Editorial

The digitalization of operations and supply chain management: Theoretical and methodological implications

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Abstract

The digitalization of intra- and inter-organizational processes offers significant opportunity for research in the field of Operations and Supply Chain Management (OSCM). This essay summarizes the contributions of the special issue papers, highlighting their focus on additive manufacturing and the encapsulation of design and production information in a digital artifact. We conceptualize the digital artifact as containing the digital genes of the associated physical object. Digital encapsulation thus involves the integration of product design information with additional information on how that design is to be translated into a physical object, delivered to the customer, and used. Building on insights from the special issue papers we identify three pathways by which digital encapsulation affects OSCM practice, as well as theory elaboration and extension. First, digital encapsulation allows each unique digitally encapsulated artifact to be acted on independently by OSCM systems. Second, digital encapsulation enables the redistribution of activities across organizational and geographic landscapes. Third, digital encapsulation facilitates interactivity of the digital artifact with external environment inputs. We conclude with a number of directions for future research.

Keywords: Digitalization; encapsulation; object orientation, operations and supply chain management theory

1 Introduction

The diffusion of digital technologies can manifest as *digitization* (the straightforward replacement of discrete processes or tools with digital analogues) or *digitalization* (the use of digital information to fundamentally revisit intra and inter-organizational decision making, processes, and architectures). In our special-issue call, we invited papers that addressed digitalization, and presented a number of potential avenues for contribution to operations and supply chain management (OSCM) theory. We outline the findings from the papers and provide a theoretical perspective on how they serve as a stepping stone for future research in the OSCM field by situating them in a landscape of merging physical and digital operational environments.

Three research papers and two technical notes comprise the special issue and collectively focus on one specific digital technology: additive manufacturing (AM). Friesike et al. (2019) investigate the emerging practice of design remixing in AM, exploring how a more fluid boundary between product design and manufacturing processes shifts economies of scale from manufacturing to design. Hedenstierna et al. (2019) propose a novel mode of operation for additive manufacturing that facilitates capacity pooling in a network of general-purpose manufacturers. Roscoe et al. (2019) address the challenges of aligning process and organizational architectures as AM capabilities are developed at an aerospace company. Baumers and Holweg (2019) use a series of experiments to investigate the role of scale in AM, while Heinen and Hoberg (2019) explore opportunities created by the digitalization of spare parts and its implications for inventory management and after-sales operations.

In the next section we discuss the contributions of the special issue papers and elaborate on the common theme that emerges: the digital merger of product design and production-process information. This merger exemplifies broader shifts for OSCM enabled by digitalization. We conclude with a discussion of the implications of digitalization for OSCM theory and methods development.

2 Review of the special issue contributions: Digital encapsulation as an emerging theme

A central thread of the papers in the special issue is the bridging of physical and digital spheres that derives from the encapsulation of product design and production-process information into unique digital artifacts: “digital encapsulation.” Digital encapsulation is addressed in all the special issue papers but is particularly salient in Friesike et al. (2019) and Hedenstierna et al. (2019). These papers explore the use of digitally encapsulated artifacts to revisit established design and manufacturing processes, and provide examples of how digital encapsulation can open new avenues for theory elaboration in OSCM.

Encapsulation is a general systems construct that is widely applied in the study of product modularity in the product-design literature, and of object orientation in the information-systems literature. In both the modularity and object-orientation domains, the encapsulation construct involves standard interfaces for interacting with other system elements while permitting modifications within the encapsulated artifact. Digital encapsulation adds the integration of product design and production-process instructions to create a stand-alone digital artifact. The digital artifact owns the information on which the physical object depends, and can define and control that object over its lifecycle (Boyapati et al. 2003; Främling et al. 2007). In its simplest form, such information is limited to production-process instructions; but it can also encompass other OSCM-related information like customer requests, logistics guidance, and product-lifecycle data. The digitally encapsulated artifact can be conceptualized as containing the genes of the associated physical object. These genes define how the artifact interacts with its environment, and how its digitally encapsulated information is expressed in a physical world. This additional characteristic of information ownership and control extends digital encapsulation beyond the traditional application of modularity (Ulrich, 1995).

In the same way that complexity of technical systems can influence organizational knowledge-processing structures (Colfer and Baldwin, 2016; Henderson and Clark, 1990), digital encapsulation similarly alters how knowledge is stored and shared, with implications for organizational governance decisions. In their SI paper, "The micro-foundations of an operational capability in digital manufacturing," Roscoe et al. (2019) observe empirically the knowledge-management challenges presented by AM when it is introduced in an aerospace company. Using a mixed-method approach, the authors develop a knowledge-based framework to explore how structures, processes, and individuals interact to underpin a new operational capability in AM. The organization benefited from an approach that was consensus based yet hierarchical, combining cross-functional teams with centers of excellence.

Collectively, the SI papers highlight the ability of digitally encapsulated artifacts to integrate and store product and process information, to direct lifecycle processes, and to dynamically bridge the demands of the physical world with virtual models and representations. These abilities present three implications for OSCM research: 1) rethinking how activities are organized when digital artifacts are unique and independent (Section 2.1); 2) redistributing activities across value chain actors and geography (Section 2.2); and 3) transitioning from closed to open, interactive systems (Section 2.3).

<< Insert Figure 1 about here >>

2.1 The organization of unique, independent digital artifacts

In "Assessing the potential of additive manufacturing for the provision of spare parts," Heinen and Hoberg (2019) use data from an industrial-equipment manufacturer to examine the potential impact of an incremental switchover of spare parts inventory to additive manufacturing on demand. They find that the encapsulation of design and manufacturing data into a unique digital artifact enables the organization to revisit the role of inventory in high-variety, low-volume settings: Incremental replacement of high-variety, slow-moving spare parts produced via batch manufacturing processes, with on-demand production of parts via additive manufacturing can lead to significant cost savings, without sacrificing customer service. This incremental switchover also raises surprising operational issues, like how to manage warehouses and material-handling systems designed and built for handling large batches rather than individual items.

The advantage of digitalization in spare-parts management reflects a broader opportunity offered by digitally encapsulated artifacts that are unique and independent from other artifacts: the ability to asynchronously organize activities. This characteristic presents the option to organize and execute activities independently for each artifact and the physical object it represents, and where needed, to replicate the resulting efforts across processes. The dependencies in complex production systems that drive sequential execution of processes are no longer binding. Tool-based manufacturing, for example, traditionally separates process design from tooling (Hopkinson et al., 2006). With AM, the product and production-process requirements are reflected in a single digital artifact. Extending digital encapsulation to logistics facilitates asynchronous operation in the supply chain, where digital objects and information on product flow are exchanged between equipment and service providers – often via real-time location systems – to inform needed next steps (Ala-Risku et al., 2010).

Traditional product development and manufacturing engineering activities focus on a product as a class. Even when improvements to product and process designs are executed concurrently, each product of a given type is managed the same way. With digitalization, each unique digital artifact can be translated into an equivalently unique physical object, making feasible continuous design and manufacturing modifications on an object by object basis. This allows for standardization or customization across all products in a class, making the design and manufacturing process for each product amenable to adjustment as new inputs are received.

Heinen and Hoberg (2019) describe how digitalization allows a firm to move away from scale imperatives, while questioning of what scale considerations—if any—are present with digitalization. In their paper titled "The economics of additive manufacturing," Baumers and Holweg (2019) use a series of experiments to assess the relationship between quantity, quality, and cost in an AM setting. They find some indication of conventional economies of scale, but only within a given build and to a point well below maximum utilization because of failure costs. However, with the independence associated with digitally encapsulated artifacts there is no constraint to increased variety within the build as setup costs are for the build, and not the individual products.

2.2 The redistribution of activities across organizations and geography

The paper "Economies of collaboration in build-to-model operations" by Hedenstierna et al. (2019) examines the relationship between Shapeways, a provider of additive manufacturing services, and Panalpina, a logistics service provider. The paper uses an analytical-modeling approach to compare a new build-to-model operation to conventional make to stock and build-to-order operations. The authors seek to understand the effects of introducing build-to-model operations into a network of general-purpose manufacturers. Manufacturers in the network pool capacity through bidirectional outsourcing, alternating roles as outsourcer and subcontractor. Pooling is possible because the AM digital file contains all information necessary to print the physical object. This ability to reallocate work allows manufacturers operating 3D printers to respond better to demand fluctuations without incurring additional capacity cost, generating "economies of collaboration."

Hedenstierna et al. (2019) provide an example of the redistribution of activities across value chain actors caused by digitalization, providing insight into how manufacturing in the presence of digitalization differs from conventional manufacturing. In a conventional context, the pattern of global supply networks and inter-firm relationships has been shaped substantively by the investments of buyer and supplier firms in specialized assets and processes (Williamson, 2008). The efficacy of digital encapsulation is not, however, predicated on the same rigid supply structures, and the very nature of AM means that assets are much more general purpose. Further, as elements of the product and production system are digitalized, processes and decisions that, by necessity, were centralized can now become distributed (Gress and Kalafsky, 2015). The reduced reliance on scale of digital technologies such as AM, further facilitates distributed, small-batch production of a greater variety of components. As a result, significant structural changes of the industrial landscape can emerge, including the redistribution of manufacturing locales, power shifts across the supply chain, disintermediation of key actors, and the entry of new actors.

As the redistribution of work across organizations and geographies reshapes physical OSCM processes, managing the associated information flows will also present new challenges for firms. Digitalized processes generate new streams of information that have value, particularly when they flow across organizational boundaries: Firms may not wish to share this information openly with other external actors. As information is consolidated in digital artifacts, it becomes more difficult to secure, creating new intellectual property risks and potential leakage of firm capabilities. The well-recognized challenges of divergent incentives among supply-chain partners, such as those associated with the sharing and use of demand information (de Treville et al., 2004), will thus likely increase. OSCM theory on relational governance has long considered how to incentivize coordination and cooperation between partners (e.g. Dyer et al., 2018): Digitalization is expected to further fuel theory development in this area.

2.3 Transitioning from closed to open, interactive systems

In the study titled "Creativity and productivity in product design for additive manufacturing," Friesike et al. (2019) study Thingiverse, the open-source maker community, to examine the interactions between designers and users of the designs, in an open-system context. Their analysis of over 200,000 open designs and design improvements for AM examined specifically the degree and mode of re-use improvement. The authors seek to understand the effect of remixing: the process of creating new products based on combinations of existing designs. The paper shows that remixing in AM shifts economies of scale from manufacturing to design, driven by the reuse and incremental improvement of the digitally encapsulated artifact. The study illustrates how digital encapsulation permits a more open, interactive system, and in so doing, highlights the limitations of closed systems, typified by traditional, tool-based manufacturing processes and supply chains.

The tension between OSCM processes based on stable and established inter-organizational interfaces (e.g., to transfer knowledge or manage incentives) and the more open and less deterministic systems centered around digital encapsulation presents substantive opportunities for theory elaboration. For example, as the desire for personalization increases, the capacity of firms to embrace their customers' heterogeneous preferences becomes a focal constraint. Digital encapsulation presents a pathway to open the closed systems on which many firms rely, reducing the associated need for predictability and determinism. By digitally encapsulating the information needed for manufacturing, delivery, and use of the individual product, customers have a greater opportunity to engage not only in product design, but also in process decisions (e.g. Srinivasan et al., 2018). Customer involvement is just one example of the increased scope for interaction in operational decision making and engagement with the external environment permitted by digitalization.

3 Looking Forward

Digitalization provides an opportunity to enrich the field and practice of OSCM. It challenges us as scholars to revisit our theory, and how we approach research in our field. While there are opportunities for new theory development, it is important to recognize that well-established theory can play a crucial role as we seek to understand the implications of digitalization for OSCM. The sharing of digitally encapsulated artifacts offers the opportunity to address issues in conventional high-volume, sequential production (Schonberger and Brown, 2017), while reinforcing traditional OSCM concepts around flow (Schmenner and Swink, 1998; Suri, 1998; Yin et al. 2017). Digitalization, where digitally encapsulated artifacts interface with connected production-control systems, allows real-time information access, empowering the firm to visualize changes in demand and resource availability, and to identify bottlenecks and process variability in a way not previously possible. Such product-process interactions, for example, can support Seru principles, facilitating more rapid and economical reconfiguration of manufacturing assets (Yin et al., 2017).

Although we have described how new forms of intra and inter-organizational exchange may emerge from encapsulation, encapsulation is not a full explanation. Approaches to encapsulation are influenced by a broader set of factors including industry standards, competing interests between suppliers and buyers, trust, and process flexibility. The process changes associated with digitalization have cascading consequences. As managers engage in sensemaking and realign intra and inter-organizational processes and governance, researchers have an opportunity to observe and identify causal factors at work. Digitalization within and across firms will continue to place conventional OSCM systems under stress. The empirical discontinuities and incongruities that manifest as key actors transition to new modes of strategizing, managing, and interacting present rich opportunities for theory elaboration.

3.1 Emerging research directions

A number of the special-issue papers adopt a design-science approach, exploring novel ways of working in real-world settings as a basis for theory development, exemplified by insights on the implications of general-purpose manufacturing for capacity pooling across manufacturing networks (Hedenstierna et al., 2019) and reuse for economies of scale in design (Friesike et al., 2019). The contributions extend beyond proposals for operational practice and toward theoretical insights that serve to strengthen and extend the corpus of OSCM theory (Oliva 2019). Digital encapsulation encourages the use of general-purpose equipment, which has implications for the production-location decision (Schonberger and Brown, 2017; Yin et al., 2017), facilitating outsourcing to localized production centers (Sasson and Johnson, 2016).

The pathways allowed by digital encapsulation represent but a subset of the implications of digitalization for OSCM. When integrated with other technologies such as real-time location systems, cloud-based platforms, or the Internet of Things, digital encapsulation allows each individual product to be modeled, tracked, and controlled. This ability to control an individual product's lifecycle from design to production to use to withdrawal from service facilitates the proactive engagement of firms in designing products for long-term adaptability to evolving customer requirements (Engel et al., 2017). Digital encapsulation in combination with artificial intelligence may facilitate autonomous operation, shifting the role of the decision maker in OSCM. Finally, the encapsulated nature of digital artifacts facilitates the integration of object-oriented processes into OSCM research and practice in a way not previously attainable. In Table 1 we outline some of the many opportunities for further research on the digitalization of OSCM.

<< Insert Table 1 about here >>

3.2 Outlook

Although the SI papers are limited to additive manufacturing, they collectively illustrate the technological, organizational, and societal changes that digitalization is likely to engender. The perspective of digital encapsulation allowed us to highlight the contributions of the SI to OSCM theory: AM exemplifies how new digital technologies provide opportunities to digitally encapsulate key OSCM information for transfer across actors in space and geography, and to permit control of open and interactive systems. This application presents opportunities to revisit firm boundaries, how organizations interact with one another and their customers within the supply chain, and the nature and location of how value is created.

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Figure 1: Pathways enabled by digital encapsulation

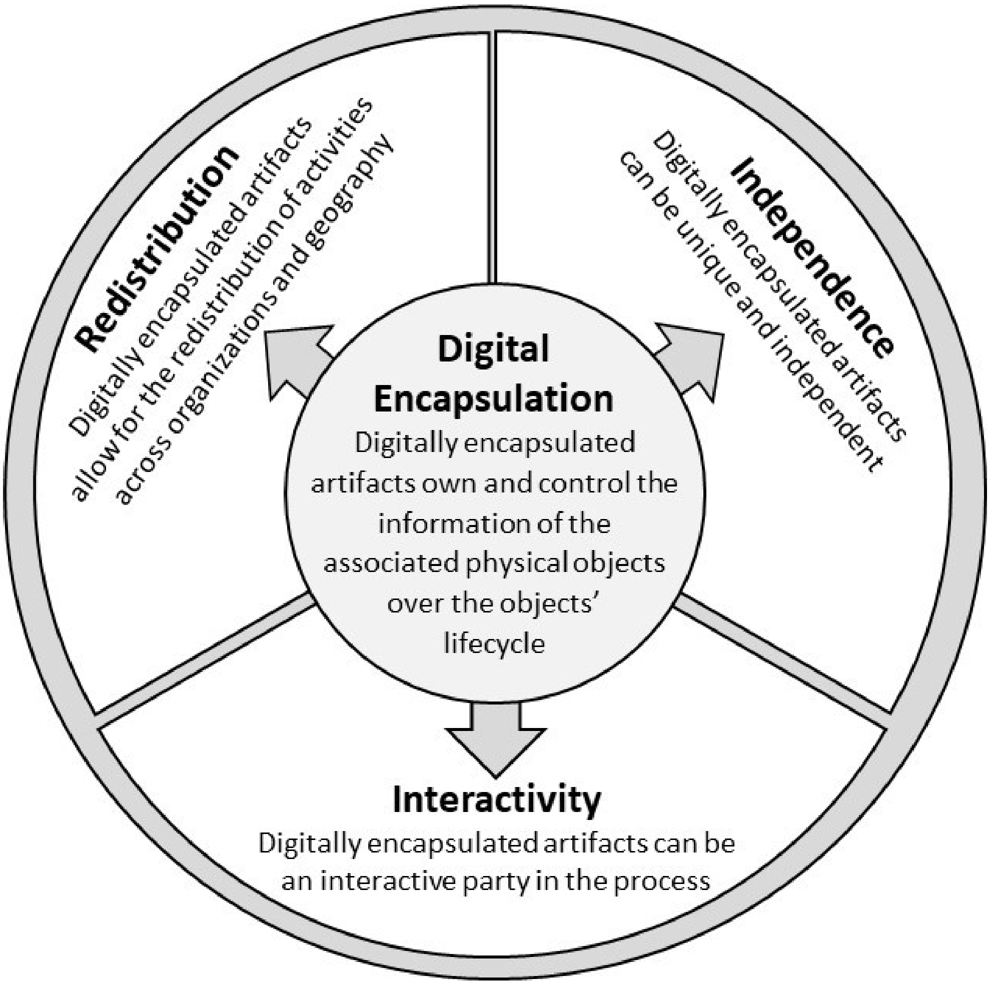

Table 1. Future research questions for the digitalization of OSCM

		Impact on processes over the product life cycle		
		Design	**Manufacturing**	**Delivery and use**
Transformation pathways of digital encapsulation for OSCM	**Independence** Each digitally encapsulated artifact can be unique and acted upon independently of others.	• Will more general purpose manufacturing technology shift economies of scale from maximizing manufacturing asset reuse to design knowledge reuse? (e.g. Friesike et al. 2019) • What happens with the concept of a product generation when individual products can be updated on an ongoing basis?	• What is the role of economies of scale and scope in digitalization of manufacturing as product diversity increases? (e.g. Baumers and Holweg 2019) • What are the implications of handling digitally encapsulated artifacts for core OSCM concepts such as inventory management and lot sizing?	• Does increased autonomy allow for further specialization, but limit value creation/service delivery of supply chain actors? • With increased independence, will specialization of actors and local optima require broader organizational search efforts?
	Redistribution Digitally encapsulated artifacts allow for the redistribution of activities across organizational and geographic landscapes	• How can digitally encapsulated artifacts be used to improve the performance of a community of designers? (e.g. Friesike et al. 2019) • What are the risks associated with the transfer of digitally encapsulated design and manufacturing know-how?	• How can digitally encapsulated artifacts be used to improve performance of the supply chain? (e.g. Hedenstierna et al. 2019) • With the redistribution and restructuring of manufacturing locales, what are the implications for power, disintermediation, and entry points for new players?	• How can digitally encapsulated artifacts be used to support business models for the sharing economy?
	Interactivity The digitally encapsulated artifact can be an interactive party in the process	• What new design practices become feasible? (e.g. Friesike et al. 2019) • Does the inclusion of user experience open up a new avenue for incremental customization?	• How to interface between interactive build-to-model and conventional manufacturing? (e.g. Heinen and Hoberg, 2019)	• How does the interaction between individuals, processes and structures create dynamic capabilities? (e.g. Roscoe et al. 2019) • What are new ways of involving interactive design for product use?