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Sustainability outcomes through direct digital manufacturing-based operational practices: A design theory approach

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ABSTRACT

Direct digital manufacturing (DDM) is a combination of product modeling and manufacturing technology that directly converts digital models to physical objects without the need for tooling. The capability of DDM to improve the sustainability of products and processes is based on changing operational practices in product design, distribution, use, and after-sales services. Although research has provided evidence of the potential impact of DDM technologies, there is limited research on how specific DDM-based operational practices add to the operational capabilities of a manufacturer and how these capabilities can be used to improve sustainability outcomes. To address this research gap, we evaluate how current and future DDM-based operational practices can be used to improve products and processes. The analyzed current practices are in prototyping, tooling, on-demand parts manufacturing, and customized parts manufacturing. Two future practices that are evaluated are DDM-based incremental product improvement and dynamic supply chain reconfiguration.

Based on the evaluation of current and future practices, we propose a design theory for the introduction of DDM into manufacturing firms for improving sustainability capabilities. The key contribution of this article is specifying the mechanisms by which a specific DDM-based operational practice improves sustainability outcomes and how each practice creates an operational practice threshold that needs to be reached before further improvement of capabilities is possible. Thus, using the theory new operational practices can be proactively developed and tested before the next threshold is reached. This in turn will help manufacturers develop strategies and investment plans for current and future DDM-based practices and to accumulate sustainability capabilities faster.

1. Introduction

Gibson et al. (2010a) defined direct digital manufacturing (DDM) as the use of additive manufacturing technologies to manufacture end-use components. DDM is the direct production of physical objects – without tooling – from a design using technologies such as 3D printing and additive manufacturing. Our definition expands DDM to include any combination of product modeling and manufacturing technology that directly converts digital models to physical objects without the need for tooling. DDM is a wider concept than 3D printing (ASTM, 2012), rapid manufacturing (Hopkinson and Dickens, 2001), or additive manufacturing (ASTM, 2012). Thus, DDM is an umbrella term for technologies that convert digital models to physical objects that can be used as prototypes, tools, parts or components, and finished products by different actors in the supply chain. This concept of DDM emphasizes the direct link from design to production rather than specific manufacturing technology. More importantly, the concept allows us to study current applications in prototyping, tooling, low-volume parts manufacturing and customized product manufacturing as distinct, but closely related, operational practices in the supply chain.

Within this context, sustainability capability in manufacturing can be defined as the ability to combine manufacturing practice with operational practices in design, distribution, use, product service, and governance for innovative and marketable combinations of products and services that contribute to sustainability. Such capabilities can be considered mechanisms for achieving sustainability outcomes.

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Despite the many environmental issues that remain to be solved (Drizo and Pegna, 2006; Chen et al., 2015), DDM is expected to enable new operational practices that reduce the need for raw materials (Gao et al., 2015; Chen et al., 2015), replace consumption with prosumption (Kohtala, 2015), and reduce energy in logistics and transportation (Gebler et al., 2014; Chen et al., 2015). Furthermore, on-demand availability of parts and spare parts has been envisioned to enable simplified logistics and extended product lifecycles and to provide different supply chain actors with the opportunity to adopt new roles and innovate sustainable solutions (Holmström and Partanen, 2014; O'Brien, 2014; Mellor et al., 2014; Gao et al., 2015; Weller et al., 2015).

Research on DDM is in a nascent stage, and adoption of 3D printing and additive manufacturing in supply chains is still limited (Mellor et al., 2014). Consequently, research on using DDM to achieve more sustainable outcomes in operational processes and across the supply chain is only just emerging (Chen et al., 2015; Ford and Despeisse, 2016). Chen et al. (2015) provides a valuable contribution to the recent DDM literature by providing an overview of DDM implications for sustainability, as well as a comparative analysis of energy use in production. Furthermore, a research agenda for investigating the potential of 3D printing for the circular economy and its potential contribution to a more sustainable society has been drafted (Despeisse et al., 2016). Ford and Despeisse (2016) analyze the sustainability implications of DDM from the perspectives of product and process redesign, material input processing, make-to-order component and product manufacturing and closed loop supply chain.

However, current research does not distinguish between the operational practices of differing complexity and contexts but instead focuses on the expected outcomes for high levels of DDM adoption (e.g., Weller et al., 2015). The lack of understanding of the benefits of direct manufacturing from digital models limits both DDM practice and future-oriented research. Without understanding potential benefits, the emergent challenges and opportunities of increasing adoption remain obscured. Current research provides examples of sustainability improvements for existing DDM-based operational practices. There is limited theoretical understanding of how current and future practices may indeed lead to improved sustainability outcomes over time.

Crucial aspects remain to be addressed, such as (*i*) which operational practices based on DDM impact sustainability; (*ii*) through which mechanisms do operational practices produce sustainability outcomes; and, from the perspective of providing guidance to manufacturing firms, (*iii*) how can new operational practices be introduced over time and (*iv*) how can long-term investments in DDM be planned to support its introduction. To address these gaps, a design theory approach is adopted in this article to explore how current DDM-based operational practice can be further developed to accumulate sustainability capabilities. The aim is to develop the theoretical understanding needed in the design and implementation of DDM-based operational practices in manufacturing firms and to guide firms in the development of sustainable operations strategies (Liu, 2013; Longoni, 2014).

The critical evaluation method and the CIMO framework of Pawson and Tilley (1997) – describing problems in the context (C) of interventions (I) triggering generative mechanisms (M) producing outcomes (O) - is used to develop design theory regarding how to introduce specific DDM-based operational practices to build sustainability capabilities. The proposed theory specifies how each practice creates an operational practice threshold that needs to be reached before further improvements of sustainability capabilities are possible. The theory builds on the assumption that sustainability capabilities of manufacturing and its supply chains are constrained by the availability of technologies (Skinner, 1996) and the extent that novel technology-based operational practices have already been introduced (David and Wright, 2003; Arthur, 2009).

This article first reviews and analyzes the mechanisms for producing outcomes in current DDM-based operational practice. This is followed by an analysis of increasing adoption of DDM-based operational practices reaching thresholds that create opportunities for innovative new practices. The analyses of current and possible future DDM-based operational practices are then combined to develop a theory of design and action (Holmström et al., 2009), proposing a road map for developing and implementing DDM-based operational practices in manufacturing firms to improve their sustainability capabilities.

2. Current DDM-based operational practice: support for tool-based manufacturing

Currently, a product can rarely be completely manufactured using DDM. Most products also require parts that are produced using tool-based manufacturing. Relying completely on DDM is possible for only a very limited number of materials and types of parts (Holmström et al., 2010). DDM is often economical for low-volume production applications (Gibson et al., 2010a, p. 363), such as for prototypes and tools for conventional manufacturing (Müller et al., 2013; Noble et al., 2014). Thus, DDM is not yet an alternative to tool-based manufacturing but is instead an operational practice that supports tool-based manufacturing.

The DDM-based operational practices currently found in the literature reflect this combination of DDM and tool-based manufacturing. The major types of DDM-based operational practices found in the literature can be described as direct digital prototyping, tooling, parts manufacturing and customization (Wohlers, 2014; Müller et al., 2013; ASTM, 2012; Gibson et al., 2010a). Each of these DDM-based practices is primarily used in combination with conventional tool-based manufacturing (Fig. 1). Therefore, manufacturing companies that invest in direct digital prototyping still use tool-based parts manufacturing for the finished product. Companies adopting the operational practice of direct digital customization directly print only those parts that need customization while relying on tool-based manufacturing for the rest of the product.

Table 1 presents our analysis of the DDM-based operational practices in support of tool-based manufacturing. Such DDM-based operational practices aim to simplify and accelerate activities in tool-based manufacturing and to reduce the need for tooling and set-up in the manufacturing of low-volume spare parts or customized parts for a product.

To analyze how DDM-based practices produce outcomes, the realistic evaluation framework CIMO (Pawson and Tilley, 1997) is used. Following the CIMO framework, DDM-based operational practices in support of tool-based manufacturing are investigated as Interventions (I). For each operational practice, the Problems in Context (C) that are addressed and the Outcomes (O) that result from implementing the practice are specified. In the analysis, outcomes are separated from the addressed problems to better distinguish unanticipated outcomes. The CIMO analysis of current operational practices identifies the Mechanisms (M) for both intended and unanticipated outcomes. By identifying the mechanisms, this realistic evaluation provides a basis for developing a theory that explains how specific operational practices generate outcomes in context. This type of theory in operations management is known as a theory of design and action (Holmström et al., 2009; Gregor and Jones, 2007).