Here, the focus is on how object interaction can be introduced to manufacturing operations, made possible by digital counterparts and direct digital manufacturing technologies. The core of the Väderstad solution design is the object-interactive services for component manufacturing and kitting. Through the object-interactive services, the materials, components, and machines interact in a cyber-physical process to create the kits and batches ordered for welding assembly, prototypes, and spare parts. The main solution elements are master data, such as product, material, part number, and kit; cyber-physical objects consisting of a physical part and digital counterpart (instances of the tube and sheet metal materials, components, and kits); manufacturing machines (laser cutters, bending, multi-operations); material handling equipment (handling robots, carriers, and automated material storage); and object-interactive services, such as nesting, manufacture, kitting, handling, and material requests.

The kits are defined as master data based on the product design. Over 500 different kits are currently defined for producing all end-product variants. Production engineering defines the configuration of the kits, selects the type of kit container,[4] and defines the placement of the components in the containers. Production engineering also specifies the grip location in the master data for a

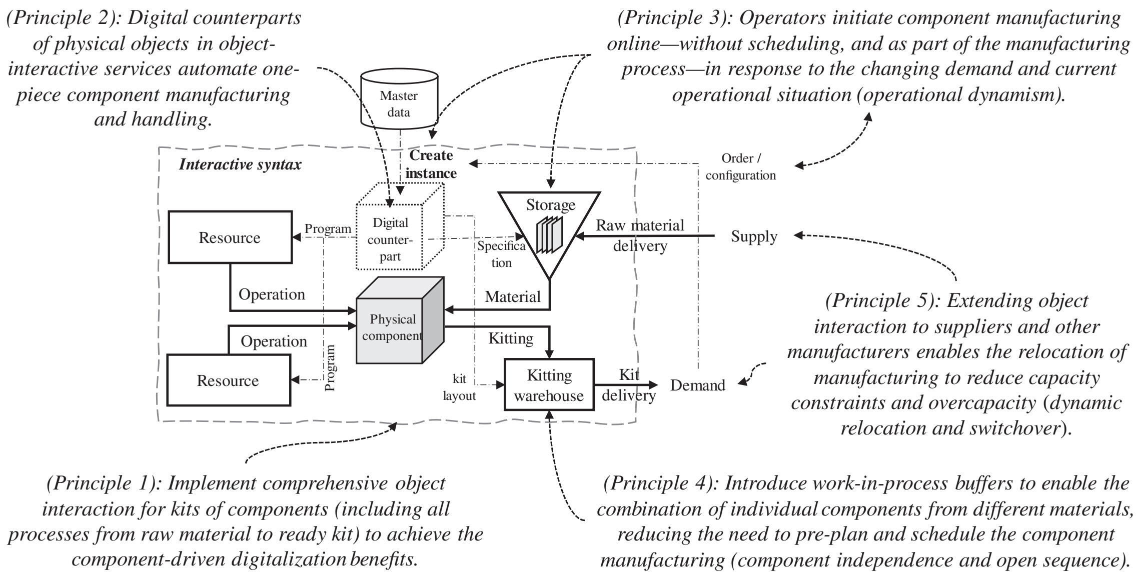

FIGURE 3 The object-interactive solution and its design principles

part number, so that robots can handle the individual components. Both the container choice and the grip specification make use of the 3D model of the component. The kits are currently specified manually; however, building on solutions to automatically specify assembly sequences, the specification could be automatic or semi-automatic in the future (Bahubalendruni & Biswal, 2018).

The digital counterparts, which are digital objects representing individual physical objects—such as material items, components, and kits—interact with manufacturing equipment, carriers, robots, and operators to produce manufacturing and logistics services. These services consist of direct digital manufacturing and kitting; planning and control, such as nesting; and tracking. The digital counterparts as well as the services are generated in the interaction between operators and the manufacturing system. Planning and control in the object-interactive solution are operational parts of manufacturing and logistics processes, not separate informational or managerial processes. Figure 3 provides an overview of the object-interactive manufacturing solution and its design principles. The Supporting Information describes the design in detail.

The core principle (Principle 1) in the Väderstad solution—the basis for the hybrid digital manufacturing operations strategy—is to aim for comprehensive object interaction, where all operations and handling from raw material to the ready kit are object-interactive services for digitalized components. As the effects achieved by Väderstad indicate, in addition to automation benefits of reduced labor, comprehensive object interaction also delivers substantial benefits of lower inventory and reduced obsolescence risk. Digitalizing all the components of a kit is the key to quickly reaching the automation benefits of direct digital kitting. Many components that are difficult to digitalize—such as part numbers requiring bending—are still procedurally purchased from suppliers and kitted through the warehouse, delaying the benefits of inventory and obsolescence reduction.

The effect of comprehensive object interaction builds on further design principles that can be identified in the Väderstad solution. Batching, warehousing batches, and inventory-based kitting become unnecessary intermediate stages in direct digital manufacturing and kitting. The information needed for a component's individual handling and manufacture is provided by the digital counterpart (Principle 2). The manufacturing need not be pre-planned and scheduled to be efficient, but it can be planned interactively and online (Principle 3), enabled by the use of work-in-process buffers to preserve the openness of the manufacturing sequence (Principle 4).

Component independence and open sequence (Principle 4) constitute a key mechanism. In the Väderstad solution, neither kit components nor batch components are constrained in terms of the time and sequence in which they are produced. These constraints are avoided through the object-interactive service for building up the assembly kit over time. When each physical component can be produced independently of the others in a kit or batch, the need for procedural planning and scheduling is reduced. This enables the shift to on-demand nesting and operator decision-making on the shop floor (Principle 3) and the move from procedural to interactive processes (Wegner, 1997). The independence between components is particularly valuable in Väderstad's sheet metal workshop. Manufacturing individual components opportunistically at different times allows for the nesting of components from different kits as well as from batch orders to reduce scrap and waste. From the perspective of a component, this combination of independence and dynamism means that neither production control nor material handling is predetermined. When a component is needed to complete a kit due in assembly, then control logic is pull-based; when a component is produced to complete a nesting and improve material efficiency, then control logic is push-based. Likewise, components with the same part number can be both kitted and batched.

When suppliers with digitalized manufacturing can be found, the object-interactive services can be extended in the supply chain, sourcing kits externally in the same way as they are manufactured and kitted internally, thus enabling the original manufacturer to redistribute manufacturing to address both capacity constraints and overcapacity (Principle 5). The extension of the object-interactive syntax beyond the boundaries of the firm opens many beneficial opportunities for both digitalizing manufacturers and their suppliers. We detail these opportunities in the discussion.

4.4 | Combining object-interactive and procedural syntax

Hybrid digital manufacturing as an operations strategy seeks to combine object-interactive services with conventional procedural control. In the previous sections, we described the benefits and principles of the object-interactive manufacturing syntax. Next, we elaborate on how Väderstad combines procedural control and object interaction in its manufacturing system. We approach the combination from three complementary perspectives: the production process, production control, and material flow.

Regarding the production process (see Figure 2), object-interactive services are only used in component manufacturing (pre-assembly). As neither welding assembly nor final assembly is digitalized, extending object-interactive services into assembly is currently infeasible. Moreover, for assembly, the space required for the handling of work-in-progress assemblies would increase if the planned sequence of orders in the procedural syntax were to be abandoned, reducing the practical feasibility of an object-interactive and parallel assembly process.

From a production control perspective, welding assembly and final assembly are procedurally controlled through the production schedule, which is based on the order book. Material and component suppliers are also controlled using a procedural syntax. The schedule consists of customer orders, sequenced based on the due date, lead time, availability of materials, and capacity. In addition to welding assembly and final assembly, the schedule also controls purchasing of some components, in sequence, using a just-in-time procedure. Most material purchases and most components are controlled using reorder point (and safety stock) procedures.[5] Control based on procedural syntax thus spans over the entire production process as well as suppliers.

As Väderstad only produces to customer orders, the production system could be characterized as pull-based, striving for just-in-time in procedurally controlled material flows. Before welding assembly, however, procedurally controlled purchasing co-exists with the object-interactive services in the sheet metal and tube workshops. The two syntaxes interact through the production schedule: The schedule provides the sequence in which orders are processed in the procedural syntax; in the object-interactive syntax, the schedule provides the orders for the production window, from which the sheet metal and tube workshops select components. The production horizon (referred to as the kitting window in the tube and sheet metal workshops) and the choice of raw material (sheet thickness or tube diameter) are the two key production control decisions the operator makes, as described in the previous section (Principle 3). Once a component has been selected for manufacturing (i.e., nested), its digital counterpart is created and granted control of its own production, which it exerts by requesting object-interactive services (Principle 2).

Through the two production decisions—the kitting window and material selection—the operator aims to have components ready for assembly as they are needed while avoiding scrap. In this object-interactive control decision, it is ambiguous whether the control is push- or pull-based. It can be considered pull-based when a material is selected to complete a kit that is needed soon. However, in the same nesting decision, the operator may extend the window to reduce scrap, establishing new kits through what can be considered push control. Further complicating a clear distinction between push and pull, some components in a nesting are MTS (batch), while others are made-to-order (kitted). Väderstad distinguishes between mandatory parts and fillers: The former term refers to components nested in response to an imminent need, and the latter refers to components that are nested to reduce scrap. Keeping the sequence open—nesting only for the next material, in contrast to optimizing a nesting schedule for all materials—allows the component manufacturing to respond to disruptions and rescheduling in assembly, to accommodate express orders (e.g., spare parts), and to use components from recently added or rescheduled orders as fillers for scrap reduction.

From a material flow perspective, the sheet metal and tube workshops start with few-to-many transformations, as the tube and sheet raw materials enter the workshops. Both workshops have internal storage of raw materials that are replenished from a raw material inventory. The interface to welding assembly is a many-to-one transformation, where kits of the tube and sheet metal components come together in welding assembly. The latter interface is interesting from a manufacturing syntax perspective. The automated kitting warehouse in the digitalized workshops acts as the interface, translating the complex material flow created by object interaction, over time, into the order-based material flow required by procedural control. Batch production in the workshops, by following the same object-interactive logic as that of kit production, replenishes buffers in welding assembly and hence connects to the procedurally controlled system through a (decoupling) inventory interface.

5 | DISCUSSION

In this study, we have used a leading-edge example for revisiting OM theory, in a similar manner to Öhman et al. (2021). In contrast to Öhman et al. (2021), the novel solution has been implemented in practice, enabling theory development based on engaged scholarship. Our main contribution is conceptualizing the novel hybrid digital manufacturing strategy for realizing the vision of Industry 4.0. Further, we contrast our findings to the literature on PPC for digitalized manufacturing, direct digital kitting, and the role of design change in facilitating the effective use of direct digital manufacturing.

When compared with manufacturing system examples in prior HM research (Peeters & van Ooijen, 2020), Väderstad's system is structurally an HM system in how it combines batch (MTS) and single-piece processing (MTO). However, the MTS/MTO distinction is not meaningful, as components for both inventory replenishment and customer orders are manufactured simultaneously, in the same process, with the same production resources, and even in the same nesting for laser cutting. Additionally, the order decoupling point is no longer foundational for an operations strategy, as it becomes an operational decision given that any individual component may be kitted or not. As a result, the object-interactive manufacturing and material handling at Väderstad challenge the fundaments of contemporary production strategies and HM research—not in the sense that they would make prior research irrelevant but rather in the sense that, in the context of Väderstad, digitalization (Industry 4.0) is finally living up to its transformational promise, presenting a manufacturing system in which established operations management theories must be revisited and reformulated.

The digitalization of manufacturing at Väderstad combines MTO and MTS through the use of digital object-interactive services. For the digitalization of manufacturing, we consequently highlight a new object-interactive syntax as a fundamental distinction from conventional manufacturing. The new HM challenge is to bridge the procedural control of conventional manufacturing and the object-interactive services of digitalized manufacturing. Procedural control works under the premise that the production process (or its steps) is configured to produce a given product and that switching from one product to another requires a reconfiguration (setup) of the process, underscoring the benefits of batch production. Additionally, physical material handling under procedural control is simple, as materials are predominantly moved and stored in batches. In comprehensively digitalized manufacturing, the digital counterpart of the physical component to be produced, initiated by a customer or replenishment order, requests manufacturing and handling operations from the manufacturing system. As a result, the physical component comes into existence through what we call object-interactive services. In this way, the digitalized manufacturing system can handle variability, complexity, and change far beyond the capability of procedurally controlled systems, with implications for the inherently procedural concept of manufacturing flexibility. This way, object-interactive syntax rewrites some old manufacturing trade-offs and opens new and interesting strategic options in manufacturing. By studying how Väderstad combines procedural- and object-interactive syntax, in what we call the hybrid digital manufacturing strategy, we have operationally observed what to date has only been possible to investigate conceptually, through simulations, or small-scale laboratory experiments.

In common with several sub-streams in the literature on the digitalization of PPC, hybrid digital manufacturing at Väderstad is based on real-time integration of manufacturing execution system and master production scheduling, as well as distributed and collaborative decision making (Bueno et al., 2020). In addition to describing an architectural solution for combining object-interactive and procedural PPC, we observed that component and kit digitalization both cumulate benefits, but in different ways, with the former improving productivity and the latter reducing warehousing. Framed as the hybrid digital manufacturing strategy, our research thus sheds light on important open questions on how to move toward smart PPC for digitalized production systems (Bueno et al., 2020).

Also, we note that the object-interactive syntax and the holonic control architecture have much in common, as both represent flexible and reactive control solutions based on the cooperation of autonomous and connected entities in the decision-making process (Derigent et al., 2021). In Väderstad, object interactions are between the digital counterpart of a physical part and the production resource that processes or handles the part. In contrast to the basic holonic architecture, the Väderstad object-interactive solution does not include the order as an object, as the hybrid digital manufacturing strategy separates object-interactive syntax from the order-controlled procedural syntax, thus simplifying the object-interactive syntax to only production resources and products.

In the tube- and sheet-metal workshops of Väderstad, the orders influence production in two ways. First, through the kitting window (i.e., how far into the order book's future the system is allowed to look when nesting), which determines the tradeoff between raw material utilization and lead time. Second, through the use of fillers (i.e., parts that are not destined for a kit), which determines the tradeoff between raw material utilization and inventory. Both stand in contrast to the typical manufacturing tradeoff between capacity utilization and lead time (Akinc & Meredith, 2015; Meredith & Akinc, 2007). This is however not to say that capacity utilization would not be important. On the contrary, and related to our above discussion on PPC for digitalized production systems (Bueno et al., 2020), we found that Väderstad has prioritized high-volume kits when introducing components into the object-interactive manufacturing system, explicitly with the objective of increasing capacity utilization and productivity.

Further, in accordance with recent service-oriented research on direct digital manufacturing (Hedenstierna et al., 2019; Jiang et al., 2022) we also find that object-oriented control is foundational for manufacturing as a service. As object-interaction simplifies planning and control of in-house component manufacturing at Väderstad, we acknowledge that this not only reduces reliance on component suppliers but also lowers the transaction costs of offering digital manufacturing as a service to external customers. Taken one step further, aside from enabling the provision and use of manufacturing capacity services, the short lead time would also allow advanced service value propositions, such as safety stock as an object-interactive manufacturing service. This trajectory contrasts with Jiang et al. (2022) who see object orientation initially introduced to effectively use external manufacturing resources and for advanced scheduling of cloud manufacturing services.

As for addressing the persistent challenges in the procedural manufacturing syntax, engineering change orders in the Väderstad solution are made through the digital counterparts, without any modification to the production process and without a need to reprogram individual production resources. In effect, this means that once a change is made to the digital product design, the next component made in the production system will be completed according to the new design. This also means that product prototypes can be made in the production process alongside normal production. This could have profound implications for new product development, where established concepts such as product generations and (annual) development cycles are, at least to some extent, expressions of manufacturing based on procedural syntax. The ability of Väderstad to easily introduce design changes and produce prototypes is a step toward generative design (Bendoly et al., 2021), which also enables opening the operation to external and ad hoc customers, participating in cloud manufacturing as a service provider.

Finally, the digital twin (e.g., Cimino et al., 2019) is a concept that has received significant attention in the literature. We found that the Väderstad solution has little in common with the ideas and examples in the digital twin literature. Instead of developing a virtual copy of the system that would interact with the physical counterparts in a bi-directional way, Väderstad has opted for more pragmatic approaches for monitoring, maintenance, management, optimization, and safety. For example, the object-interactive workshops have video recording systems, which are used to analyze and solve problems that emerge in unmanned production systems. This invites the question of whether the digital twin is necessary when learning from failure is an option.

5.1 | Further research

At Väderstad, we have observed the internal effects of introducing object interaction. Further research is needed on the theoretical implications of object-interactive syntax in operations and supply chain management. On a supply chain level, object-interactive manufacturing services have potential strategic implications for production, as the make-or-buy decision could be a daily operational choice (dynamic reconfiguration, Principle 5) rather than a strategic one. At this point, the novel concept of manufacturing syntax would benefit from conceptual research and modeling of strategic operations and supply chain implications. Possible questions include the following: How does object-interactive syntax affect supply chain structure and resilience? How does object-interactive syntax work in an inter-organizational setting with possible constraints in information sharing? Does object-interactive syntax require new forms of collaboration and agreements? Answering these questions could provide valuable input into research on how manufacturing ecosystems emerge (Helo et al., 2021). Moreover, the downstream potential of object-interactive syntax in business-to-consumer contexts would be interesting, given that enabling technological solutions are emerging for object-interactive syntax in retailing (Gustafsson et al., 2019).

The role of generative design, which has been identified as facilitating the expansive use of direct digital manufacturing Bendoly et al. (2021), would be interesting to explore further. Encapsulation of design and manufacturing knowledge in digital counterparts is presented in the literature as the basis for the collaborative provision and use of manufacturing as an object-interactive service (e.g., Hedenstierna et al., 2019), as well as for opportunistic sourcing of individual components from service providers (e.g., Akmal et al., 2022). This is in stark contrast to the findings of Friedrich et al. (2022), that manufacturers are reluctant to share designs of additively manufactured parts due to IPR concerns.[6] The contradiction indicates the need for explorative research to better understand the applicability and fit of object-interactive syntax in different manufacturing environments and for different purposes.

From the perspective of HM, our study defines a fourth type of HM system that complements sequential, parallel, and floating hybrids—hybrid digital manufacturing. We have argued that direct digital kitting is a key feature of this type of system, as it allows for not only parallel processing of several orders over time but also, at the same time, procedural syntax based on kitting from inventory. Whether kitting is a required design feature of a hybrid digital manufacturing system or whether there are alternative methods of combining procedural and object-interactive syntax remains a topic for further research.

Väderstad currently has a cost advantage regarding the in-house laser cutting of tube and sheet metal components, compared with sourcing from suppliers. However, for other types of components, and with component suppliers developing their capabilities, sourced components could be less expensive. Further research should explore methods for a cost–benefit analysis of introducing object-interactive services to identify the context-specific break-even point where the higher cost is offset by the faster response, lower inventory, and reduced engineering change costs. We note that such methods have been developed for digital spare parts (Chaudhuri et al., 2021; Heinen & Hoberg, 2019), providing a starting point for an extension to other types of component manufacturing, such as assembly kits, and higher-volume manufacturing.

Additionally, building on the internal focus of this paper, a topic for further research would be the extension of object-interactive services toward welding assembly and final assembly (Sierla et al., 2018). At Väderstad, the product is a configuration of standard components, with procedural syntax remaining an alternative. With the company currently developing automated handling and configuration of welding jigs, welding assembly will become more object-interactive but will not yet allow for the direct digital assembly of prototypes or other original equipment manufacturers' products as a service. Taking object interaction one step further in welding assembly could, for example, be done by developing object-interactive services for jigless welding, with robots holding components (Bejlegaard et al., 2018; Högel, 2017). Furthermore, to elaborate the context specificity of our proposed design principles for hybrid digital manufacturing, further research is needed that considers other types of manufacturing contexts as well as the ability and adaptability of different types of manufacturing resources, including human workers, to provide object-interactive services.

6 | CONCLUSIONS

Until paradigmatic examples emerge, Industry 4.0 remains a vision rather than an operations strategy. In our research, we argue that we are witnessing the emergence of such an example. To explain our observations we introduce a programming analogy where the digitalization of manufacturing is seen from the perspective of syntax. In the object-interactive syntax, the product to be manufactured becomes an important and active solution component of the direct digital manufacturing system. The product is not just processed (acted upon) by the production resources but also controls (interacts with) the production resources.

While the digitalization of manufacturing at Väderstad is still ongoing, the way in which the company has digitalized reveals what can be achieved and how, presenting an operations strategy that other original equipment manufacturers can follow. Based on Väderstad's ongoing implementation of a hybrid digital manufacturing strategy, we have begun to specify operational purposes for implementing an Industry 4.0 vision for equipment manufacturers: In addition to productivity improvements, the object-interactive digitalization of component manufacturing also brings structural benefits of inventory reduction, improved capacity utilization and flexibility, and higher value-added for manufacturers as users/providers of direct digital manufacturing as a service.

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ENDNOTES

[1] We consistently use the term object-interactive, instead of object-oriented because most information systems today use object-oriented programming also when implementing a procedural syntax in the operations.

[2] The technologies include advanced manufacturing technologies (additive manufacturing, laser cutters), robots and automated material handling, advanced analytics (big data, machine learning simulations), cyber-physical systems, augmented reality, and more.

[3] In October 2022 the rate of digitalization was between three and four part numbers a day, depending on whether it is old problematic or new designs that are digitalized.

[4] The kit containers are durable and stable, circulating between component workshops and welding assembly. Substituting the wooden pallets previously used by component suppliers with the circulating kit containers on their own has proven to lead to a significant cost reduction. The containers used for tubes were originally intended to be replaced every 2–3 years, but the original containers are still in use after more than 12 years.

[5] Component replenishments that are controlled by inventory safety stock and reorder point could also be seen as expressions of object-interactive syntax. Here, from the perspective of an object-interactive syntax, it is not the component that is the object, but the inventory location. However, when we focus on the component, the replenishment is to be considered procedural, involving no component interaction or use of digital counterparts for components. This ambiguity of syntax does not complicate combining the syntaxes. On the contrary, as the inventory location acts as a buffer, it simplifies the interaction with component suppliers and facilitates the combination of (1) components produced internally using an object-oriented syntax and (2) external procedurally manufactured components.

[6] For sheet metal part numbers in the Väderstad example, IPR is not perceived to be an issue.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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APPENDIX A

KEY TERMS AND SYNTAX ILLUSTRATION

Manufacturing syntax: How manufacturing is structured and organized as a process. Conventional manufacturing is a form of procedural syntax; digitalization allows for a new syntax based on the use of digital counterparts and object-interactive services.

Direct digital manufacturing, direct digital kitting: These are examples of object-interactive syntax. At Väderstad, they are implemented for supplying tube and sheet metal components to welding assembly.

Hybrid digital manufacturing: This is a novel manufacturing strategy and Väderstad's approach for combining interactive direct digital manufacturing and kitting with conventional manufacturing and warehouse kitting.

Hybrid manufacturing: This is a hybrid solution that, through combination, seeks the benefits of several different manufacturing strategies while avoiding the drawbacks.

Manufacturing as object-interactive service: Digitalized equipment produces a part without setup and tooling as specified by the digital design model and digital counterpart of the components.

Procedural control: This is a form of control that coordinates separate information processing and physical operations using orders, setups, and retooling. It is the basis for a procedural manufacturing syntax.

Object-interactive control: All information needed for manufacturing and handling is provided by the digital counterpart. Information use by manufacturing and handling is object-interactive. All sub-processes, from raw material to ready kit, are digitalized and automated.

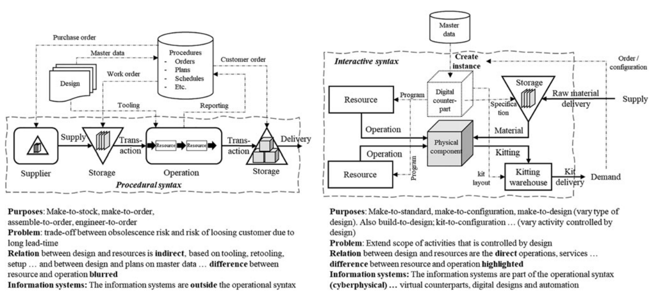
Part number: This is a specified part of a product design. At Väderstad, all components are an instance of a part number.

Component: This is an individual component of a physical product and an instance of a part number.

Digital counterpart: This is the digital part of a physical component, kit, or product. It is the cornerstone of an object-interactive manufacturing syntax, implementing manufacturing as a cyber-physical process. (Digital counterpart is as a concept related to the concept of a digital twin but is usually much simpler than a digital twin.)

Assembly kit: This is a set of components needed for an assembly.

Illustration: Procedural versus object-interactive syntax



APPENDIX B

EFFECTS OF THE DIGITALIZATION OF COMPONENT MANUFACTURING (COMPARISON OF IMPLEMENTATION WITH ALTERNATIVE)

Description	Tube workshop (object-interactive syntax)	Tube alternative (procedural syntax)	Sheet metal workshop (object-interactive syntax)	Sheet metal alternative (procedural syntax)
	Direct digital laser cutting. Automated handling and kitting.	*Batch laser cutting (inhouse), manual handling and warehouse kitting.*	*Direct digital laser cutting, multi-ops, and bending. Automated handling and kitting.*	*Component procurement (external suppliers) and warehousing. Manual handling and warehouse kitting.*
Scope	One hundred percentage of tube volume (1308 parts numbers) delivered to welding assembly (current).		One hundred percentage of sheet metal volume (3000 part numbers) delivered to welding assembly (planned).	
Facilities (m^2)	*Two thousand five hundred square meter in total.*	*Seven thousand five hundred square meter in total.*	*Two thousand two hundred square meter in total.*	*Four thousand square meter in total.*
	Storage for tube raw material (54 articles). Production facilities. Automated kitting facilities (320 kits)	Storage for tube raw material (54 articles). Production facilities for batch manufacturing. Warehousing of tube components (1308 part numbers) + facilities for warehouse kitting.	Storage facilities for 16 articles of sheet metal raw material. Production facilities. Automated kitting facilities for 300 kits of finished sheet metal components.	Warehousing of sheet metal components (3000 part numbers) + facilities for warehouse kitting.
Working capital	One thousand three hundred tons of raw material	One thousand three hundred tons of raw material	Six hundred tons of sheet metal raw material. Seventy-seven tons of kitted and batched sheet metal components.	Three thousand part numbers of sheet metal components, procured in batches.
	Forty tons of kitted tube components	*Eight hundred fifty tons* of batched tube components, *forty tons* of kitted tube components.	*4.4 MSek in total.*	*27.4 MSek in total*
Equipment	*One hundred twenty-five MSek in total.*	*Eighty-three to one hundred MSek in total.*	*One hundred sixty MSek in total.*	*4.5 MSek in total.*
	Three laser cutters, three laser cutting robots, two automated kitting warehouse cranes. Two overhead service cranes. Automated material handling equipment.	Three material handling forklifts for warehouse kitting. Two overhead material handling cranes. Three to four laser cutters.	Two laser cutters, one multi-ops machine, two bending machines, eight material handling robots, one kitting robot, two automated warehouse cranes. One overhead service crane. Automated material handling equipment.	Four material handling forklifts for warehouse kitting and batch handling. Three automated small item storage systems.
Personnel	*Six persons in total.*	*Thirty-seven persons in total.*	*Seven fulltime persons, and one partime purchaser in total.*	*Twenty-five persons in total.*
	Two machine operators working in two shifts. One production technician. One maintenance technician.	Seven warehouse and handling workers and four machine operators working in three shifts. Plus additional management overhead.	Two machine operators in two shifts. Two production technicians. One maintenance technician. One partime purchaser.	Six warehouse and handling workers in three shifts. Two inbound logistics workers and two purchasers.